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D4.1

SON functions for multi-layer LTE and multi-RAT networks (first results)

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Abstract: Five promising SON functionalities for future multi-RAT and multi-layer networks have been identified within the SEMAFOUR project, namely, Dynamic Spectrum Allocation and Interference Management, multi-layer LTE / Wi-Fi Traffic Steering (TS), Idle Mode mobility Handling, tackling the problem of High Mobility users and Active/reconfigurable Antenna Systems. This document covers the detailed description of the SON features, the Controllability and Observability analysis as well as initial directions of the SON design for the above-mentioned five use cases. Furthermore, initial performance evaluation in the realistic "Hannover scenario" is provided for the proposed TS SON algorithms.

Keywords: Self-management, Self-optimization, SON, Multi-layer, Multi-RAT, Spectrum Allocation, Traffic steering, High Mobility, Active Antenna, Controllability and Observability

Executive Summary

Self-management and self-optimization will play critical roles in the future evolution of wireless networks. The complexity of future multi-layer / RAT technologies and the pressure to be competitive, e.g. by reducing costs (Operational Expenditure OPEX, Capital Expenditure CAPEX), will be key drivers. The EU FP7 funded project SEMAFOUR (SElf-MAnagement FOr Unified heterogeneous Radio access networks) aims at designing the next SON generation, i.e. a unified self-managed and optimized system for the efficient and holistic operations of a heterogeneous mobile network [1].

One of the key goals of the SEMAFOUR project is the development of multi-RAT / multi-layer SON functions that provide closed loop solutions for the configuration and optimisation of key configuration parameters related to mobility and network resources. In this light, a number of promising use cases for future networks have been identified during the initial phase of the project. The relevance of the selected features has been also verified based on the feedback of the project Advisory Board. The most suitable functions selected for investigation within SEMAFOUR are namely:

- Dynamic Spectrum Allocation and Interference Management (DSA/IM)
- Multi-layer LTE/Wi-Fi Traffic Steering (TS)
- Idle mode mobility handling (IMH)
- Tackling the problem of High Mobility users (HM)
- Active/reconfigurable Antenna Systems (AAS)

This deliverable covers the definitions and the initial studies for the above-mentioned SON functions in the multi-layer LTE scenario (with the exception of the LTE / Wi-Fi TS case). Furthermore, this document includes the first results achieved for the selected SON functions while the final results and multi-RAT aspects will be captured in the subsequent SEMAFOUR deliverables, Deliverable 4.2 ‘SON functions for multi-layer LTE and multi-RAT networks (final results)’, Deliverable 4.3 ‘SON functions for integrated multi-layer and multi-RAT networks’, and public Deliverable 4.4 ‘SON for future networks’.

In the following, specifics of the individual use case studies covered in this deliverable are highlighted.

The ***DSA/IM use case*** studies optimization techniques for spectrum allocation adapted to the spatial and temporal load / bandwidth requirements. The first step was to perform a set of Observability and Controllability (C&O) investigations, with the main target of uncovering the potential of DSA like schemes in typical urban LTE network deployments including macro and micro cells and several frequency layers. The first and most important result from these C&O studies is that in order to properly analyse DSA-like schemes a suitable baseline is required in terms of LTE traffic steering and load balancing. A second finding is that a DSA scheme is likely to be beneficial only when the offered traffic load in the system is within certain lower and upper limits.

Significant effort has been spent in analysing the required traffic steering and load balancing mechanisms, thus this deliverable presents a detailed set of results concerning the C&O study based on which a DSA SON algorithm is proposed. The evaluation of the intra-RAT LTE DSA algorithm studies will be continued and finalized in Deliverable 4.2. The current findings are relevant and will be used further in the inter-RAT DSA studies, i.e. when including the LTE, 3G and / or GSM network layers.

The ***TS use case*** addresses QoS based traffic steering techniques between multi-layer LTE and Wi-Fi networks. Wi-Fi is being used by operators as a complementary technology to offload cellular traffic, and the current trend is to enable Wi-Fi as an integrated piece of operators’ networks. Therefore, intelligent TS between the two access networks is a key technology component. Without traffic steering in place, the Wi-Fi network can easily become congested, thus degrading the user experience and operator service quality. Moreover, both user experience and system efficiency depend on the traffic steering between the two networks. In this deliverable, two closed-loop SON algorithms, Wi-Fi RSS-based and LTE RSRP-based, are proposed and built upon the outcomes of the C&O analysis of the corresponding control parameters, which proved to be effective for network access selection control. The SON algorithms were evaluated by system level simulations in the “Hannover scenario,” an outdoor hot zone scenario with three network layers, i.e. LTE macro as well as densely deployed collocated LTE micros and Wi-Fi APs. Simulation results showed that both SON algorithms can balance the load between the two access networks. For the RSS-based algorithm the throughput analysis is presented, which shows significantly improved user throughput comparing to reference cases of “Wi-Fi if coverage” and TS with fixed RSS thresholds.

The ***IMH use case*** focuses on the optimization of the cell reselection procedure so that the UE always camps on the most appropriate cell. By being camped on a suitable cell, connection times are reduced and subsequent unnecessary handovers once the user becomes active are avoided leading to signalling, packet loss and delay reduction, which may directly affect the QoS for the user and diminish the strain on the network. An intelligent IMH would work as a pro-active load balancing mechanism, similar to Mobility Load Balancing (MLB) or traffic steering. The optimization of the cell reselection procedure could be done either by dynamically adjusting the cell reselection control parameters or by adding extra control parameters and extra complexity in the user equipment. Typically, the MLB and TS schemes focus on the connected mode, where the user is active and radio link failures and call drops may occur. For best results, the traffic steering strategies in both idle and connected mode should be aligned in order to prevent conflicts and maximize gain. However, based on the state-of-the-art and technical review, the predicted magnitude of the IMH gains are marginal. It was therefore decided not to continue to the simulation phase with this use case.

The ***HM use case*** focuses on cases when users tend to make frequent handovers, for example, when there is a dense deployment of small cells or when user velocities are high. This use case focuses on mitigating these frequent handovers and the negative impact that is caused by them both on the user and core network performance. In order to do so the SON function developed in this use case will try to predict the future mobility behaviour of users based on the trajectory that they follow through a cell. By assuming that users that follow similar trajectories through a cell will behave the same in the future a user can be steered more appropriately, resulting in fewer handovers. In this document, a modified version of the Dynamic Time Warping (DTW) algorithm is developed which identifies users that follow similar trajectories through a cell. This algorithm searches for similarities between recent measurements made by active users and measurements that are made by users that were active in the past. Results show that the modified DTW algorithm is able to effectively identify users that follow similar trajectories within certain bounds. As reducing the effects of frequent handovers on the core network is an important part of this use case, a second part of this use case focuses on quantifying these effects. For this, a theoretical model is constructed, which is then used to estimate the overhead and delays that are caused by handovers in the core network.

In the ***AAS use case*** the capabilities of modern active antenna systems are under examination, and more specifically, the effectiveness of Vertical Sectorization (VS) as a densification approach, is evaluated through simulations. The network performance is measured under various conditions in the Controllability & Observability study, revealing the necessity for a SON function to control the VS, in order to obtain densification gains. Two main control parameters were defined for the VS, namely the down-tilt per vertical sector and the transmission power per vertical sector. Moreover, crucial KPIs such as aggregated average, 5^{th} and 10^{th} percentile user throughput, system resource utilization and coverage percentage, were identified, in order to evaluate the performance of the network, and they were monitored on a per network, per cell and per pixel (geographical area of 10 x 10 meters) basis.

The C&O study results indicate that VS can provide significant capacity gains in highly loaded network scenarios, while it is limited by the increased interference created by the increased number of sectors. The performance of VS is very sensitive to the change of the down-tilt of the vertical sectors while not so much to the change of the transmission power per sector. VS performs better when there is a significant difference between the tilts of the inner and outer sectors due to reduced interference. Increased sector down-tilts lead to better user experience (increased throughput), but have a negative impact on the network coverage. Based on the insights gained from the C&O study, an initial direction for the SON algorithm, which will control the activation / de-activation of VS, is proposed. At a second stage, the optimization process for the control parameters will be examined.

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List of Acronyms and Abbreviations

3GPP	3rd Generation Partnership Project
3G	3rd Generation mobile wireless communication system (UMTS, HSPA)
4G	4th Generation mobile wireless communication system (LTE)
AAS	Active Antenna System
ACK	Acknowledgement
AKA	Authentication and Key Agreement
A-MPDU	Aggregation of MAC Protocol Data Unit
ANDSF	Access Network Discovery and Selection Function
ANQP	Access Network Query Protocol
AP	Access Point
ASE	Area Spectral Efficiency
ASN.1	Abstract Syntax Notation One
BSS	Basic Service Set
C&O	Controllability and Observability
CAC	Composite Available Capacity
CB-ICIC	Carrier Based Inter-Cell Interference Coordination
CA	Carrier Aggregation
CAP	Cell Assignment Probabilities
CC	Component Carrier
CDF	Cumulative Distribution Function
CMAS	Commercial Mobile Alert System
CN	Core Network
CPICH	Common Pilot Channel
CRS	Common Reference Signals
DL	DownLink
DSA	Dynamic Spectrum Allocation
DSL	Digital Subscriber Line
DTW	Dynamic Time Warping
DVB-T	Digital Video Broadcasting - Terrestrial
EAP	Extensible Authentication Protocol
eICIC	Evolved Inter-Cell Interference Coordination
eNB	Evolved NodeB
ENIW	Ericsson Network Integrated Wi-Fi
EPC	Evolved Packet Core
E-UTRAN	Evolved UTRAN
FFR	Fractional Frequency Reuse
FTP	File Transfer Protocol
GSM	Global System for Mobile communication
HetNet	Heterogeneous Networks
HO	Handover Optimization
HS2.0	Hotspot 2.0
HSPA	High Speed Packet Access
HSS	Home Subscriber Server
ICIC	Inter-Cell Interference Coordination
IE	Information Element
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IM	Interference Management

IRAT	Inter-RAT
ISMP	Inter System Mobility Policy
ISRP	Inter System Routing Policy
IE	Information Element
IFOM	IP Flow Mobility
KPI	Key Performance Indicator
LA	Link Adaptation
LAN	Local Area Network
LTE	Long Term Evolution
MAC	Medium Access Control
MAPCON	Multiple-Access PDN Connectivity
MDP	Markhov Decision Process
MIMO	Multiple Input Multiple Output
MLB	Mobility Load Balancing
MME	Mobility Management Entity
MRO	Mobility Robustness Optimization
NAI	Network Access Identifier
NAS	Non-Access Stratum
NWMC-TS	Non-weighted multi-criteria TS
OAM	Operation, Administration and Maintenance
OEM	Original Equipment Manufacturer
OHZ	Outdoor Hot Zone
OPEX	OPerational EXpenditure
OS	Operating System
PBCH	Physical Broadcast Channel
PDCCH	Physical Downlink Control Channel
PDN	Packet Data Network
PHY	Physical
PLCP	Physical Layer Convergence Procedure
PLMN	Public Land Mobile Network
PRB	Physical Resource Block
PSS	Primary Synchronisation Signals
QCI	QoS Class Indicator
QoE	Quality of Experience
QoS	Quality of Service
RACH	Random Access Channel
RAN	Radio Access Network
RAS	Re-configurable Antenna System
RAT	Radio Access Technology
RIM	RAN Information Message
RLC	Radio Link Control
RLM	Radio Link Management
RRC	Radio Resource Control
RRM	Radio Resource Management
RSCP	Received Signal Code Power
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
SCTP	Stream Control Transmission Protocol
SC-TS	Single criterion TS

SGW	Serving GateWay
SIB	System Information Block
SIM	Subscriber Identity Module
SINR	Signal to Interference and Noise Ratio
SNR	Signal to Noise Ratio
SON	Self-Organising Network
SSS	Secondary Synchronisation Signals
STA	Station
TA	Tracking Area
TAU	Tracking Area Update
TBD	To Be Discussed
THR	Threshold
TS	Traffic Steering
TTI	Transmission Time Interval
TTT	Time-To-Trigger
UC	User Case
UDP	User Datagram Protocol
UE	User Equipment
UL	UpLink
UMTS	Universal Mobile Telecommunications System
UPER	Unaligned Packet Encoding Rules
USIM	Universal Subscriber Identity Module
UTRA	UMTS Terrestrial Radio Access
UTRAN	UMTS Terrestrial Radio Access Network
VPLMN	Visited Public Land Mobile Network
VS	Vertical Sectorization
WAN	Wide Area Network
WCDMA	Wideband Code Division Multiple Access
WFA	Wi-Fi Alliance
WLAN	Wireless Local Area Network
WMC-TS	Weighted multi-criteria TS

Table of Contents

1 Introduction and Motivation

Self-management and self-optimization will play critical roles in the future evolution of wireless networks. The complexity of future multi-layer / RAT technologies and the pressure to be competitive, e.g. by reducing costs (Operational Expenditure OPEX, Capital Expenditure CAPEX), will be key drivers. The EU FP7 funded project SEMAFOUR (SElf-MAnagement FOr Unified heterogeneous Radio access networks) aims at designing the next SON generation, i.e. a unified self-managed and optimized system for the efficient and holistic operations of a heterogeneous mobile network [1].

One of the key goals of the SEMAFOUR project is the development of multi-RAT/multi-layer SON functions that provide closed loop solutions for the configuration and optimisation of key network parameters related to mobility and network resources. Specifically, the SEMAFOUR Work Package 4 ‘SON for Future Networks’ activity is devoted to the development and validation of new concepts and methods for self-management in multi-RAT and multi-layer networks. The end goal of the activity is to improve the overall network performance, in terms of coverage, capacity and end-user quality, while reducing the operational complexity through increased automation.

A number of promising use cases for future networks have been identified during the initial phase of the project as candidate SON functions to be investigated within WP4 [2]. The relevance of the selected features was also verified with the project Advisory Board (AB) as summarized in the restricted Deliverable 2.3 [3]. The AB consists of six major European operators who were asked to rate the candidate use cases regarding the importance for their organisation and the timeline for a potential implementation in their networks. The list of the selected use cases for future networks, in the scope of the project investigations, comprises:

- Dynamic Spectrum Allocation and Interference Management
- Multi-layer LTE/Wi-Fi Traffic Steering
- Idle Mode mobility Handling
- Tackling the problem of High Mobility users
- Active/reconfigurable Antenna Systems

The Dynamic Spectrum Allocation and Interference Management (DSA/IM) use case studies strategies and solutions for an optimized spectrum allocation and interference management in multi-layer and multi-RAT environments. The Multi-layer LTE/Wi-Fi Traffic Steering (TS) use case, investigates QoS based LTE/Wi-Fi traffic steering techniques in dense urban deployments. The Idle Mode mobility Handling (IMH) use case focuses on the optimization of the cell reselection procedure such that, ideally, the UE always camps on the most appropriate cell. The High Mobility (HM) use case targets the optimization of the handover performance of highly mobile users in case of significant degradation of the UE and network performance. Finally, the Active/reconfigurable Antenna Systems (AAS) use case looks at the optimization of activation / de-activation of antenna configurations such as Vertical Sectorization (VS) in single RAT and multi-RAT context to increase the network capacity.

In the scope of this deliverable, the main focus is to study the selected SON functions applied to multi-layer LTE networks with the exception of the TS case where the inter-RAT scenario, LTE/Wi-Fi, is investigated. Furthermore, this document covers the first results achieved for the above SON functions while the final results and multi-RAT aspects will be captured in subsequent SEMAFOUR deliverables, i.e. D4.2 ‘SON functions for multi-layer LTE and multi-RAT networks (final results)’, D4.3 ‘SON functions for integrated multi-layer and multi-RAT networks’, and finally in the public deliverable D4.4 ‘SON for future networks’.

1.1 Structure of the Document

This deliverable comprises the following technical parts for each SON function under study:

- Descriptions of the SON features are given including the discussion of the objectives, technical gap from academia and industry, main control parameters, and key measurements.
- The basic Controllability and Observability (C&O) studies are documented. Those identify the main control parameters, i.e. the parameters that will be adjusted by the SON algorithm, the

configuration parameters, i.e. the parameters that control the internal algorithm behaviour, and the monitoring KPIs and measurements as basis for the SON algorithm design. The C&O analysis provides insights in the control parameters influence on the network performance KPIs;

- Initial directions for SON design and solutions are documented. The SON algorithm will control the identified set of control parameters based on the selected measurements and monitoring KPIs. The target is to impact the performance KPIs in line with the operator-specified network objectives;
- Initial performance evaluations and behaviour's analysis of the SON algorithms in the adopted SEMAFOUR sub-scenario(s) are provided. This is limited to one of the use cases, specifically TS. For the same use case, preliminary definitions of suitable policies for the SON function are provided. Such policies specify the desired performance tradeoffs and/or targets and thereby steer the control actions of the SON function. For more elaboration on the SEMAFOUR views on the specific policies see SEMAFOUR Deliverable 5.1 [3];
- The C&O analysis and the developed SON algorithms are assessed by means of numerical simulations. For this step, the scenarios and methods developed in SEMAFOUR WP2 "Requirements, Use Cases and Methodologies" are adapted. In particular, the realistic "Hannover Scenario" is defined for system-level simulations within the SEMAFOUR project. Specialised simulation sub-scenarios which reflect the need of the individual use cases are adopted. They differ in terms of, e.g. the geographical area of interest, its size, inhomogeneous user distributions, and deployment of small cells and / or Wi-Fi Access Points (APs).

  It is worth noting that an activity to align the simulators used for the use cases analysis has been carried out in a dedicated calibration scenario in order to obtain consistent results across the project. The detailed calibration activity is planned to be documented in an Appendix of restricted SEMAFOUR Deliverable D2.4 [5]. Achievements and challenges are highlighted within the individual use case chapters; See for instance Section 3.7.3 and 6.7.

This document is organized as follows: Chapter 2 to Chapter 6 document the analysis of each individual use case, DSA/IM, TS, IMH, HM, and AAS respectively, according to the technical aspects described above. Chapter 7 concludes the document with final conclusions and the way forward.

1.2 Definitions and Terminology

This section lists the main definitions and terminology adopted throughout the document.

Multi-RAT (Multi Radio Access Technologies): Within the operator's network several radio access technologies may be present, allowing the users / user equipments (UEs) to change between them. In the context of this deliverable, the LTE / Wi-Fi scenario is considered in case of the TS use case.

Multi-Layer: Within one RAT of an operator's network several base station or cell types may be present, for example, macro cells with several sectors covering a large area, micro / pico cells covering small outdoor or indoor areas with high traffic demand, femto cells for indoor coverage, or cells with different frequencies within one RAT. In the context of this deliverable, mainly LTE macro and micro will be considered in the DSA/IM and TS studies. The definition of those cell types are provided in Table 1.

Cell type	Antenna placement	Maximum transmit power
Macro cells	over the roof-tops	40-46 dBm
Micro cells	below the roof-tops, outdoor	30-40 dBm

Table 1: Definition of LTE cell types

Multi-RAT / Multi-Layer: In some areas an operator may have Multi-RAT network where within some of the RATs several Layers are present. These deployments are sometimes also called Heterogeneous Networks. In the context of this deliverable, a combination of the elements presented above is considered for the TS use case.

Evolved Packet Core (EPC): This is the core network of the LTE system. It is the latest evolution of the 3GPP core network architecture. It is part of the Evolved Packet System (EPS), which is the complete architecture, including the Radio Access Network (RAN) and the EPC.

1.3 References

[1] EU FP7 SEMAFOUR, http://fp7-semafour.eu/en/about-semafour/

[2] EU FP7 SEMAFOUR, 'D2.1 - Definition of self-management use cases,' 2013

[3] EU FP7 SEMAFOUR, 'D2.3 - State-of-the-art in Radio Network Management Feedback from the Advisory Board Members,' 2013

[4] EU FP7 SEMAFOUR, 'D5.1 - Integrated SON Management – Requirements and Basic Concepts,' 2013

[5] EU FP7 SEMAFOUR, 'D2.4 - Reference Scenarios Modelling Methodologies,' 2013

2 Dynamic Spectrum Allocation and Interference Management

2.1 Executive Summary

This document presents the initial studies and results carried out within the Dynamic Spectrum Allocation (DSA) and Interference Management (IM) use case. The first step was to perform a set of Observability and Controllability (C&O) investigations, with the main target of disclosing the potential of DSA like schemes in typical urban LTE network deployments including macro and micro cells and several frequency layers. The first and most important result from these C&O studies was that in order to properly analyse DSA-like schemes a properly selected baseline is required in terms of LTE traffic steering and load balancing. A second finding from these initial investigations is that a DSA scheme is likely to be beneficial only when the offered traffic load in the system is within certain lower and upper limits. Significant effort has been spent in implementing and analysing the required traffic steering and load balancing mechanisms, thus this deliverable presents a detailed set of results concerning the C&O study based on which a DSA SON algorithm is proposed. Therefore, the implementation and evaluation of the intra-RAT LTE DSA algorithm studies will be continued and finalized in the Deliverable D4.2. The current findings are relevant and will be used further in the inter-RAT DSA studies, i.e. when including the LTE, 3G and / or GSM network layers.

2.2 Problem Description and Objectives

To accommodate the growing demand of mobile broadband services, operators have started to employ heterogeneous network deployments, where multiple Radio Access Technologies (RATs) and multiple RAT layers, i.e. macro and small cells (micro, pico or femto cells) are deployed in the same geographical area.

In locations with very high traffic demand, the network is deployed at maximum capacity complementing the macro cells with a number of small cells. The network dimensioning is usually performed based on the offered load in typical busy hour conditions. Therefore, although the deployed carriers are well utilized during peak hours, e.g. day time in university campus or offices, they become underutilised for the rest of the time, e.g. night time. At the same time the traffic demand may intensify in other areas of the network, e.g. in residential areas in the evening, located outside the busy hour high traffic areas.

By means of Dynamic Spectrum Allocation (DSA) the available resources (carriers) will be allocated according to the spatial and temporal traffic requirements by autonomously assigning spectrum to base stations based on the estimated temporal and spatial offered load.

Furthermore, in LTE networks the DSA can be complemented by Interference Management (IM) mechanisms, such as the further / evolved Inter-Cell Interference Coordination (feICIC). Typical outcome of these interference management mechanisms is the (semi-)dynamic assignment of the available resources (time, frequency and / or power) between LTE macro and small-cell layers operating on the same carrier frequency.

The main objective of the SEMAFOUR DSA use case is to investigate the feasibility and impact of utilising the DSA- mechanisms in typical urban network deployments and including multi-layer LTE and multi-RAT operator scenarios. Since DSA&IM have higher potential impact in high traffic areas, the studies will be limited to urban high-traffic areas and to typical busy hour traffic conditions.

Three sub-cases are considered, in time prioritized order:

- **Intra-RAT outdoor (case A)**: Dynamic spectrum allocation within an LTE network across different layers. Only the eNodeBs deployed fully under control of the network operator are considered, i.e. no residential femto cells are included in this case study. This case study is in the scope of SEMAFOUR Deliverable D4.1.
- **Inter-RAT (case B)**: Dynamic spectrum allocation for the multi-layer LTE network including bandwidth re-farming across different 3GPP technologies. This case study is in the scope of the SEMAFOUR Deliverable D4.2 (confidential).

- **Inter-RAT with femto (case C)**: Dynamic spectrum allocation for the same scenario as Inter-RAT (case B) with indoor residential LTE femto cells included. This case study is in the scope of SEMAFOUR Deliverable D4.3.

The above mentioned order of prioritisation is based on the required simulator implementation effort in each stage. The mentioned order will also help to build DSA algorithm in each subsequent deliverable upon the existing DSA mechanisms.

2.2.1 Intra-RAT Outdoor DSA & IM (Case A)

The target of this use case is to identify the conditions under which a DSA (&IM) mechanism could be utilised in heterogeneous network LTE deployments in a dense urban high traffic area. For this purpose, we have selected an initial carrier deployment within the allocated spectrum at a typical European LTE operator, as identified in Table 7 in Deliverable D2.4 (restricted) [7]:

- LTE Macro 800 f1 = 805 – 815 MHz
- LTE Macro 1800 L1 f2 = 1805 – 1815 MHz (primary carrier)
- LTE Macro 1800 L2 f3 = 1815 – 1825 MHz (secondary carrier)
- LTE Micro 1800 f3 = 1815 – 1825 MHz

The frequency layers f1, 805 – 815 MHz, and f2, 1805 – 1815 MHz, are assumed to be always available to all subscribers. Only the frequency layer f3, 1815 – 1825 MHz, is to be controlled by these first DSA studies, as illustrated in Figure 1.

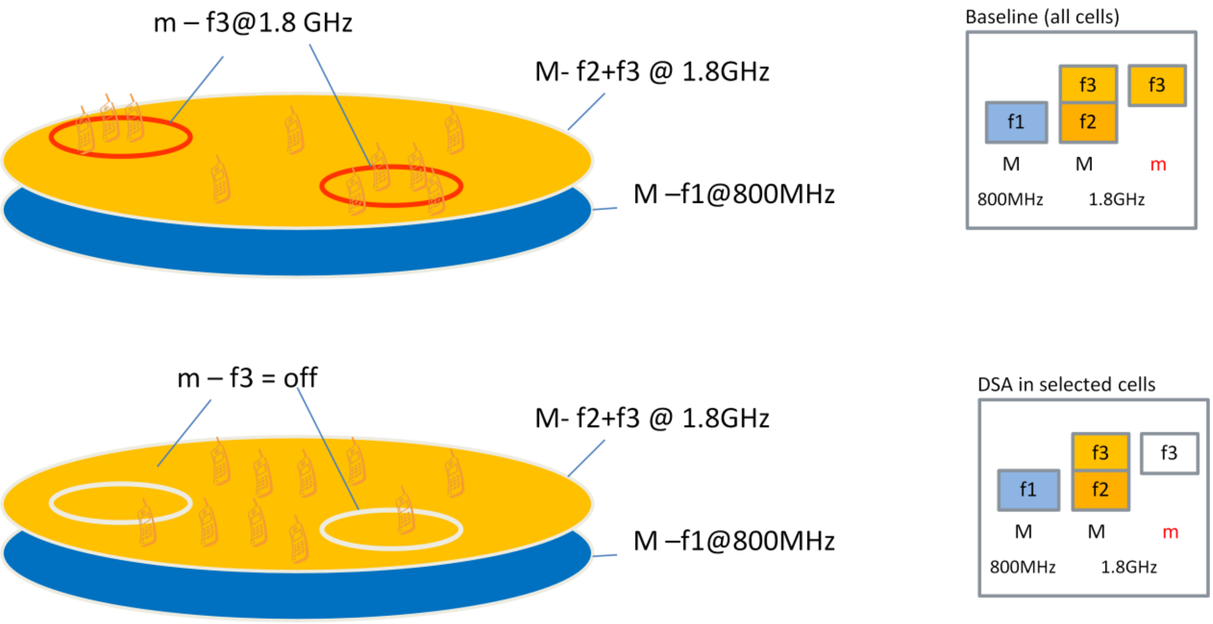

Figure 1: Illustration of DSA mechanism in a macro (M) and micro (m) LTE cell deployment scenario: all available carriers are active (top) and micro cell carrier switched off in selected micro cells (bottom)

The DSA case study is divided into two phases. In the first phase, a Controllability and Observability (C&O) study is carried out in order to disclose the impact of the load distribution on the DSA system performance in terms of a defined set of KPIs. In these studies the performance of the DSA mechanism is evaluated by manually configuring the carriers in the network. A smaller network deployment area is utilised in the C&O studies where UEs and their mobility is explicitly modelled, including basic traffic steering and load balancing algorithms [6]. These are referred to as microscopic simulations, and are described in Section 2.7.2. In the second phase, the automatic DSA is evaluated and a proposal for the intra-RAT DSA SON algorithm is derived. In this second phase the simulations will be carried out for a large geographical area (12 km x 16 km) that covers the entire Hannover scenario [7]. These are referred to as macroscopic simulations, in Section 2.7.1. In the macroscopic studies the UEs and their mobility are not simulated anymore, and the evaluation is done based on pixel level traffic load instead. Just as in the microscopic simulations, basic traffic steering and load balancing mechanisms are considered.

2.3 State-of-the-art

2.3.1 Academic Publications

A number of algorithms and concepts for Dynamic Spectrum Allocation (DSA) and Interference Management (IM) in cellular networks have been developed in the past 15 years. Dynamic spectrum access has been studied extensively in the context of cognitive radio concepts. A good overview discussing and differentiating the different flavours of dynamic spectrum access can be found in [13]. The academic literature on DSA&IM relevant for the corresponding SEMAFOUR use case can be mainly split into the thematic groups "Dynamic Spectrum Allocation for spatial and temporal varying traffic demands" [14]-[23] and "Interference Management and Interference Coordination for heterogeneous networks with focus on femto cells" [24]-[26].

The results in [14]-[16] have been derived in the IST projects DRiVE and its follow up OverDRiVE, which focus on spectrum efficient unicast and multicast services over dynamic multi-radio networks in vehicular environments. The RATs considered in DRiVE and OverDRiVE are UMTS and Digital Video Broadcasting-Terrestrial (DVB-T). In this approach DSA is split into spatial and temporal DSA. The operation of a temporal DSA relies on the assumption that time-varying traffic patterns seen on individual RAN that share the spectrum with other RANs are different across the observed RANs. A pre-requisite for the application of temporal DSA is load prediction. Simulation results for perfect and imperfect load prediction are presented. Both inter-RAT and intra-RAT DSA aspects are considered while developing the DSA-algorithm. Simulations show that DSA has 30% higher spectrum efficiency compared to fixed channel assignment.

Further development of the DSA concept is described in [17]-[21]. The study in [17] analyses DSA algorithm including spectrum bidding, by the participating DVB-T and UMTS systems, that considers inter-related biddings among different cells due to inter-cell interference. Further, [20], [21] illustrates a DSA, again divided in spatial and temporal DSA, where the temporal DSA is coordinated by so called Regional Spectrum Brokers (RSB). The RSB considers interference by geographical and radio technology coupling parameters and solves the spectrum assignment problem using integer linear programming approach. The simulation results in [20] show higher gains (26.15% over fixed assignment) of the RSB combined with integer linear programming than the DSA approach from OverDRiVE (17.65% over fixed assignment). In [18], graph-theoretical DSA models are applied to heterogeneous GSM / CDMA network and tested to both random and realistic network layouts. It is shown that the proposed DSA algorithms scale with large networks and they produce efficient spectrum allocations also when the physical interference is modelled by appropriately choosing the interference region around the base stations. A more general view for the architecture and implementation of this concept is shown in [19]. In [22], Markov chains analytical approach is used to model the DSA process. The results show that there is a break-even point when deploying DSA, which depends on the system load and the relative cost of DSA to the cost per bit of the participating communication systems. In [23], a two-dimensional Markov chain based analysis is presented of a DSA algorithm between wide metropolitan area network (WMAN) and cellular network with simulation results reporting blocking probability and spectrum utilization gains for DSA over fixed spectrum assignment.

In [24] the cell association and interference management for LTE heterogeneous networks (macro overlaps with pico, femto and relay nodes) is addressed. The simulation results show that the deployment of small-cell range extension and fixed partitioning of the spectrum band already provide significant gains when compared to simple frequency re-use of one. Further, an analysis is given for a heuristic distributed algorithm for dynamic sub-band partitioning and user associations complemented by transmit power control. The heuristic algorithm uses light-weight coordination signalling messages between neighbouring (or overlap) cells and provides significant throughput and delay gains over frequency re-use one.

Different fractional frequency re-use (FFR) schemes are investigated in [25] that divide the available spectrum in sub-bands that are re-used differently for cell centre users and cell edge users at the macro layer. Additionally, the different sub-bands are allocated to the small cells depending on their location with respect to the macro cell (i.e. whether the small cell is within or outside the cell centre). The proposed optimal static fractional re-use divides the available macro layer spectrum in seven sub-bands where one sub-band is used in the cell centre areas while the cell edge users are served in frequency re-use six fashion (i.e. effectively having six-sector macro cells). For the small cells a frequency sensing (based on the received signal strength indicator-RSSI) and selection is proposed. This optimal static FFR scheme proved to work best from the simulation results [25] in comparison with the other ‘conventional’ FFR schemes under static load conditions. However, it is indicated that it may not work optimally under dynamic traffic load variation.

A decentralized spectrum allocation strategy for femto cells is proposed in [26] that aim at maximizing the area spectral efficiency (ASE in bps / Hz / km^2) conditioned on a desired throughput per user per macro or femto cell layer. In analogy to the ALOHA principle [27] the authors introduce a random spectrum access scheme for femto cells, which they call Frequency-ALOHA spectrum access. The maximum ASE of the femto cell network is shown to be unchanged with addition of hotspots beyond a threshold. At low femto cell densities, the highest femto cell ASEs is attained when each femto cell accesses the entire available spectrum. In higher densities, femto cells should use a decreasing fraction of the spectrum. Additionally, requirement of equal per-user throughputs in each layer results in assigning greater than 90% of spectrum to the macro cell while an even division of spectrum occurs when femto cells are required to provide significantly higher data rates than the macro cells.

2.3.2 Standardization

The LTE interference mitigation and inter-cell interference coordination (ICIC) activities in 3GPP have started already in Release 8. In particular in RAN3 interference mitigation in heterogeneous network scenarios has been the focus of the Study Item of carrier based ICIC (CB-ICIC) for Release 10-11 [8] [9]. The reasons for introducing CB-ICIC in addition to Release 8 ICIC and R10-11 eICIC are the following:

- Release 8 ICIC is an intra-carrier frequency domain solution that works on a physical resource block (PRB) resolution. However, the disadvantage of the Release 8 ICIC solution is that it only is applicable for data channels, while not being applicable for control channels such as the physical broadcast channel (PBCH), primary synchronisation signal (PSS), secondary synchronisation signal (SSS), physical downlink control channel (PDCCH).
- Enhanced ICIC (eICIC) was introduced in Release10 / 11. eICIC is a downlink time-domain interference coordination solution that requires time-synchronization between the involved cells. In order to harvest the full gain from eICIC, explicit UE support is required for configuration of radio resource management (RRM), radio link management (RLM) and channel state information (CSI) measurement restrictions along with advanced receivers, e.g., including common reference signal (CRS) interference cancellation techniques.

The LTE Release 10-11 CB-ICIC Study Item includes three use cases proposed and reported in 3GPP [10]:

1. OCS: Operational Carrier Selection. The Operational Carrier is the carrier an eNodeB selects to use for its own operation among a list of carriers given by operation, administration and maintenance (OAM). This use case applies to macro and pico scenarios and operates at modest time scales (at least several seconds in case of high interference). Each base station has a Base Carrier (BC) configured by OAM. Depending on the capacity needs a base station may require Additional Carriers (AC) once the interference situation has been checked. This is depicted in the example of Figure 1.
2. Downlink interference management for macro-pico scenarios: This use case refers to the case of optimizing Carrier Aggregation (CA) operation if macro and pico are using two or more carriers; it includes techniques for coordinating cross- component-carrier (CC) scheduling between macro and pico to avoid the PDCCH interference problems. The scope is to have a coordinated

mechanism facilitating for the users on macro and pico to use different carriers as Primary Cell (PCell) for their users (when possible).

3. Uplink interference management for macro-pico scenarios: The scenario considered is when a macro connected UE interferes in uplink with a pico cell, while not being able to detect the pico cell. Both the macro and the pico share at least one carrier. RAN3 has identified the several solutions with RAN1 impact as potential candidate solutions, to enhance uplink interference mitigation, that are based on the principle that identification of the interfering MUE may be needed.

Release 12 is continuing what was started in LTE Release 11 but with the scope of assessing the above issues in RAN1 [9]. More specifically RAN1 evaluates the performance benefits of having interference management on carrier resolution between different eNodeB in the defined heterogeneous network environments [12]. In addition, RAN1 includes also:

- Study inter-node signalling needed for robust autonomous solutions, where each eNodeB node selects to use the carrier(s) that maximize the overall network performance (RAN3).
- Focus on solutions with no physical layer impact that would work for both legacy Release-8 / 9 UEs, as well as benefit from optimizations available for Release-10 / 11 UEs supporting carrier aggregation. Thus the solutions shall rely on existing UE features in different Releases. Realistic assumptions for availability of UE measurements and power consumption are to be used.
- Focus on solutions which do not require tight synchronization between eNodeBs.

The formal decisions regarding the CB / eICIC items to be further investigated and evaluated in the Work Item phase of LTE Release 12 are expected to be taken in the 3GPP RAN plenary meeting in December 2013.

2.3.3 Industry Products and Solutions

Current cellular network deployments do not utilize DSA solutions as illustrated in this use case. However, there are products and solutions in the wireless cellular markets today that pave the way for future DSA deployment. This section briefly describes these related products and solutions.

First, a common practice today at operators deploying GSM networks in 900 MHz band (for coverage) and in 1800 MHz band (for capacity) is to dynamically switch ON and OFF the 1800 MHz capacity cells according to the traffic demand for energy saving purposes, see [27] as one typical example. The control algorithm monitors the GSM traffic level and controls the activation of 1800 MHz capacity layer by switching off the capacity cells when and where the traffic drops below certain pre-defined thresholds (usually at night hours). If the 1800 MHz capacity layer is already deactivated the algorithm continues to monitor the traffic level and if there is a traffic increase activates back the 1800 MHz capacity cells.

Second, there are state of the art base stations provided from all major vendors, see [29]-[32], that are multi-standard (or multi-radio) base stations and support GSM, UMTS, and LTE wireless cellular standards as well as various frequency bands that are defined for these standards. This flexible base station product enables the operators to easily migrate their networks as the traffic and customer population evolves in future. Note that current re-configuration of these base stations is not dynamic but rather static and that it is not always possible to re-configure the base station remotely via a software update.

Finally, one example that is related to the DSA concept is trialled for wireless cellular communications in the public safety domain. The U.S. public safety market is evolving rapidly with the combined introduction of public and private LTE networks. These networks have available spectrum that is often unused. Therefore, a dynamic spectrum arbitrage solution is trialled [33] that allows unused spectrum to be easily reallocated across networks to where it is needed most by combining prioritization of users on the network with a real-time auctioning process.

The traffic monitoring capability, as currently used for the energy saving purpose, can be extended in future by traffic monitoring on several frequency bands and enriched with geographical information. It is expected that further enhanced multi-standard base stations will be provided by the vendors that can be reconfigured remotely and almost real-time. This enhanced traffic monitoring and real-time base station reconfigurations combined with spectrum controlling / arbitrage functions consist of the necessary ingredients for pure DSA implementations in the future.

2.3.4 Summary and Recommendations

The academic publications typically propose complex optimization DSA approaches, which might be difficult to implement in practice. Further, DSA algorithms are proposed without considering feedback control loops to adapt the spectrum allocation when the system conditions are changing (e.g. traffic spatial and temporal characteristic). The evaluations of the DSA performance are not based on real-life configurations in terms of propagation conditions, system bandwidths and granularity, etc. Finally, little attention is given on the interaction and inter-dependence between the DSA and interference management schemes.

SEMAFOUR aims at DSA algorithms that are practical and implementable in heterogeneous 3GPP based networks (in terms of RATs and spectrum bands) without major changes in standards. The envisaged DSA algorithm should react and adapt to the changes in traffic's spatial and temporal characteristics and the study in SEMAFOUR will also evaluate the adaptability and convergence of the designed solution. Finally, the performance of the DSA in SEMAFOUR will be evaluated in realistic propagation scenarios including its inter-relation with interference management schemes as presented in Section 2.3.2.

The standardization effort in the ICIC area shows the impact of modelling the interference cancellation on the network performance. In a study involving dynamically changing the spectrum allocation aspects, it is important to evaluate the best possible outcome from the given set of frequencies before triggering a change in the allocation. Therefore the ICIC mechanisms will be considered for the evaluation in the (confidential) deliverable D4.2, *SON functions for multi-layer LTE and multi-RAT networks,* in SEAMFOUR (D4.2).

2.4 Architecture

DSA-IM functional architecture is represented in Figure 2. Figure 2 is general and applies to all Cases, A, B and C given in Section 2.2. In the following a functional description of the components is given.

The functional block given as DSA in the Figure 2 is the core part and it includes the SON algorithm for switching on and off the capacity layer, which, in the scope of this deliverable is the 1800 f2 layer. Such a SON algorithm will be running on a long time scale and will be dependent on the evaluated KPIs. The KPIs that are used by the SON algorithm are given in Section 2.5.

For a fair evaluation of the DSA&IM use case, additional basic / simple functions, which are not strictly part of DSA itself, need to be implemented. These functions are "Load calculation", and "Traffic Steering". These functions, together with "Interference Management" act on a short time scale as represented in the Figure 2.

A brief description of the components of the functional architecture is given below and more details are provided in the deliverable D2.2 [36].

- **Load Calculation**: The load is evaluated for each cell based on the ratio of the spectrum that is required to serve the offered traffic in the cell and the total available spectrum in the cell.
- **Interference Management** acts between cells sharing the same frequency carrier(s). In this deliverable no explicit interference cancellation is modelled, but it is assumed that interference scales with the cell load. A model for an ICIC scheme will be included in the subsequent confidential deliverable D4.2.
- **Traffic Steering**: In the initial phase of the use case work, presented in this deliverable, traffic steering is done in two steps. At the first level of traffic steering, the cell selection process will be controlled. The initial cell selection only takes the received RSRP values into account (i.e. no traffic steering based on service-application or QoS). In the considered scenario this would crowd the lowest frequency layer (LTE 800). In order to avoid this, the cell selection bias values are introduced. This method is used to steer traffic along the different cell layers (e.g. LTE macro 800, LTE macro 1800, etc.). In the considered scenario co-located cells of the same frequency band, i.e.

LTE macro 1810 and LTE macro 1820, have the same RSRP values towards the user. For that reason a cell selection based on RSRP values is not possible. Therefore, the cell with the lowest load is chosen as serving cell. Co-located cells of the same frequency layer are considered as primary and secondary cells.

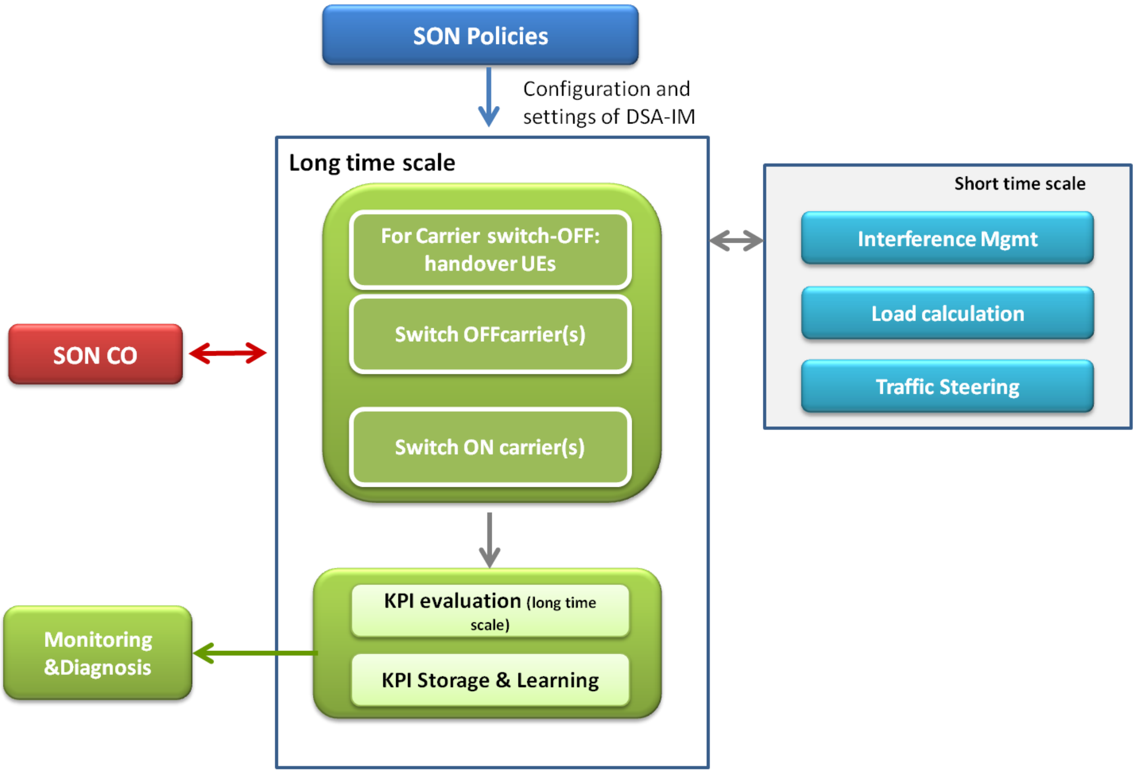

Figure 2: DSAIM SON Functional Architecture

The decisions taken over a long time scale are based on the evaluation of the KPIs that are considered for decision making of the SON algorithms. The KPIs considered for DSA SON algorithm are explained in Section 2.5. Based on these KPIs one can either turn on a new carrier or turn-off an existing carrier. While turning off the existing carrier, it is required to handover the UEs that are connected to the respective carrier in order to ensure that the UE's perceived experience is not compromised during the switching process.

The KPIs that are monitored by the DSA algorithm will also act as inputs to the monitoring and diagnosis functional block. The input and the output parameters are continuously monitored by the SON CO functional block. More details of the SON CO and Monitoring & Diagnosis functional blocks are explained in Integrated SON Management Requirements and Basic Concepts, D5.1.

2.5 Main Monitoring KPIs

The following KPIs are used as input to the SON algorithm:

- **Average cell load:** The average cell load is calculated as the ratio of the number of resource blocks used in a given cell to the total number of resource blocks available in the cell. The average cell load will act as the trigger for the SON algorithm. It gives a fair indication of the requirement or over-availability of the amount of spectrum available to serve the users in the serving region of the cell. A higher average cell load will indicate the requirement of additional spectrum. A lower average cell load will indicate the under usage of the spectrum in the region and therefore a possibility to reduce the spectrum to reduce interference in that frequency in neighbouring cells.
- **Number of unsatisfied users for a given pre-set service data rate:** Any user, who gets lesser data rate than the requested rate for the guaranteed bit rate (GBR) service, is considered

to be an unsatisfied user. The average cell load might hide the details within the time frame where the averaging of load is carried out. The possibility of having bursty user arrivals with constant bit rate service in a small time frame might cause more unsatisfied users. Capturing them in the form of number of unsatisfied users in each averaging period will help the SON algorithm to allocate spectrum also depending on these unsatisfied users.

For DSA performance monitoring, the following KPIs can be used:

- **Average cell load:** See above.
- **Number of unsatisfied users:** See above.
- **Average UE throughput:** In the presence of non-GBR service users, user throughput could be used as a measure of how much the SON algorithm impacts the user performance.
- **Overall network spectral efficiency:** Network spectral efficiency is measured as the number of bits transferred on an average over a unit bandwidth and unit time. The measurement is taken over the entire network as the DSA algorithm in one cell could potentially change interference and load situations in many neighbouring cells.

2.6 Main Control and Configuration Parameters

The control parameters are the parameters that are used by the DSA SON algorithm to make a change in the network. In essence, a SON algorithm would change the states of the control parameters based on the observed KPIs. The major control parameter that will be changed during the operation of DSA SON algorithm is the enabling / disabling of cells.

- **Enable / Disable cells:** The basic control parameter will be the turning-on and turning-off of different cells / carriers based on the evaluated network performance. This is a parameter that will be controlled by the DSA algorithm.

In addition to the control parameter, there are other parameters that affect the functioning of the SON algorithm itself. These parameters will not be the end product of the SON algorithm but the parameters that will impact how the decision making process of the SON algorithm is done. Such parameters used in the DSA algorithm study are listed below.

- **Measurement time interval:** This parameter defines the time between two consecutive iterations of the DSA algorithm. It also defines the duration in which KPIs are computed which are then used as basis for the decisions. This is a parameter that controls the proper functioning of the DSA algorithm.
- **Cell load thresholds:** The cell load thresholds $CellLoad_{activate}$ and $CellLoad_{de-activate}$ are used as parameters to trigger the enabling or the disabling of the cell. These threshold values are compared against the average cell load values measured during a given iteration of the DSA algorithm. The load measurement can be based on the resource block utilization in a given cell. The intention of having cell load thresholds as a control parameter is to explore the possibility of triggering the turning-on and turning-off of different cells at different load values depending on the impact on the KPI values. This is a parameter that controls the proper execution of the DSA algorithm.

2.7 Simulation Modelling and Tools

The simulations for the DSA use case will be carried out in a large geographical area of 12x16 km^2 that covers the entire Hannover scenario. The considered scenario involves 528 cells of which 132 cells operate in 800 MHz frequency band, 195 cells operate in 1810 MHZ and 1820 MHz frequency band. There are also 6 micro cells involved in the university area in the scenario which is depicted as a hotspot. All cells are having a bandwidth of 10 MHz to work with.

The simulations will be explained using two different sets of simulation types, namely macroscopic simulations and microscopic simulations.

In order to make the simulation times more reasonable a macroscopic simulator will be used for simulations on the DSA scenario. In macroscopic simulations no individual UEs will be generated but an average offered traffic is generated from each pixel in the network. All cell KPIs are derived from these traffic intensity maps as well as predicted RSRP and SINR maps. UE KPIs are computed in a post-processing step based on the cell KPIs.

In order to understand the momentary changes in the load and / or user throughput, a detailed simulator is required. For this reason a second simulator has been implemented which models UEs explicitly and with a higher time resolution compared to macroscopic simulations. Due to complexity reasons these simulations are restricted in simulated time and simulated area.

For combined DSA and IM simulations it is planned to run mainly macroscopic simulations. Shortly before and after a DSA step occurred it is planned to zoom in at certain areas and then run microscopic simulations in order to investigate the impact on cell and UE KPIs more detailed and also model IM algorithms. The microscopic simulator is also used in the C&O study for the investigations of different frequency assignments to cells in order to get a detailed view on the impact on cell and UE KPIs.

2.7.1 Macroscopic Simulations

The generated traffic density will be based on traffic intensity maps varying with a time step of 60 minutes [7], i.e. new traffic per pixel values will be available from the traffic intensity maps for every hour. UE mobility is not simulated in these macroscopic DSA simulations.

Each pixel of the traffic intensity map contains averaged offered traffic to the network which is considered to be served by different cells. The traffic distribution in each pixel is computed via so called Cell Assignment Probabilities (CAPs) [34] which are based on predicted RSRP values of the cells. This basic traffic steering mechanism ensures that not only the strongest cell serves all the traffic in a pixel, but rather is distributed over the cells in a realistic way. Additionally, the computation of the CAPs can be manipulated via a Cell Selection Bias [35]. These bias values are subtracted from the RSRP values that are assumed to be measured at the pixel to determine which cell will act as the serving cell for that pixel. By assigning different cell types (e.g. macro 800, macro 1800, micro 1800) with different bias values, the RSRP values and therefore the CAP values of the corresponding cells can be manipulated. The RSRP predictions used for the simulations are not differentiated between the carrier frequencies of 1810 MHz and 1820 MHz, since they are in the same frequency band. Consequently, co-located cells which differ only in the frequency carrier but not in the frequency band are received equally strong at any point in the network. This circumstance requires an additional traffic steering scheme. It is implemented in a way so that UEs are always assigned to the cell (of the co-located cells) with the lowest load.

The macroscopic simulations are not carried out on a TTI time scale and therefore a mechanism for estimating the downlink interference as experienced by the users located in particular pixels needs to be computed. This is based on an iterative process wherein it is initially assumed that all the cells are transmitting all the time and using the full bandwidth. Based on this initial worst case assumption the SINR is calculated for each pixel. Using the SINR values and offered traffic values a cell load is computed. Assuming that the interference power of a cell scales linearly with the cell load, the SINR values are re-computed. The iterative process is stopped if the cell load values for two consecutive iterations do not differ more than 1%.

The cell load values themselves are computed via a scaled truncated Shannon function. Based on this function the required spectrum per pixel and per cell is computed as follows

$$Required\ bandwidth = \begin{cases} 0, & SINR < SINRmin \\ \dfrac{OfferedTraffic}{0.6 * \log_2(1+SINR)}, & SINRmin < SINR < SINRmax \\ \dfrac{OfferedTraffic}{0.6 * \log_2(1+SINRmax)}, & SINR > SINRmax \end{cases}$$

where SINRmin = -6.5 and SINRmax = 19 dB. These boundaries model SINR values where no transmission is possible or the highest modulation and coding scheme might be used.

The quotient of the total required bandwidth of a cell and its available bandwidth is considered to be the cell load, which is capped at 100%.

It is important to note that the possible interference management part between the cells is not considered in this calculation and also not considered in the C&O related simulations. When the interference management schemes are introduced in the future deliverables, the SINR calculations will change as the interfering cell might be muted when the data transmission is on-going in the considered cell, thus experiencing no interference at all. This comes at the cost of loss of resources in the muting cell where the data transmission is not possible. The interference management schemes will be included in the subsequent deliverables.

2.7.2 Microscopic Simulations

For the microscopic simulations, a detailed simulator, in the following referred to as the microscopic simulator, is used. The simulator simulates UE level details and has a time resolution of 100 milliseconds. Due to higher time resolution than in the macroscopic simulations, momentary cell load peaks and / or UE throughput drops that might be overseen in the macroscopic simulations will be captured in the microscopic simulations.

For microscopic simulations UEs are modelled explicitly. They are considered to pop up at the beginning of the simulation and then travel through the network along predefined traces which have been computed prior to the simulations and are available for pedestrian and indoor users. Various KPIs, such as RSRP and SINR values, UE throughputs, cell load and throughput values, are computed and evaluated every 100 ms.

The traffic steering between different frequency layers is done in a slightly different way compared to the macroscopic simulations. In macroscopic simulations CAPs which also include handover probabilities are used to estimate the amount of traffic per pixel which is served by the cells. These probabilities are not needed for the microscopic simulations as UEs are modelled explicitly. UEs get connected to the best server considering the mentioned Cell Selection Bias, i.e. they get connected to the cell with the strongest manipulated RSRP value. For co-located cells the UEs are assigned to the one with the minimum load. The cell load is determined in a similar way as in the macroscopic simulations section.

As UEs travel through the network the RSRP conditions might change which might trigger a handover from one cell to the other. The handover algorithms which are implemented model a 3GPP compliant handover procedure but taking cells of all frequency layers into account, i.e. handovers can be triggered across different frequency layers. The handover algorithm also takes cell individual offset values for the given cell to cell relation into account. Co-located cells of the same frequency band are treated in the same way as the macroscopic simulator. The cell with the lowest load is chosen as target cell.

The amount of resources required by the UEs will amongst other things depend on the scheduler that is being used. Ideally, a scheduler will efficiently allocate the available bandwidth amongst the users connected to the cell. One such way of modelling the distribution of available resources amongst the connected users is given in Figure 3. As shown in the flow chart, total bandwidth used by the cell will depend on the number of users connected to the cell and also on the SINR values experienced by these users. When the computation of bandwidth completes, the final resulting bandwidth will be used for the calculation of the load of the cell. The load is computed as the ratio of the used bandwidth (resulting bandwidth when 'Stop' criterion is reached in the flow chart) to the total available bandwidth.

It is worth noting that during the calculation of the bandwidth, different UEs might get different amount of bandwidth. This allocation of UE specific bandwidth is termed as Effective Bandwidth (BW_{Eff}) and is used for the calculation of the UE level KPIs. The UE throughput is thus calculated using the BW_{Eff} and the Truncated Shannon function as,

$$Throughput = \begin{cases} 0, & SINR < SINRmin \\ 0.6 * \log_2(1 + SINR) * BW_{Eff}, & SINRmin < SINR < SINRmax \\ 0.6 * \log_2(1 + SINRmax) * BW_{Eff}, & SINR > SINRmax \end{cases}$$

where SINRmin = -6.5 dB, SINRmax=19 dB.

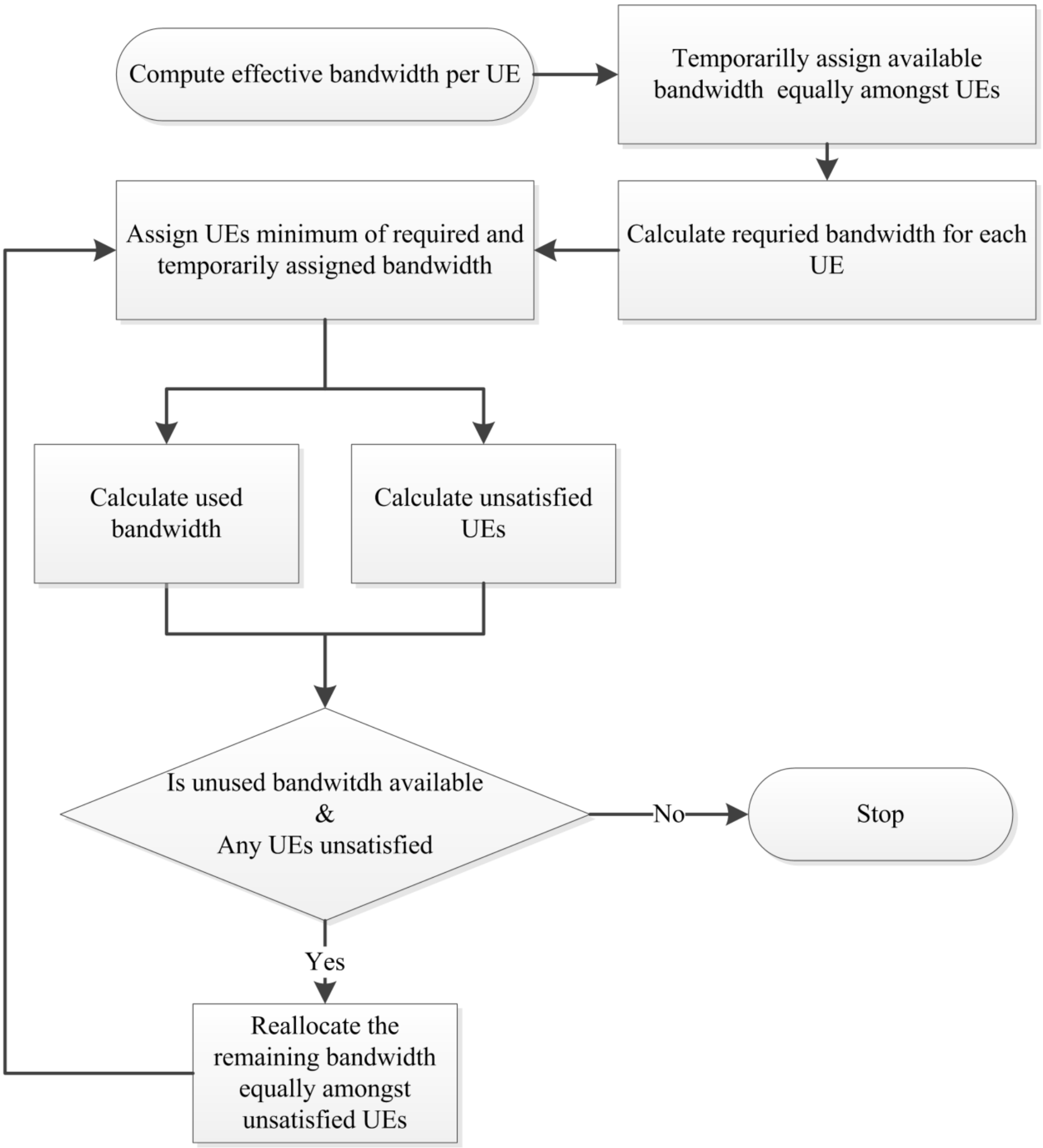

Figure 3: Effective Bandwidth Computation.

2.8 Controllability and Observability (C&O) Analysis

A Controllability and Observability (C&O) study is carried out in order to investigate the impact of changing the control parameters on the measured KPIs. For the C&O study, the microscopic simulator is used to get a deeper understanding of the impact of the controllable parameters to be used in the DSA.

2.8.1 Methodology and Objectives

In the C&O study, the frequency layer 1815-1825 MHz is used dynamically, i.e. either by creating a cell by allocating the 1815-1825 MHz spectrum or by removing an existing cell in the 1815-1825 MHz spectrum. This frequency band can be used by both micro cells and macro cells. The macro cells are also assigned an 1805-1815 MHz frequency layer and / or an 805-815 MHz layer (see Figure 1). The 1805-1815 MHz spectrum cell and the 1815-1825 MHz spectrum cell are always co-located whereas 805-815 MHz spectrum cell need not be collocated with the 1805-1815 MHz cell. The simulation sets as indicated in Table 2 are carried out. In these baselines the 805-815 MHz and 1805-1815 MHz frequency layer is assumed to be turned on at all times. Only the frequency layer of 1815-1825 MHz is assigned / removed as described in the table for macro and micro cells. In the C&O

study, the decisions of assignment / removal as given in Table 2 is carried out for all the cells in the corresponding cell type, i.e. when macro is assigned with 1825-1825 MHz band, all the macro cells are assigned this spectrum. In essence, the individual cell level assignments are not carried out in the C&O analysis.

Simulation set	Macro assignment of 1815-1825 MHz band	Micro assignment of 1815-1825 MHz band
Baseline 1	Yes	No
Baseline 2	No	Yes
Baseline 3	No	No
Baseline 4	Yes	Yes

Table 2 : Simulation sets used for C&O study

The objective of these simulations is to understand the impact of having different frequency layer assignment types in macro and micro cells and understand their impact on the cell load values and user throughputs. It will also serve as an indicator as to when it is beneficial to use each of the different possible simulation settings. All the simulations for the C&O study are carried out using the microscopic simulator.

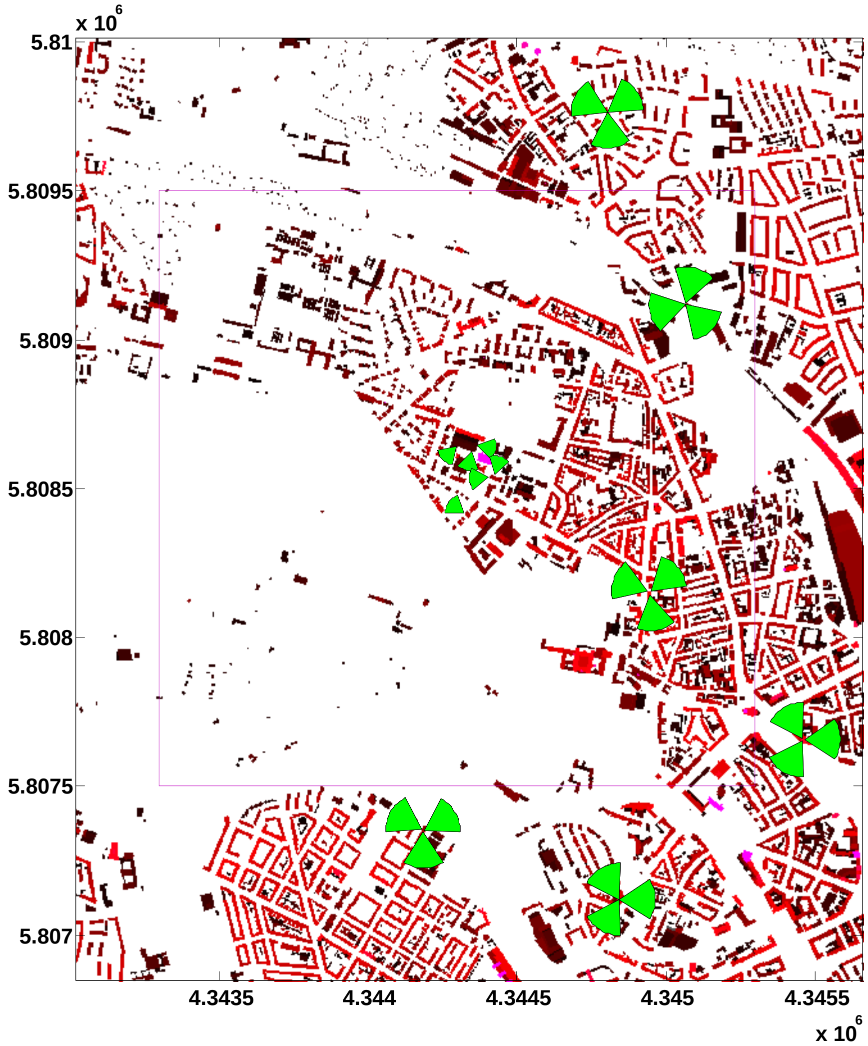

Figure 4: Network Geometry for DSAIM C&O Scenario with Hotspot in Campus Area with micro cells being located in the centre of the figure

2.8.2 C&O Scenario

The scenario that will be considered for the C&O studies is the university campus area. This specific scenario is considered for the C&O study as it poses the challenge of time varying traffic wherein the DSA is expected to give gains. In such a university area, the students will offer a lot of traffic during the day. However, there might be almost no traffic produced in the evening or during night time. The low power nodes (micro cells in the C&O study) are installed at the campus area to satisfy the traffic demands of the students. Figure 4 shows the deployment of six micro cells (located in the centre of the figure) in the campus area (magenta rectangle) and the resulting geometry. The micro cells are used to serve the traffic in the vicinity of the campus. There are also macro cells located inside and outside of the considered area that have the coverage over the whole area.

In microscopic simulations UEs are assumed to travel along predefined traces. The number of UEs / traces and their traffic demand directly impact the offered load in the network and the interference. For the C&O study a set of 414 traces has been chosen that pass through the university campus area. Only the UEs that are in this campus area are evaluated and therefore, the cells that do not have any users connected to them from this region will have zero cell loads. The UEs are considered to be active all the time once they enter the campus area. Furthermore, it is assumed that all the UEs request the same constant bit rate (CBR) service.

2.8.3 Simulation Results

In order to investigate the correlation between available resources, cell load values, SINR and UE throughput values, multiple simulations with different network baselines and different CBRs have been evaluated.

Figure 5 shows the CDF of the UE throughput values for four different network baselines (see Table 2). Here, all the simulated UEs arrive with a CBR download service request of 256 Kbps.

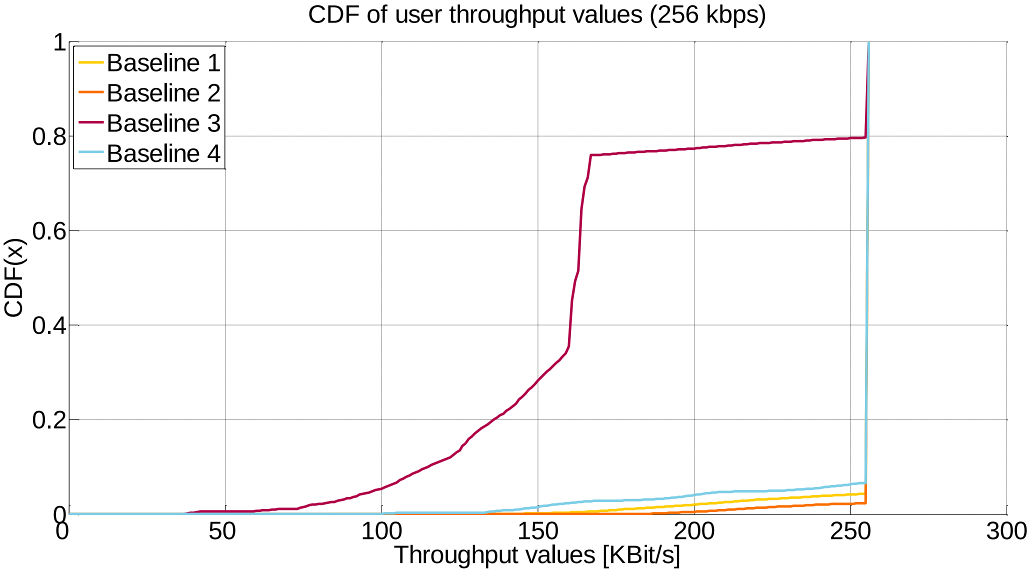

Figure 5: CDF of UE throughput values for a CBR of 256 Kbps

It can be seen that almost all the UEs get their desired bit rate if additional cells are activated. Only for baseline 3 when just macro 800 and macro 1810 cells are activated 75% of the UEs did not get their desired bit rate. However, the curves for network baseline 2, 3 and 4 differ only slightly.

The corresponding cell load values are presented in Figure 6. The figure shows the averaged load values of each cell in the scenario to which users have been connected in any of the simulations. As some of the cells, for example cell index 411 or cell index 437, do not have any users from the university connected to them, they have zero cell load. The four bars per cell correspond to the four network baselines, as indicated by the numbers on top of the bars. Four main colours will indicate the type of cell, i.e. whether it is a macro 800 (purple shade), macro 1810 (blue shade), macro 1820 (green shade) or micro 1820 (red shade) cell. The macro cells in the 1810 MHz and 1820 MHz band are co-located in the deployment and they will have consecutive cell index values in the figure. For example, cell index 317 of 1810 MHz band and cell index 318 of 1820 MHz is co-located. In all the baselines, macro 800 (cell index 18, 99,107) and macro 1810 (cell index 313, 315, 317, 411, 437, 465) cells are turned on. Macro 1820 (cell index 314, 316, 318, 412, 438, 466) cells are turned on for baseline 1 and baseline 4 whereas micro 1820 (cell index 523, 524, 525, 526, 527, 528) cells are turned on for baseline 2 and baseline 4.

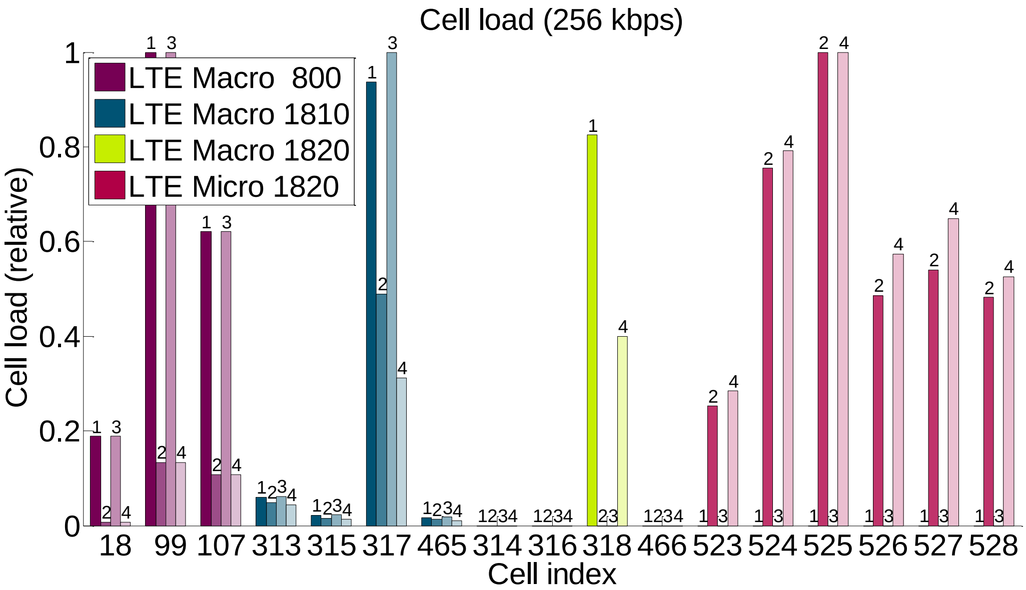

Figure 6: Cell load values for a CBR of 256 Kbps

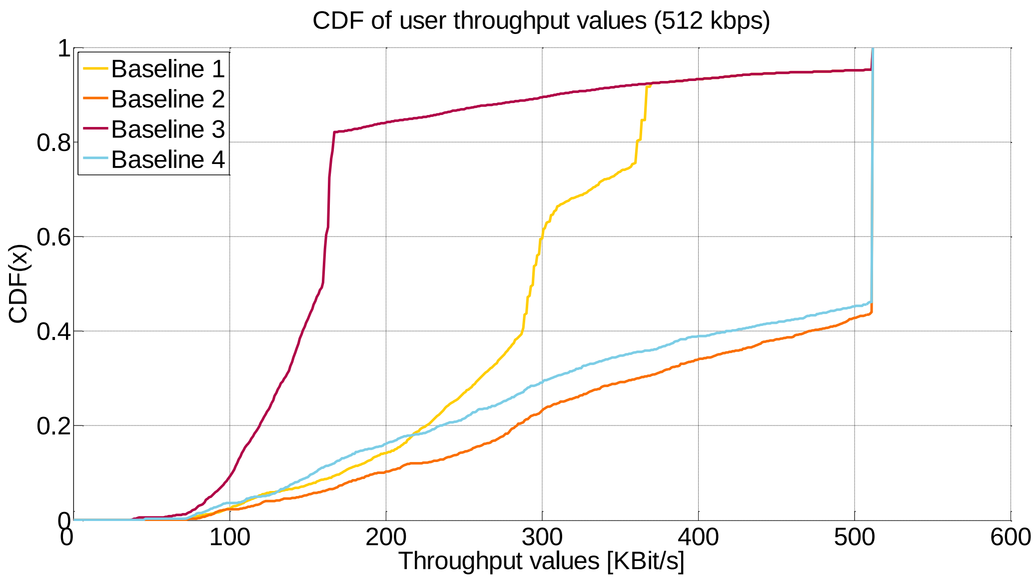

Figure 7: CDF of UE throughput values for a CBR of 512 Kbps

Figure 6 reveals the drawback of the current implementation of the traffic steering scheme. Using only the cell selection bias for different cell types might overload certain cells even though other cells could serve a certain part of the offered traffic. Load balancing algorithms as they might be used already in real networks are therefore of high importance for the performance of DSA algorithms. The implementation of such algorithms is on-going and will be part of the deliverable D4.2.

For higher requested bit rates (512 Kbps), the UE throughput curves differ more significantly as can be seen in Figure 7. With this figure, it becomes apparent that baseline 2 and baseline 4 clearly outperform other baselines but not all the UEs are satisfied in these baselines as well. Also, it is difficult to differentiate between the performance of baseline2 and baseline 4 as they perform equally well. In Figure 8 it can clearly be seen that almost all the available micro cells are overloaded.

A further increase of the bit rate and the overall request for resources reveals an upper bound for the benefit of DSA. Assuming a requested bit rate of 1024 Kbps leads to a severe overload in most of the serving cells, see Figure 9. In Figure 10, it can be clearly seen that the baseline 4 which has all cells being activated clearly outperforms the other network configurations even though the overall SINR situation is the worst, see Figure 11. This is due to the fact that the SINR contributes only in a logarithmic way to the UE throughput values whereas the available bandwidth contributes in a linear way.

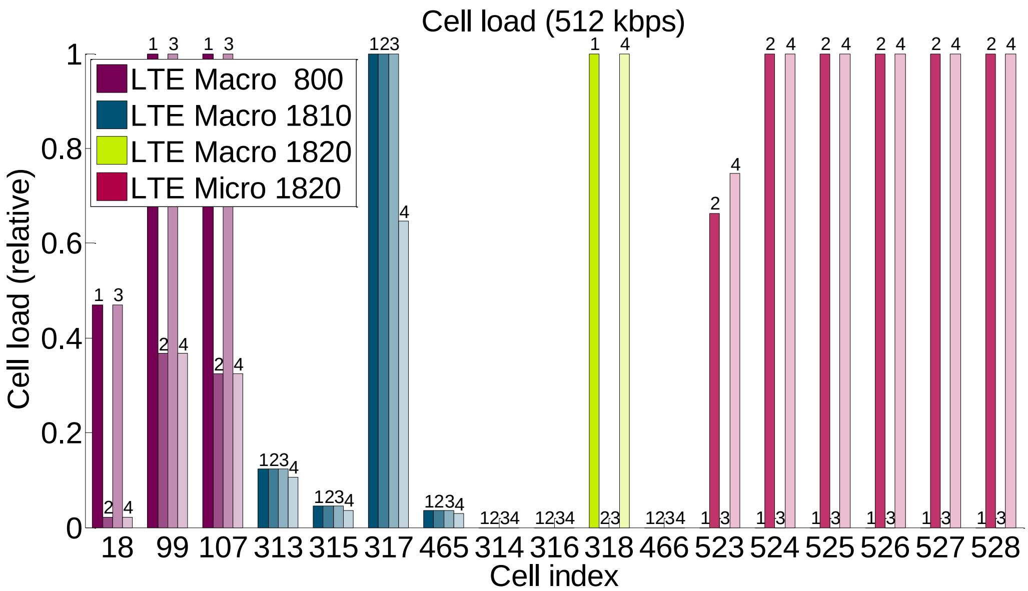

Figure 8: Cell load values for a CBR of 512 Kbps

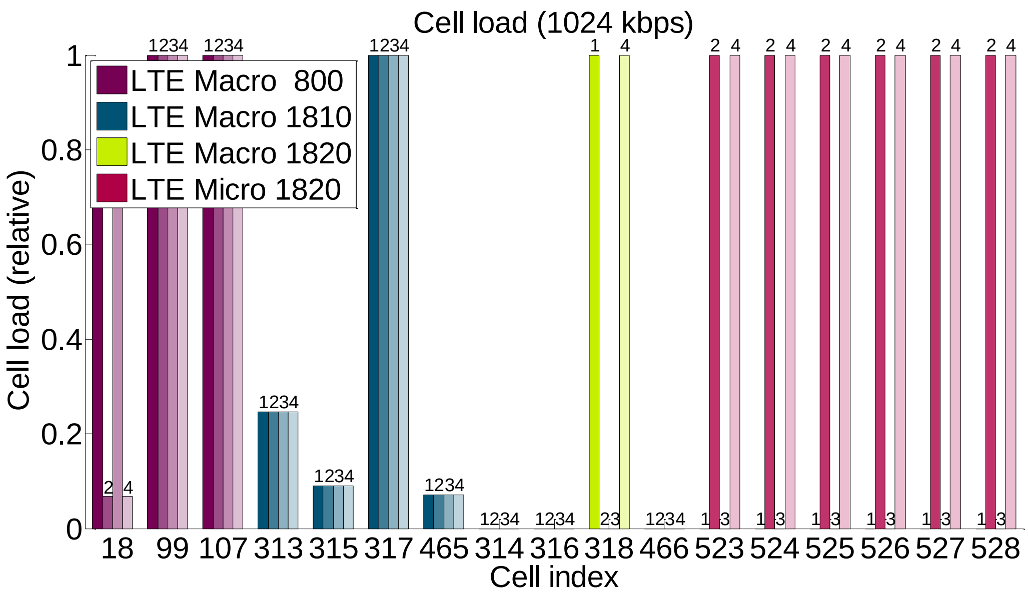

Figure 9: Cell load values for a CBR of 1024 Kbps

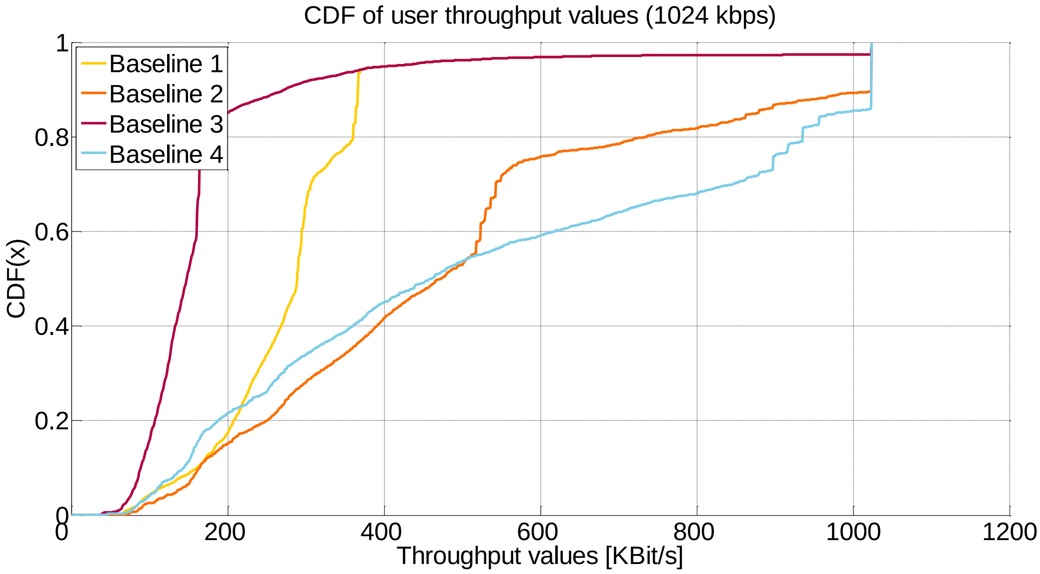

Figure 10: CDF of UE throughput values for a CBR of 1024 Kbps

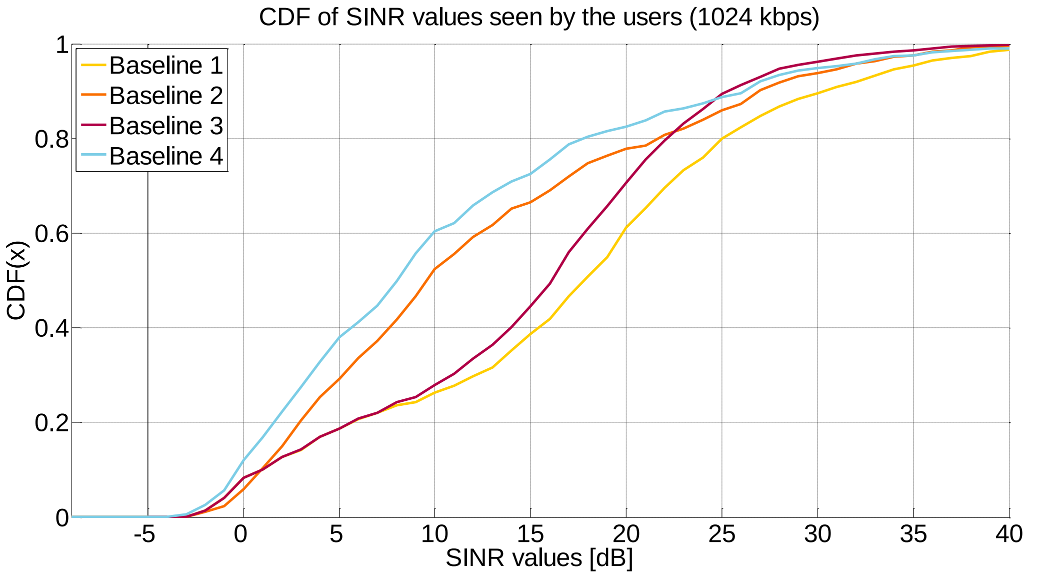

Figure 11: CDF of UE SINR values for a CBR of 1024 Kbps

2.8.4 C&O Analysis Outcome and Way Forward

From the results shown in Section 2.8.3, it is not very clear as to when having the additional spectrum of 1820 MHz in macro cells is beneficial. Both baseline 2 and baseline 4 have very similar performance but for very high loads where the system is already choked and therefore, results could be difficult to interpret. In order to fully understand the impact of DSA a state-of-the-art load balancing algorithm has to be implemented. Especially in situations of high load in which DSA algorithms are assumed to be beneficial, the additional cells might get overloaded. If the UEs are not handed over to less loaded cells, their satisfaction level might be impacted. As UE throughput values and cell load values mainly depend on the SINR a model of ICIC schemes also has to be implemented in order to compute realistic SINR values. Therefore, it is necessary to have a look at the same results with a good load balancing (both intra-frequency and inter-frequency) algorithm and a good implementation of an ICIC mechanism. Having these additional features might help to better understand when to reduce the spectrum to reduce the interference and when to increase the spectrum to reduce the load levels in other frequencies and/or cells.

The C&O analysis also revealed an upper bound in terms of offered load to the network beyond which DSA is not beneficial anymore. If the offered traffic exceeds a certain threshold it is most beneficial to activate as many cells as possible. The additional resources clearly outweigh the raise of the interference. It is important to note that this upper bound is very high and by then the network is already choked with most of the users being unhappy even with the presence of additional spectrum.

2.9 SON Function

The function of the SON algorithm in DSA use case is to automate the activation and de-activation of a carrier in macro / micro cells in order to optimize the network performance. The network performance is measured using the KPIs described in Section 2.5.

2.9.1 SON Algorithm

Based on the results of the C&O study a first proposal for a SON function has been derived. It is important to note that this is just a first proposal and might be enhanced through an iterative process based on simulation results and new insights in the control parameter impacts and the behaviour of the algorithm.

The SON algorithm uses some of the inputs from the network to help assist its decision making. Such input parameters are assumed to be accumulated at the end of each measurement interval and used for the decision making of the algorithm. They will be reset at the beginning of every measurement interval. Currently, only average cell load (computation explained in Section 2.5) is used by the proposed SON algorithm.

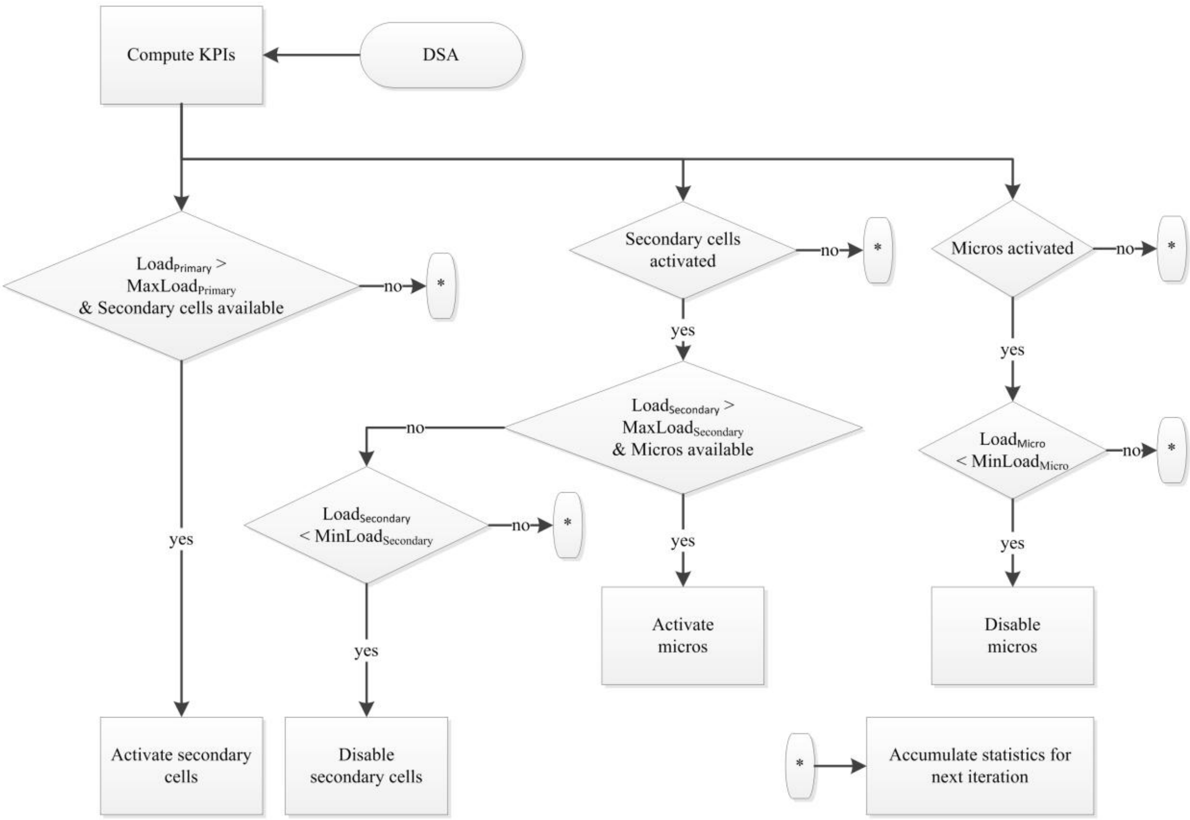

Figure 12: Flowchart of the SON algorithm per cell cluster for DSA use case

It is again important to note that an improved version of the DSA algorithm might use additional values. The above mentioned parameters will initially be accumulated in each cell. However, the SON algorithm acts on cell clusters which represent geographical areas. Consequently, the mentioned parameters are combined (accumulated, averaged, etc. depending on the parameter) and then evaluated for the whole cluster. Furthermore, cell clusters are enabled if the activation condition is fulfilled. This is necessary for example if multiple micro cells reside in the coverage area of a macro cell, as in the investigated C&O scenario. The cluster definition is assumed to be computed in the planning phase of the network or derived from neighbour relations that are utilized for mobility purpose.

The proposed algorithm is illustrated in the flowchart shown in Figure 12. As a starting point, only the average cell load will be used as the KPI in the decision making process of the algorithm. The secondary cells (for example, the macro 1820 MHz cell in the co-located case of macro 1810 MHz cell and macro 1820 MHz cell) are activated when the load in the primary cell (macro 1810 MHz cell) increases above a threshold ($MaxLoad_{Primary}$). When the secondary cell is activated, it will gather the KPIs corresponding to it. The SON algorithm turns-off this frequency layer if it finds that the load in this cell is less than a threshold ($MinLoad_{Secondary}$). The micro cells are activated only when the average cell load in secondary cells will exceed ($MaxLoad_{Secondary}$). These micro cells are turned-off when their average cell load levels drop below ($MinLoad_{Micro}$). In this way the algorithm allocates and removes the spectrum amongst different cells to decrease the impact of varying cell load on the user experience.

2.10 Conclusions, Remarks, and Way Forward

The C&O study investigated different network baselines which represent the extreme case of DSA when a frequency layer is assigned exclusively to all the cells of a network layer or to all possible cells. Based on the results obtained in the C&O study, the following conclusions can be drawn.

- The current simulation results with and without overlapping spectrum between macro and micro cells give very similar performance. Therefore, it is not directly apparent as to when to reduce the spectrum usage in the macro cells so that the micro cells can benefit from the reduced interference and when to add more spectrums in macro layer to satisfy the hungry users in spite of causing more interference to other users in micro cells.
- The current simulation results did not consider the load balancing algorithms across different cells which leads to unnecessarily overloaded cells when other cells can share the traffic volume. Therefore a state-of-the-art load balancing and traffic steering algorithms needs to be implemented in order to fully investigate the potential of DSA benefits.

The limitations of the current simulations will be addressed in the continued work by using a load balancing algorithm and also by taking ICIC modelling into consideration. The load balancing across frequency layers will be given higher priority as it will also help to understand the multi-RAT use case scenarios, thereby justifying the amount of effort being put in to develop a load balancing algorithm. In further work, macroscopic simulations on the big scenario will also be performed, which will be necessary for investigations of the macro cell interference when DSA algorithms are applied.

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3 Multi-layer LTE / Wi-Fi Traffic Steering

3.1 Executive Summary

The mobile networks become increasingly heterogeneous with multiple technologies and multiple layers. Along with this trend, the integration of Wi-Fi and cellular networks has drawn great attention in the telecommunication industry. Without traffic steering in place, the Wi-Fi network can easily become congested, thus degrading the user experience and operator service quality. Both user experience and system efficiency depends on the traffic steering between the two networks. The traffic steering between a multi-layer LTE network and a Wi-Fi network was studied in this use case.

An extensive literature review has identified the need of TS studies in heterogeneous environments with layered network deployment and mixed user profiles. In the first phase of the study presented in this deliverable, two close-loop SON algorithms were proposed based on the outcomes of C&O analysis of two control parameters, i.e. Wi-Fi RSS threshold and LTE RSRP threshold for connecting to Wi-Fi.

The algorithms were evaluated by system level simulations in an outdoor hot zone scenario with three network layers, i.e. LTE macro, and densely deployed co-located LTE micro and Wi-Fi AP. Simulation results showed that the algorithms can balance the load between the two accesses and improve user throughput significantly comparing to reference cases of Wi-Fi if coverage and TS with fixed RSS or RSRP thresholds.

3.2 Problem Description and Objectives

Explosive growth in data traffic with limited availability of new licensed spectrum imposes pressures on operators to seek for technology evolution and unlicensed frequency bands. Most smart phones today are dual mode phones supporting both cellular and Wi-Fi interfaces. Therefore, Wi-Fi has been used by operators as a complementary technology to offload cellular traffic.

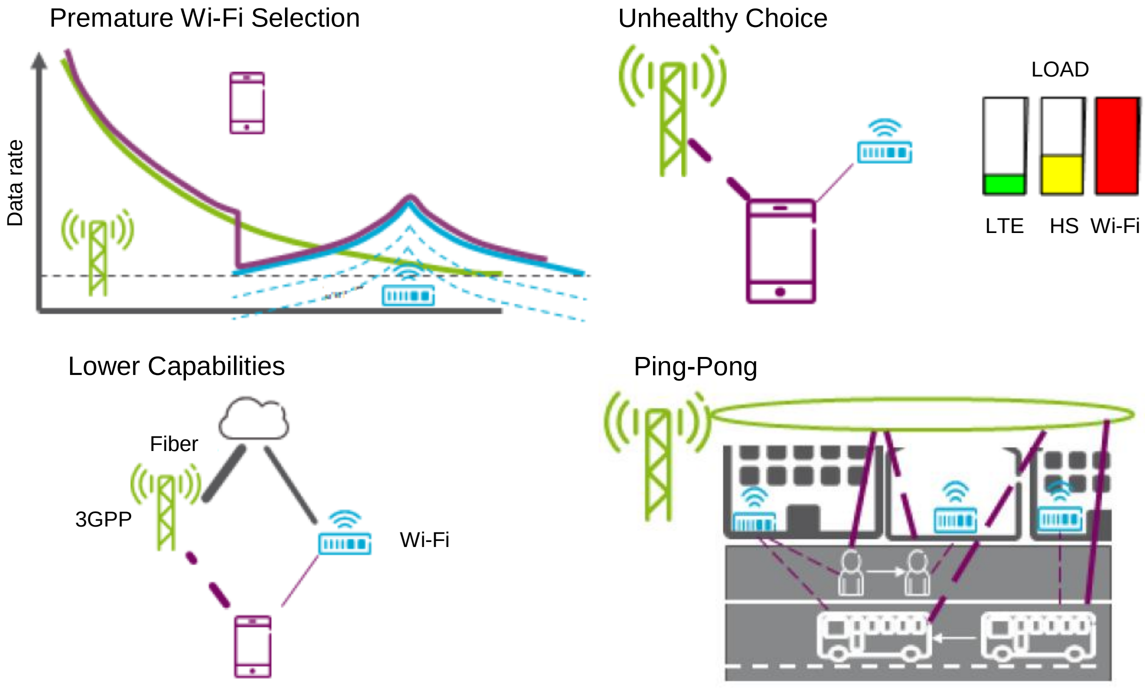

Figure 13: Four key challenges at the Wi-Fi / Cellular boundary (Source: 4G Americas [95])

However, the network selection between the cellular and Wi-Fi networks is usually manually controlled by users and set as connecting to Wi-Fi when available. As depicted in Figure 13, the weak signal strength (Premature Wi-Fi Selection), high load (Unhealthy Choice) and limited capability (Lower Capability) of the Wi-Fi network will degrade end user experience as the user can get better service in the cellular network. Another example of reduced end user experience is due to ping-ponging between Wi-Fi and cellular accesses with user mobility. There are different implementations of network selection and TS from various User Equipment / Operating System / Original Equipment Manufacturer (UE / OS / OEM) vendors that result in different behaviours and inconsistency in the decision making process in devices [95].

With high user expectations in terms of service availability and quality, there is a trend in the telecommunication industry to enable Wi-Fi as an integrated piece of the operators' networks. Intelligent TS between the two access networks is a key technology component to fulfil the target. The future cellular network will be highly heterogeneous with multiple layers that have different coverage range and capability. This makes the multi-RAT TS more challenging since TS solutions have to be able to handle the interworking between Wi-Fi and all the layers in cellular networks.

The Multi-layer LTE / Wi-Fi TS use case targets solutions for QoS based LTE / Wi-Fi TS techniques in dense urban deployments. The integration and management of different network layers, i.e. LTE macro and micro cells, and RATs, i.e. LTE and Wi-Fi, are within the scope of this use case. The overall goal is to improve the end user experience and the network performance via a more efficient utilization of Wi-Fi and cellular network assets while minimizing additional complexity.

In the first phase of the study presented in this deliverable, the objective is to understand the gap between the state-of-the-art and the SEMAFOUR targets, propose SON solutions based on the analysis, evaluate the SON solutions through simulation studies, and identify research directions for the next phase of the use case.

3.3 State-of-the-art

This section gives an overview of the state-of-the-art in TS between LTE and Wi-Fi and some related topics. Both solutions from the academic world as from standardization bodies are discussed. A summary of the gap between the state-of-the-art and the research targets of the SEMAFOUR project is given in the end of this section.

3.3.1 Academic Publications

Algorithms for TS between multiple technologies including LTE and Wi-Fi have been considered in the academic literature in the past years. Algorithms differ from each other by the goals that are pursued by steering the traffic and the criteria and metrics they take as input for the RAT selection decision making. Based on the number of criteria[1]exploited, TS algorithms are categorized into three groups and summarized below.

Single criterion TS (SC-TS) algorithms ([38] [67] [68] [84]): They are based solely on comparison of parameters with a specific threshold or relative comparison of two quantities at a given time instant. One example is choosing the RAN whose signal strength is larger than a pre-specified threshold, e.g. connect to Wi-Fi in case UE measures $RSS_{Wi\text{-}Fi} > RSS_{threshold}$.

Given simplicity as an advantage of the SC-TS algorithms, they usually cannot deliver optimum performance and might result in system instability, e.g. Ping-Pong handovers.

Non-weighted multi-criteria TS (NWMC-TS) algorithms ([42] [43] [44] [62] [68] [76]): Multi-criteria refers to extension of the single criterion by the introduction of additional criteria and / or auxiliary parameters such as hysteresis, time-to-trigger (TTT), averaging interval. The 'non-weighted' approach assumes 'equal importance' of all considered criteria / parameters.

In [62], both the handover initiation and decision taking depend on the available data rate of the Wi-Fi and LTE networks. From the performance evaluation of the algorithm it is learnt that the proposed algorithm, combined with a TTT mechanism, improves the capacity of both the LTE and Wi-Fi networks.

[1] *Criteria* refer to a function used to trigger specific TS behaviour, e.g. comparison of two measured values.

The NWMC-TS algorithms achieve better stability and / or effectiveness in improving system and user performance with a price of additional number of measurements and control sequences.

Weighted multi-criteria TS (WMC-TS) ([45] [46] [47] [48] [52] [58] [59]): In this case, a utility function is created in which various arguments play a role, e.g.: network load, achievable user / cell throughput, resource consumption costs, price per unit of data, QoS etc. In addition, the importance of each of these arguments might individually be weighted to best reflect user and / or operator preferences. A UE will connect to the RAN that maximizes the utility function.

In [52], the goal is to distribute load and SNR among the available RATs, even when the system load is not heavy. Both the bandwidth requested by the user, the load status of the different RATs and user preference to a particular RAT are taken into account by the algorithm. Simulation of the algorithm shows that it improves the utilisation of the radio resources of the RATs and reduces the call blocking probability. In [58], a network selection algorithm is proposed which takes the quality of experience (QoE) perceived by the user into account. The steering algorithm proposed in [59] aims to minimise the number of unsatisfied users in the network by moving unsatisfied users from LTE eNBs to less loaded eNBs, Wi-Fi access points or LTE femto cells. Simulation results from both the studies show a significant performance boost in network resource utilisation and user experience when employing the algorithm.

The superior performance of the WMC-TS algorithms come with a cost of high complexity.

Most papers focus on showing the benefits of TS through RAT selection, without considering the multi-layer heterogeneity of future LTE networks. In addition, most papers have some kind of 'uniformity' in the considered user population (e.g., all users are static or all users are mobile, all users generate the same type of traffic implying that all users have the same type of QoS requirements, etc.). So, further developments on TS algorithms that take the multi-layer heterogeneity of future LTE networks and the diversity of users into account are needed.

Several important aspects in the design of TS algorithms are extracted from the papers.

- Relative comparison of RANs operating in different frequency bands based solely on measured signal strengths is not recommended as this may lead to false alarms for cell congestion situations.
- Stability of TS decisions is essential in avoiding false alarms and ‘Ping-Pong’ effects. Averaging of measurements over certain time interval and / or comparison of measured values with an absolute threshold can be introduced to increase system stability.
- Identification of a good balance between algorithm complexity and accuracy is required. This should prevent network overload by measurement and control sequences.

In Appendix A.1, a more detailed summary of the references mentioned above can be found. Also other TS related publications (not necessarily considering both LTE and Wi-Fi or containing algorithms) are considered in this appendix.

In Appendix A.2, the categorization of TS algorithms is further elaborated.

3.3.2 Standardization

3.3.2.1 3GPP Specification

Several interworking solutions between 3GPP and Wi-Fi are available in the 3GPP core network. In particular, Wi-Fi interworking with Evolved Packet Core (EPC) is defined in 3GPP Release-8 [71], [72]. Release-8 requires that all user traffic is carried over a single radio interface at any given time, i.e. either over LTE or Wi-Fi networks. Release-10 introduces the UE functionality of simultaneous connections to both access networks [73]. Multiple Connections via 3GPP and non-3GPP access (MAPCON) allows offloading control at Packet Data Network (PDN) granularity. Alternatively, UEs capable of IP Flow Mobility (IFOM) may establish a single PDN connection via multiple access networks.

Today, typically, policies pre-provisioned statically in the UE, determine how different radio accesses shall be used by the UE. 3GPP Release-8 has specified, and enhanced in subsequent releases, an advanced policy control to assist UEs to perform network discovery and selection more dynamically. A UE supporting Access Network Discovery and Selection Function (ANDSF) [71], [72], can receive access network discovery information, i.e. the list of access networks available in the vicinity of the UE, and the policies listed below:

- Inter System Mobility Policies (ISMPs), Release-8: Information about operator preferences for routing all user traffic over Wi-Fi or cellular access;
- Inter System Routing Policies (ISRPs), Release-10: Information about operator's preferences for routing of individual PDN connections (MAPCON) or IP flows (IFOM and non-seamless Wi-Fi offload) over Wi-Fi or cellular access.

Note that non-seamless Wi-Fi offload is the most basic interworking solution. The traffic is not routed through the operator's core network and there is no service continuity when the UE moves out of Wi-Fi coverage.

Currently, there are several on-going Wi-Fi related work and study items. Worth to mention is the Release-12 Wi-Fi / 3GPP Radio interworking study item [78] which is investigating RAN level enhancements for Wi-Fi interworking. The target of the study item is to evaluate LTE-Wi-Fi and UTRA-Wi-Fi interworking procedures in order to enhance the interworking with better user experience, more operator control and better access network utilization. At the time of writing, the solution direction(s) preferred within this study item is still uncertain.

3.3.2.2 Wi-Fi Alliance

Wi-Fi Alliance (WFA) is an organization that certifies IEEE 802.11-compliant products based on certain standards of interoperability. One recent WFA certification is Wi-Fi CERTIFIED Passpoint™ which incorporates technologies from the WFA Hotspot 2.0 specifications. Hotspot 2.0 (HS2.0) focuses on improving Wi-Fi hotspot user experience with seamless and secure Wi-Fi connectivity.

HS2.0 is emerging in a series of releases, the first of which was completed in June 2012 [81]. Release 1 features are based on existing IETF / IEEE specifications with WFA modifications, many of which facilitate interworking between 3GPP and Wi-Fi networks. The standardized Extensible Authentication Protocol (EAP) methods for GSM Subscriber Identity Module (SIM) and UMTS Authentication and Key Agreement (AKA) provide seamless authentication for SIM / USIM devices which increases user confidence and ease in using Wi-Fi and drives traffic onto Wi-Fi networks. To enable network discovery and selection, a modified set of Information Elements (IEs) are available to devices through Access Network Query Protocol (ANQP) based on IEEE 802.11u specifications. The IEs include 3GPP Cellular Network Info, Wide Area Network (WAN) Metrics as an indicator of backhaul load, etc. Besides, Basic Service Set (BSS) load indicating air channel utilization and stations attached is broadcasted as a beacon element. These ANQP and beacon information elements are available in Passpoint™ certified devices.

HS2.0 Release 2 is expected to be finalized in Dec 2013. It supports immediate account provisioning for online signup of non-subscription users. And a standardized operator policy interface to devices is defined to give operator ability to control consistent operation of all devices. The specification is not publicly available at the time of writing.

3.3.2.3 IEEE 802.11

The IEEE 802.11 specification family provides basis for implementing Wi-Fi communication. The specifications standardize PHY and MAC layer protocols for Wi-Fi. After the first IEEE 802.11 standard in 1997, a number of amendments have been released specifying enhancement and operation details for Wi-Fi [81], among which the most relevant ones are listed in Table 3. It should be noticed that the IEEE 802.11 specifications are recommendations to industry and usually only a subset of the specifications are supported by products in market. To improve interoperability, WFA has launched a series of certification for the industry as described in Section 3.3.2.2.

IEEE 802.11 Standard / Amendments	Description
802.11-2012 802.11a/b/g/n/ac*/ad	PHY / MAC specifications * Only draft is available
802.11e	QoS enhancements
802.11u	Improvements related to authentication, network discovery and selection

Table 3: List of IEEE 802.11 standard and amendments

3.3.3 Industry Products and Solutions

The telecommunication industry has started working on 3GPP / Wi-Fi interworking and has released white papers [95] [96] [97] and several proprietary solutions exist to enable more intelligent offloading to Wi-Fi such as NSN Smart Wi-Fi Connectivity [92], Ericsson Network Integrated Wi-Fi (ENIW) [93] and Qualcomm's Connectivity Engine [94]. TS between the two systems is on the roadmap of the products from these companies, but there is a clear need to have better understanding on the topic to design and improve the solutions.

Meanwhile, the companies are building up patent portfolios to strengthen their positions in this area. Most patents are related to the measurements and procedures that enable the steering of UEs from one system to another. But the intelligence in the steering decision is rarely covered by patents and subject to investigation.

More advanced TS solutions will be available in market in the years to come, and outcomes from the SEMAFOUR project are expected to contribute to these future solutions.

3.3.4 Summary and Recommendations

Most multi-RAT TS studies in academia focus on the TS algorithm investigation with homogeneous deployment, i.e. macro cellular cells only, and with a uniform user profile for all simulated users in terms of mobility and / or QoS requirements. So the developments on TS algorithms that take the multi-layer heterogeneity of future LTE networks and the diversity of users into account are needed. Furthermore, very few close-loop SON solutions have been proposed. The standardization bodies started putting efforts in supporting TS between cellular and Wi-Fi accesses but without sufficient knowledge about the performance of different potential solutions. The telecommunication industry has realized the need of intelligent TS features and is looking for optimum solutions. The objective of this UC fills in the gap between the academia state-of-the-art and the need from the industry well.

3.4 Architecture

The 3GPP Wi-Fi TS architecture is covered in detail in the SEMAFOUR Deliverable 2.2 [98], both in terms of functional and non-functional aspects. Figure 14 illustrates a simplified view of the functional blocks which constitute the closed loop TS SON function. In the following, Section 3.5 and 3.6 define the monitoring KPIs and control parameters which are chosen for investigation in this deliverable and are analysed in the results Section 3.8 and 3.10, respectively.

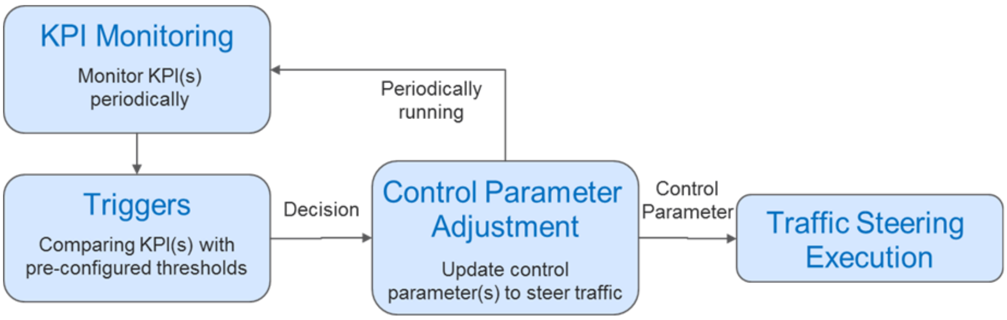

Figure 14: Simplified Flow-chart of the Closed loop TS SON function

3.5 Main Monitoring KPIs

Different types of monitoring KPIs could be used as feedback information to influence the steering of users between LTE cells and Wi-Fi APs. The most relevant measurements could be grouped in three main categories: load level KPIs, cell / node wise performance KPIs and UE performance KPIs.

The load measurements can be used to estimate whether a sufficient amount of bandwidth / resources are available to establish, or maintain a particular traffic type. The measurements can be performed per radio access technology, specific cell / access point, QCI / QoS class or at a given rate, and may require averaging to smooth instantaneous peaks.

Measurements which reflect the cell / node wise performance can be used to predict the satisfaction of established and new traffic types in terms of, e.g. the percentage of UEs for which the average throughput / transfer delay is above / below a particular threshold.

The UE performance category includes all those measurements that reflect, on a per UE basis, the connection quality such as, e.g. average throughput / transfer delay, page download time or actual BLER. They can be used for instance to trigger actions to improve the performance of the established connections.

Note that the measurements can be derived for a given time interval (hundreds of milliseconds, minutes, hours, etc.) and could be measured per radio access technology, LTE / Wi-Fi.

In the next section we will describe the KPIs used in this deliverable.

3.5.1 Adopted Monitoring KPIs

In both LTE and Wi-Fi networks the resource utilization is adopted as main monitoring KPIs in the C&O and SON studies illustrated in the results sections, Section 3.8 and 3.9. The definitions of the adopted load level measurements, representing the resource utilization, are defined in the following. For further details on the KPIs, for instance about their averaging, please consult Section 3.9.

In LTE the adopted load information are alike the standardized load information exchange, transferred over the X2 interface between neighbour cells, as follows:

- **LTE radio Resource utilization (Res):** This metric indicates the percentage of physical resource blocks (PRBs) utilization [75] in a cell. The measure is an effective load measure with certain traffic type assumptions, e.g. finite buffer file downloading in this study. Limitation of this measure comes with full buffer users. As an extreme case, a single resource-hungry non-guaranteed bit rate user may consume 100% of the physical resources within the measured period leading to Res = 100% during such period.
- **LTE Cell Utilisation (CU):** This metric is based on the Composite Available Capacity (CAC) [78] measure, that is, the amount of available PRBs in a cell accounting for the satisfaction of the existing users, control channel utilization and non-radio limitations such as backhaul as well. In this study, only radio resources are assumed limited and thus the CU is determined as the fraction of required PRBs of the total available in a LTE cell in order to serve all connected UEs with a certain minimum bit rate.

In Wi-Fi, the selected resource utilization metrics are based on fields of the BSS Load Element specified by the IEEE standard [80] and certified by the Hotspot 2.0 Specification [81]:

- **AP channel busyness:** The resource utilization of an AP is given as the percentage of channel busy time. The channel is considered as busy if there is at least one active connection associated to the AP and the AP or a station (STA) is transmitting or attempts to transmit. The measure is similar to the *Res* in LTE and the analysis on the *Res* presented earlier in this section applies to the AP channel busyness as well.
- **AP station count:** This metric is the number of stations currently associated with the AP. Although this metric does not necessarily reflect the total traffic (Mbps) served by the Wi-Fi access point, it has been observed that the achievable UE throughput decreases quadratically with the number of UEs served [63] [64]. Thus ‘high load’ in terms of number of UEs served is always equivalent to low achievable UE throughput; hence, the offloading to Wi-Fi is not desirable.

The KPI selection for this deliverable was determined based on considerations on the performance impact and complexity, i.e. high impact and limited complexity are desired. However, those measures have limitations as for instance may not account for a minimum UE satisfaction level when reaching a certain resource utilization level. As possible extensions, some of other KPIs, e.g. 5^{th} percentile and average UE throughput could be used as well either as individual criteria or utility functions that combine more than one KPI.

3.6 Main Control and Configuration Parameters

This section describes the most relevant control parameters which are adjusted by the TS functionality and the configuration parameters that can be used to internally control the TS functionality affecting its behaviour. Using these parameters, an operator can define allowed levels and thresholds that trigger specific algorithm behaviours and control the offloading / onloading towards Wi-Fi / LTE. The objective of the SON algorithm will then be to self-configure and self-optimize the selected control parameters. In the following the parameters adopted in this deliverable are defined.

3.6.1 Use of UE Measurements

The UE measurements of interest in this deliverable reflect the channel quality experienced by a UE as listed below:

- **LTE Reference Signal Received power (RSRP)** as defined in 3GPP [74].
- **Wi-Fi Radio Received Signal Strength Indicator (RSSI)** as defined by IEEE 802[85]. Note that the RSSI is actually an arbitrary integer value mapped internally in the UE to the signal strength in dBm. However, for simplicity we will assume it as an RSS measure. Nevertheless, alternatively, all the presented mechanisms could use the RSSI measure instead.

The control parameters selected for the studies in this deliverable are the related thresholds, i.e. the RSRP and RSS thresholds. Those thresholds define the level of the UE measurement at which specific TS behaviour occur. E.g. offloading to Wi-Fi will target UEs with UE measurement above or below a given threshold. The SON TS algorithm will change those thresholds in order to reach the optimization target.

Other relevant UE measurements which are used as configuration parameters are the range of the RSRP and RSS thresholds and the thresholds step-up / step-down size, i.e. the step increase / decrease applied to the measurement when TS conditions apply.

3.6.2 Configuration Parameters

The thresholds related to the load levels can change the algorithm behaviour and belong to the configuration parameter category. Examples of those are the low / high utilization thresholds for LTE and Wi-Fi (e.g. THR_{L-L}, THR_{L-W}, $THR_{H-L,}$, THR_{H-W} in Section 3.9.1) which define the minimum / maximum load level at which a cell should operate in order to avoid underutilization / congestion issues such as QoS disruption.

Additional parameters that could be considered for their impact on the SON algorithm are listed in the table below together with their descriptions.

Parameter name	Description
Observation period	This parameter defines the rate at which a monitoring KPI is evaluated and TS actions may take place.
Load observation period	This parameter defines the rate at which the load measurement is collected.
Load filtering factor	This parameter defines the filtering factor applied to the load measurements.

Table 4: List of miscellaneous configuration parameters

3.7 Simulation Modelling and Tools

3.7.1 System Modelling Assumption

The LTE system modelling is fully compliant with the 3GPP Release 8 specifications. The system has 20 MHz bandwidth at 1.8 GHz. A macro layer and a micro layer operate at the same frequency band with transmission power of 46 dBm and 33 dBm, respectively. The antenna configuration is 2x2 MIMO. Proportional fair scheduling is used in simulations.

The Wi-Fi system modelling is based on the 802.11n PHY / MAC specifications [85] [86] with 20 MHz bandwidth and 3 channels at 2.4 GHz. The transmission power is 20 dBm. The antenna configuration is 2x2 MIMO. The enhanced MAC features of 802 .11 n, i.e. Aggregation of MAC Protocol Data Unit (A-MPDU) and block acknowledgement (ACK) [86], are disabled in the first phase of the simulations presented in this deliverable. These two features can reduce transmission overhead and improve system efficiency and will be enabled in the next phase of the study. A detailed modelling assumption summary including a RSS to physical data rate table can be found in Appendix A.3.

3.7.2 Simulators Description

Two system level simulators are used to evaluate the TS SON algorithms. Both tools are capable of running dynamic multi-RAT simulation, and differ in the level of modelling abstraction. The same system modelling assumptions are configured in the simulators, and a dedicated calibration procedure has been performed between them. Therefore, consolidated conclusions can be drawn with strong confidence based on simulation results from the two tools.

As pointed out in Section 3.3, LTE and Wi-Fi TS is a research area with multiple potential technical solutions that are subject to investigation. The solutions need to be studied in different environments, e.g. indoor and outdoor, and scenarios, e.g. co-located and standalone APs. Given the scope of the topic, the project will benefit from the use of the two simulators which enhance the capability of TS studies in both the breadth and the depth.

3.7.2.1 Simulator I: Layered Radio Network Simulator

Simulator I is a java-based layered radio network simulator developed by Ericsson. The simulator is designed for modelling the radio network and protocol layers for different RATs. For the LTE system, PHY, MAC and RLC layers are simulated with detailed RRM and LA modelling on a per TTI basis. For the Wi-Fi system, PHY, PLCP and MAC layers are simulated with carrier sensing, packet collision and LA explicitly modelled. Handover within each network and cross networks is implemented based on signal strength or other specified criteria. In a higher protocol layer, IP packets are generated with application options including FTP downloading / uploading, web browsing and VoIP.

3.7.2.2 Simulator II: Dynamic System Level Simulator

Simulator II is a Matlab-based dynamic system level simulator developed by NSN. The tool models the user mobility and mobility management procedures in high detail. For instance it computes standard-compliant UE measurements of, e.g. RSRP and RSRQ, measurement events and reports including averaging, errors, and quantization aspects [74]. Detailed RRM functionalities, such as link adaptation and packet scheduling, are replaced by higher level modelling, e.g. analytical mapping curves and abstract assumptions, e.g. the system operates at the average BLER target. The above applies to both radio access technologies, LTE and Wi-Fi. As a note, the interference modelling has been addressed in detail in the following reference [77]. The Wi-Fi MAC modelling is based on references [63]-[65]. The tool is suitable for SON studies such as TS, load balancing, mobility enhancements, etc. thanks to its reasonable runtime which is faster than real-time.

3.7.3 Simulators Calibration

A calibration activity has been carried out to align the two simulators described above. Two separate calibrations have been performed for the LTE and the Wi-Fi layers, respectively. The same calibration scenarios have been imported to the simulators and a number of user-level KPIs have been evaluated.

Perfect alignment in serving cell selection and received signal power and very close SINR has been achieved. Static users and full buffer traffic model has been utilized. The detailed calibration activity are planned to be documented in an appendix of restricted SEMAFOUR Deliverable D2.4, and achievements and challenges are highlighted in this section.

Perfect alignment in serving cell selection and received signal power and very close SINR have been achieved. The difference in individual user throughput is within a range of ±20% between the two simulators in the LTE layer, and a similar level of alignment is achieved in 75% of the APs in the Wi-Fi layer. For users served by the other 25% of the APs the user throughput difference is more than 50%. The reason resides in the different ways of the Wi-Fi system modelling, and an analysis is given in Appendix A.3.2. It should be noticed that the full buffer traffic assumption in the calibration is a worst case scenario in terms of user throughput difference. Furthermore, as the analysis shows the difference only appears in the cases where several APs share the same Wi-Fi channel and interfere with each other. In bursty traffic conditions (such as the finite buffer studies in this deliverable) the Wi-Fi performance improves and the interference coupling between APs is expected to have less impact on the achieved TS and SON results. Similarly, for future analysis at 5 GHz where much more number of channels is available, the difference between the results from the two simulators will be further reduced or eliminated.

In case of LTE throughput the results included in this deliverable show significant differences despite the good LTE calibration results mentioned above. Nevertheless, the observed trends in the results in terms of 5th percentiles and average throughput versus the RSS / RSRP threshold settings are very similar. Unfortunately, in the time-frame of this deliverable it was not possible to achieve a better calibration between the simulators. Therefore, at this stage the presented TS C&O and SON results generated with the different simulations tools cannot be compared directly.

3.8 Controllability and Observability (C&O) Analysis

3.8.1 Methodology and Objectives

The objectives of these C&O studies are to identify the main LTE and / or Wi-Fi traffic steering parameters and their impact on the system level performance. The studies were conducted in the simulation environments described in Section 3.7.2. A simplified network traffic scenario with static UEs (no mobility), downlink finite buffer traffic only and no advanced intra-LTE traffic steering mechanisms included (like eICIC) was used. The studied network deployment included LTE macro layer, outdoor LTE micro layer and outdoor Wi-Fi layer with access points co-located with the LTE micro cells according to the description in Section 3.8.2. Three types of LTE / Wi-Fi traffic steering mechanisms have been investigated, depending on the set of parameters which control the traffic offloading to / from Wi-Fi:

1. **RSS-based**: One RSS threshold, *RSS_thr*, is applied to determine which UEs are connected to the Wi-Fi layer following the rule:

   IF RSS > RSS_thr, THEN

   UE served on Wi-Fi (3-1)

   ELSE

   UE served on LTE

2. **RSRP&RSS-based**: One RSRP threshold, *RSRP_thr*, in combination with one RSS threshold, *RSS_th*, are applied to determine which UEs are connected to the Wi-Fi layer, following the rule:

   IF RSRP < RSRP_thr AND RSS > RSS_thr, THEN

   UE served on Wi-Fi *(3-2)*

ELSE

UE served on LTE

3. **RSRP-based:** Two RSRP threshold parameters *RSRP_thr_low* and *RSRP_thr_high* in combination with one RSS *minimum connectivity* threshold, *RSS_min*, are used to determine which UEs are connected to the Wi-Fi layer, following the rules:

UE in a co-located LTE / Wi-Fi cell:

IF RSRP > *RSRP_thr_high* AND RSS > *RSS_min*, THEN (3-3)

UE served on Wi-Fi

ELSE

UE served on LTE

UE in a non-co-located LTE / Wi-Fi cell:

IF RSRP < *RSRP_thr_low* AND RSS > *RSS_min*, THEN (3-4)

UE served on Wi-Fi

ELSE

UE served on LTE

In the traffic steering mechanisms #1 and #2 the RSS threshold parameter, *RSS_thr*, is used to control the coverage area of the Wi-Fi and is set to values equal or above the minimum sensitivity level for the considered Wi-Fi systems, *RSS_min*. In method #2 the *RSS_thr* was used as control parameter. In method #3 the *RSS_min* parameter is simply assumed to be depending on the minimum sensitivity level for the considered Wi-Fi system implementation, which depends on carrier frequency, bandwidth, type, etc. For simplicity we assume that all Wi-Fi nodes (AP and STA) have the same *RSS_min* capability. In the traffic steering mechanisms #3, instead of the *RSS_thr* parameter the new RSRP threshold, *RSRP_thr_high*, is used; while the *RSRP_thr_low* parameter has the same role as the *RSRP_thr* in the mechanism #2.

In these first C&O studies we do not include any measurement uncertainties or sources of error. This means that the LTE RSRP and the Wi-Fi RSS(I) measures at the UE are assumed to be estimated perfectly and are reliably reflecting the actual channel conditions.

In practice, the LTE RSRP measurements are subject to relatively small estimation errors due to standardized procedures and time averaging. In the case of Wi-Fi RSS(I) the situation is quite different: the RSS(I) measurements and estimation accuracy are not specified in terms of absolute values in the current IEEE standards nor are part of the Wi-Fi Alliance certification. E.g. reference [66] clearly concludes on the unreliability of the RSS measures in today's Wi-Fi devices.

In the traffic steering mechanisms #3, the RSSI threshold is not used anymore as TS control parameter; hence, RSS inaccuracy issues mentioned above have less impact and the TS outcome becomes more predictable from LTE RAN perspective. The main effect of UE measurement uncertainties and errors is that the not all UEs selected for on/offloading would actually benefit from these traffic steering actions, hence the overall user and system performance will be degraded compared to the ideal case with no UE measurement errors.

3.8.2 C&O Scenario

The outdoor hot zone (OHZ) scenario documented in SEMAFOUR deliverable D2.4 [83] is adopted in the TS use case for both the C&O studies and SON evaluations. Please note that [83] is not a public available document. The main characteristics of the scenario are described in this section.

The OHZ scenario is characterized by an outdoor hotspot located in the city centre of Hannover. The traffic intensity in the hotspot is significantly higher than the surrounding areas as depicted in Figure *15*. The numbers besides the nodes represent to the cell indexes in the results presented in Section 3.8 and 3.10. To meet the high traffic demand, 28 co-sited outdoor LTE micros and Wi-Fi APs are deployed in the hotspot. Due to the dense AP deployment and limited number of Wi-Fi channels at

2.4 GHz, an AP may sense one or several other APs operating at the same channel which reduce the channel accessibility and capacity of the AP. Planned Wi-Fi channel assignment is assumed, and the principle of channel assignment is explained in Appendix A.3.6.

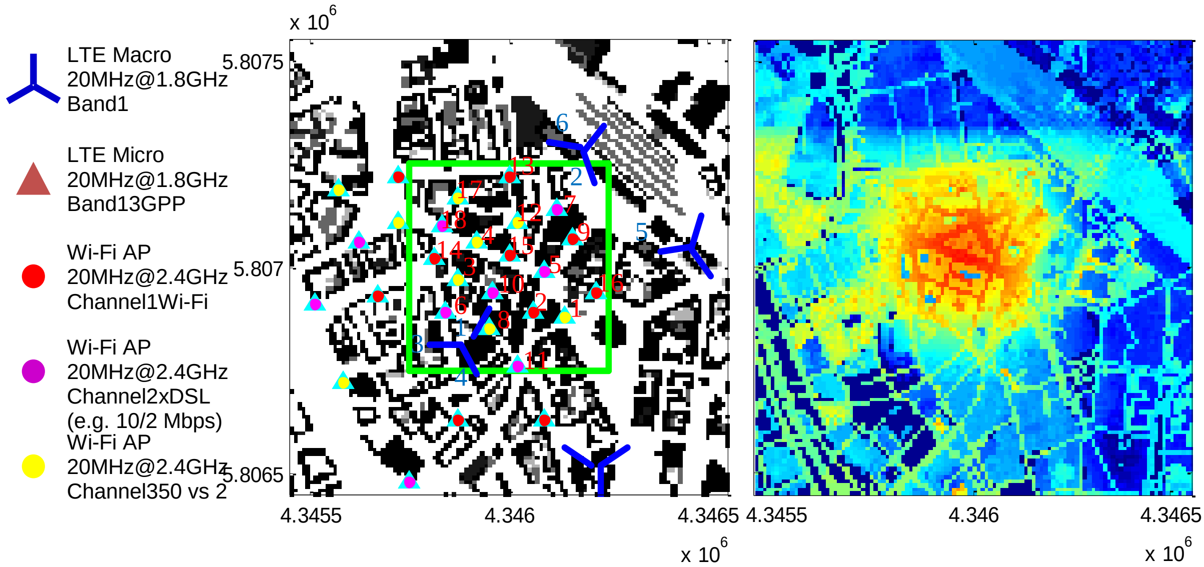

Figure 15: The OHZ scenario network layout (left) and traffic intensity map (right)

FTP file downloading from stationary users generates downlink traffic in the network. A file size of 5 MB and a user Poisson arrival rate of 16 arrivals per second are configured which gives totally 80 MB offered traffic per second in the scenario area. The DL and UL traffic ratio is 6 to 1. The principles and procedures of choosing the traffic settings are further described in Appendix A.3.4 and A.3.5.

The spatial distribution of the offered traffic follows the traffic intensity map shown in Figure 15. The north part of the area has no new cells deployed and the traffic intensity in the area is reduced to avoid overloading the serving LTE macro cells. The modification is detailed in Appendix A.3.3. Overall the scenario provides a challenging real world condition for TS studies.

Simulation results are collected from a 500x500 meters reference area which is highlighted by the green square in Figure 15.

3.8.3 Impact of Measurements and Control Parameters

The control parameters of the evaluated TS mechanisms were the RSS threshold (*RSS_thr*) [dBm] and the RSRP threshold (*RSRP_thr*) [dBm] values. Additionally, and considering the traffic intensity in the network area of interest, the RSRP offset for LTE micro cells (load balancing between LTE macro and micro layers) has been used, see Section 3.8.3.1.

3.8.3.1 Intra-LTE Load Balancing

No advanced mechanisms for intra-LTE load balancing are included in the study of this deliverable. To have a reasonable load sharing between the LTE macro and micro layers, several fixed RSRP cell selection offset for the micro cells have been investigated as a part of the C&O study. The approach is to simulate the C&O scenario without the Wi-Fi layer. Due to the high offered traffic, one or both of the macro and micro layer becomes overloaded depending on the RSRP offset setting. Since the Wi-Fi layer will mainly share traffic load with the micro layer, one principle of the offset selection is to avoid macro from being overloaded. On the other hand a too high offset may cause radio link failure for high mobility users. Therefore, the minimum offset which prevents the macros from being overloaded is selected to apply in simulations, and the selected value is 6 dB.

3.8.3.2 RSS-based Mechanism

The RSS-based mechanism uses an RSS threshold value which is applied to determine when an UE is served (offloaded) to a Wi-Fi access point. The RSS threshold values can be cell specific, i.e.

depending on the estimated LTE load in a given cell the algorithm sets an appropriate RSS threshold value to be used by the UEs to connect to the strongest Wi-Fi access point (see Section 3.8.1, eq (1)).

In case of co-located LTE micro and Wi-Fi deployment and considering the different transmit power levels of the LTE micro (33 dBm) and the Wi-Fi access point (20 dBm), the use of a RSS threshold has as effect that LTE micro cell serves only the UEs with low RSS towards the co-located Wi-Fi AP, hence potentially balancing the overall performance between 'cell-centre' (on Wi-Fi) and 'cell-edge' (on LTE) UEs, see Figure 16.

In case of non-co-located LTE (macro) and Wi-Fi deployment, the offloaded UEs can be anywhere in the LTE cell coverage area, depending where the Wi-Fi AP is located, hence the 'cell-centre' and 'cell-edge' UE differentiation is not introduced.

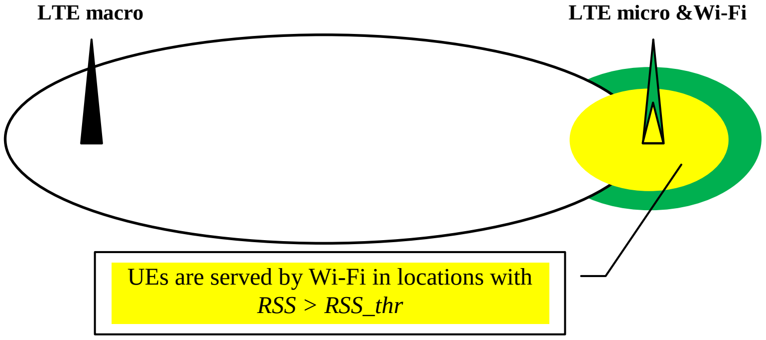

Figure 16: RSS-based offloading mechanism in LTE macro and co-located LTE micro & Wi-Fi deployment scenario.

3.8.3.3 RSRP&RSS-based Mechanism

The *RSRP&RSS-based* mechanism was aimed to target control on both LTE and Wi-Fi coverage areas (see Section 3.8.1, Equation (3-1)).

In case of co-located LTE micro and Wi-Fi deployment, the benefit of this mechanism is expected to strongly depend on the RSRP threshold value because the offloading area excludes the micro 'cell-centre' and 'cell-edge' UEs, due to the RSRP and RSS offloading conditions in eq. (2). In case of non-co-located LTE (macro) and Wi-Fi deployment, the use of RSRP and RSS thresholds provides improved control on the LTE macro 'cell-edge' area to be offloaded to the nearby Wi-Fi APs; hence potentially better load-balancing can be achieved. This type of control would be needed especially when Wi-Fi APs are deployed at the 'edge' of the LTE macro coverage area as depicted in Figure 17.

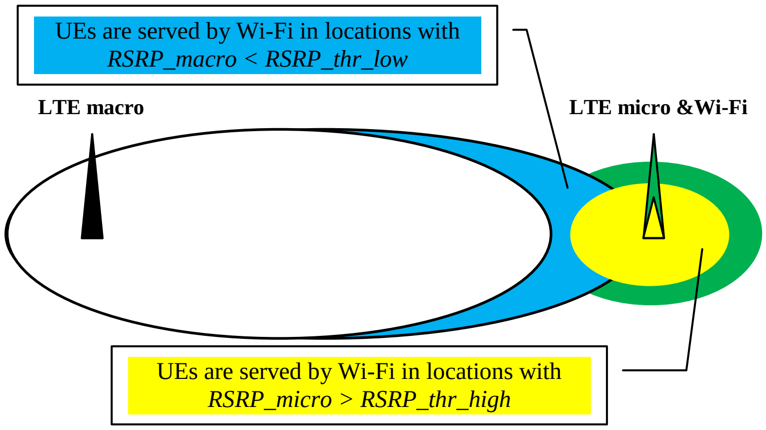

Figure 17: RSRP-based offloading mechanisms in LTE macro and co-located LTE micro & Wi-Fi deployment scenario.

3.8.3.4 RSRP-based Mechanism

The general functionality of this traffic steering mechanism can be explained based on Figure 17 by first recognizing that the *RSRP_macro* and *RSRP_micro* UE measurements are within different value ranges, hence for the purpose of LTE-Wi-Fi TS they can be compared to the different RSRP thresholds, *RSRP_thr_low* and *RSRP_thr_high*, respectively. Secondly, the selection of the UEs with "*RSS* > *RSS_thr*" condition, used to determine which UEs are in good Wi-Fi signal coverage, can also be achieved by a similar RSRP condition when the RSRP is measured relative an LTE cell with co-located Wi-Fi access. Hence, for a (macro) cell without co-located Wi-Fi access the condition to be used to connect to Wi-Fi is "*RSRP_macro* < *RSRP_thr_low*", while in the case of a (micro) cell with co-located Wi-Fi access the condition to be used to connect to Wi-Fi is "*RSRP_micro* > *RSRP_thr_high*" (see Section 3.8.1, eq (3)).

3.8.3.5 Main Results and Analysis

3.8.3.5.1 Wi-Fi if Coverage (reference)

The Wi-Fi coverage is used as reference for the traffic-steering mechanisms proposed in previous sections. In the Wi-Fi coverage offloading scenario the UEs connect to Wi-Fi AP whenever they detect an RSS value above the minimum connectivity level of *RSS_min* = -92 dBm.

3.8.3.5.2 RSS-based Mechanism

Simulated user session split among the three layers and user throughput statistics with respect to different RSS thresholds are shown in Figure 18.

The offered traffic in the Wi-Fi layer rapidly increases with a decrease in the RSS threshold. In the scenario where Wi-Fi is reachable for most users, the sensitivity of user access selection to the RSS threshold was evident. The RSS threshold have strong impact on the offered traffic of the Wi-Fi and LTE micro layer and only limited impact on the LTE macro layer. The peaks of the average and 5th percentile user throughput appear at different RSS thresholds. Therefore SON algorithm tuning should depend on if the average or the 5th percentile throughput is considered as an optimization target.

When the Wi-Fi layer was disabled by setting the RSS threshold to infinity, user throughput was still better than the case where a bad RSS threshold was set. This emphasizes the importance of an intelligent TS mechanism to user experience and network efficiency. The minimum simulated RSS threshold was -85 dBm instead of -92 dBm since the APs became so congested that most user throughput approached to zero when the threshold was set to less than -85 dBm.

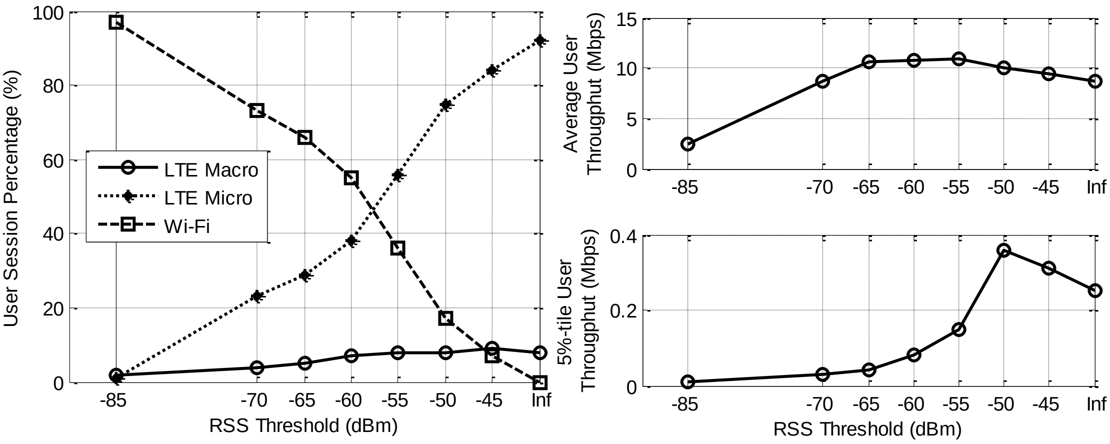

Figure 18: Simulated user session percentage (left) and DL user throughput (right) respect to different fixed RSS thresholds

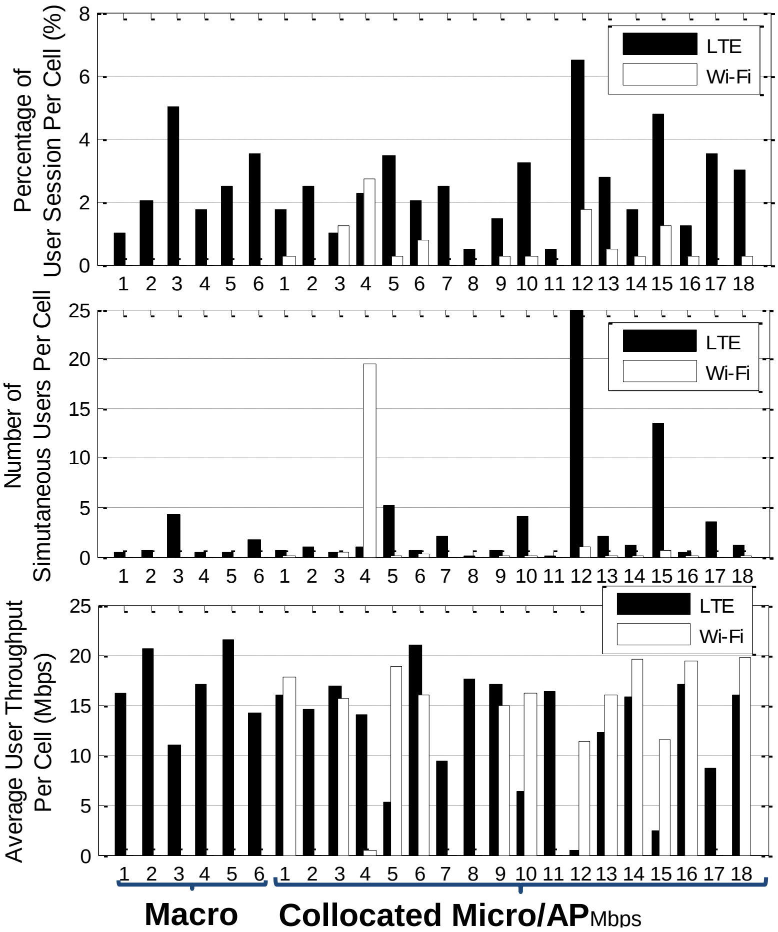

Figure 19: Percentage of user session per cell (upper), number of simultaneously active users (middle) and average DL user throughput (lower) per cell when using a fixed RSS threshold = -50 dBm

Among the fixed RSS threshold settings, -50 dBm gives the best 5th percentile user throughput. The per cell KPIs for a RSS threshold of -50 dBm are illustrated in the bar plots in Figure 19.

The percentage of user sessions per cell is the number of user sessions per cell divided by the total number of simulated user sessions. It was largely unbalanced among the cells. This is a typical situation in reality where perfect planning usually cannot be assumed. SON algorithms need to be effective to cope with such conditions.

Micro 12, 15 and AP 4 were overloaded with very high numbers of active users. The user throughput of these three cells was very low due to the congestion, and the overall 5th percentile user throughput was to a large extent affected by these cells.

Between a pair of micro and AP, the offered traffic was typically higher in the micro layer in most cells, while at the same time the average user throughput was more balanced. For Micro/AP 6 and 9, the Micro user throughput was even higher than the AP user throughput with higher offered traffic in the micros. This is due to the fact that a micro has more radio capacity than an AP. Comparing to an LTE cell, an AP has 20 MHz shared DL/UL bandwidth instead of two dedicated 20 MHz bands for DL and UL. Even though totally three Wi-Fi channels are available, one AP can sense up to 3 other co-channel APs and share the same channel among them given the dense AP deployment. Furthermore, the Wi-Fi system efficiency decreased rapidly with more number of active users per AP especially in the absence of the A-MPDU and the block ACK. The imbalance in the cell capacity is typical in multi-RAT scenarios and the SON function needs to be effective in this situation.

3.8.3.5.3 RSRP&RSS-based Mechanism

The simulated user session split in the Wi-Fi and LTE network layers versus fixed RSRP and RSS thresholds settings (the same in all cells) are shown in Figure 20.

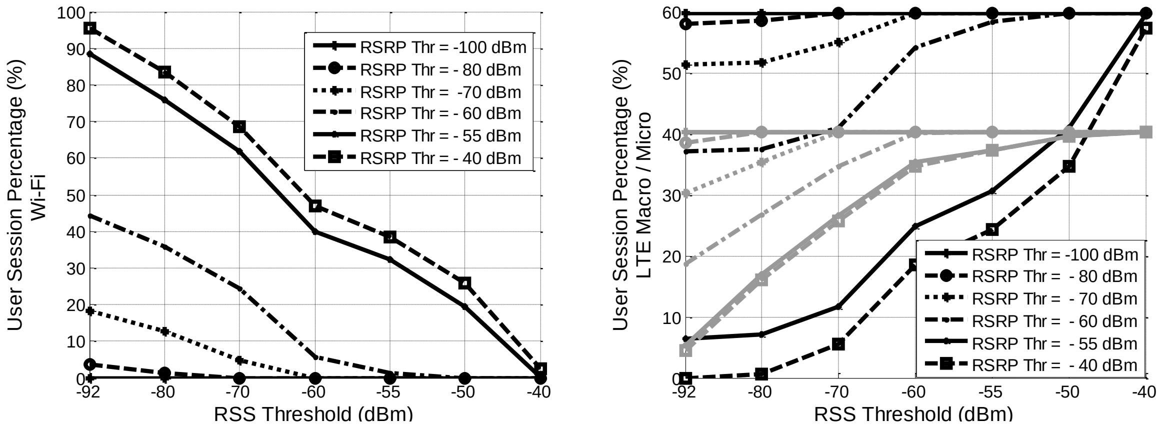

Figure 20: Simulated user session percentage on Wi-Fi (left) and LTE network layers (right), Macro (grey) and Micro (black), versus different fixed RSRP and RSS thresholds settings

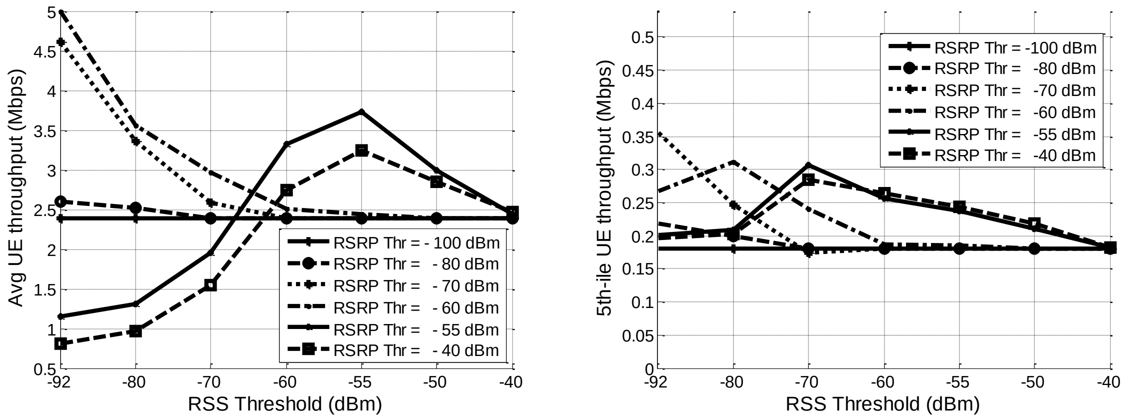

Figure 21: Simulated DL user throughput statistics, average (left) and 5th percentile (right), versus different fixed RSRP and RSS thresholds settings

The RSRP threshold of -40dB corresponds to the setting where all UEs are candidate for offloading, because their measured RSRP is always below this threshold value. For this setting, on the left-side plot in Figure 20 it can be observed that the number of Wi-Fi user sessions can be well controlled with the RSS threshold parameter, achieving offloading rates between 95% down to 0%, when the RSS threshold is swept from -92 dBm to -40 dBm. On the corresponding curves on the right-side plot in Figure 20, we can note the split between the macro and micro user sessions changing from 5%-0% to 40%-60%. In general, the same trends are observed as in the case of the RSS-only threshold mechanism (i.e. high RSRP threshold of -40dB) presented in Figure 18.

The simulated downlink user throughput statistics versus fixed RSRP and RSS thresholds settings (the same in all cells) are presented in Figure 21.

These results have been used to identify an optimum setting for the RSRP and RSS threshold settings. The optimisation criterion has been to achieve the best 5th percentile user throughput performance under the requirement of balanced performance across the LTE macro, LTE micro Wi-Fi layers. The balanced user performance is especially important between the LTE micro and Wi-Fi due to the co-located deployment scenario and the expected frequent on/off-loading between these two cell layers. The optimum RSS / RSRP threshold settings are expected to depend mostly on the relative density of macro and micro cells, when all micro cells have a co-located Wi-Fi AP. In non-co-located type of deployments, the micro cells without Wi-Fi are likely to capture more traffic even for low RSS threshold values, which would indicate that a different RSS threshold should be used for optimal performance.

Figure 22 shows the downlink 5th percentile user throughput results for two different RSRP threshold values and their corresponding RSS thresholds. For all other RSRP threshold values the 5th percentile performance results were lower.

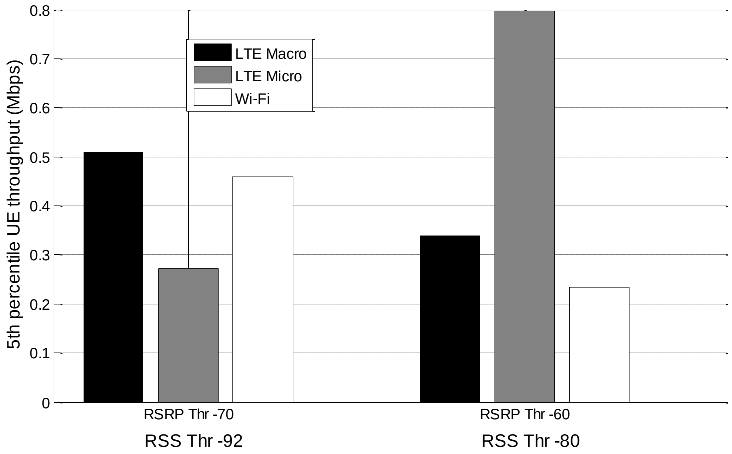

Figure 22: Simulated downlink 5th percentile user throughputs achieved on each network layer for two different RSRP threshold settings

For completeness, we have also identified the threshold settings which maximize the average UE throughput or maximize the 5th percentile UE throughput in the overall network. The summary of these investigations in terms of the optimal RSRP and RSS threshold values for different target performance metrics are listed in Table 5. In these results we have identified two pairs of RSS and RSRP threshold value which yield the best 5th percentile or average users throughput values.

	***RSRP_thr* [dBm]**	***RSS_thr* [dBm]**	**Throughput [Mbps]**	**Notes /reference**
Maximum Average UE throughput	-60	-92	5.0	Figure 21 left
	-55	-55	3.8	
Maximum 5th percentile UE throughput	-70	-92	0.35	Figure 21 right
	-60	-80	0.30	
Balanced 5th percentile UE throughput	**-70**	**-92**	**0.35**	Figure 21 right Figure 22

Table 5: The RSRP and RSS threshold values which maximize the different network performance metrics in the RSRP&RSS-based traffic steering mechanism

Based on these results it was identified the setting with *RSRP_thr* = -70dBm and *RSS_thr* = -92dBm which satisfies overall (in average over all cells) the chosen optimisation criterion. The *RSS*_thr = -92dBm value, which is equal to the lower limit of the Wi-Fi connectivity (below this RSS value UEs are assumed not to be able to connect to any Wi-Fi AP), indicates that it is potentially more beneficial to utilise only the LTE RSRP measurements, and threshold, to control the traffic steering to/from Wi-Fi. This option is explored further in the following sections.

3.8.3.5.4 RSRP-based Mechanism

In these investigations we fix the Wi-Fi connectivity threshold to *RSS* ≥ *RSS_min* = -92dBm and assume that all UEs have similar Wi-Fi receiver capabilities and Wi-Fi equipment performance. For Wi-Fi access, in the non-co-located (macro) cells the UE RSRP condition to be used is "*RSRP_macro < RSRP_thr_low"*, while in the case of a co-located (micro) cell the condition to be used is "*RSRP_micro > RSRP_thr_high"* (see Section 3.8.1, eq (3)).

The simulated user session split in the Wi-Fi and LTE network layers versus fixed *RSRP_thr_low* and *RSRP_thr_high* thresholds settings (the same in all cells) are shown in Figure 23. In general, the same trends are observed as in the case of the RSS-only threshold mechanism (i.e. high RSRP threshold of -

40dBm) presented in Figure 18 and Figure 20. As it can be observed on the right-side plot in Figure 23, the *RSRP_thr_high* has no impact on the number of sessions for the users served by the macro layer.

The simulated downlink user throughput statistics versus fixed RSRP thresholds settings (the same in all cells) are presented in Figure 24. At a first look the trends shown in these curves may seem contra intuitive, especially the drop in average user throughput (Figure 24 left) for certain *RSRP_thr_low* threshold values. The first observation is that, when *RSRP_thr_low* = -100dBm there are practically no macro UEs to be potentially offloaded to Wi-Fi regardless of the *RSRP_thr_high* settings and 40% of UEs are always served by macro cells. However, the *RSRP_thr_high* parameter controls the offloading from the micro cells to Wi-Fi, between 0% and 60%. For *RSRP_thr_low* = -100dBm and *RSRP_thr_high* in the range -100dBm to -60dBm, a significant fraction of UEs is on Wi-Fi, thus the average UE throughput performance is improving. When the *RSRP_thr_high* is increased further to -40dBm the Wi-Fi offloading rate is decreased, and because of the heavily loaded LTE cells the average UE throughput drops. This behaviour is 'smoothed' out for higher *RSRP_thr_low* settings because even with the higher *RSRP_thr_high* there are still enough UEs on Wi-Fi to keep the overall system performance from degrading.

As consequence of increasing offloading rates, beyond a certain *RSRP_thr_low* value the performance of Wi-Fi UEs will start degrading, thus lowering the overall performance too. This effect especially visible in the 5^{th} percentile UE throughput results (Figure 24 left), by looking at the very different behaviour for *RSRP_thr_low* = -80dBm. With this setting, the lowest throughput UEs are an approximately equal blend of LTE and Wi-Fi UEs, while for all other *RSRP_thr_low* values, either the LTE or Wi-Fi UEs dominate the overall 5^{th} percentile throughput values.

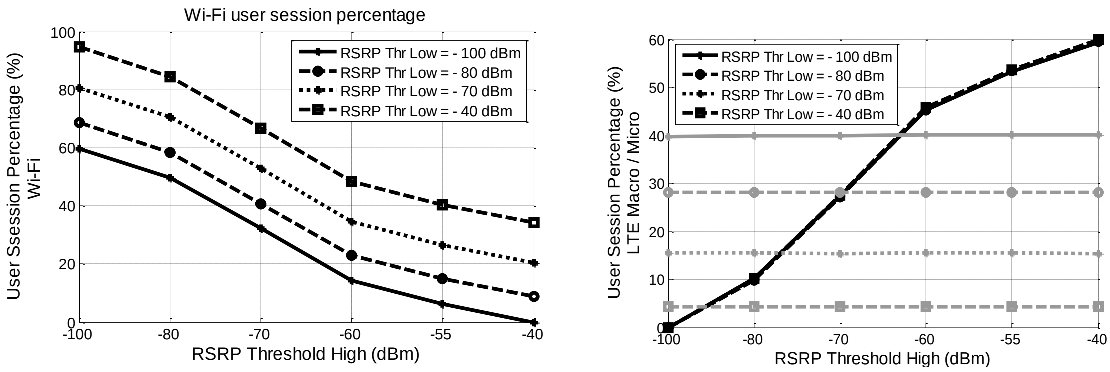

Figure 23: Simulated user session percentage on Wi-Fi (left) and LTE network layers (right), Macro (grey) and Micro (black), versus different fixed* RSRP_thr_low *and* RSRP_thr_high *thresholds settings

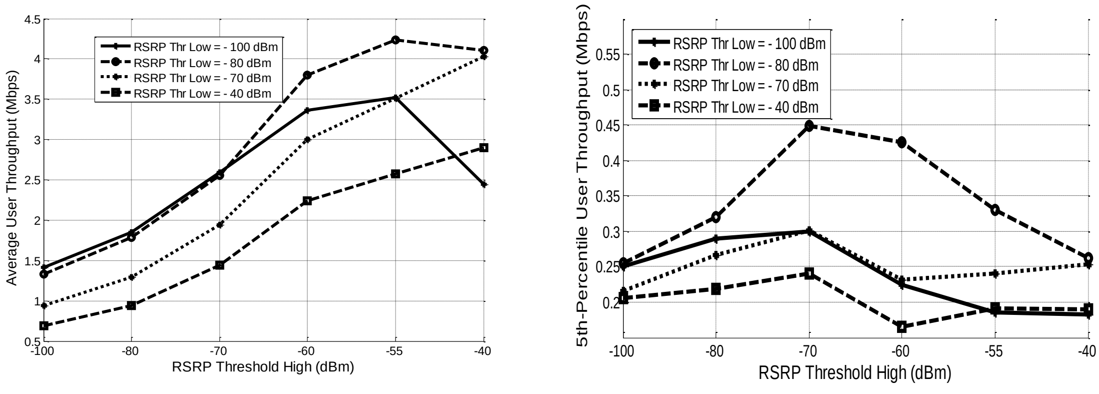

Figure 24: Simulated DL user throughput statistics, average (left) and 5^{th} percentile (right), versus different fixed* RSRP_thr_low *and* RSRP_thr_high *thresholds settings

To identify an optimum setting for the two RSRP thresholds we use the same optimisation criterion as for the RSRP&RSS-based studies: achieve the best 5^{th} percentile user throughput performance under the requirement of balanced performance across the LTE macro, LTE micro Wi-Fi layers. Figure 25 shows the downlink 5^{th} percentile user throughput results for two different pairs of *RSRP_thr_low* and

RSRP_thr_high threshold values. For all other RSRP threshold values the 5th percentile performance results were lower. For completeness, we have also identified the threshold settings which maximize the average UE throughput or maximize the 5th percentile UE throughput in the overall network.

The summary of these investigations in terms of the optimal RSRP threshold values for different target performance metrics are listed in Table 6. Also in these results there are two pairs of *RSRP_thr_low* and *RSRP_thr_high* threshold value which yield the best 5th percentile or average users throughput values. In these results, we can conclude that for a fixed *RSRP_thr_low* = -80dBm (RSRP_thr in Table 5) the proposed TS mechanism can successfully control the overall system performance by adjusting the *RSRP_thr_high* parameter.

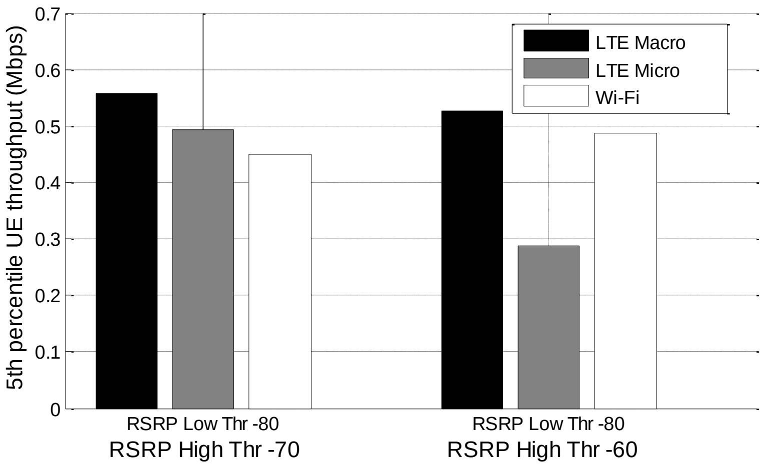

Figure 25: Simulated downlink 5th percentile user throughputs achieved on each network layer for two different set of RSRP threshold settings

	***RSRP_thr_low* [dBm]**	***RSRP_thr_high* [dBm]**	**Throughput [Mbps]**	**Notes/references**
Maximum Average UE throughput	-80	-55	4.7	Figure 24 left
	-80	-60	3.8	
Maximum 5th percentile UE throughput	-80	-70	0.45	Figure 24 right
	-80	-60	0.44	
Balanced 5th percentile UE throughput	**-80**	**-70**	**0.45**	Figure 24 right Figure 25

Table 6: The RSRP threshold values which maximize the different network performance metrics in the RSRP-based traffic steering mechanism

Furthermore, it is of interest to observe also how the achieved performance is actually spread across the different cells, especially because the offered load is not uniformly distributed in the study area (see Section 3.8.2). In Figure 26 we show the per cell results achieved with the optimal RSRP threshold settings for balanced 5th percentile UE throughput across the layers. The main observation from these results is that there are several co-located micro / Wi-Fi cells where the number of user sessions on Wi-Fi is significantly higher compared to the LTE user sessions, e.g. cell and 13 15. In these cells the 5th percentile user throughputs are significantly higher for the micro cell compared to its co-located Wi-Fi AP.

Because of the current misalignment of the absolute LTE performance numbers between the simulators, these results cannot be compared at this stage with the RSS-based C&O results presented in Section 3.8.3.5.2. However, it could be noted that both mechanisms identify pretty close offloading areas, i.e. the corresponding RSS threshold for the optimal RSRP Threshold High equal to -70 dBm is -52.2 dBm (details on the scaling between RSS and RSRP for a co-located scenario are provided in

Section 3.9.1.2). This RSS value matches nicely with the optimal RSS thresholds of -55 / -50 dBm identified in Section 3.8.3.5.2 for the RSS-based mechanism.

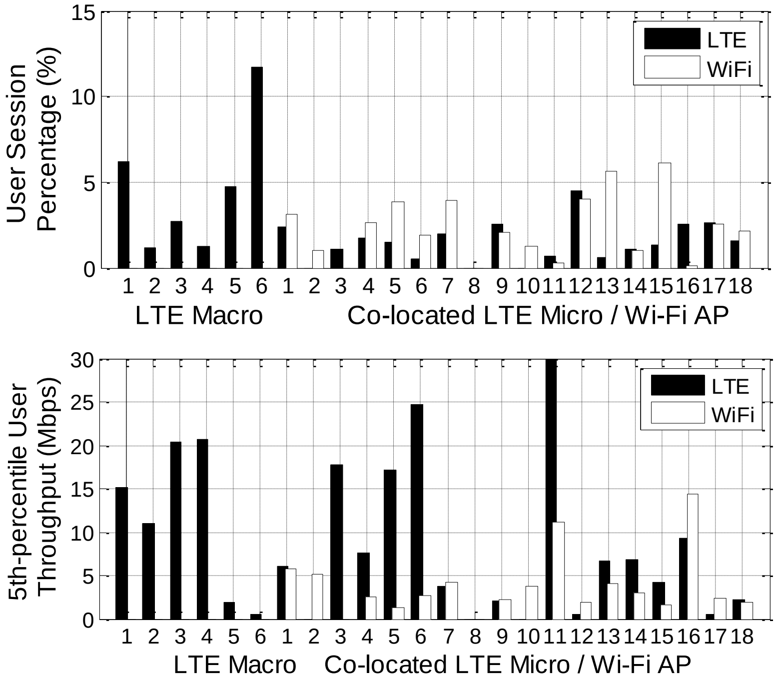

Figure 26: Simulated user session percentage (upper) and 5th percentile DL user throughput (lower) per cell with fixed RSRP_thr_low = -80 dBm and RSRP_thr_high = -70 dBm

3.8.4 C&O Analysis Outcome and Way Forward

The following observations summarize the outcome of the C&O study:

- The *RSS-based* mechanism is a simple and effective way to control the coverage area of the deployed Wi-Fi APs and it is especially useful for offloading micro 'cell-centre' UEs when LTE and Wi-Fi access are co-located. The optimal *RSS_thr* value is in the range of -45 dBm to -60 dBm.
- The *RSRP&RSS-based* mechanism is a more complex mechanism and allows a better offloading control of the macro/micro 'cell-edge' UEs. The optimal *RSS_thr* value is in the range of -60 dBm to -80 dBm combined with an *RSRP_thr* in the range -50 dBm to -60 dBm. In the case of co-located LTE and Wi-Fi access deployment this mechanism can give the best results by setting a high *RSRP_thr* value (e.g. above -40 dBm), practically disabling the *RSRP-based* mechanism, and reverting to the *RSS-based* mechanism.
- The RSRP&RSS-based mechanism can be successfully replaced by the RSRP-based mechanism, which still uses two control parameters in the form of two RSRP threshold values. The optimal *RSRP_thr_low* value is -80 dBm. In the case of co-located LTE and Wi-Fi access deployment this mechanism can give the best results by setting a high *RSRP_thr_low* value (e.g. above -40 dBm), and using an optimal *RSRP_thr_high* value in the range of -70 dBm to -40 dBm.
- The RSS and RSRP threshold settings listed above were determined for typical urban, but dense co-located micro / Wi-Fi network deployment. In other urban deployment scenarios with different micro / Wi-Fi cell density the optimal *RSS_thr* and *RSRP_thr_high* are expected to be in the same range. Per cell optimization by means of SON algorithm is still required due to varying traffic load and site specific radio coverage characteristics. However, the *RSRP_thr_low* depends on the relative location of the micro / Wi-Fi cell within the macro cell coverage area.
- Given the different traffic levels and irregular coverage area of the macro / micro / Wi-Fi cells the optimal RSS and / or RSRP threshold values should be determined separately per LTE cell.

The presented RSS-based C&O studies (Section 3.8.3.5.2) prove that the RSS threshold has strong impact on the load of the Wi-Fi and LTE micro layer and only limited impact on the LTE macro layer. It indicates that a RSS-based SON algorithm can define one RSS threshold per Wi-Fi AP and use co-located micro load to update the threshold. With non-co-located deployment, one RSS threshold may be defined for each pair of an AP and a LTE cell. The non-co-located deployment study is planned for the next phase of the project.

Analysing the main findings from the presented RSRP&RSS-based (Section 3.8.3.5.3) and RSRP-based (Section 3.8.3.5.4) C&O studies, the RSRP-based mechanism has been selected as a viable alternative to the RSS-based mechanism, and to be used in the evaluation of LTE / Wi-Fi TS SON algorithms. The selection of the RSRP-based mechanism has been made based on: a) higher 5^{th} percentile user throughput (Table 5 vs. Table 6) and b) the observation that the accuracy of the RSS measurements could in practice be significantly lower compared to the LTE RSRP measurements [66].

The identified threshold values, *RSRP_thr_low* = -80 dBm and *RSRP_thr_high* = -70 dBm, which better meet the chosen optimization criterion will be used as starting point to configure the RSRP-based SON algorithm. The RSRP-based mechanism provides optimal performance when Wi-Fi APs are deployed co-located with LTE cells by using both *RSRP_thr_low* and *RSRP_thr_high* parameters. In the non-co-located deployments this mechanism could use only the *RSRP_thr_low* parameter, effectively selecting ‘cell-edge’ UEs for offloading. Hence, depending on the LTE cell and Wi-Fi AP deployment layout, the overall performance of the LTE layers could be improved compared to the case of co-located deployment. This investigation will be performed in the frame for SEMAFOUR deliverable D4.2 (confidential).

Based on the learning from the C&O study, the way-forward is captured below:

- An RSS-based SON function with both LTE and Wi-Fi cell load information as monitoring KPIs is expected to improve user experience and network utilization and should be developed and evaluated. The RSS threshold can be broadcasted from either a LTE cell or a Wi-Fi AP to UEs.
- The optimal *RSS_thr* value depends on the targeted average LTE cell load level and the targeted load in the Wi-Fi access point. Two load measures, i.e. AP channel business and AP station count, have been proposed in Section 3.6.2 where the effectiveness and limitation of the two measures are discussed.
- As alternative to the RSS-based algorithm the use of the RSRP-based mechanism is proposed, which can accommodate two different configurations, with either of the *RSRP_thr_low or RSRP_thr_high* enabled, for the non-co-located (macro or micro) and co-located deployments, respectively. The SON algorithm can easily generate these configurations based on network deployment information and, e.g. accordingly set the threshold information broadcasted by a given LTE cell.
- The optimal *RSS_thr* and *RSRP_thr_low / high* depend on the targeted average LTE cell load level and the offered traffic. This means that any intra-LTE load balancing mechanism is likely to have to interact with the SON offloading algorithm when setting these threshold values.
- In order to more accurately evaluate the achievable gains it would desired to introduce measurement imperfections on the RSRP and RSS UE measurements, to better reflect behaviour of real-life equipment. It is believed that this is especially important for the Wi-Fi RSS measurements [66] where the absolute measurement errors are expected to be larger compared to the LTE RSRP measurement errors.

3.9 SON Functions

3.9.1 SON Algorithms

Two SON algorithms, i.e. RSS-based and RSRP-based algorithms, are described in this section. In the first phase of the study presented in this deliverable, the TS decision is made when a session is started and no further access selection changes are done during a session.

3.9.1.1 RSS-based SON Algorithm

The RSS-based SON algorithm is a single control parameter SON function with the RSS threshold as the control parameter and radio resource utilization in LTE and Wi-Fi as monitoring KPIs. The algorithm targets at optimizing user experience and network efficiency by avoiding congestion and balancing traffic load between LTE and Wi-Fi.

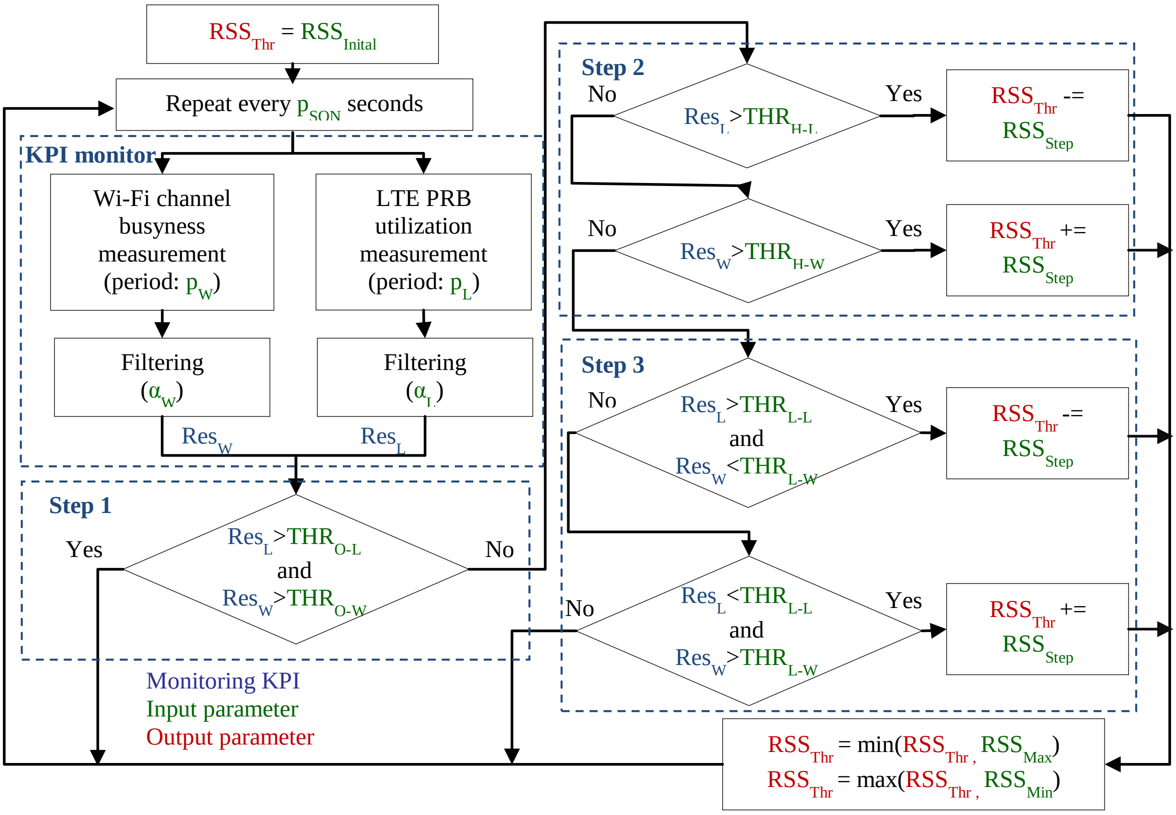

Figure 27: Flowchart of the RSS-based SON algorithm

The SON algorithm keeps monitoring LTE and Wi-Fi radio resource utilization and triggers RSS threshold adjustment based on a comparison of the utilization with some threshold values. This procedure is illustrated in Figure 27 and a description of input parameters and settings is given in Table 7.

Parameter	**Description** L: LTE, W: Wi-Fi	**Setting**
p_{SON}	Periodicity of SON algorithm execution	1 sec
p_L / p_W	Periodicity of cell resource utilization calculation	1 / 1 sec
α_L / α_W	Parameters controlling resource utilization filtering	0.9 / 0.9
RSS_{Step}	Step size of RSS threshold adjustment	1 dB
$RSS_{Initial}$	Initial value of the RSS threshold	-45 dBm
RSS_{Min} / RSS_{Max}	Minimum and maximum values of the RSS threshold	-92 / -45 dBm
THR_{O-L} / THR_{O-W}	Overload threshold for resource utilization	95 / 95 %
THR_{H-L} / THR_{H-W}	High utilization threshold to trigger offloading	80 / 70 %
THR_{L-L} / THR_{L-W}	Low utilization threshold to trigger onloading	45 / 35 %

Table 7: RSS-based SON algorithm input parameter description and settings

The radio resource utilization (Res) is measured periodically and filtered before being compared with the thresholds. The low pass filtering is defined by the equation below:

$$\mathrm{Res}(n) = (1-\alpha) * \mathrm{Res}(n-1) + \alpha * \mathrm{Res}_{measured}(n) \qquad (3\text{-}5)$$

In LTE the resource utilization (Res_L) is represented by a cell PRB utilization percentage. In Wi-Fi, an AP channel busyness measure is applied for the purpose. The channel is considered as busy if there is at least one active connection associated to the AP and the AP or a STA is transmitting or attempts to transmit. The Wi-Fi resource utilization (Res_W) is the percentage of channel busy time.

Note that both the resource utilization indicators are not direct measures of cell load since they don't compare user demand with system capacity. In a worst case, a full buffer best effort user may use up the radio resources and keep pushing the RSS threshold to its upper or lower bound. Additional mechanisms must be designed to solve this issue which is a planned activity for the next SEMAFOUR WP4 deliverable.

Furthermore, the two indicators should not be compared with each other because the capacity of the two systems may be different and they don't have the same impact to user experience and system efficiency. Therefore, the utilization indicators are compared against separate thresholds in the SON algorithm.

An RSS threshold may be maintained either for each AP or each pair of Wi-Fi AP and LTE cell. In the former case, an LTE cell needs to be assigned to each AP as a neighbour in order for the algorithm to get the Res_L. In this study, the co-located micro is configured as the neighbour of an AP.

The filtered resource utilization KPIs are compared with the pre-configured thresholds as follows:

- **Step1**: check if both the systems are overloaded, and stop steering traffic to any system in this case to avoid flooding one system.
- **Step2**: otherwise, if any system is considered as highly loaded the RSS adjustment will be triggered to start offloading. The LTE system is given a higher priority in this implementation.
- **Step3**: if neither system is highly loaded the algorithm checks the opportunity to onload a low load cell to improve user experience and network efficiency.

The algorithm evaluates the radio resource utilization and adjusts the RSS threshold periodically. The periodicity (p_{SON}) and the adjustment step size (RSS_{Step}) determine the sensitivity and stability of the algorithm. The output of the algorithm (RSS_{Thr}) is made available to corresponding nodes, e.g. UEs, eNBs and / or APs to control the UE access selection, i.e. selecting Wi-Fi if RSS is above RSS_{Thr}.

The setting of the input parameters needs to reflect operators' policies. For example, a policy giving high priority to LTE users can be realized by setting low LTE RSS thresholds and high Wi-Fi RSS thresholds. The values set in Table 7 target at a balanced user throughput in the two systems.

The algorithm itself provides a higher priority to the LTE system since the LTE high load condition is checked before the Wi-Fi system. It may be improved by giving flexibility of selecting which system is checked first. Another potential modification is to avoid further congesting an overloaded cell by always checking overload conditions in both systems before adjusting the RSS threshold. These algorithm modifications will be further investigated in the next phase of the study.

3.9.1.2 RSRP-based SON Algorithm

The RSRP-based SON algorithm is a dual control parameter mechanism, which uses the LTE cell resource utilisation as an input KPI to adjust the RSRP threshold values, with a simple step up / down algorithm driven by a LTE cell utilisation (CU) metric. In order to differentiate between the fixed RSRP thresholds used in the C&O studies, *RSRP_thr_low* and *RSRP_thr_high*, in the RSRP-based SON algorithm studies we use the naming *RSRP_THR_LOW and RSRP_THR_HIGH*, respectively.

The selected CU reflects the fraction of required PRBs of the total available in a LTE cell in order to serve all connected UEs with a certain minimum bit rate ($R_{MIN\text{-}L}$). The CU is evaluated periodically with a certain observation period (CU_{Per}) and filtered according to equation (3-6), where α_L is the smoothing factor and n is the index of the observation period.

$$\mathrm{CU}_{\mathrm{Lfil}}(n) = (1-\alpha_L) * \mathrm{CU}_{\mathrm{Lfil}}(n-1) + \alpha_L * \mathrm{CU}_{\mathrm{L}}(n) \tag{3-6}$$

The filtered CU (CU_{Lfil}) is then used to drive a step up / down algorithm for adjusting the RSRP threshold. The algorithm ensures that the controlled RSRP threshold value remains between the pre-set minimum and maximum values.

Based on the C&O investigations we have identified that the *RSRP_THR_LOW* parameter can be set to fixed value for all macro cells of interest in the investigated area, thus only the *RSRP_THR_HIGH* for the micro cells is SON controlled, according to the flowchart in Figure 28. The corresponding SON parameter configurations are listed in Table 8. The RSRP and RSS signal level conditions in Section 0, eq (3), are then used to determine in each LTE cell and for each UE whether to serve its traffic on Wi-Fi or LTE.

It should be noted that the RSRP_THR_HIGH used in the RSRP-based SON algorithm is highly correlated to the RSS_thr used in the RSS-based SON algorithm (Section 3.10.3.1). As matter of fact, for a UE in a given location there is certain scaling between the RSS and RSRP values measured towards a co-located Wi-Fi AP and LTE cell. Part of the scaling depends on the difference in definition between the measurements: RSS is the received power over the full Wi-Fi system bandwidth [85] while RSRP is the average power per resource element (RE) [74]. Therefore the measure scales based on the carrier frequency, the difference in transmission power between the two networks and the difference in system bandwidth between the two measurements. Other factors for the scaling are for instance due to the antenna characteristics and heights which could be specific per pair of co-located LTE cell and AP. It is reasonable to assume these parameters are known in a co-located scenario.

In the investigated SEMAFOUR scenario (Section 3.7.1 and 3.8.1), the scaling factor is fixed and equal for any co-located cell pair, and can be calculated as follows at the system bandwidth for Wi-Fi of 20 MHz:

$$\Delta(\text{RSS-RSRP}) \approx Ptx_{\text{Wi-Fi\_dBm}} - Ptx_{\text{micro\_dBm}} + 10*\log10\left(\frac{\text{RSS Bandwidth}}{\text{RSRP Bandwidth}}\right) = 17.8 \text{ dB}. \quad (3\text{-}7)$$

This assumption is assumed to be realistic for in the considered deployment where all LTE micro cells are identical and all Wi-Fi APs are identical. The additional scaling due to the different carrier frequencies is neglected in Equation (3-7) because LTE operates in the 2.6GHz and Wi-Fi at 2.4GHz bands.

As an example, the UE will measure an RSS value of -92 dBm when receiving an RSRP = -110 dBm in a given location. In general the scaling factor can be determined per co-located cell pair.

Parameter	**Description**	**Setting**
$R_{MIN\text{-}L}$ (per UE)	Assumed LTE UE minimum bit rate for estimating the cell utilisation metric (CU)	4 Mbps
CU_{Per}	LTE cell utilisation observation period	1 sec
α_L	LTE cell resource utilization smoothing factor	0.3
CU_{Lfil}	LTE cell utilisation filtered	See eq (5)
$THR_{O\text{-}L}$	Overload LTE cell utilisation threshold	Not used
$THR_{H\text{-}L}$	High LTE cell utilisation threshold	80%
$THR_{L\text{-}L}$	Low LTE cell utilisation threshold	60%
RSS_min (fixed)	Minimum Wi-Fi RSS for connectivity	- 92dBm
RSRP_THR_LOW (fixed)	LTE RSRP threshold for UEs connected to a macro cell	- 80dBm
RSRP_THR_HIGH (SON controlled)	LTE RSRP threshold for UEs connected to a micro cell	See Figure 28.
RSRP_thrHStep	RSRP_THR_HIGH step value	5 dB
RSRP_thrHInit	RSRP_THR_HIGH initial value	- 70dBm
RSRP_thrHMin	RSRP_THR_HIGH minimum value	- 110dBm
RSRP_thrHMax	RSRP_THR_HIGH maximum value	- 40 dBm

Table 8: RSRP-based SON algorithm parameter configuration

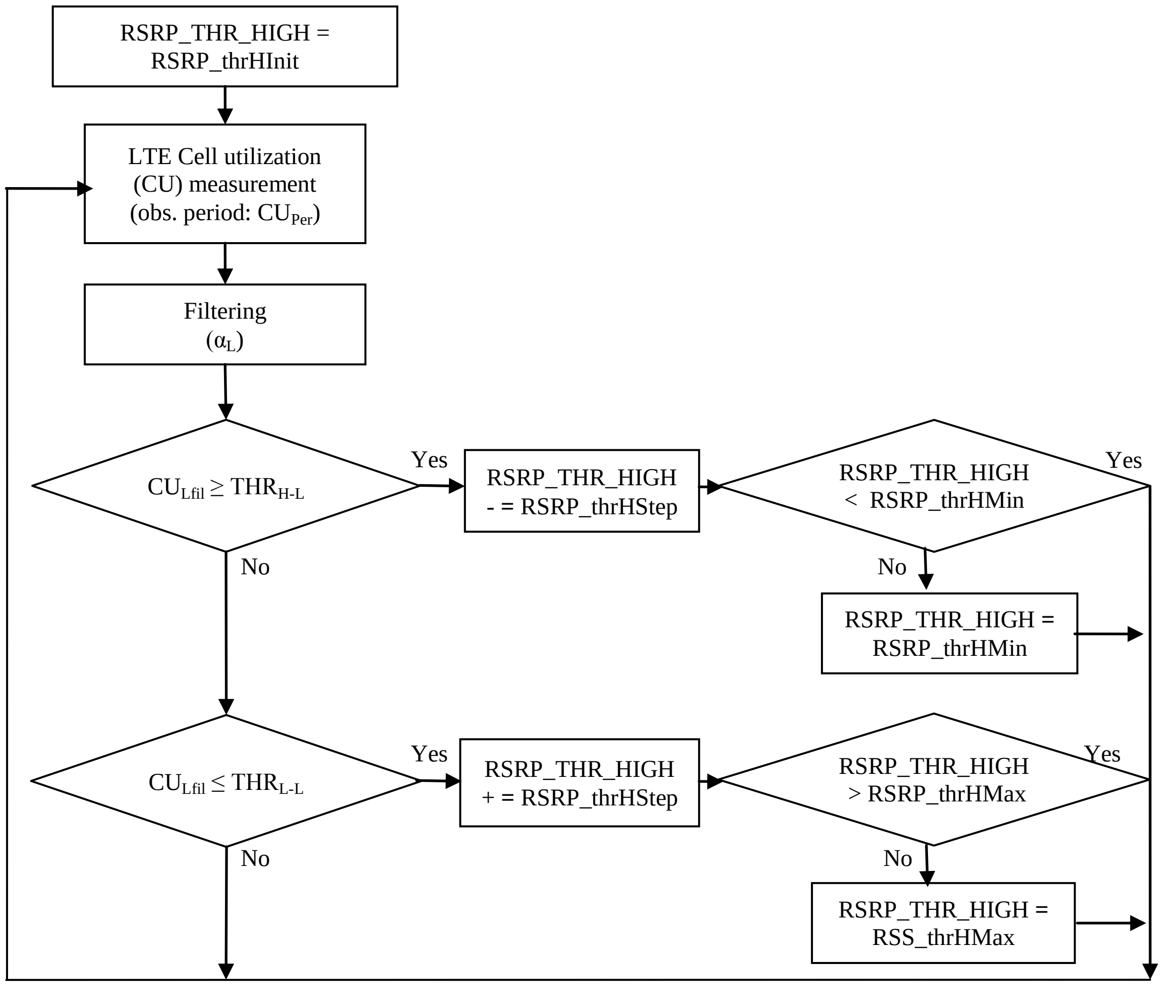

Figure 28: Flowchart for the RSRP -based SON algorithm for adjusting the RSRP_THR_HIGH threshold value in a micro cell with co-located Wi-Fi access.

3.9.2 Operator Policies

Given the adopted monitoring KPIs, the operator policy for network access preference could be realized by configuring different values to the cell utilization thresholds explained in Section 3.9.1.1 and 3.9.1.2.

For example, if an operator wants to prioritize LTE users regardless the user experience in Wi-Fi the THR_{O-W} and THR_{H-W} in Table 7 should be set to high values, e.g. equal to or even greater than 100% and THR_{H-L} should be configured to small values. With such settings, offloading to Wi-Fi will be triggered when the LTE cell utilization reaches the small THR_{H-L} and traffic will be steered to Wi-Fi even if the AP has been congested.

Given the method described above, the policy of LTE prioritized, Wi-Fi prioritized and balanced performance can be realized with sufficient flexibility to adjust the level of preference.

3.10 Initial Performance Evaluation

3.10.1 Methodology and Objectives

Based on the C&O studies, two SON algorithms, RSS-based and RSRP / RSS-based, were developed and implemented in the simulators. The SON functions were simulated with the modified OHZ scenario and results were analysed and compared with baselines and C&O outcomes. Sensitivity and stability of the SON algorithms were investigated by tuning SON configurations and changing traffic modelling assumptions.

The objective is to understand the performance of the SON functions, identify limitations and propose future studies based on the initial evaluation.

3.10.2 Scenario

The performance evaluation scenario used for evaluating the two SON algorithms was the same as the C&O scenario as described in Section 3.8.2.

The C&O studies have revealed the use of the selected control parameters in the basic Wi-Fi TS mechanisms and their overall impact on system / user KPIs. The C&O results highlighted the expected spatially non-homogenous performance due to the different traffic load in the different cells when a fixed setting of TS parameters is used for all the cells. Therefore in the SON studies the selected TS parameters are adjusted automatically and independently in each LTE cell based on the estimated load levels (LTE and Wi-Fi).

Furthermore, it was also observed in the C&O results that for optimal user performance, the Wi-Fi TS mechanism should be operated differently in the cells without co-located Wi-Fi access (in this study macro) compared to the cells with co-located Wi-Fi access (in this study micro).

3.10.3 Performance Evaluation

3.10.3.1 RSS-based SON Algorithm

The performance evaluation of the RSS-based SON algorithm described in Section 3.9.1.1 is summarized in this section. The numerical study was performed by the Simulator I described in Section 3.7.2.1.

3.10.3.1.1 SON Parameter Setting

Based on the C&O study, the SON parameters were configured as listed in Table 7. The resource utilization thresholds for Wi-Fi were set lower than the ones for LTE since the radio capacity of an AP is less than a micro as discussed in Section 3.8.3.5.2. The RSS threshold was initialized to the upper bound. The combination of the high α_L/α_W and the 1 dB step size made the algorithm response to traffic change promptly without losing stability. This aspect is further analysed in Section 3.10.3.1.4.

3.10.3.1.2 User Throughput Evaluation

The user throughput statistics obtained from the SON simulation are summarized in Table 9 and Figure 29 (right), and compared with the C&O results. The statistics were collected after the SON algorithm had been running for 50 seconds to exclude the phase of the RSS threshold adjustment from the initial value. The four fixed RSS thresholds were chosen either as baselines or because they were best performed among the simulated thresholds. The throughput gains over the baselines were significant. The average user throughput was slightly higher than the best fixed threshold (-55 dBm).

	5^{th} percentile user throughput (Mbps)	Average user throughput (Mbps)
RSS-based SON function	0.63	11.1
Baseline: Wi-Fi if coverage offloading Fixed RSS threshold = -85 dBm	0.01	2.4
Baseline: LTE only Fixed RSS threshold = inf	0.25	8.8
Best 5^{th} percentile user throughput Fixed RSS threshold = -50 dBm	0.36	10.0
Best average user throughput Fixed RSS threshold = -55 dBm	0.15	10.7

Table 9: DL user throughput comparison between RSS-based SON function and baselines

The gain in the 5th percentile throughput was 75% comparing to the best fixed threshold (-50 dBm). The results imply that the SON function is capable of approaching and exceeding the performance of the best fixed RSS thresholds in terms of user experience.

Figure 29 (left) shows the overall and per layer DL user throughput distribution. The micro and Wi-Fi layers had similar throughput distribution which proves that the SON function successfully avoided any layer from being more congested than the other.

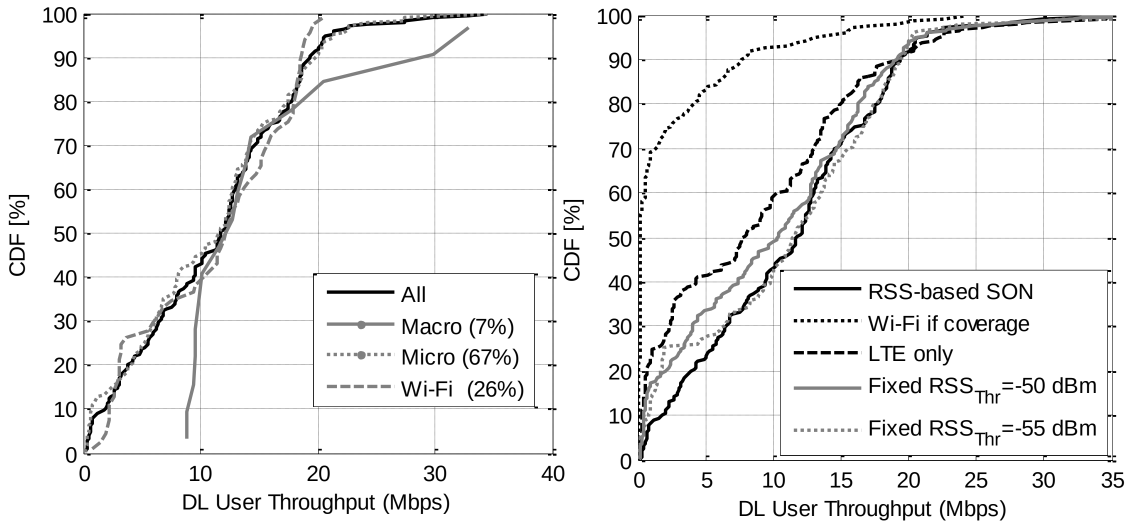

Figure 29: Left: Per layer CDF of DL user throughput with the SON function (values in bracket are percentages of user session); right: CDF of DL user throughput with the SON function and the baselines

3.10.3.1.3 SON Algorithm Behaviour Analysis

When the SON algorithm adjusts the RSS threshold, it increases or decreases the opportunity that nearby users are connected to LTE or Wi-Fi by changing cell sizes. In other words, the algorithm does not know for certain if any user traffic will be steered after one adjustment step. Given this limitation, it is difficult for the algorithm to target at short term optimization even though the RSS threshold may be updated quite frequently. Another limitation comes from the assumption that the steering is only executed when a session is initialized and not afterwards.

On the other hand, the algorithm should be able to respond to system load changes fast enough and reach to a stable optimal threshold when the offered load does not change rapidly. The SON investigation in this deliverable focuses on testing if and how fast the optimum threshold can be reached with constant average offered traffic. SON function evaluation in a more dynamic situation, e.g. with offered load changes and user mobility, is planned as future activities.

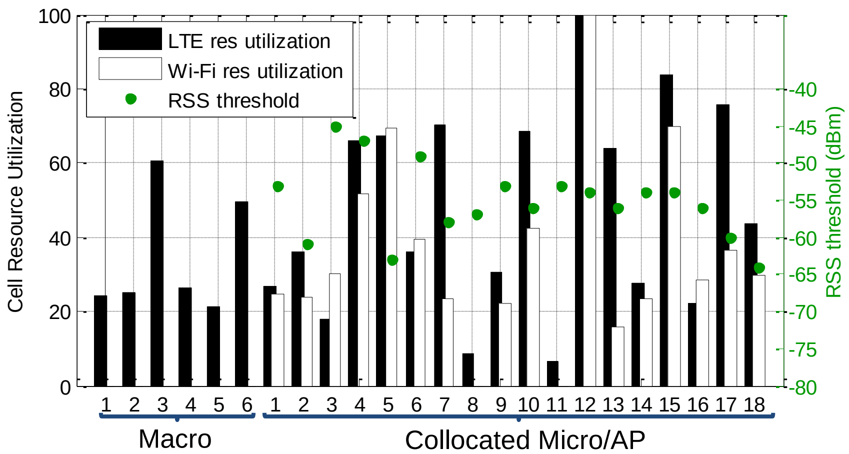

Figure 30: Cell resource utilization (left y-axis) and the RSS threshold (right y-axis) of each cell

Figure 30 shows the per AP RSS threshold and the per cell resource utilization after the SON algorithm had been running for 100 seconds. The thresholds of most APs were between -65 to -45 dBm which was proved as a range of optimum thresholds by the C&O study for the evaluated scenario. The individual optimization of each AP gives more degree of freedom comparing to the fixed RSS threshold settings. The load of the co-located AP / micro 4, 12 and 15 was more balanced after the SON optimization comparing to Figure 19, which explains the gain of the SON algorithm in the 5th percentile user throughput.
The resource utilization was successfully balanced between the co-located micro and AP with slightly higher utilization in micros. This can be explained by the different THR_H and THR_L configurations to the two systems in Table 7.

3.10.3.1.4 SON Algorithm Sensitivity and Stability Analysis

The sensitivity and stability of the SON algorithm depends on SON configuration, traffic types, user mobility and system load variations. The first two aspects are analysed in this section, and a more in-depth analysis is planned for the next phase of the study.

To illustrate the analysis, the RSS threshold adjustment and cell resource utilization during 100 seconds in the cell pair of AP / micro 5 is shown in Figure 31 and a throughput comparison is summarized in Table 10. The reference setting as specified in Table 7 is compared with three modified configurations.

With the reference setting (A), the RSS threshold initial adjustment phase, i.e. the monotonically decreasing period, took 30 seconds, and the fluctuation after the initial phase was in a range of approximately 8 dB around -65 dBm.

A smaller filter parameter (α) delayed and sometimes suppressed the SON reaction to the arrival and removal of a user session. The SON may become more stable with a delayed response to actual resource utilization changes. Figure 31 shows that the filtering made the threshold fluctuation larger. So a small α does not necessarily stabilize the threshold and the large α=0.9 performed better in the evaluated scenario. Its effects on the SON performance in other scenarios are subject to further analysis.

The high $RSS_{Initial}$ setting made it closer to the known optimum thresholds. When it was set to a lower value, i.e. -80 dBm, the SON algorithm still could reach a stable threshold but with a longer transition period of 40 seconds.

The overall average user throughput with the modified configurations was close to the reference case. However, degradation in the 5th percentile user throughput was observed. The explanation is not straightforward. As shown in Section 3.8.3.5.2, the 5th percentile throughput was mainly determined by a few cell pairs where both LTE and Wi-Fi are highly loaded. The RSS thresholds set for the most congested cell pair 12 are -54, -56 and -57 dBm for the case A, B and C, respectively. With the smallest AP cell size, the case A gave a more balanced load between the AP and micro in the cell pair 12 hence better 5th percentile user throughput. However, the trend in the RSS threshold setting was the opposite in cell pair 5 as shown in Figure 31. Further investigation is required to draw general conclusions.

SON function	AP5 average user throughput (Mbps)	Micro5 average user throughput (Mbps)	Overall 5th percentile user throughput (Mbps)	Overall average user throughput (Mbps)
(A) α = 0.9, $RSS_{Initial}$ = -45 dBm	13.5	10.2	0.63	11.1
(B) α = 0.3, $RSS_{Initial}$ = -45 dBm	17.4	8.7	0.35	10.7
(C) α = 0.9, $RSS_{Initial}$ = -80 dBm	18.1	9.2	0.21	11.0
(D) File size=1 MB User arrival rate=60	14.0	7.5	1.06	8.7

Table 10: DL user throughput comparison for SON algorithm sensitivity analysis

As it is stated in Section 3.9.1.1, using resource utilizations as monitoring KPIs makes the SON algorithm sensitive to file sizes. A modification in traffic modelling parameters was made to analyse the SON performance with a smaller file size but a higher user arrival rate. The results showed a shorter transition period and a smaller variation in the stabilized threshold as expected. However, the throughput statistics were not comparable to the other cases as the total offered traffic was different.

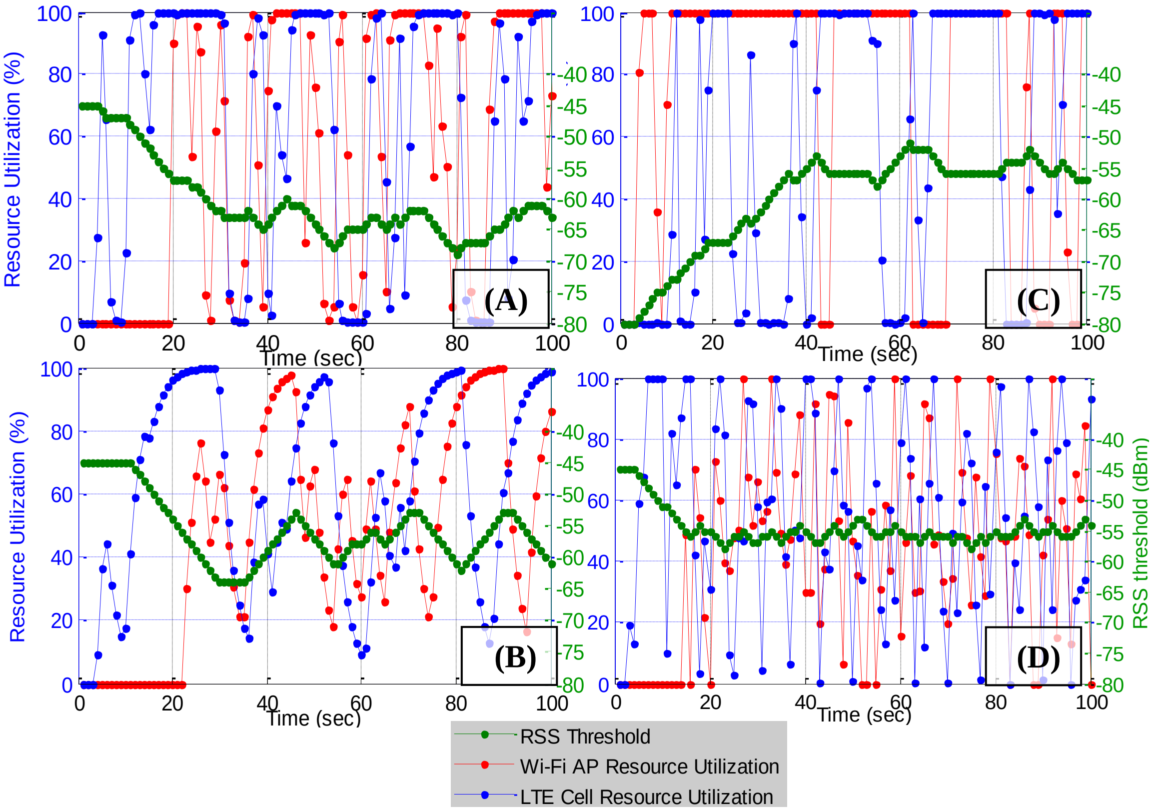

Figure 31: RSS threshold adjustment and cell resource utilization variation in AP/micro 4 (A): reference, (B): α=0.3, (C): $RSS_{Initial}$=-80 dBm, (D) file size=1 MB user arrival rate=60

3.10.3.1.5 Way Forward

The capability of the RSS-based SON function to improve user experience and system efficiency was proven by comparing it to static access selection in the evaluated scenario. A number of topics for future investigation were identified through the study:

- Additional monitoring KPIs that better reflect cell load in both LTE and Wi-Fi must be added to the SON function to cope with full buffer traffic and improve SON performance
- The SON function needs to be evaluated in additional scenarios with, e.g. different network load levels, user mobility, mixed and / or more dynamic traffic, standalone Wi-Fi APs, indoor environments, etc.
- Analysis and optimization of SON configurations in different scenarios

In order to further improve user and system performance, enhanced and / or additional SON functions need to be proposed to

- Steer on-going sessions instead of only selecting a RAT when a session is started
- Configure a RSS threshold for each pair of Wi-Fi AP and LTE cell instead of each AP to enhance flexibility
- Reinforce controllability by enabling per-UE steering capability (See example in Appendix A.2).

3.10.3.2 RSRP-based SON Algorithm

The performance evaluation of the RSRP-based SON algorithm described in Section 3.9.1.2 is evaluated in this section. The numerical study was performed by the Simulator II, described in Section 3.7.2.2. In the proposed RSRP-based SON algorithm a static *RSRP_THR_LOW* threshold is applied to UEs connected to a macro cell, while a dynamic *RSRP_THR_HIGH* threshold is applied to UEs connected to a micro cell.

3.10.3.2.1 SON Parameter Setting

The RSRP-based SON algorithm is initialised based on the RSRP thresholds values identified in the C&O studies (see Section 3.8.3.5.3). The parameters are summarised in Table 8 (in Section 3.9.1.2).

The *RSRP_THR_HIGH* is adjusted by the SON algorithm in steps of *RSRP_THR_HIGH_thrStep* = 5 dB (up or down). The observation period for the cell utilisation (CU_{Per}) is set to 1 second and the CU metric is filtered according to Equation (3-5) with a smoothing factor of α_L = 0.3. The LTE minimum data rate used to estimate the CU metric, $R_{MIN\text{-}L}$, was set to 4 Mbps (per UE).

The initial value for the *RSRP_THR_HIGH*, *RSRP_THR_HIGH_thrInitial*, was set to -70 dBm aligned to what the C&O studies indicated as being the optimal setting when combined with the fixed *RSRP_THR_LOW* of –80 dBm.

3.10.3.2.2 SON algorithm behaviour analysis

In order to analyse the proposed SON algorithm it is of interest to look at its behaviour across the cells in the investigated area. The traffic load is non-uniformly distributed (see 3.8.2) and it is expected that the LTE cells with higher offered traffic will adjust the RSS threshold differently compared to the less loaded LTE cells.

In Figure 32 we show the results obtained when simulating the network and the SON algorithm with the settings listed in Table 8.

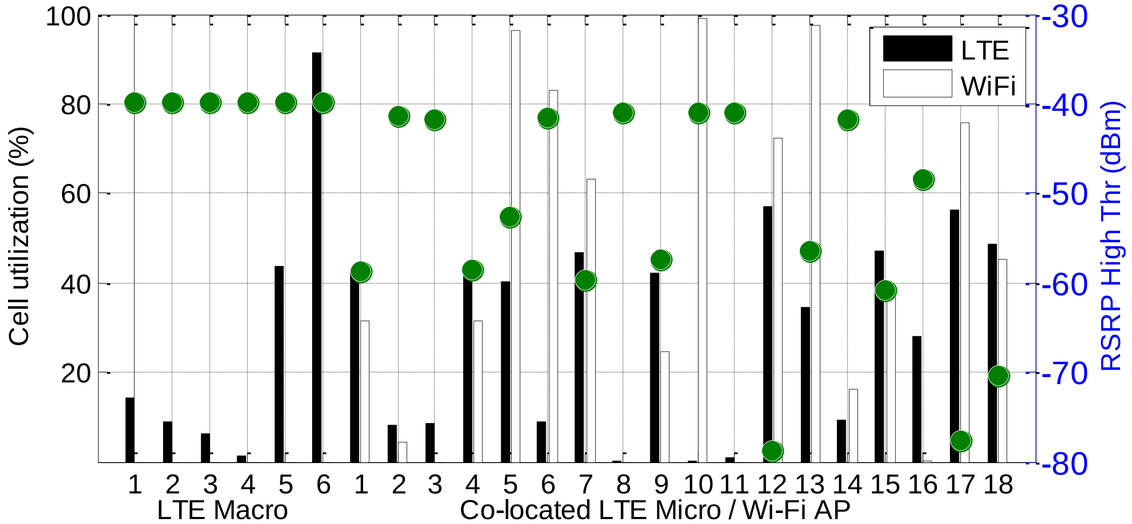

Figure 32: Average LTE / Wi-Fi cell resource utilization and the achieved RSRP_Thr_High value at each LTE Micro, for a fixed RSRP_Thr_Low = -70dBm

The first observation can be made on the outcome of the SON algorithm in the macro cells (index 1 to 6 in Figure 32). The LTE macro cells 5 and 6 are significantly more loaded compared to the other macro cells because these two cells / sectors point directly towards the traffic hot zone area (see Figure 15). However, the offloading opportunities for macro index 6 are only partial as this cell covers a large area with no micro or Wi-Fi deployment.

A second observation relates to the utilisation (CU) metric observed in the Wi-Fi cells: all APs have 100% utilisation, meaning they serve at least one UE during any observation period. This indicates good utilisation of the Wi-Fi network but does not provide insight on the achieved user throughput performance. The corresponding co-located LTE micro cells all have a CU metric below the upper threshold (80%), i.e. the SON algorithm correctly achieved the targeted traffic offload.

A third important observation is that in all LTE micro cells with significant traffic load, i.e. cell index 12, 17, and 18, the *RSRP_THR_HIGH* has converged to values below the initial value of -70 dBm. This indicates that in the micro cells with high expected load the initial value of the *RSRP_THR_HIGH* could be lower than -70 dBm and in the range of -80 dBm to -70 dBm. In the other micro cells, with low traffic load (index 2, 3, 6, 8, 10, 11, 13, 14 and 16), the *RSRP_THR_HIGH* has converged to the higher value or even to the highest value -40dBm.

Figure 33 shows the time trace of the average LTE cell resource utilisation and Wi-Fi cell utilisation and the evolution of the *RSRP_THR_HIGH* value for the high loaded micro cell 17. It can be observed that the SON algorithm is able to react quickly to the large load fluctuations which occur in the cell, i.e. the *RSRP_THR_HIGH* value is decreased from the maximum allowed value of -40 dBm down to the minimum value of -110 dBm in only 14 steps (Δ = 70 dB) which take 14 s given the observation time of 1 s. This fast reaction is mainly due to the relatively large step size of 5 dB. Given this fast convergence, the algorithm results are rather insensitive to the setting of the initial value.

However, the algorithm has no means to reduce the overload situation that the micro 17 experiences (cell utilization equal to 100% for several seconds), because offloading is allowed only for sessions at the setup phase, i.e. the algorithm avoids that further sessions are started in an overloaded cell. This example illustrates the potential benefit from steering additionally on-going sessions, if needed.

The optimal *RSRP_THR_HIGH* value depends on the targeted average LTE cell load level and on the measured load level. The setting of the parameter $R_{MIN-L,}$ i.e. the LTE UE minimum bit rate for estimating the cell utilisation metric will then impact the achieved *RSRP_THR_HIGH* values and therefore the level of offloading to Wi-Fi.

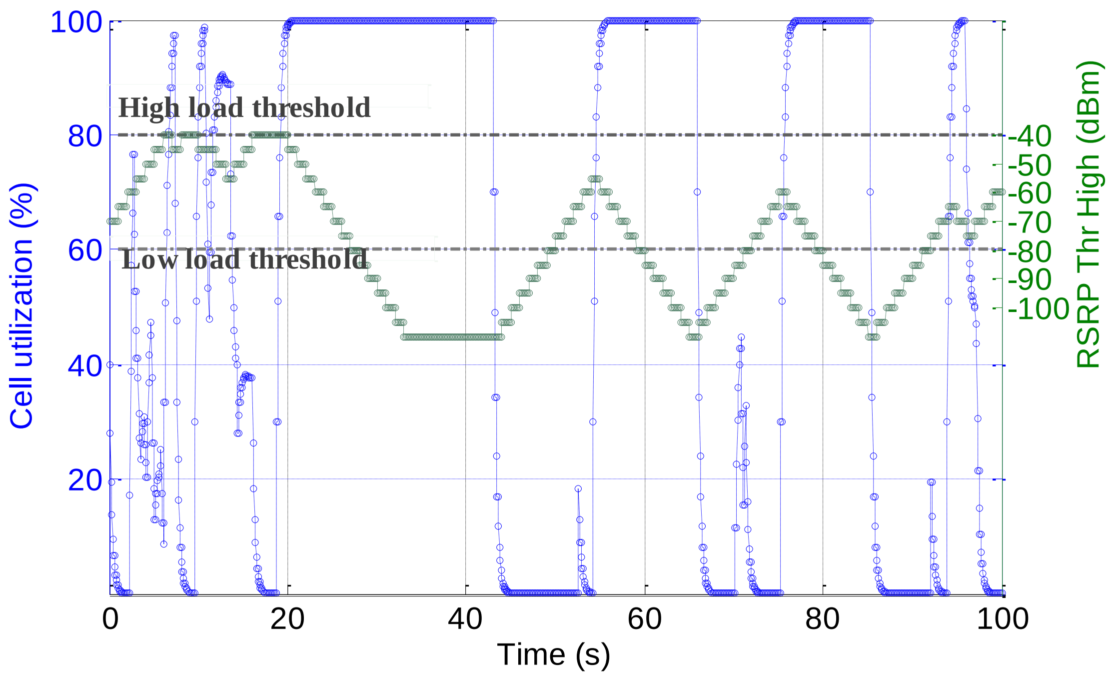

Figure 33: Time trace of the average LTE / Wi-Fi cell resource utilization and the achieved RSRP_Thr_High value at each Wi-Fi AP, for a fixed RSRP_Thr_Low = - 70 dBm in micro17.

3.10.3.2.3 Analysis of the outcome and way forward

The functionality of the RSRP-based SON TS algorithm depends on monitoring the average LTE cell load level and on the LTE RSRP measurements performed by the UEs. The target of the SON algorithm is to keep the average LTE cell load metric within a pre-defined range of 60% to 80%, by steering traffic to / from Wi-Fi as needed. To initiate off/on-loading to / from Wi-Fi, two RSRP thresholds parameters are used and assumed to be available to all the LTE UEs. The

RSRP_THR_HIGH threshold value depends on the targeted average LTE cell load and can be successfully used when the LTE cell has co-located Wi-Fi AP deployed (micro cell). The RSRP_THR_LOW parameter can / should be used in non-co-located deployments, when the LTE cell does not have Wi-Fi AP, such as typical macro cells.
The SON results show that the RSRP_THR_LOW threshold value can be set to a fixed value for all macro cells of interest per geographical area to -80 dBm, while the RSRP_THR_HIGH is adjusted automatically by the SON algorithm in the range of -110 dBm to -40dBm.
The next steps are to analyse in detail the throughput performance gain of the SON algorithm and to enhance it accounting also for the load in the Wi-Fi access point. For the estimate of the load of a Wi-Fi access point a simple measure can be the number of UEs served. Although this metric does not necessarily reflect the total traffic (Mbps) served by the Wi-Fi access point, it has been observed that the achievable UE throughput decreases quadratically with the number of UEs served [63] [64]. Thus 'high load' in terms of number of UEs served is always equivalent to low achievable UE throughput; hence, the offloading to Wi-Fi is not desirable.

The current misalignment of the absolute LTE performance numbers between the simulators, at this stage prevents the direct comparison of the RSRP-based SON algorithm results with the RSS-based SON algorithm performance presented in Section 3.10.3.1.

3.11 Conclusions, Remarks, and Way Forward

Traffic steering between a multi-layer LTE network and a Wi-Fi network was studied in this use case. The topic has not been well studied in academia, especially in heterogeneous environments with layered network deployment and mixed user profiles. In this deliverable, two SON algorithms were proposed and evaluated in a scenario with three network layers, i.e. LTE macro, LTE micro and Wi-Fi.

For each SON algorithm, up to two control parameters, i.e. RSS and RSRP thresholds, or two RSRP thresholds have been selected and evaluated in the C&O studies and proved as effective in controlling the UE radio access selection. The C&O outcomes led to the development of the RSS-based and RSRP-based algorithms, which were evaluated by system level simulations in an outdoor hot zone scenario. The behaviour and analysis of the RSS-based and RSRP-based algorithms were studied showing balancing load properties between the two access networks. The analysis of the throughput gains was presented for the RSS-based algorithm which show improved user throughput performance compared to the reference cases of Wi-Fi if coverage and fixed RSS threshold TS. The stability and sensitivity of the algorithm was also proved in the evaluated scenario.

A number of topics for future investigation have been identified through the study:

- Better calibration of the simulation tools to allow direct comparison between the performances of the analysed SON algorithms
- Additional monitoring KPIs that better reflect cell load in both LTE and Wi-Fi must be added to the SON function to cope with full buffer traffic and improve SON performance
- Additional monitoring KPIs that better reflect the user performance (experience) such as average and 5th percentile throughput
- The SON function needs to be evaluated and optimized in additional scenarios with, e.g. different network load levels, user mobility, mixed and / or more dynamic traffic, standalone Wi-Fi APs, indoor environments, etc.

In order to further improve user and system performance, enhanced and / or additional SON functions need to be considered to be able to provide several SON policy options and strategies to the operator, such as:

- Steer on-going sessions instead of only selecting a RAT when a session is started
- Reinforce controllability by enabling per-UE steering capability and performance metrics (See one example in Appendix A.2)

In the subsequent SEMAFOUR Deliverable D4.2 (confidential) we will address the topics listed above with main focus on the in-depth quantitative analysis of the proposed SON mechanisms.

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4 Idle Mode Handling

4.1 Executive Summary

The use case Idle Mode Handling focuses on the optimization of the cell reselection procedure so that the UE is always camped on the most appropriate cell. By being camped on a suitable cell, connection times are reduced and subsequent unnecessary handovers once the user becomes active are avoided.

An intelligent Idle Mode Handling would work as a pro-active load balancing mechanism, similar to mobility load balancing (MLB) or traffic steering (TS) for connected mode.

The optimization of the cell reselection procedure could be done either by dynamically adjusting the cell reselection control parameters or by adding extra control parameters and extra complexity in the user equipment.

Most MLB and TS schemes focus on the connected mode, where the user is active and RLFs and call drops may occur. However, the idle mode should not be neglected just due to the lack of an active session. If the users are well distributed while in idle, the number of handovers subsequent to the user switching to connected mode will be minimized. This will translate into signalling, packet loss and delay reduction, which may directly affect the QoS for the user and diminish the strain on the network. However, the magnitude of such gains is significantly smaller than that of traffic steering in connected mode. For best results, the traffic steering strategies in both idle and connected mode should be aligned in order to prevent conflicts and maximize gain.

The first step in the use case study was to perform a state of the art investigation and a technical review. Based on these and the predicted magnitude of the gain, it was decided not to continue to the simulation phase with the use-case. The technical reasons for this are explained in detail in the following Sections 4.4.1 and 4.5. For sake of completeness all the technical details of the originally planned use case have been included.

4.2 List of Definitions

This section lists the main definitions and terminology adopted in the context of this use case.

Camped on a cell**:** UE has completed the cell selection/reselection process and has chosen a cell. The UE monitors system information and (in most cases) paging information.

DRX cycle**:** UE specific time interval between monitoring Paging Occasions.

Serving cell: The cell on which the UE is camped.

Strongest cell: The cell on a particular carrier that is considered strongest according to the layer 1 cell search procedure [100],[101].

Suitable Cell: This is a cell on which an UE may camp.

Connected state: Refers to RRC_connected in LTE.

Idle state: Refers to RRC_idle in LTE.

4.3 Problem Description and Objectives

Choosing the right cell for the UE to camp on between different available layers and RATs is controlled by the cell reselection procedure, which is parameterized by typically static values. This procedure could be optimized by taking into account more dynamic information such as the cell load, the UE speed and UE characteristics (mean idle period, traffic type and session lengths). By doing so, the UE will have access to tailored cell reselection settings that will improve its QoS when it becomes active.

The objective of the SON function to be developed for the Idle Mode Handling use case is to automatically adjust the cell reselection parameters in order to improve the UE and network performance. The control parameter values determine when and which cell the UE performs cell reselection to. It is therefore important that control parameter tuning is done in a dynamic way reflecting the UE traffic patterns, UE speed and the network/cell load.

4.4 State-of-the-Art

4.4.1 Academic Publications

Several papers that deal with cell reselection optimization have been found during the literature scan and the most relevant findings are listed below. Of special importance is [113] and [115] that conclude that, at best, idle mode optimization can only bring minimal QoS gains over connected mode optimization. This only strengthens our conclusion that cell reselection optimization adds additional complexity without delivering substantial gains.

[106] looks at EUTRAN and UTRAN and proposes to reduce current UE battery consumption in idle mode by performing fewer measurements of neighbouring cells. Similar to EUTRAN, in UTRAN the UE will perform measurements when the quality of the current cell drops below a threshold $S_{intrasearch}$. High values of this parameter will yield to more measurements at the UE side.

The paper proposed optimizing the value of $S_{intrasearch}$ based on the mean received energy per chip of the pilot channel experienced in the network. Results show that by applying this technique in four networks (real data) the battery consumption can be diminished by a maximum of 16% without affecting the number of cell reselections performed by the UE.

[107] is a detailed sensitivity analysis for cell-reselection in WCDMA which has similar rules to LTE. The paper uses the downlink camping cell quality (1^{st} percentile of the CPICH Ec/No distribution) and UE stand-by time as KPIs. By comparing different combinations of control parameters (DRXcycle length vs. $T_{reselection}$, effect of velocity and RF environment, $T_{reselection}$ vs. hysteresis, $S_{intrasearch}$ and $Q_{qualmin}$) the authors propose a set of optimal parameter values.

[108] proposes a MLB scheme based on cell reselection that works in coordination with MRO. The conventional MLB schemes based on HO conflict with MRO and the simulation results show that the conventional MLB scheme cannot achieve load-balancing gain without some degradation in HO performance. The authors use cell ranking and define throughput gain as a KPI.
The proposed scheme can realize load balancing effectively on a par with conventional schemes without any degradation in HO performance. The simulation results have also shown that the proposed scheme is particularly effective in an environment where a lot of small-size data packets are transmitted by a large number of users, which is highly applicable to current mobile networks. In such case, more than 10% and 90% gains can be obtained in the total throughput and 5th percentile user throughput, respectively.

[109] suggests a scheme that reduces the signalling by sending an inter-technology update to the network only when the UE loses coverage of the previously used technology. The performance of this scheme is tested against that of the approach of camping on the preferred technology whenever coverage of that technology is available. LTE spotty coverage is assumed. The results indicate small benefits that can be obtained by using better techniques to reduce inter-technology updates.

[110] focuses on LTE cell reselection and reliability of UE mobility state detection. The paper proposes a scheme with dual simultaneous filtering as an alternative for determining the UE mobility class and just determines when a cell-reselection should occur.

- A long filter is used for gradual changes (due to low mobility) , i.e. Q_{hyst} is low and $T_{reselection}$ is high
- A short filter is used for abrupt changes (due to high mobility), i.e. Q_{hyst} is high and $T_{reselection}$ is low

Looking at the combined probability of medium/high vs. low mobility state, it can be seen that the low- and medium/high-speed users can still be differentiated with reasonable accuracy. This suggests that the mobility state detection based on the number of reselections can still work well enough for the purpose of the algorithm.

[111] investigates the potentials of traffic steering in the idle state by evaluating the absolute priorities framework in a multilayer LTE macro cell scenario. A SON algorithm sets the absolute priorities for different LTE frequencies based on the load and coverage conditions of each layer. The absolute priorities are set for each individual UE and included in the RRC_CONNECTION_RELEASE

message. By using this approach better load balancing is achieved, along with improved user experience and network capacity. The only drawback of this method is that the absolute priorities are set to a constant value the whole time the UE is idle and are only updated after the UE has become active and then switched to idle once more.

[112] looks at traffic steering both in connected and idle mode in a scenario comprising of HSPA macros and picos and LTE picos. For the idle mode, absolute priorities are set for the different layers in the scenario. Due to 3GPP limitation on how these absolute priorities can be assigned, only 2 candidate sets of absolute priorities were found. The paper results highlight that using absolute priorities (as opposed to not using them) allows controlling the load distribution between layers and with 100% LTE penetration, macro offloading is increased.

[113] investigates the potentials of traffic steering in idle state by evaluating the absolute priority and dedicated priority framework in a multilayer LTE macro cell scenario. The absolute priorities approach has proven to overload the prioritized layers while the other layers remain underutilized.
If dedicated priorities are provided to the terminal via the *ConnectionRelease* signalling, this results in users being more evenly distributed between layers but also improved average user throughput.
The paper also investigates the consequences in terms of handovers and cell reselection rate, which could be considered as the costs of the approach in terms of signalling and UE power consumption. Using the dedicated priorities scheme decreases the signalling overhead generated by the mobility events significantly due to the fact that idle-to-connected ping-pongs (and vice versa) are minimized due to the handover/ reselection rate reduction.
The paper also concludes that under no circumstances, sole idle mode traffic steering could outperform Traffic Steering in connected mode due to its slower adaptation to the load variations.

In [115] several inter-frequency / traffic steering methods are evaluated:
- Traffic steering in idle mode, using absolute priorities
- Traffic steering at connection setup
- Traffic steering handovers in connected mode
- Traffic steering at connection release by configuring absolute priorities

The paper draws the following conclusions. Absolute priorities are sufficient in initial LTE deployments (single carrier), when LTE terminal penetration is low and the system is not loaded. When multiple carriers/bands are available, performance results show that by leveraging absolute priorities and traffic steering at connection setup it is possible to achieve close-to-optimum utilization of available resources. In fact, the combination of traffic steering methods attains most of the achievable gains in terms of user throughput over all users and its behaviour is consistent in all scenarios.

4.4.2 Standardization

In an LTE network, a registered UE can find itself in one of two states: connected or idle. While in connected mode, the network has all the information necessary regarding the UE for communication and several identifiers assigned to it. Once the UE is no longer in a session, it will switch itself to idle state in order to save battery. The mobility of a connected UE is handled by handover procedures while in idle this is done by cell reselection procedures. More specifically, the UE searches for a suitable cell and tunes to its control channel. This is known as "camping on the cell".

4.4.2.1 Cell Selection vs. Cell Reselection in LTE

Cell selection and cell reselection procedures in LTE are described in [99]. A UE that has just been switched on will look for a suitable cell to connect to via the *cell selection* procedure. After this procedure the UE will be camped on that cell. While in this state, the UE shall regularly search for a better cell according to the *cell reselection* criteria. If a better cell is found, then that cell is selected. The change of cell may imply a change of RAT.

The UE performs measurements for cell selection and reselection purposes as specified in [102] and the cell selection and reselection flows are presented in Figure 34.

In the case of cell selection, the criterion S as described by the equations below has to be fulfilled:

$$S_{rxlev} > 0 \ AND \ S_{qual} > 0$$

where:

$$Srxlev = Q_{rxlevmeas} - \left(Q_{rxlevmin} + Q_{rxlevminoffset}\right) - P_{compensation}$$

$$S_{qual} = Q_{qualmeas-}(Q_{qualmin} + Q_{qualminoffset})$$

The parameters and their values are included in Table 11.

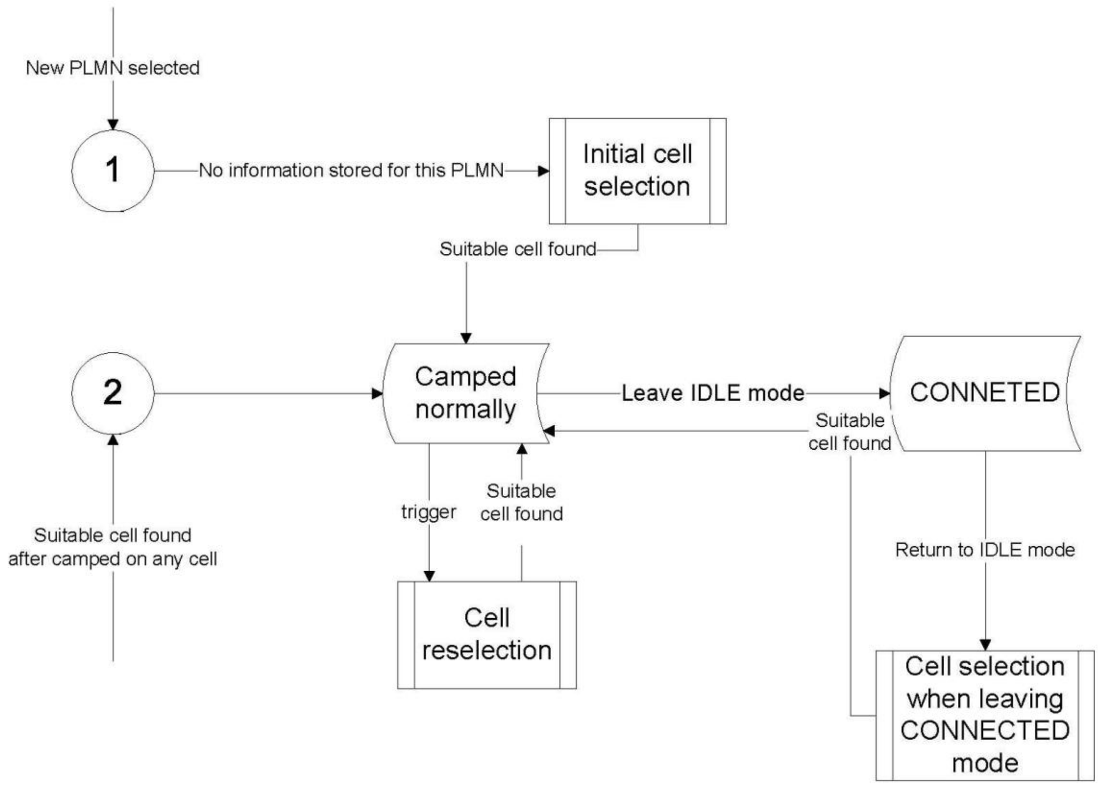

Figure 34: Cell selection and cell reselection

The signalled values $Q_{rxlevminoffset}$ and $Q_{qualminoffset}$ can be ignored. They are only applied when a cell is evaluated for cell selection as a result of a periodic search for a higher priority PLMN while camped normally in a VPLMN.

4.4.2.2 Cell Reselection

As specified in [99], cell reselection procedures make use of priorities allocated to different frequency layers. These can be global priorities (Absolute Priorities) or dedicated (Dedicated Cell Reselection Priorities), both are described below.

The ***Absolute priorities*** of different E-UTRAN frequencies or inter-RAT frequencies may be provided to the UE via system information, or by inheriting from another RAT at inter-RAT cell (re)selection.

The limitation of absolute priorities is that they are the same for all UEs. As a result, all UEs will always try to move to higher priority layers when in its coverage area. This may cause overload of this layer and due to constant measurements, the battery life of the UE is also shortened.

By using ***Dedicated Cell Reselection Priorities,*** the drawback of absolute priorities may be solved. Dedicated priorities are included in the *ConnectionRelease* message and are UE specific. The dedicated priorities are dynamic and may be adjusted based on load and coverage conditions. For the load estimation, the concept of Composite Available Capacity (CAC) [104] can be utilized, declaring the amount of resources that each cell has free. Dedicated priorities also have a validity timer associated (T320). When this timer runs out, the dedicated priorities are no longer valid and the UE shall perform cell reselection according to absolute priorities.

In both cases, equal priorities between different RATs are not supported.

Parameter name	Parameter definition	Parameter value range
Srxlev	Cell selection RX level value (dB)	Not specified
Squal	Cell selection quality value (dB)	Not specified
$\boldsymbol{Q_{rxlevmeas}}$	Measured cell RX level value	RSRP
$\boldsymbol{Q_{qualmeas}}$	Measured cell quality value	RSRQ
$\boldsymbol{Q_{rxlevmin}}$	Minimum required RX level in the cell (dBm), signalled in SIB1 [103]	(-140..-44)dB
$\boldsymbol{Q_{qualmin}}$	Minimum required quality level in the cell (dB)	Not specified
$\boldsymbol{Q_{rxlevminoffset}}$	Offset to the signalled $Q_{rxlevmin}$ taken into account in the Srxlev evaluation as a result of a periodic search for a higher priority PLMN while camped normally in a VPLMN	0 default (2..16)dB
$\boldsymbol{Q_{qualminoffset}}$	Offset to the signalled $Q_{qualmin}$ taken into account in the Squal evaluation as a result of a periodic search for a higher priority PLMN while camped normally in a VPLMN	Not specified
$\boldsymbol{P_{compensation}}$	max(P_{EMAX} –$P_{PowerClass}$, 0) (dB)	Not specified
$\boldsymbol{P_{EMAX}}$	Maximum TX power level a UE may use when transmitting on the uplink in the cell (dBm) defined as P_{EMAX} in SIB1	(-30..33)dBm
$\boldsymbol{P_{PowerClass}}$	Maximum RF output power of the UE (dBm) according to the UE power class as defined in [114]	23dBm

Table 11: Cell selection S criteria parameters

In the case of system information use, an E-UTRAN frequency or inter-RAT frequency may be listed without providing an absolute priority (i.e. the field *cellReselectionPriority* is absent for that frequency). If dedicated priorities are provided in dedicated signalling, the UE shall ignore all the priorities provided in system information.

When the UE, in *camped normally* state, has only dedicated priorities other than for the current frequency, the UE shall consider the current frequency to be the lowest priority frequency (i.e. lower than the eight network configured values).

The UE shall inherit the priorities provided by dedicated signalling and the remaining validity time (i.e. T320 in E-UTRA, T322 in UTRA), if configured, at inter-RAT cell (re)selection. T320 is included in the *ConnectionRelease* message (IE t320) [103] and T322 in [105] with the following possible values: [5, 10, 20, 30, 60, 120, 180] minutes.

[102] states that the UE shall search every layer of higher priority at least every $T_{higher\_priority\_search} = (60 * N_{layers})$ seconds, where N_{layers} is the total number of configured higher priority E-UTRA, UTRA FDD, UTRA TDD carrier frequencies according to the measurement rules in [102] and [103].

4.4.2.3 E-UTRAN Inter-Frequency and Inter-RAT Cell Reselection Criteria

For LTE inter-frequency and inter-RAT cell reselection rules are described in detail in [99].

In short, the UE will perform cell reselection to a higher priority layer when it determines that the quality/signal level of the target cell is above a certain predefined threshold $Thresh_{X,\,HighQ}$ / $Thresh_{X,\,HighP}$ for a certain period of time ($Treselection_{RAT}$). Also the UE is not allowed to do cell reselection if it has been camping on the current cell for less than 1 second.

For equal priority layers, the UE will follow the cell ranking criteria that takes into account the signal levels of the serving and neighbour cells and a given Offset per serving–neighbour couple ($Qoffset_{s,n}$) and Hysteresis (Q_{hyst}) value.

For cell reselection to a lower priority layer, the quality of the cell the UE is camped on has to be lower than a preconfigured threshold ($Thresh_{Serving, LowQ}$) while the quality/signal level of the target cell is higher than a second threshold ($Thresh_{X, LowQ}$ / $Thresh_{X, LowP}$) for a certain period of time ($Treselection_{RAT}$).

4.4.2.4 UE Mobility States Parameter Scaling

In [99], different UE mobility states are specified. Some parameters (Q_{hyst} and $T_{relesection}$) may be scaled based on the UE's speed class. The eNB signals the information that allows the UE to place itself in a speed category (threshold and timer) and the corresponding scaling factors. The UE will keep track of the number of cell reselections it performs in the signalled time window, compare this to the signalled threshold and place itself in a speed category. The UE will then apply the corresponding scaling rules.

4.4.3 Summary and Recommendations

Based on the results provided by the literature study (e.g. [113] and [115]), we conclude that the gain achievable by cell reselection optimization is minimal on its own and small in comparison with that delivered by traffic steering in connected mode. Further refinements of the cell reselection procedure may be possible if extra complexity is added in the RAN node (i.e. eNB by computing and signalling sets of parameter value to be used by different UE categories in terms of speed, traffic pattern, etc.) and in the UE (e.g. computing various categories it could be placed in) but the expected gain would not justify this.

4.5 Architecture

As no SON function has been developed in this Use Case, this section is empty.

4.6 Main Monitoring KPIs

As no SON function has been developed in this Use Case, this section is empty.

4.7 Main Control and Configuration Parameters

As no SON function has been developed in this Use Case, this section is empty.

4.8 SON Function

As no SON function has been developed in this Use Case, this section is empty.

4.9 Conclusions, Remarks, and Way Forward

While there are a multitude of parameters that could be used to tune cell reselection and extra complexity could be added, it is our belief that, as shown also by recent research papers (especially [113] and [115]), that idle mode traffic steering alone cannot outperform traffic steering in connected mode. Even an alignment between traffic steering in idle and connected mode will only bring some minor advantages and these in terms of UE battery consumption and some reduces signalling.

In light of the above conclusion, we decided closing this use case without any further investigation.

4.10 References

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5 Tackling the Problem of High Mobility Users

5.1 Executive Summary

When there is a dense deployment of small cells or when user velocities are high, users tend to make frequent handovers. This use case focuses on mitigating these frequent handovers and the negative impact that is caused by them both on the users and the core network. In order to do so the SON function that will be developed in this use case will try to predict the future mobility behaviour of users based on the trajectory that they follow through a cell. By assuming that users that follow similar trajectories through a cell will behave the same in the future a user can be steered more appropriately, resulting in fewer handovers. In this document, a modified version of the dynamic time warping algorithm is developed that identifies users that follow similar trajectories through a cell. This algorithm searches for similarities between recent measurements made by active users and measurements that are made by users that were active in the past. Results show that the modified Dynamic Time Warping (DTW) algorithm is able to effectively identify users that follow similar trajectories within certain bounds.

As reducing the effects of frequent handovers on the core network is an important part of this use case, a second part of this use case focuses on quantifying these effects. For this, a theoretical model is constructed which is then used to estimate the overhead and delays that are caused by handovers in the core network.

5.2 List of Definitions

This section lists the main definitions and terminology adopted in the context of this use case.

Active Trace*:* A series of user measurements made by a user that is currently active. New measurements are regularly added to this series.

Cost Matrix*:* A matrix that expresses the distance between every element of an active series and every element of a reference series.

Reference Trace*:* A series of users measurements to which active traces are compared.

Trajectory Classifier*:* The component of the High Mobility SON function that is responsible for classifying users according to their trajectories.

Warping Path*:* A path through a cost matrix that starts in the upper left element of the matrix, ends at the lower right element of the matrix and where any element on the path can only be reached from the element to the left, top, or top left.

SGW*:* The Serving GW is the point of interconnection between the radio-side and the EPC. It is the anchor point for the intra-LTE mobility (i.e. in case of handover between eNodeBs) and between LTE and other 3GPP accesses.

MME*:* The Mobility Management Entity deals with the control plane. It handles the signalling related to mobility and security for E-UTRAN access. The MME is responsible for the tracking and the paging of the UEs in idle mode.

5.3 Problem Description and Objectives

When there is a dense deployment of small cells or when user velocities are high users tend to make frequent handovers. Such situations might occur in city centres where there are a high number of cells that cover a relatively small area or on a highway where users travel at a high velocity. In these cases the frequent handovers made by the users might cause a serious degradation of UE and network performance. The impact on the performance may be seen in:

- A reduced QoS experienced by the users with high mobility due to:
    - A cell stay time that is relatively short in comparison to the call time, to the time that it takes to make a handover and to the duration of the data outage during the handover.

  - An increased number of call drops for users with high mobility as a result of the high frequency of their handovers.
- An increased signalling and data overhead in the core network due to handover signalling and data forwarding.

In order to avoid the performance degradation of both the UEs and the network, this use case develops techniques that will classify users according to their mobility behaviour and steer them to appropriate cells such that the handover frequency becomes lower and the negative effects of frequent handovers are reduced without considerably influencing other QoS parameters like throughput. In a dense deployment of small cells this can be done by steering users that have high mobility to a macro cell where they can stay connected to for a longer time while steering users that have low mobility to smaller micro and pico cells. When there are no larger cells to steer users to, but the frequent handovers are caused by the high velocity of users, the frequency of handovers can be limited by more intelligently handing over users by for instance not handing them over to cells through which they only pass for a small amount of time, for instance near the edge (see Figure 35).

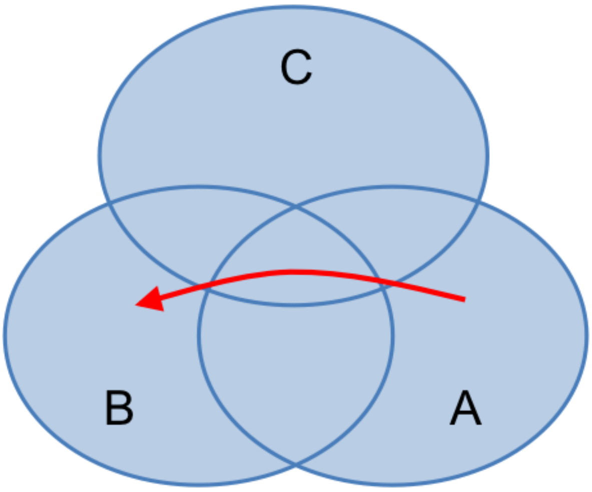

Figure 35: The user only passes through the edge of cell C while it is still covered by cells A and B.

As mentioned before the high mobility SON function will classify users according to their mobility behaviour and predict their mobility future based on this classification by assuming that all users in the same mobility class will behave the same in terms of cells they will visit in the future, velocity at which they will travel and so on. The rationale behind this is that users do not just move in a random fashion but that users follow certain trajectories along roads. Users that travel on a highway for instance will tend to stay on that highway and will thus likely handover to the same cell as other users that travel on the highway while users in a residential area along the highway will not. In a city centre users that come from a certain street will at a crossroad less likely take a street that will lead them back to the same direction where they came from.

Users can be steered within the same layer and RAT but also between different layers (macro, micro, pico cells) and/or RATs (LTE, UMTS, etc.) depending on their mobility behaviour and the availability of layers and RATs to steer them to.

As one of the reasons of reducing frequent handovers is avoiding overhead of both signalling and data traffic in the core, this use case will also include both a theoretical and a simulation study on what the actual impact of handovers on the core network is. Furthermore the limitations imposed on handovers by the core network and the impact thereof will also be investigated. The core network might for instance cause timing constraints on the execution of a handover. By investigating these limitations this study will be able to provide a more realistic way for modelling handovers in the simulator that is used for studying this use case. First, this study will be performed in a theoretical way, investigating the 3GPP standards. The outcome of this theoretical analysis is presented in this deliverable. Next, an extensive experimental study will be executed on a real testbed with the OpenEPC platform. This will give further insights in the signalling overhead in the EPC in a real-life experimental environment. This is foreseen for next deliverables.

The following section (Section 5.4) will describe the state-of-the-art of both aspects of this use case. Sections 0 until 5.11 will focus on reducing frequent handovers, specifically how users can be classified depending on the trajectory that they follow through a cell. In Section 5.12 the theoretical study of the impact of handovers on the core network will be presented. Finally conclusions and the way forward for both studies are described in Section 5.13.

5.4 State-of-the-art

5.4.1 Academic Publications

Frequent handovers and the problems that are caused by them have been described in a number of papers like [121] and [132]. [133] measures the 3G and 3.5G network performance from fast moving cars and high-speed trains. Results show that the performance in these cases is very low.

Solutions for reducing frequent handovers by learning where handovers occur have been studied in a number of academic papers. In [131] for instance the algorithm learns the locations where unnecessary handovers occur and decides, based on previous experience whether to permit or prohibit handovers in these locations. These algorithms are however designed to be deployed on femto cells and meant to operate in an indoor environment. They also only take the position of users into account and not their past behaviour.

In most publications concerning RAN activities, whether they involve simulations or actual experiments, core network signalling latencies are taken into account. However, they are mostly simply estimated. In [121], Zhang et al. tried to quantify handover signalling latency and overhead, by correlating it to the delay on UDP/TCP packets received by a UE. The same goes for [122] and [123]. This is, however, a very indirect approach, since these are measurements performed outside of the core network. In this use case, we want to measure actual latencies of messages sent within the EPC itself. This requires an actual deployment implementation of the EPC. Since such an implementation is not easily available, the content of the research of this use case should be considered quite new. In [124], Mohan et al. performed similar research, however, instead of handovers, they were focussing on signalling related to setting up a call from a UE.

5.4.2 Standardisation

Handover between base stations, both inter- and intra-RAT as well as between different layers has been standardised by 3GPP [136]. [120] also specifies the "Speed dependent scaling of measurement related parameters" which adjusts the time-to-trigger depending on the UE speed.

The X2AP [138] provides ways to exchange of information like last visited cell information between the source and target eNodeBs during handover.

[139] describes the LTE Positioning Protocol (LPP) a way to provide location information to a UE based on position-related measurements obtained by one or more reference sources.

3GPP Release 11 contains TR 37.803: 'Mobility enhancements for Home Node B (HNB) and Home enhanced Node B (HeNB)' [140]. This technical report describes the addition of an X2 interface between Home eNodeBs to ease mobility between Home eNodeBs. Furthermore it also describes a better integration between Home NodeBs and Home eNodeBs and the core network.

3GPP Release 11 contains also TR 36.839 [141]. This report captures the conclusions and decisions from the Release 11 Study Item on the mobility enhancements for heterogeneous networks (HetNet) and will set the basis for the related Release 12 Work Item. Specifically, it includes observations on the mobility state estimation (MSE). The MSE is not as accurate in HetNet environments as in macro-only deployments since it does not take into account the cell size. Thus, MSE enhancements should be considered to improve the mobility performance of HetNets.

5.5 Architecture

The main architecture of the high mobility SON function is described in Deliverable 2.2 [127]. A schematic overview is shown in Figure 36. In summary, the high mobility SON function contains the following components:

- A **Trajectory Classifier** that maps each user to a trajectory class that fits best for this particular user. The Trajectory Classifier will base its decisions on measurements it receives from the UE.
- A **Trajectory Identifier** that identifies the different distinct trajectories that are often followed by users. The Trajectory Identifier will base its decisions on the information that has been gathered from users that have visited the cell in the past. New trajectories can be identified when the Trajectory Classifier can no longer adequately map all users to an existing trajectory. This can happen because of roads that are temporarily or permanently closed down, or new ones that are constructed.
- A **Mobility Type Classifier** that maps each user to a mobility class like stationary users, pedestrians, users inside a train, etc. Unlike trajectory classes, mobility types are statically defined and do not change over time.
- A **Policy Mapper** that maps each user to a traffic steering policy based on its trajectory and mobility type. This policy can for instance be steering the user to a macro layer or keeping it camped on the pico layer, etc.
- A **Traffic Steerer** that actually decides when and to which cell to handover users based on the user's policy, its trajectory class and its mobility type.

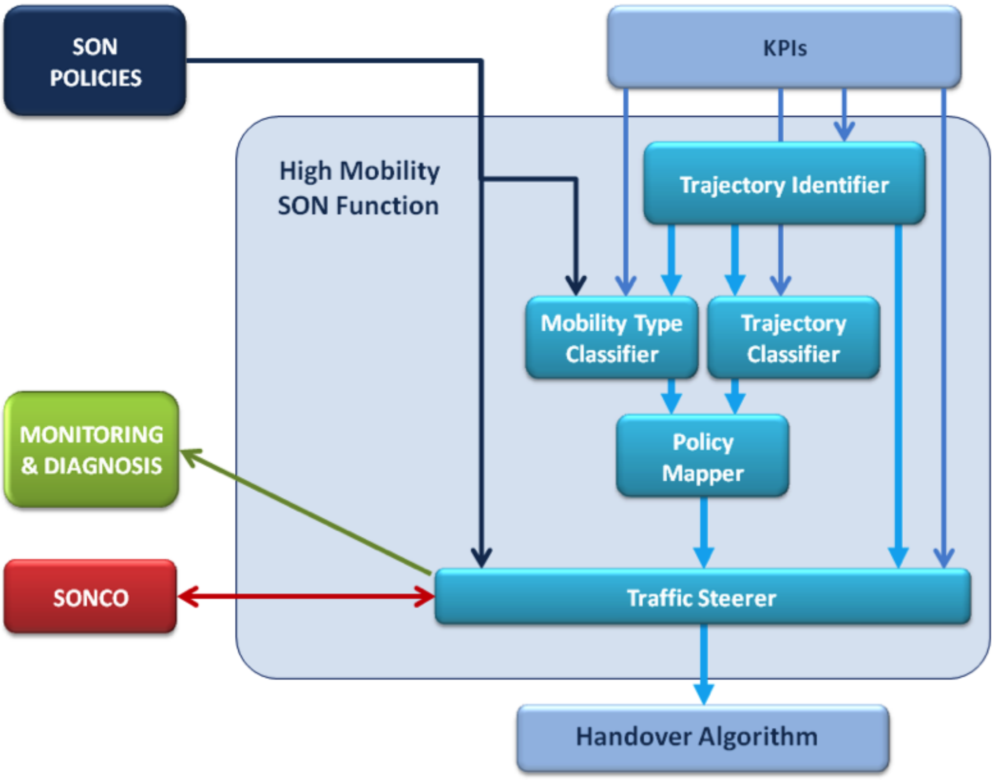

Figure 36: The general architecture of the high mobility SON function.

The work in this deliverable will focus on the Trajectory Classifier and how well users that follow similar paths through a cell can be identified as this is one of the most important components of the high mobility SON function.

5.6 Classification Algorithm

The goal of the Trajectory Classifier is to map the trajectory of a user that is currently active onto the trajectory of another (reference) user at a particular period in the past based on measurements that were recorded by both users. See Section 5.6.1 for more information about the measurements that are used for this purpose. By assuming that two users that follow the same trajectory through a cell will behave the same in the future regarding their mobility and handover behaviour the user's future behaviour can then be predicted based on this information. Users do however not necessarily need to follow exactly the same trajectory. In order to predict the future of a particular user we are especially interested in the recent past of the user. As we want to determine at what point along the trajectory of the reference user the recent measurements of the active user match with these of the reference user we will try to find the best match between a suffix of the measurements of the active user and an interval somewhere in the entire trace of the measurements from the reference user as is illustrated in Figure 37. In this figure you can see that the highlighted part of the active trace is matched with the highlighted part of the reference trace. The matched part of the active trace ends at the most recent measurement but this is not necessarily the case for the reference trace. Note that the time axis merely indicates in what direction time progresses and does not indicate absolute time. In reality the reference trace has been recorded at an earlier point in time but when series are compared only the relative times between measurements are considered.

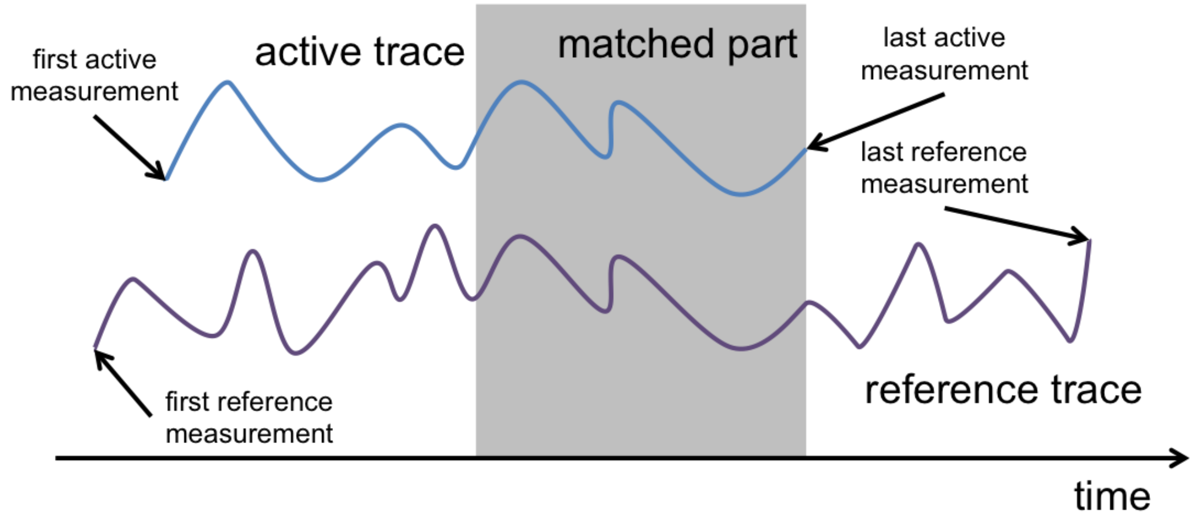

Figure 37: A suffix of the active trace is matched with an interval somewhere in the reference trace.

Because the measurements that are sent to the eNodeB by users that follow similar trajectories can slightly differ due to slight deviations in the trajectory that is followed, by different user velocities, time variations in fading, etc., it is not just possible to compare the measurements of both the active and reference users by looking for, for instance, the longest common substring. In order to make this matching more resilient against slight variations in the measurement data, a modified version of the Dynamic Time Warping (DTW) algorithm is used.

The Dynamic Time Warping algorithm is used in signal processing to find an optimal alignment between two time series (like the measurements coming from the users) [128]. Dynamic Time Warping determines the distance between two time series $X = (x_1, \ldots, x_M)$ and $Y = (y_1, \ldots, y_N)$ by determining the so called optimal warping path through the cost matrix $C \in \mathbb{R}^{M\times N}$ whose elements $C_{m,n}$ express the distance $c(x_m, y_n)$ between the elements x_m and y_n of the respective series. A warping path through this cost matrix is a series $p = (p_1, \ldots, p_L)$ with $p_l = (m_l, n_l) \in \{1, \ldots, M\}\times\{1, \ldots, N\}$, satisfying the restrictions that $p_1 = (1, 1)$, $p_L = (M, N)$ and $p_l = (m_l, n_l)$ with $l \in \{2, \ldots, L\}$ can only be reached from $p_{l-1} \in \{(m_l - 1, n_l), (m_l, n_l - 1), (m_l - 1, n_l - 1)\}$, i.e. a warping path is a path through the cost matrix that starts at (1, 1) and goes to (M, N) by either increasing the row index, increasing the column index or increasing both at the same time. The cost or distance of a warping path is given by the total cost of the elements along the path:

$$\sum_{l=1}^{L} c(x_{m_l}, y_{n_l})$$

The optimal warping path is the warping path that has the lowest total cost of all possible warping paths. The optimal warping path can be efficiently determined by constructing an M×N matrix D in which each element (m, n) contains the minimal total cost to match the prefix of length m of X with the prefix of length n of Y. Each element (m, n) of this matrix (except from the ones on the first row and column) is calculated by adding the cost $c(x_m, y_n)$ to the minimum of D(m - 1, n), D(m, n - 1) and D(m - 1, n - 1). The values of the elements of the first row and column are calculated by adding the cost to the value of the elements to the left or above respectively.

Pseudo code for the dynamic time warping algorithm is given below. In this code an additional row and column are added to the matrix D whose elements, except for the element in the upper left corner are initialised to infinity so that the elements in the first row and column can be treated as the other values in the matrix.

```
D := array[0..M, 0..N]
D[0, 0] := 0

for m := 1 to M
    D[m, 0] := infinity
end

for n := 1 to N
    D[0, n] := infinity
end

for m := 1 to m
    for n := 1 to n
        D[m, n] := c(X[m], Y[n]) + min(
            D[m - 1, n],
            D[m, n - 1],
            D[m - 1, n - 1]
        )
    end
end
```

Listing 1: Pseudo code for the Dynamic Time Warping algorithm.

Appendix B.1 demonstrates the Dynamic Time Warping algorithm step-by-step on two short strings and also gives a more elaborate example.

The major shortcoming of the DTW algorithm is that it matches two time series entirely. As mentioned before, this is not desirable. First, we are more interested in the more recent past of the active user as its behaviour in the future will be influenced more by this than by its earlier behaviour. Furthermore there are two goals: First, to match an active user with a reference user without having to match the latest measurement of the active user with the last reference measurement as this usually is when the reference user left the cell; Secondly, to proactively make decisions before the active user also leaves the cell.

In order to do so the DTW algorithm has been adapted as follows: the matrix that is used to calculate the intermediate distances is filled backwards, i.e. the DTW algorithm is applied to the reverse series. By doing this each element of the matrix then contains the minimal total cost when only matching the suffixes of both measurement series up to that point. During construction of the matrix we then keep a current best match and update it each time we calculate the value of an element. By doing this, by the time we reach the upper left corner of the matrix (the element that corresponds to the first elements in both series) we have found the best matching suffixes of the measurement series of the active and reference user.

In order to match a suffix of the measurement series of the active user with any interval of the measurements of the reference user, the end of the measurement series of the active user along the elements of the measurement series of the reference user is shifted and the modified DTW algorithm is applied for the entire active series and the subseries of the reference user starting from the first measurement up to the measurement that is aligned with the end of the measurement series of the active user as is illustrated in Figure 38.

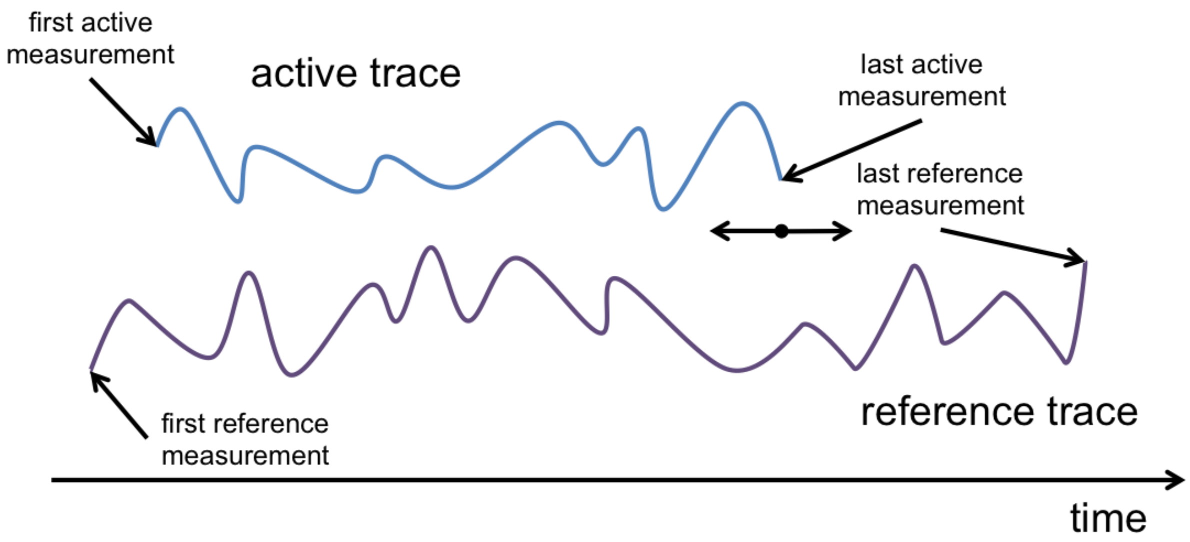

Figure 38: The active trace is shifted over the reference trace and the modified DTW algorithm is applied each time.

As the modified DTW algorithm is able to find matches of subseries of different lengths, it is important that the length of the warping path is taken into account when determining the optimal warping paths. In order to do this, distances will be represented using pairs (v, w). The component v represents the value of the distance and is a value between 0 and 1. When v has value 0 this means that there is an exact match between two measurements. When v has value 1 this means that two measurements are completely different. The component w represents the importance or weight of the value. The exact meaning of the importance depends on how the distance between measurements is defined but as a general rule the weight should be higher when the distance is based on more information, for instance a longer warping path. Therefore the addition of two distances is defined as follows:

$$(v_1, w_1) + (v_2, w_2) = \left(\frac{v_1\, w_1 + v_2\, w_2}{w_1 + w_2}, w_1 + w_2\right)$$

As can be seen from this formula, the value of the sum is equal to the weighted average of both addends while the weight of the sum is equal to the sum of the weights.

Two distances are compared by ignoring the weights and just comparing their values:

$$(v_1, w_1) < (v_2, w_2) \Leftrightarrow v_1 < v_2$$

Due to the way that addition is implemented, tuples will be compared based on the average cost of the elements along the warping path.

Considering every possible suffix of both series has a disadvantage: shorter suffixes will be favoured over large suffixes as it is more likely to find a short perfect match than it is to find a longer one. In order to mitigate this problem the initial cost can be set to a value like (1, x) with x ≥ 0. As after a series of additions, the resulting value of the tuple is the weighted mean of all added values, the importance of this initial distance will become less important as more values are added to it. By using a tuple with non-zero weight as the initial value, longer matches will be favoured over shorter matches. Note that adding (v, w) to (1, 0), i.e. x = 0, will result in (v, w) removing the influence of the initial value altogether.

Another problem, which arises when allowing the algorithm to match every combination of suffixes, is that the cost matrix can be traversed mainly horizontally or vertically as this produces warping paths of the same length as going diagonally. Going mainly vertically or horizontally is however less favourable as this will match shorter portions of either one of the compared traces for the same length of warping path. This is not a problem with the original DTW algorithm as it matches the entire series. In order to mitigate this problem an additional cost can be added when traversing the cost matrix in the vertical or horizontal directions but not when going diagonally. This will 'encourage' the algorithm to match longer portions of both series. Like the initial cost, this additional cost will have the form (1, x) with $x \geq 0$. In pseudo code this looks like:

```
distances[i, j] := cost + minimum(
    distances[i - 1, j] + extraCost,
    distances[i, j - 1] + extraCost,
    distances[i - 1, j - 1]
)
```

Listing 2: An extra cost is added when the cost matrix is traversed horizontally or vertically.

Given all the adaptations to the DTW algorithm, the algorithm that will be used for matching the measurements of an active user with measurements of a reference user looks like:

```
bestMatch    := None
bestDistance := infinity

for start := 1 to m
    distances := array [1..start + 1, 1..n + 1]

    for i := 1 to start
        distances[i, n + 1] := infinity
    end

    for j := 1 to n
        distances[start + 1, j] := infinity
    end

    distances[start + 1, n + 1] := initialCost

    for i := start downto 1
        for j := n downto 1
            cost := calculateDistance(
                referenceMeasurements[i],
                activeMeasurements[j]
            )

            distances[i, j] := cost + minimum(
                distances[i + 1, j] + extraCost,
                distances[i, j + 1] + extraCost,
                distances[i + 1, j + 1]
            )

            if distances[i, j] < bestDistance
                bestMatch    := (start, i, j)
                bestDistance := distances[i, j]
            end
        end
    end
end
```

Listing 3: Pseudo code for the Modified Dynamic Time Warping algorithm.

As the (Modified) Dynamic Time Warping algorithm takes some time to execute it might have an impact on the execution speed of the handovers. This will in practice not be a large impact as the algorithm starts executing at an early stage and by the time a handover is required, enough data has been gathered for the traffic steerer to make an appropriate decision. Furthermore the result of the traffic steering algorithm is used to steer users and to hand them over to more appropriate targets, not to make the handover decision itself.

5.6.1 User Measurements

The trajectory classifier will classify users based on measurements sent by them to the source eNodeB (SeNB). These measurements must exhibit a number of properties. First they must be sent sufficiently frequent in order for the trajectory classifier to make actual decisions. Furthermore they must allow distinguishing between users that travel along different streets through a cell.

The trajectory classifier will use measurement reports that are sent by the UE to its serving eNodeB as a consequence of a reporting configuration that was configured by the serving eNodeB [136] as user measurements as they satisfy the properties that are mentioned above. These measurement reports are sent by the UE to its SeNB whenever a certain condition involving the RSRP or RSRQ of its serving cell and neighbouring cells is met. The SeNB can configure reporting conditions at the UE that trigger these measurement reports. With each reporting configuration an entering condition and a leaving condition is associated. The UE continuously monitors the RSRP and/or RSRQ of its serving and neighbouring eNodeBs. Whenever the entering condition holds for a certain cell, a timer is started for that cell. This timer is stopped when the condition no longer holds, after which it can be started again from 0 once the entering condition holds again. When the timer expires after a certain amount of time, called the time-to-trigger, a parameter that is proper to the reporting configuration, the cell is added to the list of cells for which that reporting configuration is triggered. A measurement report is then sent to the UE's SeNB containing that list of cells and their corresponding RSRPs/RSRQs. The same thing happens for the leaving condition: for each triggered cell the leaving condition is evaluated. When the condition holds for a period equal to the time-to-trigger, the cell is removed from the list. In this case it depends on another parameter proper to the measurement configuration, called the report-on-leave flag, whether or not a measurement report is sent. If this flag is true, a measurement report is sent, otherwise no measurement report is sent. With each reporting configuration a third parameter is associated which is called the hysteresis. This is an offset that is taken into account when evaluating the entering and leaving conditions. Furthermore each reporting configuration also has parameters that are specific to its type.

If a SeNB configures a number of reporting configurations at the UEs it serves, it will, at every point in time, for each of the UEs it serves, have a list of cells that are triggered for each reporting configuration. Each time a new measurement report is sent the list of cells of one of the reporting configurations of the UE is updated, yielding a new list of cells that are triggered for each reporting configuration. The consecutive updates of these lists of cells that are triggered for all reporting configurations will serve as the measurements on which the modified DTW algorithm will be applied. In order to apply the modified DTW algorithm to the measurements we first have to define a distance function between two different measurements. The distance d(a, b) between two measurements a and b is defined as:

$$d(a,b) = \left(\frac{\sum_{i \in R} \frac{|a_i \cap b_i|}{|a_i \cup b_i|}}{|R|}, 1 \right)$$

where R is the set of reporting configurations that are configured at the UE, a_i and b_i denote the sets of reported eNodeBs for reporting configuration i of respectively measurements a and b and |S| denotes the number of elements in a set S.

5.7 Main Monitoring KPIs

The overall performance of the SON function to limit the handover frequency that will be developed in this use case, will be assessed by measuring the handover frequency directly and by measuring KPIs on which the handover frequency has a direct influence. These KPIs are:

- **Signalling overhead**: the amount of signalling traffic that is sent through the packet core, expressed in (a multiple of) bit/s. Shown as a line plot over time and/or a dial marked with low medium and high markings.

- **Handover frequency**: the amount of handovers per second a user makes.
- **Radio link failures**: the number of radio link failures experienced.
- **Packet loss ratio**: the fraction of packets that is lost. Noticeable packet loss can be caused by data outage at the frequent handovers.
- **User throughput**: the mean throughput achieved by the users, relative to the desired throughput.

In order to assess the ability of the Trajectory Classifier to identify users that follow a certain trajectory these KPIs are irrelevant. Instead, the performance of the Trajectory Classifier will be studied using a single KPI: its ability to identify the part of a trajectory that actually overlaps between two users. This measure is defined as follows:

$$match\ score = 1 - \frac{length\ of\ overlapping\ part\ of\ matched\ active\ and\ reference\ traces}{\max\left(length\ of\ matched\ part\ of\ active\ trace, length\ of\ matched\ part\ of\ reference\ trace\right)}$$

Figure 39 shows the different parts of the equation: the length of the purple path is used in the numerator while the maximum of the lengths of the red and blue paths is used in the denominator.

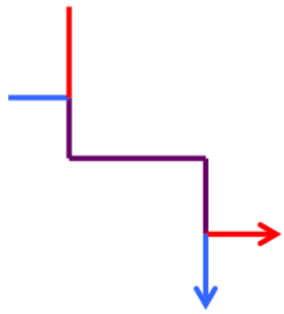

Figure 39: The lengths that are used for calculating the match score.

5.8 Main Control and Configuration Parameters

The control parameters that have been studied in this deliverable are the initial cost and the extra cost. These are parameters that are internal to the trajectory classifier and are described below:

- When performing the modified time warping algorithm the **initial cost** should not necessarily be 0, any other positive value can also be used. By using a non-zero value as the initial cost, due to the way values are compared, longer matches will be favoured over shorter matches as the influence of the initial cost will become lower as the length of the match grows.
- When going sideways or downwards through the cost matrix when performing the modified time warping algorithm a certain **extra cost** can be taken into account. This cost will let the algorithm prefer more values of both sequences instead of matching many values of one sequence with few values of the other sequence. This has an influence on the matches that are made by the trajectory classifier.

Furthermore there are also a number of parameters that might also have an influence on the behaviour of the trajectory classifier but are not studied within the scope of this deliverable:

- List of **reporting configurations**: the most important control parameters are the reporting configurations that are used to match user traces. The reporting configurations that are configured determine when and for what reason users will send measurements to their Serving eNodeB and thus determine the amount of information that is available for the trajectory classifier to base its decisions on and the quality thereof. The different reporting configurations themselves have a number of configuration parameters of their own which depend on the type of the reporting configuration:
    - Each reporting configuration has an associated **hysteresis** value that determines how large the difference between a measured value and the value it is compared to needs to be in order to trigger an event. The measured value needs to be higher than the value it is compared to (whatever this value may be) plus the hysteresis value. When the

hysteresis value is low (close to 0) the event will be triggered fast and frequently as small changes in the measured value can cause the value to rise above and drop below the value it is compared to quickly.

- Like the hysteresis each reporting configuration has an associated **time-to-trigger** that determines how long the entering or leaving condition needs to be true for the cell to be triggered. A low time-to-trigger will again cause frequent triggering of events as the entering or leaving conditions that are associated with the event only need to hold for a small amount of time while a high time-to-trigger will cause less frequent triggering.
- The third and final configuration parameter that is common to all types of reporting configurations is the **report-on-leave** flag that determines whether the UE should send a measurement report when the leaving condition is triggered or not. When report-on-leave is false changes will not be reported until the entering condition of the same reporting configuration triggers again for the same cell or for another cell. Setting the report-on-leave parameter to false will lead to fewer measurement reports and to less accurate information at the eNodeB.

Some of the events have one or more thresholds associated with them to which the measured value is compared. In case of an RSRP threshold this value can be configured between -140 dBm and -44 dBm in steps of 1dBm [125]. In case of RSRQ this threshold can be configured between -19.5 dB and -3 dB in steps of 0.5 dB. The values of these thresholds determine when an event is triggered and thus is available for the trajectory classifier.

5.9 Simulation Modelling and Tools

The simulations that were performed to assess the ability of the trajectory classifier to classify users according to their trajectory were performed using the iMinds simulator. This simulator is written in C++ using the OMNeT++ simulation library [129]. The simulator is a dynamic system level simulator that simulates users, base stations and their behaviour and interactions. The architecture of the simulator is shown in Figure 40.

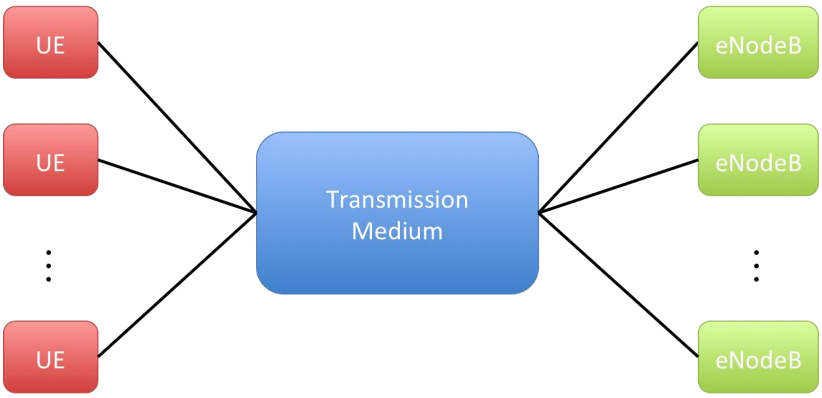

Figure 40: Architecture of the iMinds simulator.

For each simulated user there is a corresponding component in the simulator. The UE component is for every individual user responsible for:

- Call setup and tear down
- Generation of traffic
- UE behaviour as described in the 3GPP standards
  - CQI reporting
  - Measurement reporting
  - Transmission and reception of data traffic

Like for every UE, there is also a corresponding component in the simulator for every individual eNodeB. This component is responsible for:

- Admission control
- Handover
- Scheduling
- eNodeB behaviour as described in the 3GPP standards

All components that represent users and base stations are connected to the transmission medium. This component is responsible for the transmission of radio messages between UEs and eNodeBs. It calculates the pathloss, Rx power and SINR between UEs and eNodeBs and determines whether messages arrive or not and it also introduces transmission delays. The mobility of the users is also implemented in this component.

It is also possible to connect the iMinds simulator to the SONLAB platform that is being developed by atesio [130]. The architecture of this is shown in Figure 41.

In this case the mobility of the users and the calculation of the pathloss is done by SONLAB and queried by the transmission medium. In the future this set-up will be used to get access to the Hanover data, this is however out of the scope of this deliverable.

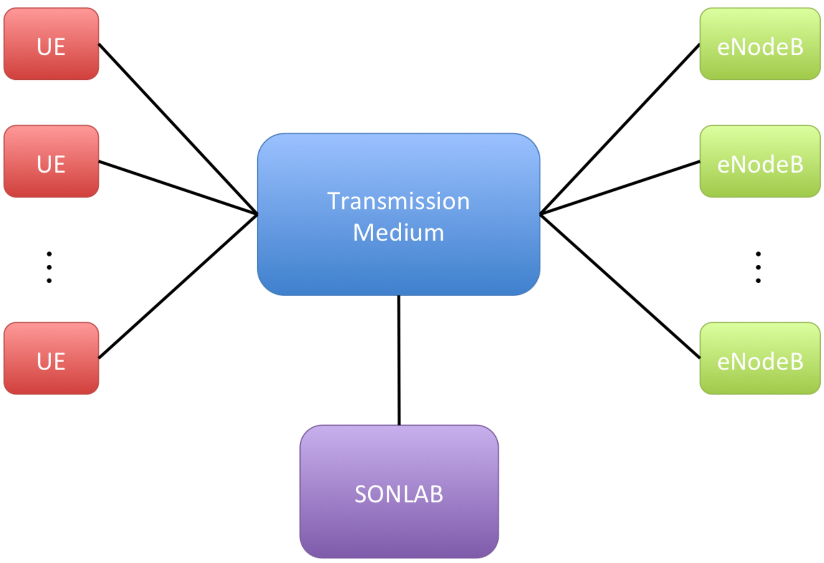

Figure 41: Architecture of the iMinds simulator, coupled to the SONLAB platform.

5.10 Controllability and Observability (C&O) Analysis

5.10.1 Methodology and Objectives

The goal of the Controllability and Observability analysis is to assess how well the proposed classification algorithm is able to distinguish between users that follow the same trajectory through a cell and other users. At a later stage this information can be used to steer users according to their trajectory; this is however outside the scope of this deliverable.

The first part of the study will concentrate on how well the algorithm can actually match users that follow exactly the same trajectory. For this users are made to follow exactly the same rectangular path through the simulation area and their measurements are matched with each other. Later on slight variations are made to the trajectories that are followed by the users. The goal of this is to check how resilient the algorithm is to these variations and to determine the good parameters and thresholds for the matching algorithm. First variations in the velocity of the users will be applied: instead of using a fixed velocity for all users, a user's velocity will change each time it starts to follow a new segment. The velocity will be chosen uniformly from an interval of a certain width that is centred at the average velocity. Varying the velocity will introduce variations in the intervals between different measurements or even reverse the order of certain measurements, introduce additional ones and/or remove existing ones. This will have an impact on the ability of the algorithm to match measurement series.

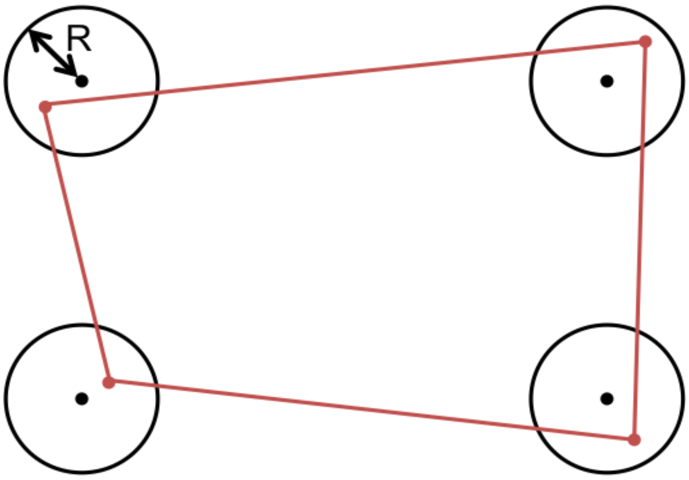

Figure 42: The locations, that users travel to, are chosen randomly within a certain radius R from the centre of a crossroad.

Secondly slight variations in the trajectory of the users will be introduced. Instead of letting users move from point to point along the trajectory, users will move between points chosen uniformly inside a circle with a certain radius around the points as is illustrated in Figure 42. The radius of this circle is called the maximum deviation.

Introducing these variations will again have an impact on the ability of the algorithm to match measurement series.

In the second part of the study the resilience of the algorithm against false matches will be studied. False matches can occur when there is very little measurement data or when the distance calculation of two measurements that are too far apart yields a result that is too low. The goal of this study is again to check if the algorithm is able to distinguish between users that have different trajectories and to determine appropriate values for the parameters and thresholds of the algorithm. In order to do so we will try to match measurements of users with measurements of reference users that move in the opposite direction. In this case we will again consider users that follow exactly the same trajectory and have the same velocity.

5.10.2 C&O Scenario(s)

In order to assess how well the trajectory classifier is able to classify users a simple hexagonal configuration as is illustrated in Figure 43 is used. The simulation area contains 16 three-sector cells with an inter-site distance of 500m. Note that the simulation area wraps around near the borders.

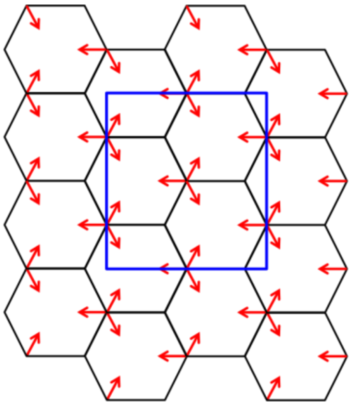

Figure 43: Users follow a rectangular path through the simulation area.

In this scenario, users move through a regular rectangular lattice. The reason for this configuration is that it allows a great amount of control about how users move and through which cells they move. This makes it much easier to track the different events in detail, which is very important for the initial part of the study.

At a later stage we will also test the trajectory classifier in a more realistic setting, using the Hanover scenario, where base stations and streets through which users move have a more random configuration. For this study we will use the data provided by the SONLAB platform. This work however does not fall within the scope of this deliverable and will be performed at a later stage.

5.10.3 Impact of Measurements and Control Parameters

Figure 44 shows the average match score of matches of a certain number of active measurements for various velocity intervals. For these simulations the maximum deviation is 0, i.e. users move exactly from point to point along the trajectory. The interval from which the user's velocity is chosen is varied between simulation runs. The interval ranges from 0 m/s to 5 m/s and is centred around 5 m/s. The reporting configuration that are used are all A4 events with a hysteresis of 2dB and time to trigger of 0.48s, the thresholds range from -76 dBm to -60 dBm in steps of 2 dB

As can be seen in Figure 44 the match score becomes lower (i.e. the traces are matched with higher accuracy) as the number of matched measurements becomes higher. The figure also shows that when there are a sufficient amount of measurements (> 50) the algorithm is able to match users traces well, even when the velocities of the users vary much.

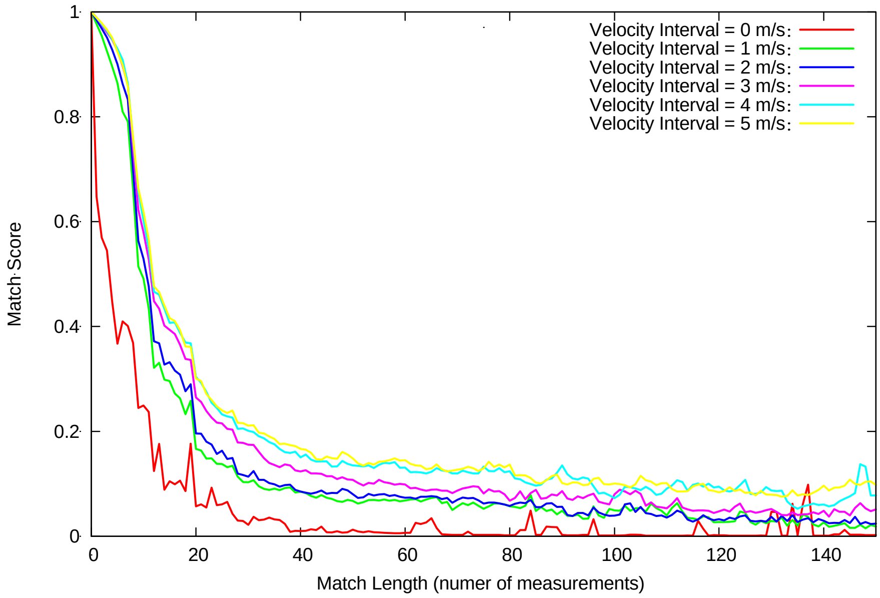

Figure 44: The matches become more accurate as the length of the match increases.

The reason for the higher accuracy with which the algorithm can match the traces is twofold. First of all the algorithm has more data to make a more accurate match. Secondly, more measurements also generally mean that the measurements span a larger time and a longer distance. As, even when users follow exactly the same trajectory and have the same velocity, measurements are not sent when the user is at the same location or even do not arrive in the same order, slightly different parts of the trajectories can be matched. In case there are only a small number of measurements the error that is made relative to the travelled distance is much higher than when there are many measurements.

Figure 45 shows a plot for the trajectory classifier's ability to match traces when the velocities are chosen from different intervals for various maximum deviations. As can be seen in this figure, when users follow (nearly) the same trajectory (deviations up to 5 metres), the ability for the trajectory classifier to match trajectories decreases when the difference in velocity increases. For higher deviations this does not apply and the ability to match traces mainly depends on the deviations between trajectories. The reason for this is that when the maximum deviation becomes higher, the actual trajectories that are followed by the users become so different that they no longer just introduce deviations in the arrival times of the measurements but change the measurements entirely such that the changes in arrival times that are introduced by the different velocities are no longer of any significance. Note that the bad match scores are actually a desired outcome: when users follow sufficiently different trajectories no longer it is useful to match them as their future behaviour will most likely also be different.

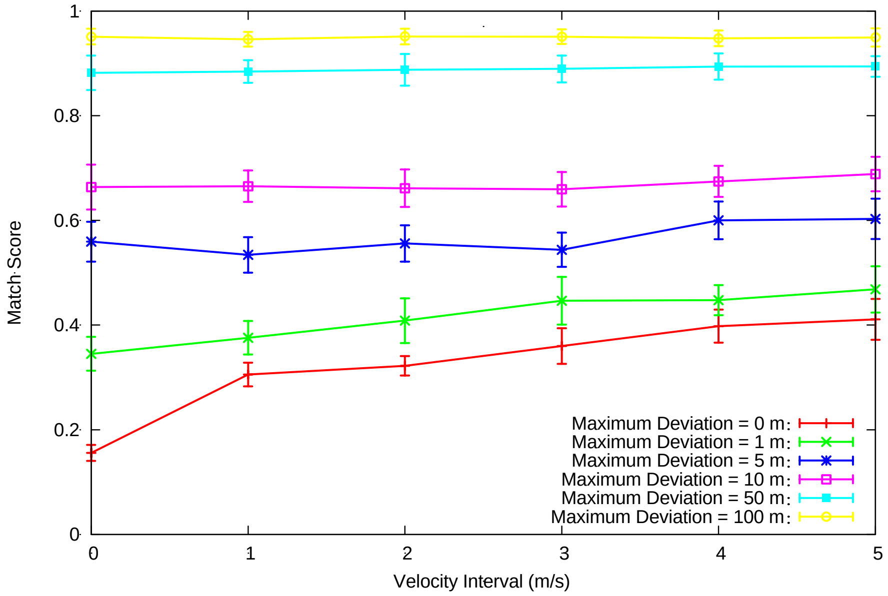

Figure 45: The matches become less accurate when the velocity intervals and/or the deviation in position increases.

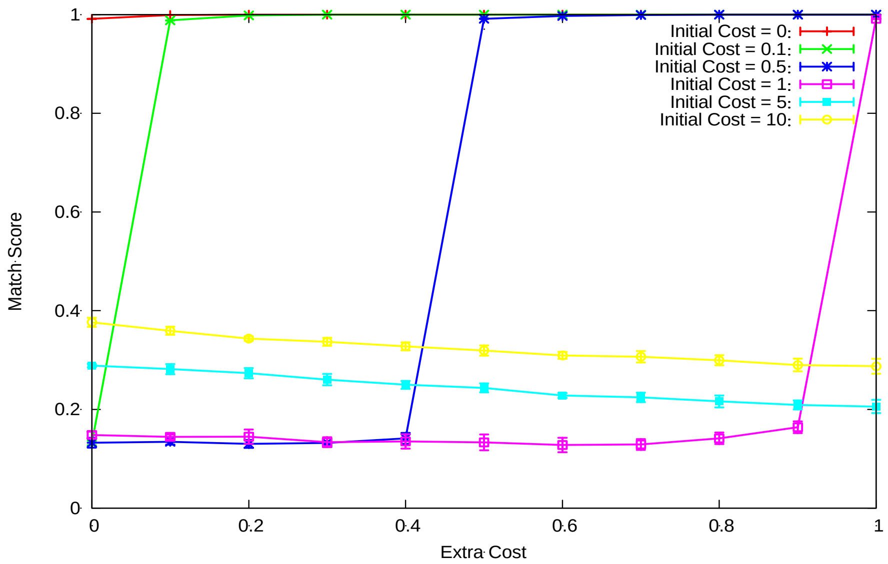

Figure 46: When the extra cost is higher than the initial cost the algorithm is no longer able to make accurate matches.

Figure 46 shows a plot with the extra cost that is added when moving horizontally or vertically through the cost matrix on the x-axis and the ability to match users on the y-axis for various initial costs. A first thing that is to be noticed is that the ability to match user trajectories is virtually constant up to the point where the extra cost becomes larger than the initial cost. At this point the algorithm is no longer able to match user trajectories. The reason for this is that when the extra cost is greater than the initial cost, going horizontally or vertically no longer results in a lower score than just ending the match. This will cause the algorithm to stop early which results in short matches. As short matches are more likely not to have overlapping parts as mentioned before, this will result bad match scores. Furthermore this plot shows that the extra cost does not influence the ability to match series much. The initial cost has a much greater influence and, as can be seen from the curve for which the initial cost is

0, an initial cost is necessary in order for the algorithm to make a proper match. This again is because when there is no initial cost, the algorithm will more likely make short matches as it is more likely to make short matches instead of long ones. When the initial cost becomes too high the algorithm is encouraged to match too many values which results in worse matches again.

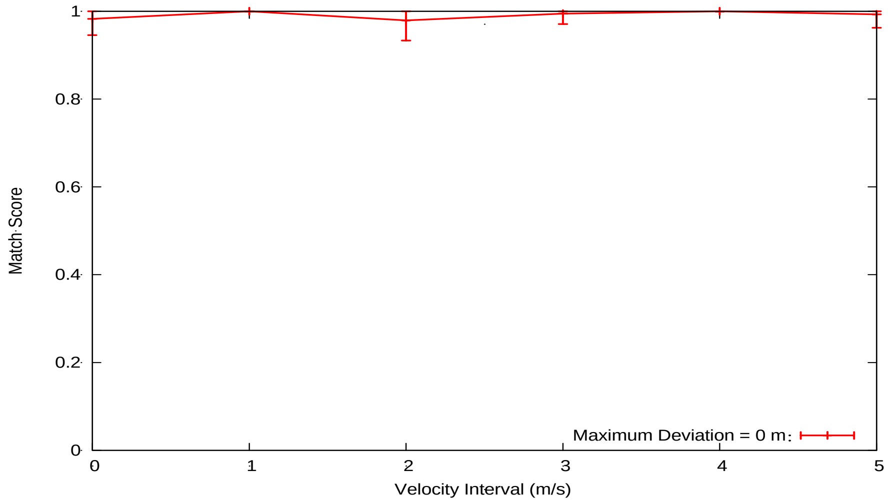

Figure 47: The algorithm fails to make any matches of users that move in the opposite direction than the reference traces, regardless of the speed of the users.

Figure 47 shows the algorithm's ability to match active traces with traces of users that move in the opposite direction. As can be seen in this figure the match score is always bad, regardless of what parameters are used. This shows that the algorithm will not match users that do not move in the same direction through a cell.

5.10.4 C&O Analysis Outcome and Way Forward

The C&O analysis shows that the modified Dynamic Time Warping algorithm is able to correctly match users that follow similar trajectories through a cell, even when there are small deviations in the user's velocities and/or positions. Furthermore the algorithm is also able to distinguish between users that do not follow the same trajectory.

The modified Dynamic Time Warping algorithm can now be used to implement the trajectory classifier and other components of the High Mobility SON function as is explained in Section 5.11.

5.11 SON Function

The trajectory classifier will be one of the most important parts of the eventual High Mobility SON algorithm and will serve as a basis for the SON algorithm since many other components of the High Mobility SON function will depend on the trajectory classifier.

The identification of new trajectories by the trajectory identifier will be performed based on information from the trajectory classifier. When the trajectory classifier is not able to match a user on any previously identified trajectories it will inform the trajectory identifier. The trajectory identifier will keep track of these users and will try to detect whether a significant portion of these users follow the same trajectory. When this is the case a new trajectory class can be formed. The trajectory identifier will use a similar algorithm as the modified DTW algorithm that is used by the trajectory classifier to identify common patterns among unmatchable users. Furthermore when the trajectory classifier does not find any matches for a particular trajectory the trajectory identifier will remove that trajectory. This can for instance happen when there is a change in the environment.

The trajectory classifier also provides information to the traffic steerer about which part of the trajectory that matches with the reference trace. This information is used by the traffic steerer to estimate how long the users will still stay in the cell and how urgent a handover decision is.

5.12 Signalling Overhead in the Core Network During Handover

In the previous section, SON functions were studied in the context of high mobility users. In order to provide realistic values for the signalling overhead in the Evolved Packet System (EPS), which then can be used as input for future simulations that will be executed as part of the SON study, there is a need to quantify this overhead. In this section the signalling overhead in the core network will be studied in a theoretical way. In a next phase, planned for the coming deliverables, experiments will be executed with OpenEPC to measure this on a real test platform and validate the theoretical analysis.

The EPS comprises the EPC and the Evolved UTRAN (E-UTRAN) and is a purely packet switched system [135]. In the 3GPP standards, different types of handovers are specified in the EPS. The handover type depends on what Radio Access Technologies are involved (LTE, UMTS, GSM, etc.) and between what layers the handover is performed (macro, micro, pico, femto). In this study, the handover type that is considered is limited to LTE-LTE handover between two eNodeBs on the macro layer with no MME/SGW relocation. This is the type of handover that is considered in the High Mobility Use Case simulations. The objective is to quantify the signalling overhead in the EPC by calculating the transmission time of the messages and the processing time within the different entities. The transmission time will be based on the message size according to the 3GPP standards. For the processing time, estimations will be used. The calculated and estimated values will later be verified and tweaked by executing designated experiments with OpenEPC [134]. Depending on the OpenEPC features, also multi-RAT handovers will be evaluated.

OpenEPC is a prototype test platform that contains all components of an EPC network (MME, SGW, PGW, PCRF, SGSN, ANDS…) and a major part of the functionality of the 3GPP EPC standard:

- Network Mobility Management
- Policy and Charging Control
- AAA and subscriber management
- Accounting and charging
- Client mobility support
- User-data plane realization

OpenEPC will be used to perform EPC experiments on a real testbed to measure signalling overhead in the core network during handovers.

An overview diagram of the OpenEPC architecture is shown in Figure 48.

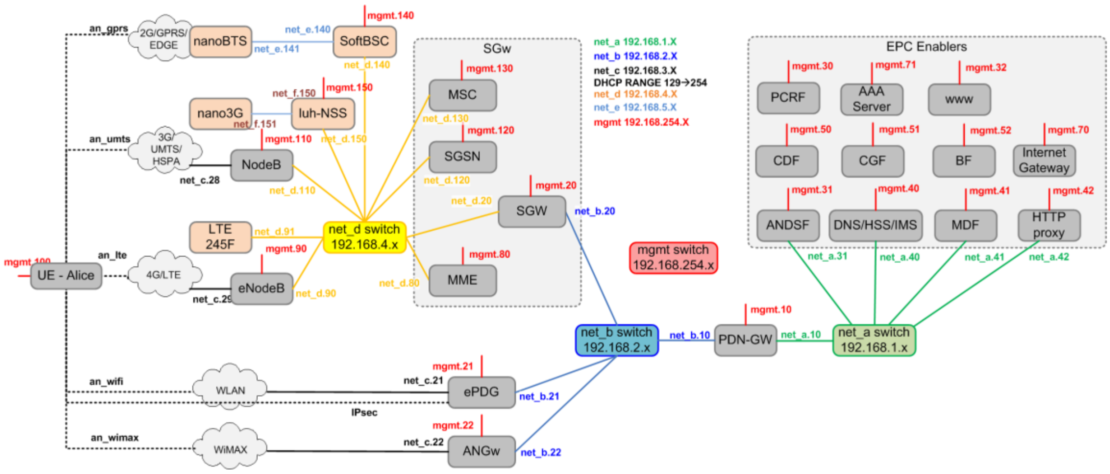

Figure 48: OpenEPC architecture

In the 3GPP specs [135], the X2-based intra-LTE handover is described in detail. An overview figure of the handover procedure is shown in Figure 49.

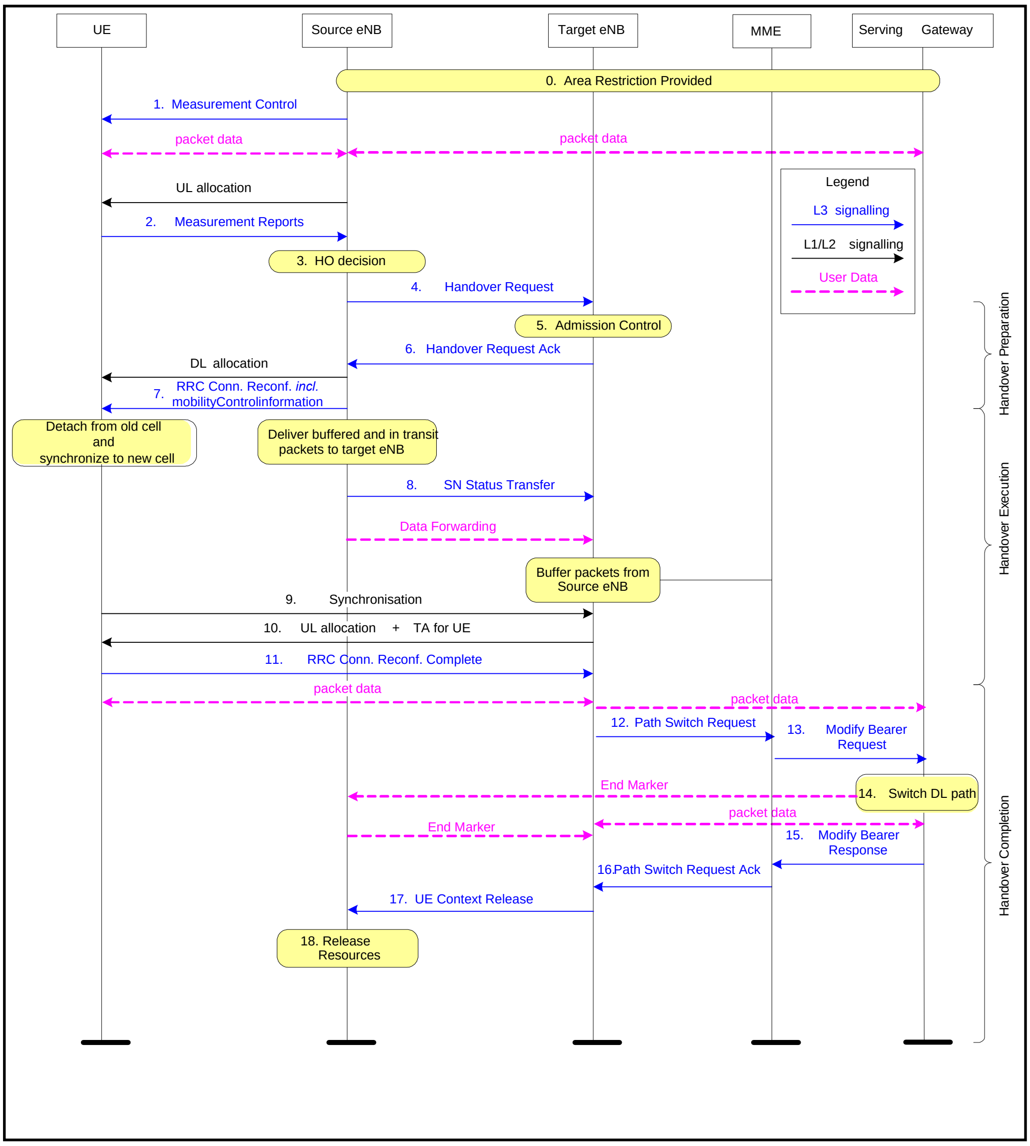

Figure 49: X2-based handover procedure

In the EPC X2 based handover, three phases exist during a handover. First, there is the handover preparation phase, then the handover execution phase, and finally the handover completion phase.

The core network entities that are involved during a handover are:

- MME (control plane entity)
- SGW (data plane entity)
- Source eNodeB (SeNB)
- Target eNodeB (TeNB)

In this type of handover, a User Equipment (UE) moves from the SeNB to the TeNB. The decision of performing a handover is made in the core network. It is the eNodeB to which the UE is connected, that will determine when to perform a handover, based on measurement reports that are created by the UE and that are sent to the eNodeB.

Layer 3 signalling happens between the following entities:

- UE and SeNB (LTE-Uu interface, RRC protocol)
- SeNB and TeNB (X2 interface, X2-AP protocol)
- TeNB and MME (S1-MME interface, S1-AP protocol)
- MME and SGW (S11 interface, GTP-C protocol)

Note: For signalling between the UE and the MME, the Non Access Stratum protocol is used (the eNodeB acts as a kind of relay node).

During the preparation phase, only the UE and the SeNB and TeNB are involved. The SeNB makes a decision on performing a handover, based on the UE and radio level information, and on the restriction data provided by the EPC, i.e. MME. Then the SeNB selects a TeNB. The SeNB and TeNB may need to buffer data during the handover execution phase. Packets on the downlink that are still sent to the SeNB will be buffered and sent to the TeNB, where the packets are also buffered until the handover of the UE is completed. In this phase, the SeNB already establishes a downlink data path for user plane traffic towards the TeNB

During execution phase the UE detaches from the SeNB and attaches to the TeNB. The SeNB then forwards data received over the downlink path from the SGW to the TeNB.

During completion phase the MME informs the SGW to switch user plane path for the DL data traffic. Resources are released in the SeNB

To quantify the signalling overhead during the X2-handover, we define following parameters in Table 12.

Parameter	***Description***
P_{UE}	Processing overhead at UE
P_{SeNB}	Processing overhead at SeNB
P_{TeNB}	Processing overhead at TeNB
P_{MME}	Processing overhead at MME
P_{SGW}	Processing overhead at SGW
$T_{UE\text{-}SeNB}$	Transmitting overhead between UE and SeNB
$T_{UE\text{-}TeNB}$	Transmitting overhead between UE and TeNB
$T_{SeNB\text{-}TeNB}$	Transmitting overhead between SeNB and TeNB
$T_{TeNB\text{-}MME}$	Transmitting overhead between TeNB and MME
$T_{MME\text{-}SGW}$	Transmitting overhead between MME and SGW
T_{HOReq}	Transmission time of Handover Request
$T_{HOReqAck}$	Transmission time of Handover Request ACK
$T_{SNStatus}$	SN Status transfer
$T_{UEContextRel}$	UE Context Release
$T_{RRCConnReconf}$	Transmission time of RRC conn reconf (incl. mobility control information)
$T_{RRCConnReconfComplete}$	Transmission time of RRC conn reconf complete
$T_{PathSwitchReq}$	Transmission time of path switch request
$T_{PathSwitchReqAck}$	Transmission time of path switch request ack
$T_{ModBearerReq}$	Modify Bearer Request
$T_{ModBearerResp}$	Modify Bearer Response
P_{HOReq}	Processing time of Handover Request
$P_{AdmCtrl}$	Processing of admission control
$P_{PathSwitchReqAck}$	Processing time of Path Switch Req Ack
$P_{SNStatus}$	Processing time of SN status transfer
$P_{RRCConnReconfComplete}$	Processing time of RRC Conn Reconf Complete

$P_{SyncNewCell}$	Detach from old cell and sync to new cell (Time to perform synchronization and get UL on the target cell is included here)
$P_{RRCConnReconf}$ $P_{HOReqAck}$	Processing time of RRC Conn Reconf Processing time of Handover Req Ack
$P_{ReleaseResources}$	Processing time of releasing the resources
$P_{UEContextRelease}$	Processing time of UE Context Release
$P_{SwtichDLPath}$	Processing time of switching the DL Path
$P_{ModBearerReq}$	Processing time of Modify Bearer Req
$P_{PathSwitchReq}$	Processing time of Path Switch Request
$P_{ModBearerResp}$	Processing time of Modify Bearer Response
O_H	Total handover signalling overhead

Table 12: X2-based handover parameters

The handover overhead will be expressed in terms of latency in microseconds. The delay that occurs during the transmission of the signalling messages will be estimated by calculating the message size of the different control messages.

The transmission and processing parameters can now be expressed as follows:

$$\mathbf{T_{SeNB\text{-}TeNB}} = T_{HOReq} + T_{HOReqAck} + T_{SNStatus} + T_{UEContextRel}$$

$$\mathbf{T_{SeNB\text{-}UE}} = T_{RRCConnReconf}$$

$$\mathbf{T_{UE\text{-}TeNB}} = T_{RRCConnReconfComplete}$$

$$\mathbf{T_{TeNB\text{-}MME}} = T_{PathSwitchReq} + T_{PathSwitchReqAck}$$

$$\mathbf{T_{MME\text{-}SGW}} = T_{ModBearerReq} + T_{ModBearerResp}$$

$$\mathbf{P_{TeNB}} = P_{HOReq} + P_{AdmCtrl} + P_{PathSwitchReqAck} + P_{SNStatus} + P_{RRCConnReconfComplete}$$

$$\mathbf{P_{UE}} = P_{SyncNewCell} + P_{RRCConnReconf}$$

$$\mathbf{P_{SeNB}} = P_{HOReqAck} + P_{ReleaseResources} + P_{UEContextRelease}$$

$$\mathbf{P_{SGW}} = P_{SwtichDLPath} + P_{ModBearerReq}$$

$$\mathbf{P_{MME}} = P_{PathSwitchReq} + P_{ModBearerResp}$$

The handover preparation time $\mathbf{T_{HP}}$ can be expressed:

$$\mathbf{T_{HP}} = T_{HOReq} + P_{HOReq} + P_{AdmCtrl} + T_{HOReqAck} + P_{HOReqAck} + T_{RRCConnReconf} + P_{RRCConnReconf}$$

The handover execution time $\mathbf{T_{HE}}$ is:

$$\mathbf{T_{HE}} = MAX(P_{SyncNewCell} + T_{RRCConnReconfComplete} + P_{RRCConnRefonfComplete}, T_{SNStatus} + P_{SNStatus})$$

The handover execution time is the outage time that occurs during a handover as seen from the UE perspective.

Handover completion time $\mathbf{T_{HC}}$ is:

$$\mathbf{T_{HC}} = T_{PathSwitchReq} + P_{PathSwitchReq} + T_{ModBearerReq} + P_{ModBearerReq} + P_{SwtichDLPath} + T_{ModBearerResp} + P_{ModBearerResp} + T_{PathSwitchReqAck} + P_{PathSwitchReqAck} + T_{UEContextRel} + P_{UEContextRelease} + P_{ReleaseResources}$$

The total signalling overhead is:

$$\mathbf{O_H} = T_{HP} + T_{HE} + T_{HC}$$

5.12.1 Assumptions

The message sizes, which are used as a basis for our transmission time calculations, are retrieved from the 3GPP specs, taking into account that the content of the message depends on the specific context in which the message is sent, as several message fields are conditional or optional. Furthermore, on some of the interfaces, Abstract Syntax Notation One (ASN.1) Unaligned Packet Encoding Rules (UPER) is applied on the messages, resulting in message sizes that are difficult to predict. Therefore, we created sample messages and encoded them via an online UPER encoding tool [116]. Baseline message sizes are used based on typical included fields, as described here in the assumptions. In order to also create upper and lower boundaries for signalling overhead in the EPC, we also considered minimal message sizes, which are in this case equal to our baseline, and maximal message sizes, which are bound to the Ethernet MTU size of 1500 bytes.

Here is a summary of the assumptions:

- No optional fields are considered in the messages
- Conditional fields are only considered when needed
- Only default bearer is considered in the messages
- 1 Gbps links are assumed between the entities
- IPv4 is used on the links between the entities
- Ethernet is used on the links between the entities
- When packets are sent over Stream Control Transmission Protocol (SCTP) [143], one message per SCTP packet is assumed, thus only one chunk per SCTP packet
- When packets are sent over SCTP, SACKS are taken into account. No gaps in the stream are considered
- No retransmission considered
- No procedure abortion considered
- Max messages sizes are calculated based on MTU of 1500 bytes in Ethernet

5.12.2 Signalling Messages

In this section we describe all the messages that are sent during a X2-based handover on the different interfaces between the core entities. Following interfaces are used during the handover:

X2	3GPP TS 36.423 [117]
S1	3GPP TS 36.413 [118]
S11	3GPP TS 29.274 [119]
LTE-Uu	3GPP TS 36.331 [120]

X2 Interface

Messages that are sent via X2 between the SeNB and TeNB are using the SCTP protocol. The messages are described in the 3GPP standard with ASN.1 and are encoded via UPER.

To encode the messages with UPER according the ASN.1 description, we used a free online tool [116].

- **Handover Request:** This message is sent by the SeNB to the TeNB to request the preparation of resources for a handover. The description of the message in the 3GPP standard and the example value we used for encoding is included in [140] Section 9.1.1.1.
- **Handover request acknowledge:** This message is sent by the TeNB to inform the SeNB about the prepared resources at the target. The description of the message in the 3GPP standard and the example value we used for encoding is included in [140], Section 9.1.1.2.
- **SN status transfer:** This message is sent by the SeNB to the TeNB to transfer the uplink/downlink PDCP SN and HFN status during a handover. The description of the message in the 3GPP standard and the example value we used for encoding is included in [140], Section 9.1.1.4.
- **UE Context release:** This message is sent by the TeNB to the SeNB to indicate that resources can be released. The description of the message in the 3GPP standard and the example value we used for encoding is included in [140] Section 9.1.1.5.

S1-MME Interface

Messages that are sent via S1-MME interface between the eNodeB and MME are using SCTP protocol. The messages are described in the 3GPP standard with ASN.1 and are encoded via UPER.

To encode the messages with UPER according the ASN.1 description, we used a free online tool [116].

- **Path Switch Request:** This message is sent by the eNodeB to request the MME to switch DL GTP tunnel termination point(s) from one end-point to another. The description of the message in the 3GPP standard and the example value we used for encoding is included in [141], Section 9.1.5.8.
- **Path Switch Request Ack:** This message is sent by the MME to inform the eNodeB that the path switch has been successfully completed in the EPC. The description of the message in the 3GPP standard and the example value we used for encoding is included in [141], Section 9.1.5.9.

S11 Interface

Messages that are sent via S11 interface between the MME and SGW are using GTPc V2 protocol over UDP.

- **Modify Bearer Request:** This message is sent as part of the X2-based handover without SGW relocation on the S11 interface by the MME to the SGW. The description of the message in the 3GPP standard is included in [142], Section 7.2.7.
- **Modify Bearer Response:** This message is sent on the S11 interface by the SGW to MME as part of the X2-based handover without SGW relocation. The description of the message in the 3GPP standard is included in [142], Section 7.2.8.

Overview Message Sizes

In Table 13, an overview is given of the different signalling messages for the X2 and S1-MME interface, including all the L3 and L2 headers, which are sent over SCTP. Here, it is assumed that packets are sent via an IPv4 link over an Ethernet connection. Sizes are in number of octets. In the SCTP protocol, also SACK packets are sent in response to an SCTP messages. These are also taken into account in the calculation of the transmission latency. SCTP SACK packets have a minimal length of 28 bytes when there are no gaps in the stream. Together with the IP and Ethernet headers, the overhead for SACK is 74 bytes.

Type	*Payload (baseline)*	*Payload (min)*	*Payload (max)*	*SCTP*[1]	*IP*	*Ethernet*[2]
X2-AP Handover request	180	180	1452	28	20	26
X2-AP Handover request ack	30	30	1452	28	20	26
X2-AP SN status transfer	34	34	1452	28	20	26
X2-AP UE context release	16	16	1452	28	20	26
S1-MME Path switch request	62	62	1452	28	20	26
S1-MME Path switch request ack	55	55	1452	28	20	26

[1] for SCTP, only one stream is assumed and only one chunk per packet

[2] for Ethernet, 18 octets are needed for the header, and 8 octets for the checksum.

Table 13: Message size of X2-AP and S1-MME interface messages

In Table 14, an overview is given of the different signalling messages for the S11 interface, including all the L3 and L2 headers, which are sent over UDP. Here, it is assumed that packets are sent via an IPv4 link over an Ethernet connection. Sizes are in number of octets.

Type	*Payload (baseline)*	*Payload (min)*	*Payload (max)*	*UDP*	*IP*	*Ethernet*[1]
S11 Modify Bearer Request	62	62	1472	8	20	26
S11 Modify Bearer Response	58	58	1472	8	20	26

[1] for Ethernet, 18 octets are needed for the header, and 8 octets for the checksum.

Table 14: Message size of S11 interface messages

5.12.3 Latency in the Core Network During an X2 Handover

Transmission Latency of the Signalling Messages

In previous sections we identified all the parameters that contribute to the total latency in the core network during a handover. We calculated the sizes of the messages that are sent over the different interfaces in the core network when a handover is performed.

First, a simple calculation results in the transmission time of the messages that are sent between the core entities:

$$T = {}^{L}/_{R}$$

T is transmission time, L is the message size and R is the transmission rate of the link.

R is assumed to be 1 Gbit/s.

In Table 15, a summary is given of the transmission time for the different messages.

Parameter	*Transmission time (μs) Baseline*	*Transmission time (μs) Min*	*Transmission time (μs) Max*
T_{HOReq}	2.624	2.624	12.8
$T_{HOReqAck}$	1.424	1.424	12.8
$T_{SNStatus}$	1.456	1.456	12.8
$T_{UEContextRel}$	1.312	1.312	12.8
$T_{PathSwitchReq}$	1.68	1.68	12.8
$T_{PathSwitchReqAck}$	1.624	1.624	12.8
$T_{ModBearerReq}$	0.928	0.928	12.208
$T_{ModBearerResp}$	0.896	0.896	12.208

Table 15: Transmission time of signalling messages

For the transmission time of the ‘RRC conn reconf’ and ‘RRC conn reconf complete’ messages that are sent on the wireless LTE link we took following values for UL and DL data transmission in LTE, which were calculated in [124].

Parameter	*Transmission time (μs) Baseline*	*Transmission time (μs) Min*	*Transmission time (μs) Max*
$T_{RRCConnReconf}$	10800	10800	10800
$T_{RRCConnReconfComplete}$	20900	20900	20900

Table 16: Transmission time of RRC messages

Processing Latency During a Handover

Next to the transmission latency of the signalling messages in the core network, the total latency consists of the processing latency in the core entities that occurs during a handover. In this case, the processing latency comprises the processing time of the messages, processing of algorithms, releasing resources, detaching and attaching the UE to a new cell.

In Table 17, an overview is shown of the processing delays in the core entities that have been used in the analysis in this deliverable. These assumptions were obtained from [124] and are used as a baseline. As it is hard to have exact values, we also provided minimum and maximum values. This will lead to a range of total handover latency. Note that these values are estimations and will be further validated and fine-tuned when having results from the OpenEPC experiments on a real hardware test-bed. An extensive sensitivity analysis could be performed to outline the impact of the different unknown variables on the total latency. A simple One-Factor-At-a-Time (OFAT) sensitivity analysis is included further in this section.

Parameter	*Processing time (μs) Baseline*	*Processing time (μs) Min*	*Processing time (μs) Max*
P_{HOReq}	1000	1000	5000
$P_{AdmCtrl}$	1000	1000	5000
$P_{PathSwitchReqAck}$	1000	1000	5000
$P_{SNStatus}$	1000	1000	5000
$P_{RRCConnReconfComplete}$	1000	1000	5000
$P_{SyncNewCell}$	30000	10000	100000
$P_{RRCConnReconf}$	1000	1000	5000
$P_{HOReqAck}$	1000	1000	5000
$P_{ReleaseResources}$	1000	1000	10000
$P_{UEContextRelease}$	1000	1000	5000
$P_{SwtichDLPath}$	5000	1000	10000
$P_{ModBearerReq}$	1000	1000	5000
$P_{PathSwitchReq}$	5000	1000	10000
$P_{ModBearerResp}$	1000	1000	10000

Table 17: Processing time during handover

Total Latency

Based on all the input parameters, a total latency that occurs during a handover was calculated

Description	*Latency (μs) Baseline*	*Latency (μs) Min*	*Latency (μs) Max*
Total preparation time	14804.05	14804.05	30825.60
Total execution time	51900.00	31900.00	125900.00
Total completion time	15006.44	7006.44	55062.82
Total latency	81710.49	53710.49	211788.40

Table 18: Total latency during a handover

Sensitivity Analysis

To get further insight in what parameters have the most impact on the total latency, already a simple sensitivity analysis was done by plotting the total latency (baseline) when both $P_{SyncNewCell}$ (switchover time) and the Handover Request message size was varied over a certain range. The result is shown in Figure 50. This shows that the most impact of the total latency lies with the detachment and attachment time of the UE, and that the impact of the Handover Request message size is minimal.

Further extensive sensitivity analysis could be performed but was outside the scope of this use case.

5.12.4 Traffic Overhead in the Core Network during an X2 Handover

In the 3GPP specs, indirect data path forwarding is performed during a handover. This means that all downlink data that still arrives at the SeNB during a handover will be buffered and redirected to the TeNB until the downlink data path has switched in the SGW. This results in data overhead in the core network on the X2 interface from the SeNB to the TeNB. To quantify the amount of extra data, we first calculate the total time during which packets are forwarded. This is shown in Table 19 for baseline, min and max handover parameters.

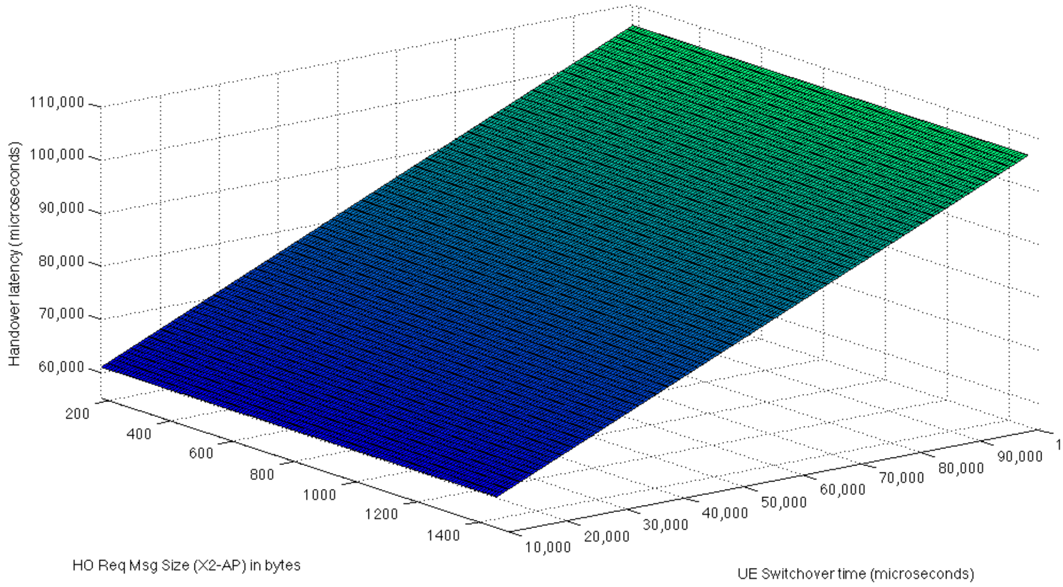

Figure 50: Simple sensitivity analysis

Parameter	*Latency in µs (base)*	*Latency in µs (min)*	*Latency in µs (max)*
Handover execution time T_{HE}	51900	31900	125900
$T_{PathSwitchReq}$	1.68	1.68	12.8
$P_{PathSwitchReq}$	5000	1000	10000
$T_{ModBearerReq}$	0.928	0.928	12.208
$P_{ModBearerReq}$	1000	1000	5000
$P_{PathSwitchReq}$	5000	1000	10000
Total latency	62902.61	34902.61	150925.01

Table 19: Traffic overhead in core network

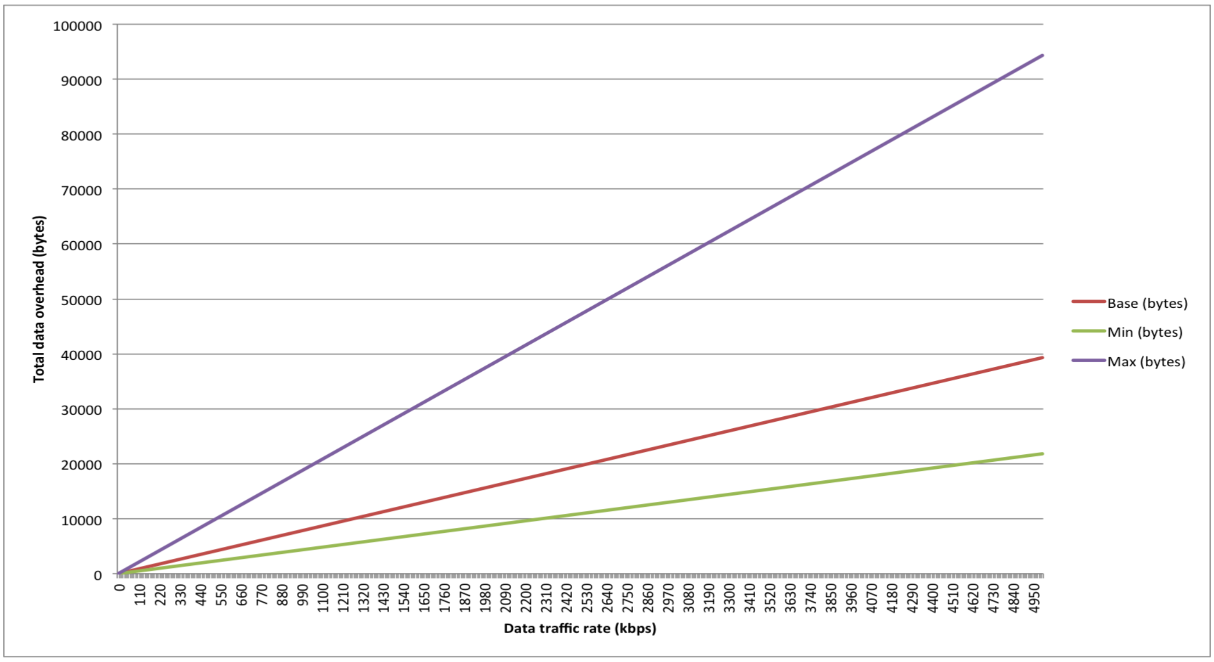

Figure 51: Data traffic overhead in the core during a handover

Now, for different data rates, we can calculate the total data overhead that is generated in the core network on the X2 interfaces by indirect data forwarding during a handover. This is shown in Figure 51.

5.13 Conclusions, Remarks, and Way Forward

In this deliverable it has been discussed an algorithm to distinguish between users that follow different trajectories through a cell and group users that follow similar trajectories. This algorithm is based on the Dynamic Time Warping algorithm that is used in signal processing. The DTW algorithms was adapted such that it is able to find the best match of any suffix of one time series (measurements from a reference user) with any interval of another series (measurements from an active user). The ability of the algorithm to match users that follow similar trajectories was then assessed in an environment where a single user repeatedly follows the same trajectory as a reference user and measurements made by it are compared to earlier measurements collected from the reference user. Afterwards variations in the velocity and trajectory of the active user were introduced. Results show that the modified Dynamic Time Warping algorithm is able to identify users that follow the same trajectory even when there are slight variations in their velocities and/or trajectories, and to distinguish between users that follow different trajectories.

The developed classification algorithm will serve as an important part of the SON function that will be developed in the future. It will be used to classify users but also to identify new trajectories.

During the first study on handover latency in the Evolved Packet Core, the intra-RAT X2 based LTE handover was considered. By theoretically calculating example signalling message sizes and making estimations for the processing time in the different entities, the total latency in the core network during a handover was estimated. This value is a start for further validation and tweaking by performing experiments on a real test-bed with the OpenEPC platform. Furthermore, the total data traffic overhead during a handover was quantified, to see the impact of a handover in the core network when there is data transmission in progress. These results can be used as input for the simulations that are performed in the High Mobility Use Case for calculating the benefits of reducing handovers.

5.14 References

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6 Active/Reconfigurable Antenna Systems

6.1 Executive Summary

In this use case the capabilities of modern Active Antenna Systems (AAS) are under examination, and more specifically, the effectiveness of Vertical Sectorization as a network densification approach, is evaluated through simulations. The network performance is measured under various conditions in the Controllability & Observability study, revealing the necessity for a SON function to control the VS, in order to obtain densification gains.

Based on an extensive literature study, two main control parameters were defined for the VS, namely the down-tilt per vertical sector and the transmission power per vertical sector. Moreover, crucial KPIs such as aggregated average, 5^{th} and 10^{th} percentile user throughput, system resource utilization and coverage percentage, were identified, in order to evaluate the performance of the network, and they were monitored on a per network, per cell and per pixel (geographical area of 10x10 meters) basis.

The C&O study results indicate that VS can provide significant capacity gains in highly loaded network scenarios, while it is limited by the increased interference created by the increased number of sectors. The performance of VS is very sensitive to the change of the down-tilt of the vertical sectors while not so much to the change of the transmission power per sector. VS performs better when there is a significant difference between the tilts of the inner and outer sectors due to reduced interference. Increased sector down-tilt s lead to better user experience (increased throughput) but have a negative impact on the network coverage. Based on the insights gained from the C&O study, the process of creating an initial SON algorithm which will control the activation / de-activation of VS, is proposed. At a second stage, the optimization process for the control parameters will be examined.

6.2 Problem Description and Objectives

The AAS use case aims at developing a SON algorithm that will take advantage and make optimum use of the advanced features that currently available Active Antenna Systems have to offer. For a single-RAT network the AAS feature that is considered is Vertical Sectorization (VS) for increased network capacity while for a multi-RAT network the focus is on the parameter optimization of a multi-band antenna. During the first phase of the use case work, presented in this deliverable, the focus has been VS and the development of a SON algorithm that will improve network performance by vertically sectorizing the appropriate cells with optimum values for key parameters such as tilt and power per sector.

The VS feature of the active antenna system has been known to have a large impact on the network capacity [144]. The VS splits a cell into two cells, inner cell and outer cell respectively. The inner cell has a smaller coverage area and makes an ideal candidate to serve a hotspot region of the network, since all of the sector's resources are used to serve this small area close to the eNB, with potentially large number of users. This will act as a network densification process. The disadvantage of this densification approach is the introduction of additional interference components to the users in the surrounding cells. In order to obtain the densification gains in terms of capacity improvement, a SON function is necessary to decide when to activate / de-activate the VS process.

When the VS feature is enabled, a single cell is split into two cells: inner and outer cell, respectively, as shown in Figure 52. The coverage area of the inner cell, which is shown in dark orange colour, is small and it covers the region close to the base station. The coverage area of the outer cell, shown in yellow colour, is larger and covers the region outside of inner cell's coverage. The inner sector provides additional capacity to users close to the base station, and increases performance for the users close to the base station, while the outer sector makes sure that the total coverage of the cell is not compromised. The available transmission power of the previously un-sectorized cell is divided between the inner and outer sectors.

Though the amount of resources in terms of available resource blocks is doubled in the same region there will be additional interference introduced, which reduces the SINR in both inner and outer sectors, thus limiting the capacity gain due to the densification, i.e. activation of the vertical sectorization. If the amount of traffic served by the single non-vertical sectorized cell is small, then the gains from activating VS will be minimal, since there will be some improvement of performance due to the densification, but there will also be performance degradation due to increased interference. On the other hand, when the non-vertical sectorized cell is heavily loaded and users are getting unsatisfied because of low transmission speed, then the users can benefit greatly due to the increase in available resource blocks. In this case the gains due to densification can be much greater than the losses due to increased interference, and under these circumstances it would be beneficial to activate VS. Therefore, it is necessary to understand the circumstances in which it is beneficial to activate the VS feature and circumstances in which it is beneficial to deactivate the VS feature. To that end, a C&O study has been carried out in order to provide insights about the effect that each sectorization parameter has on the network performance. The activation rules will be determined using both the C&O study, and optimal control theory. Once the VS feature is enabled, it is also important to optimize the antenna parameters like antenna down-tilt and transmission power per sector that give the higher performance in both inner and outer cells. In the following, AAS stands for Active Antenna System, and RAS stands for Re-configurable Antenna System, which are different flavours of the same system. The latter terminology (RAS) is used when the same antenna system is used to serve different RATs (multi-RAT case).

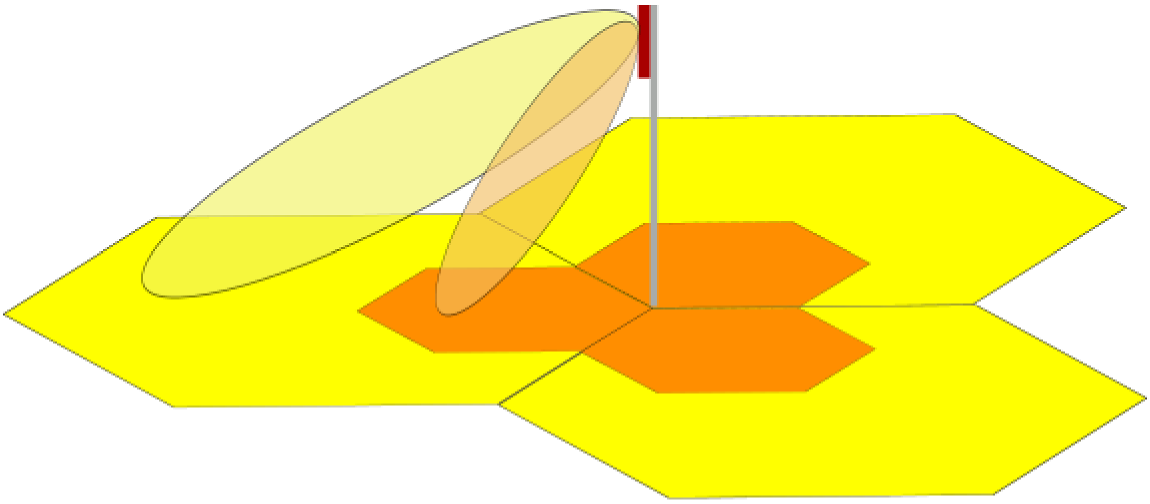


Figure 52: Illustration of Vertical sectorization and the resulting geographical serving areas of each sector

The aim of the AAS use case is to design a SON mechanism that allows activating the VS-AAS when traffic conditions for obtaining densification gains are met. The only assumption in the use case is that the deployed macro antennas are capable of providing the VS feature.

AAS also offers advantages in the case of multiple co-located RATs. We use in this case the term RAS instead of AAS. Having a multi-band antenna system makes it possible to support a multi-RAT network using the same antenna. For example, a Kathrein 742265 antenna [154], which supports 824-960 MHz and 1710-2180 MHz bands, can be used to support GSM and LTE at the same time. Both these cells will not have exactly the same serving region due to other site installations and also due to differences in propagation between the two frequency bands. In such a scenario, one can improve the network performance by considering KPIs from both the RATs to optimize the antenna parameters. Also, one can utilize the coupling between the optimal values of the RAS parameters across RATs, if it exists, for developing the SON algorithm.

Only the scenario concerning the single RAT VS use case of AAS will be considered in this deliverable.

6.3 State-of-the-art

The impact of vertical sectorization on the network performance has been previously studied and various publications and standardization discussions that have been engaged with this subject are presented below.

6.3.1 Academic Publications

The work of Osman et al. [144] shows a large improvement in the capacity of the network that can be achieved with VS. Although the network scenario and the antenna pattern under assumption are idealistic cases, the results give the order of improvement that can be achieved by using the VS feature of AAS. The related work by the same authors [145] shows the impact of optimizing antenna parameters like antenna tilt for performance optimization under VS. Also, the results show that the antenna tilt has the maximum impact on the UE throughput performance in comparison to the impact of vertical half power beamwidth. In [146] it is shown that the gain earned from VS depends on the difference of the down-tilt angles of the inner and outer sectors and more specifically, in order for VS to deliver better performance than other schemes, e.g. horizontal sectorization the difference between the inner and outer down-tilt angles must be greater than 4^o. In [4] the excess interference between the inner and outer sectors is studied, by observing the adjacent channel interference ratio, and a new power control scheme which minimizes interference, is proposed. In [147] it is shown that changing the antenna tilt has an impact on radio propagation modeling in case of 3D antenna propagation.

6.3.2 Standardization

In the standardization fora, there has been a long discussion in terms of antenna modelling, impact of VS, scenarios to be considered for evaluation of VS, etc., [149]- [153]. The standard document [150] contains all the details of the AAS deployment scenarios, antenna model, AAS transmitter and AAS receiver characteristics. Further detailed AAS antenna model related 3GPP standard contributions show the different vertical and horizontal beam pattern modelling [151] compared to the previously used standard 3GPP antenna model.

6.3.3 Summary and Recommendations

The AAS use case brings the SON algorithm for the VS feature to the table. All prior-art that has been mentioned, investigates different aspects of VS in a static way, in the sense that the network or cell performance is evaluated in case VS (under various configurations) is active. The activation / de-activation of VS with optimized configuration parameters based on the current load imposed on the network, has not been researched before. It is worth mentioning that the use case considers a scenario with large geographical area having varying deployment properties (like larger and smaller inter-site distances). The propagation model used in the simulations is a more realistic ray tracing model, which captures the effect of the impact of antenna configuration changes in a more accurate way than the traditionally used statistical propagation models.

6.4 Architecture

The functional architectural block diagram used in AAS use case is given in Figure 53. The AAS use case functional block features involve KPI monitoring functional block, multi-RAT specific AAS SON functional block and the VS specific SON functional block. A brief description of the functional blocks specific to AAS use case is given below and detailed description can be found in [158].

Functional description of the AAS components:

- ***AAS specific KPI monitoring***: This module / function perform the necessary calculations for the activation / deactivation of the AAS functionalities, based on the measured KPIs. This function is divided into two sub-functions:
    - ***Load calculation:*** This sub-function calculates the load (in terms of resource utilization) per cell on a medium time scale (order of minutes)
    - ***Interference Monitoring:*** This sub-function monitors the inter-cell interference with a focus on cells belonging to the same site, and cell-edge user performance (used for the VS sub-use case)
- ***VS-SON:*** This module / function performs the necessary actions for the activation / de-activation of Vertical Sectorization. This function is divided into five sub-functions:

- *UE cell reselection:* Upon activation or de-activation of the VS feature the UEs within the coverage range of that cell(s) are called to perform a handover or cell reselection, respectively, since the cell ID will change.
- *Power per sector calculation:* This sub-function calculates how the available antenna power is going to be divided among the two sectors (inner and outer).
- *Sector tilt calculation:* This sub-function calculates the electrical tilt of the inner and outer sectors.
- *Vertical beam-width calculation*: This sub-function calculates the vertical beam-width of the inner and outer sectors.
- *VS Feature ON / OFF*: The activation / de-activation of the VS feature can be seen as a special sub-case of the power per sector sub-functions. If the power for the inner sector is set to 0 Watts then the VS feature is practically OFF (only one cell exists).

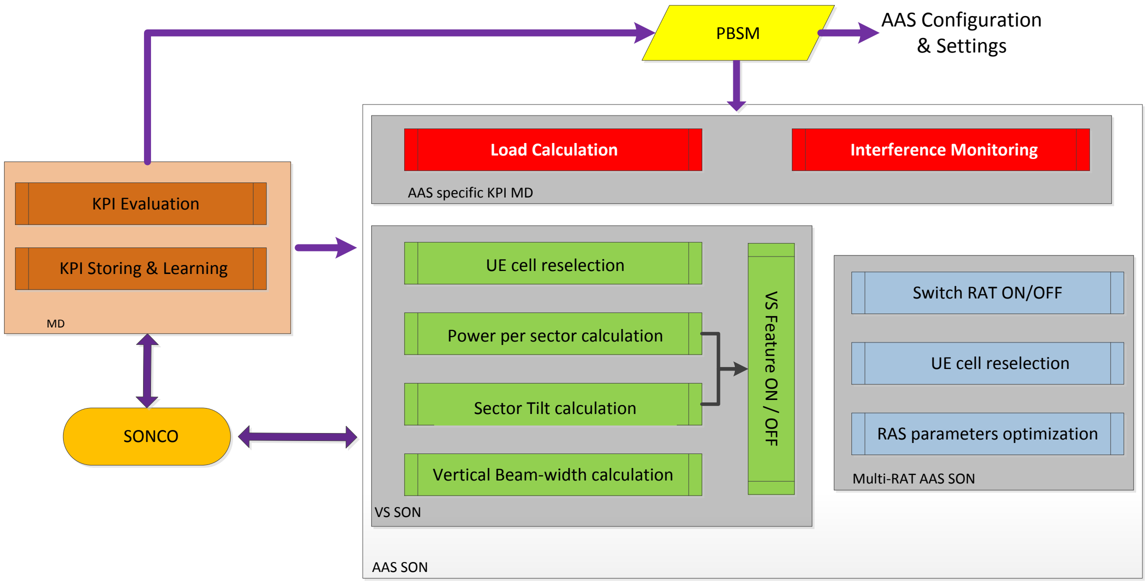


Figure 53: AAS Use Case Functional Architecture

The above mentioned architecture, describes the minimum required steps for the activation of VS. Once the decision to activate the VS feature has been taken by the SON function, the rest of the above mentioned sub-functions will be activated in order to calculate the proper parameter values for the activation and to inform the UEs of the imminent change in network layout. While the UE cell reselection sub-function is independent from the other sub functions, the other three (power, tilt and beam-width calculations) are expected to operate in synergy with one another.

- ***Multi-RAT AAS SON:*** This module / function performs the necessary actions for multi-RAT SON functionality. The multi-RAT aspect of the function will only be investigated during the second phase of the use case work This function is divided into four sub-functions:
  - *Switch RAT ON / OFF*: This sub-function takes the decision of activating / de-activating a RAT based on the measured KPIs and the input of other sub-functions.
  - *UE cell reselection:* Upon activation or de-activation of a RAT, the UEs within the coverage range of that cell(s) are called to perform a cell reselection.
  - *RAS parameters optimization:* This sub-function determines the optimum values for the RAS parameters based on measured KPIs.
- ***KPI Evaluation***: UE KPIs as well as Cell KPIs, e.g. Average Throughput, cell-edge throughput, Spectrum efficiency of the cell are evaluated on a medium time scale (order of minutes).
- ***KPI Storing & Learning***: Cell and UE KPIs are stored on, e.g. daily basis so that the system learns if and how the traffic in various areas has a repetitive behaviour on, e.g. daily, weekly

basis (in a certain business area the traffic may be high at day and low at night time in week days).

6.5 Main Monitoring KPIs

The KPIs that can be monitored to understand the impact of VS can be separated into three main categories, namely System-level KPIs (aggregated user statistics over all the cells of the network), Cell-level KPIs (aggregated user statistics of a specific cell) and Coverage area-level KPIs (aggregated user statistics over an area of 10x10 meters).

The cell level utilization and 5th user throughput percentile will be considered as algorithm input, for the initial stage of the SON algorithm development.

6.5.1 System-level KPIs

The system level KPIs will constitute the ones that will be aggregated at the OAM level. The KPIs that are considered here include:

- Average, 5th and 10th percentile user throughput
- Average, 5th and 10th percentile of file transfer time
- CDF of user throughput and file transfer times
- Ratio of blocked calls to the call attempts
- System utilization metric which is measured in terms of average power consumed by the cells

6.5.2 Coverage area-level KPIs

These KPIs will be issued for a given geographic area for specific analysis of the situation and they will depict the performance experienced by the users only in that area. If some users in the area are not covered by any cell, their statistics are only taken into account for the calculation of the coverage ratio and the RSRP cdf.

- Average, 5th and 10th percentile user throughput
- Ratio of blocked calls to the call attempts
- Aggregated average user throughput
- CDF of the Reference Symbol Received Power (RSRP) values from the users in the area
- Coverage ratio based on an RSRP value threshold of -120 dBm

6.5.3 Cell-level KPIs

The cell level KPIs are specific to individual cells. They include,

- Average, 5th and 10th percentile user throughput
- Cell utilization in terms of average power utilization
- Average aggregated bit rate
- Ratio of blocked calls to the call attempts

6.6 Main Control and Configuration Parameters

Based on the findings of the literature study, the following parameters have been chosen to act as control parameters for the SON functionality, meaning that these are the parameters that the algorithm controls in order to optimize the performance of the VS feature. The effect that these parameters have on the performance of the VS feature will be evaluated in the C&O study, and then, assuming that the findings of the C&O study agree with the findings of the literature study, they will be used as control parameters for the SON algorithm. The control parameters that will be used are the following:

- <u>VS activation / deactivation switch</u>

  From the previously carried out studies, it is known that the VS feature will benefit for certain deployment and traffic scenarios. When more traffic is concentrated close to the base station then the VS is expected to be beneficial. If the traffic is more uniform, then the VS might lead to a situation of higher interference for the users in the network and hence might negatively impact the observed KPI. Therefore it is required to have control over activation / deactivation of the VS feature depending on the impact on the observed KPIs.

- Power per sector (inner and outer sector)

  When the VS feature is deactivated then the entire power available for the cell is used by the single cell that existed before. If the VS feature is activated, then the resulting two sectors needs to share the same amount of power and provide similar coverage while improving the system performance. Therefore it becomes important to distribute the power optimally to each of the newly formed sectors.

- Tilt per sector (inner and outer sector)

  From the previously carried out studies [145] it is known that the antenna tilt will play a major role in performance improvement. The tilt values of both the inner and the outer sector will be changed in order to obtain higher performance.

6.7 Simulation Modeling and Tools

The simulations for the AAS use case are carried out for a geographical area of 5 x 7 km in the centre of Hannover. This area includes an urban and a suburban area, which means that the VS feature can be evaluated under different conditions. This area contains 84 macro cells operating at 1800 MHz frequency band and isotropic pathloss predictions are used derived from the TUBS ray tracing model. The traffic simulated is both outdoors and indoors. The simulator used for carrying out the C&O study does not have a SON algorithm for activating / deactivating the VS feature, but offers the opportunity to evaluate system and cell performance when VS is applied in all the cells and when it is applied in none of them. In the second phase of the C&O study, the effect of individual cell sectorization will be examined. The simulator is aligned, as much as possible, with the simulators that are used across the project, through the calibration activity mentioned earlier, in order to obtain consistent results. For the C&O study, only the frequency band of 1800 MHz will be used. Basic reasoning behind this choice is that the macro 800 MHz layer will be used as the coverage layer by most of the operators. Making changes in the VS AAS use case will affect the coverage and therefore operators might be hesitant to change the settings. Macro 1800 MHz is used for capacity reasons in the macro layer and therefore one could try out different parameters that could potentially affect the coverage.

The simulator used for the AAS use case is a LTE system level simulator, which does not simulate multipath fading or mobility of users, since it was deemed that mobility is not the most critical aspect to evaluate the merits of VS. However, it is important to note that there will be impact on the highly mobile users due to the doubling of the number of cells (and corresponding reduction of their size). This will lead to more handovers which could lead to poor user experience. However, a state-of-the-art mobility robustness optimization algorithm is expected to come in handy during these situations and therefore, mobility will not be considered in this use case. Without taking mobility or multipath fading into account, there is no need for TTI level simulations, and thus, this is an event based simulator and not a TTI based simulator. A number of “satellite” tools are used in conjunction with the main simulator. The main purpose of these tools is to pre-process and prepare the input files, such as network layout, isotropic pathloss prediction, traffic intensity maps, etc., for the simulator.

The call arrival process in the simulator is based on the probability of calls arriving at a specific location in the simulated area (pixel based, using 10 x 10 meter pixels) which is calculated from the traffic intensity map. The traffic simulated is data traffic (not voice) and the size of each data call to be completed is selected either in a deterministic way, i.e. the size of all calls is the same and equal to a predefined value, or from some kind of distribution (exponential, log-normal, etc.). For the purpose of the C&O study, the size of the data calls is chosen deterministically and it has been set to be 2 MBs. Once a call has been generated the serving base station is selected based on the best Reference Signal Received Power (RSRP) and admission control is performed for that call in the selected base station. Based on the calculated SINR of each call and the available system Band Width (BW), the throughput is calculated based on the truncated Shannon function, which is shown below.

$$Throughput, Thr = \begin{vmatrix} Thr = 0 & \text{for } SNIR < SNIR_{MIN} \\ Thr = \alpha.S(SNIR) & \text{for } SNIR_{min} < SNIR < SNIR_{MAX} \\ Thr = Thr_{MAX} & \text{for } SNIR > SNIR_{MAX} \end{vmatrix}$$

Where:

S(SNIR) Shannon bound: $S(SNIR) = \log_2(1+SNIR)$

α Attenuation factor (0.6 in our simulations)

SNR_{MIN} Minimum SNIR (-10dB in our simulations)

Thr_{MAX} Maximum throughput (4.4 bit/sec/Hz in our simulations)

$SNIR_{MAX}$ SNIR at which max throughput is reached S^{-1} (22dB in our simulations)

It must be noted, that for the SINR calculations, it is assumed that all neighbouring base stations transmit at full power, even if they only serve one user. This assumption is justified by the fact that only data traffic (FTP) is simulated, which is a greedy kind of traffic, and thus, the scheduler will assign all available resources, to one user, if this user is the only one being served by the cell. At a later stage, other types of traffic will be simulated, e.g. Constant Bit Rate traffic, which means that the calculation of SINR will have to be altered, since in that case the interference from neighbouring eNBs will be more or less proportional to the amount of resources used by that eNB at any specific time interval. The most important capabilities / characteristics of the simulator are given as follows.

Cell size	Macro
Environment	Urban & Suburban
Type of cells	Outdoor
Served traffic	Mixed (outdoor & indoor UEs)
Number of users	Based on traffic intensity map with scaling factor
Traffic distribution	With Hotspots
Type of traffic	Data Traffic
Mobility	Static users
Simulation time-scale	Event based (not per TTI)
Multipath-fading	No, as event based simulations are carried out (no finer time-scale)
Antenna model	Model proposed by Kathrein that is under review in 3GPP [153]
Scheduling	Resource Fair sharing (frequency domain)
MIMO	Simplified modelling of MIMO through modified Shannon curves (attenuation factor in above equation)
ICIC	No
Propagation	TUBS Ray tracing model [157]
Simulations Time-scale	Hours

Table 20: Simulator capabilities and modelling assumptions for the AAS use case

6.7 Controllability and Observability (C&O) Analysis

The C&O study aims at evaluating the effect that the manipulation of the various control parameters given in Section 6.6 has on the performance of the network measured using the KPIs described in Section 6.5. The various monitoring KPIs are used to evaluate the network performance while sweeping control parameter values spanning a four-dimensional space (VS activation / deactivation; power share; tilt inner; tilt outer) of various combination possibilities. From the analysis of the controllability study results, the principles of a SON algorithm can be derived which will affect the network as intended per individual case.

6.7.1 Methodology and Objectives

The method used for C&O study is to sweep through a reasonable set of the control parameter combinations described in Section 6.6 and see its impact on the different KPIs described in the Section 6.5. The set of values chosen for the sweeping is based on the insights gained from literature review, i.e. a reasonable range of values for the VS parameters that lead to optimum network performance.

Amongst the control parameters, VS activation / deactivation is a binary operation. Scenarios with different traffic distribution are studied with and without VS feature and the KPIs are measured. This will act as an indication as to when VS might be beneficial.

When the VS feature is activated, the power available at the eNB must be shared between two cells, the inner and the outer cell. In order to study the impact of having different power distribution between two cells on the KPIs, the samples given in Table 21 are chosen from the vast sample space. This will give a basic understanding of possible power adjustment mechanism for SON algorithms.

% of total power for inner cell	% of total power for outer cell
25%	75%
40%	60%
50%	50%
60%	40%
75%	25%

Table 21: Selected samples from the vast sample space of possible power allocation between inner and outer cells

When it comes to optimization of the antenna parameters for the inner and outer cells, the antenna down-tilt is expected to be of utmost importance [145]. The values used for inner and outer tilts during the C&O study, are given in Table 22 below.

Inner cell tilt angle	Outer cell tilt angle
{6°, 8°, 10°, 12°,14°}	{0°, 2°, 4°}

Table 22: Pre-fixed values of tilts for inner and outer sectors used for C&O study

The aforementioned selected values of the control parameters, for both the transmission power and the sector tilt, are based on the insights gained from the literature review.

6.7.2 C&O Scenario(s)

For the controllability study scenario, an area of 5x7 km in the centre of Hannover has been selected, which includes both urban and suburban areas, as described in Section 6.7. Even though VS is applied in all the cells in the simulation area, the statistics and various KPIs that are measured during the simulations only concern a smaller area of 3x5 km within the larger AAS area, which is called the statistics area. This action is necessary in order to leave out of our study the border effects that are created close to the edges of the simulated area. Figure 54, depicts both the simulated and the statistics area (grey rectangle), including the location and orientation (azimuth) of the cells in that area.

The colour map of Figure 54, depicts the relative traffic intensity of the various areas of Hannover. The numbers in the colour map, do not represent a specific value, just the relationship between the traffic intensity of the various pixels (relative values). For the controllability study, VS is not applied in specific cells (as will be the case when a SON algorithm is applied), but to the entire network (every cell in the simulation area is vertically sectorized) and the performance of the network and specific cells, are compared to the original scenario where no VS is applied. A very high load is selected, in order to push the network to its limits, and make the advantages of VS more obvious. Under this load, more than 10% of the cells in the network operate at full capacity (100%) and start dropping data calls, while about 50% of the cells operate at more than 60% of their capacity.

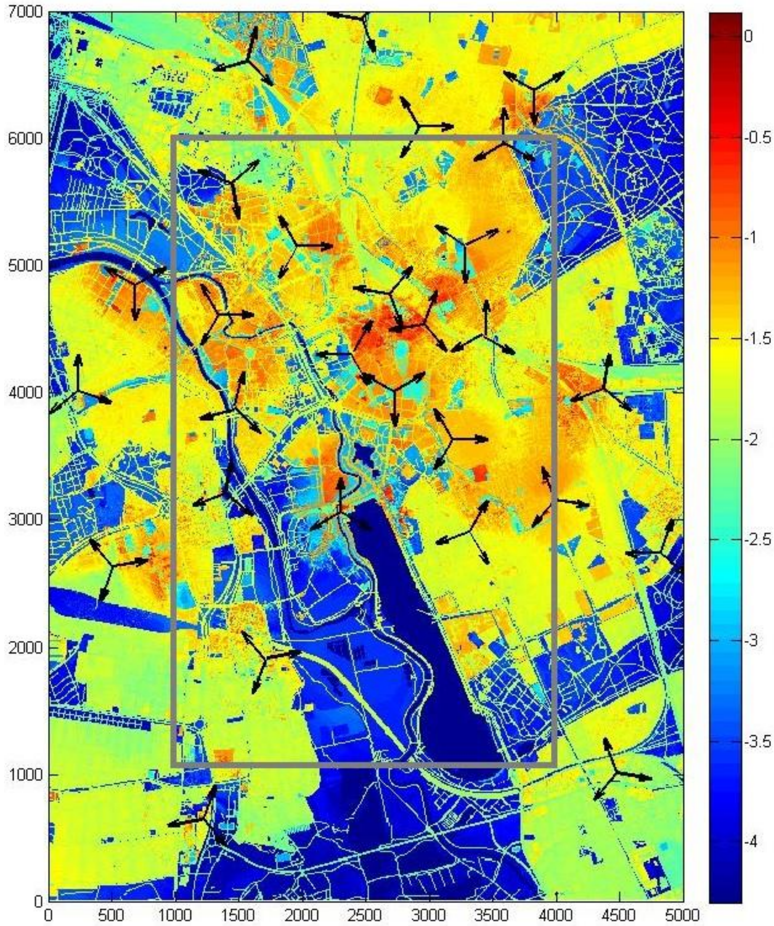


Figure 54: AAS simulated area & statistics area (axes in meters)

6.7.3 Impact of Measurements and Control Parameters

In this section, the most important results of the controllability study are presented. The presented statistics and KPIs regard user performance, aggregated on a per network and/or per cell (sector) level. In the following plots, the reference scenario is denoted as "No VS", while the scenarios where VS is applied are denoted as "*Tilts x/y*", where *x* is the electrical tilt of the inner sector and *y* is the electrical tilt of the outer sector, in degrees. It must be noted, that all the cells already have a mechanical tilt of 4 degrees. Therefore any additional electrical tilting will be done upon this mechanical tilting. As mentioned above, the effect of two major control parameters is examined in the controllability study, the tilt per sector and the power per sector.

6.7.4 Tilt Per Sector

In this Section, the effect of VS on the performance of the network and the effect of different tilts for the inner and outer sectors will be examined. Throughout this Section, the available power of each cell is evenly split between the two sectors, when VS is active, i.e. a split of P_{inner} / P_{outer} = 50 / 50 is used (20 Watts per sector). In the results presented below, the scenario 'Tilts 6 / 0' represents the case where no change has been made in the electrical tilt of the outer sector (while the mechanical tilt remains at 4^0) and as such it depicts the initial situation where VS is simply activated with no tilt optimization. It can be used to evaluate the merits of VS, when no tilt optimization is used, against the reference scenario. Figure 55 below, depicts the 10^{th} user throughput percentile aggregated over the entire statistics area, and Figure 56 depicts the call coverage percentile (coverage ratio) as defined in Section 6.5.2, also aggregated over the entire statistics area, for various scenarios. It must be noted that an RSRP threshold of -120 dBm was used for determining the coverage percentage, i.e. users which experience an RSRP lower than -120 dBm are not covered by the network. This threshold was selected based on the real life measurement results of the 'LTE Trial' project carried out by TNO and Huawei [159]. Since the RSRP threshold for coverage is an implementation issue, different values can be used by different operators, which in turn will affect the coverage percentage of their network.

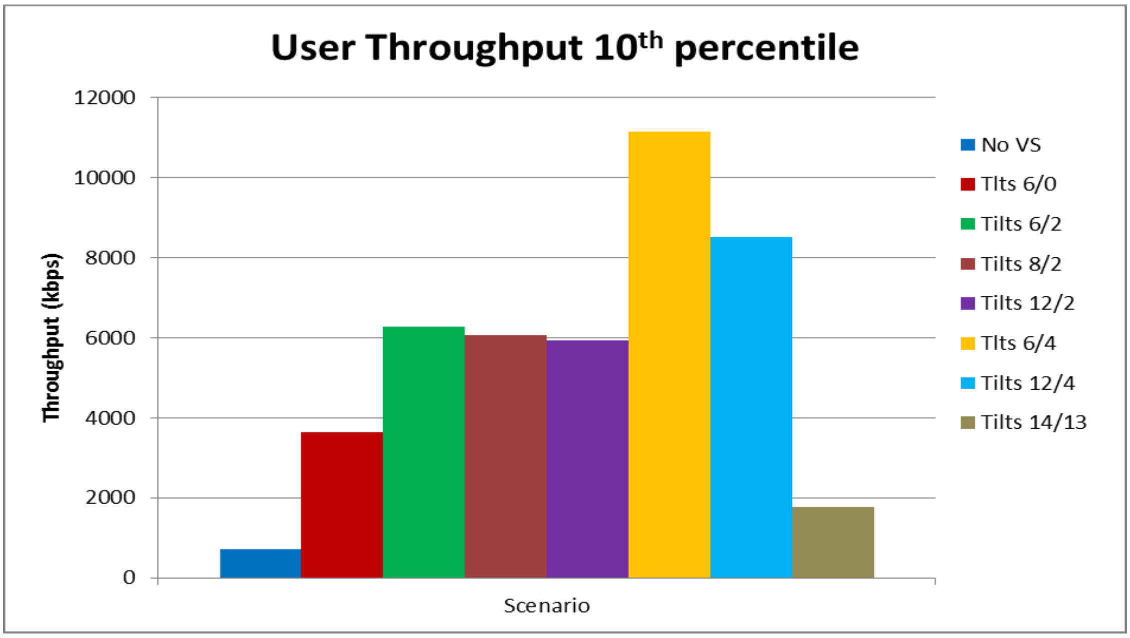


Figure 55: Lower 10^{th} user throughput percentile (Aggregated over the entire network)

The 10^{th} user throughput percentile for the reference scenario is very low (720 kbps) which is a consequence of the extremely high load. In this scenario, multiple cells in the network operate at their capacity limit. A significant improvement in user throughput is observed for every scenario where VS is applied. The throughput for scenarios with the same outer sector tilt, is comparable, and only decreases slightly with increasing inner sector tilt. This is due to the fact that the larger the inner sector tilt, the smaller its coverage area and the fewer users it will serve with the same resources. At the same time, the users that are no longer served by the inner sector, are now served by the outer sector, thus the outer sector has to serve an increasing amount of users with the same amount of resources which causes the performance to drop. It is important to keep in mind that VS will not be beneficial for every cell in the network, thus the user throughput over the whole network should be regarded as a relative measure.

An interesting point is that the reference scenario seems to perform worse, even than the scenario with extreme tilts for the sectors (Tilts 14/13). This should be examined along with the coverage figure. The 10^{th} user throughput percentile for the extreme scenario is only better than the reference scenario because there are fewer users served by the cells, since it is obvious that the no coverage percentage has increased drastically. Thus, with fewer users to serve, these users get better throughput. In general, it seems that the larger the tilts the better the user throughput, but the increased tilts have an impact on coverage which has to be considered.

From Figure 56, it is obvious that when the tilt of the outer sector is the same, the coverage percentage is also the same. This is logical since the outer sector provides the coverage while the inner sector boosts the performance of the users close to the eNB. The small difference in the scenarios with an outer tilt of 4^o can be explained by the interference effects on the border between the two sectors and the amount of users located there. Finally, for the extreme tilts scenario, the percentage of users that have no network coverage has increased by a factor of ten, compared to the reference scenario but still remains in low levels, which is an indication that this area of Hannover is very well covered with eNBs. Even so, the extreme tilts have a significant impact on the experienced user RSRP, which deteriorates the user performance. Figure 57 below, depicts the RSRP values per pixel of the geographically covered area (each pixel corresponds to a 10x10 meter area), for the reference and the extreme tilts scenarios. From Figure 57, it is obvious that even though the RSRP remains above -120 dBm (which is the no coverage threshold) in most areas, for the extreme tilts scenario, it has decreased significantly compared to the RSRP of the reference scenario, which leads to worse network performance.

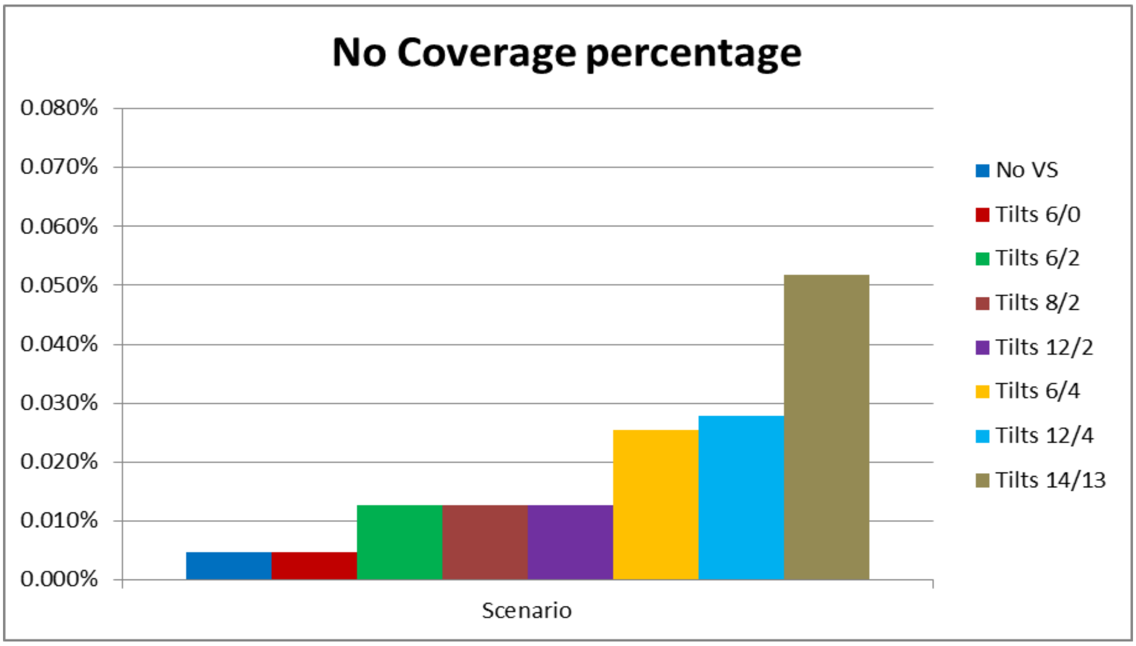
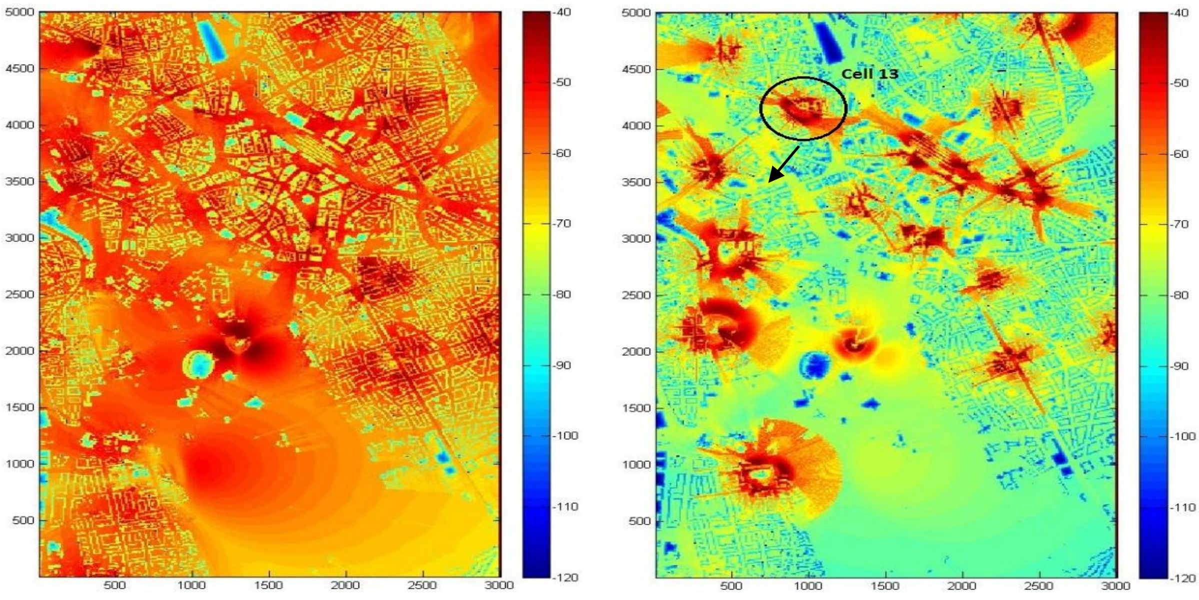


Figure 56: No Coverage percentage (Aggregated over the statistics area)



(a) ***(b)***

Figure 57: RSRP per pixel for (a) the reference scenario and (b) the extreme tilts scenario

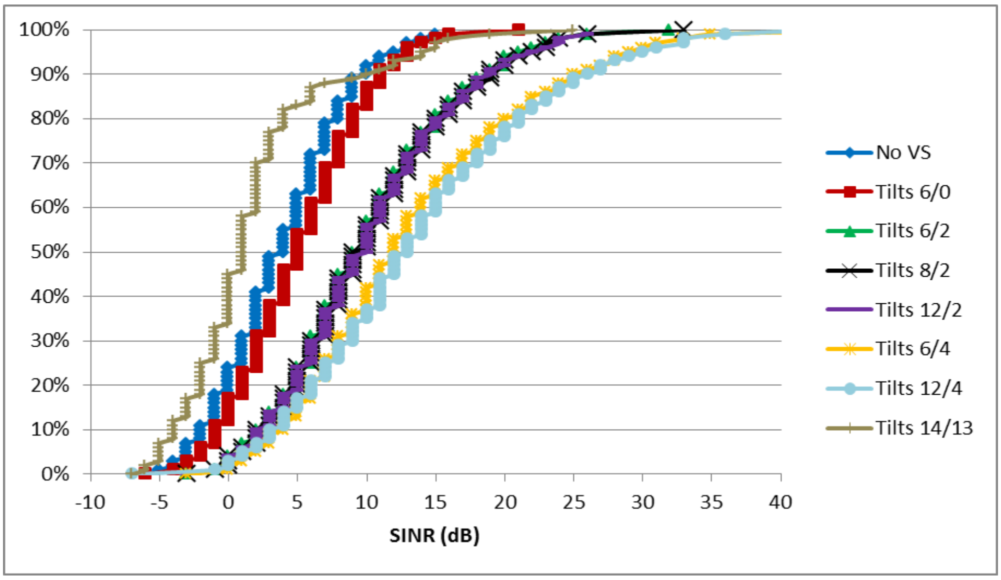


Figure 58: User experienced SINR CDF for the outer sector of cell 13

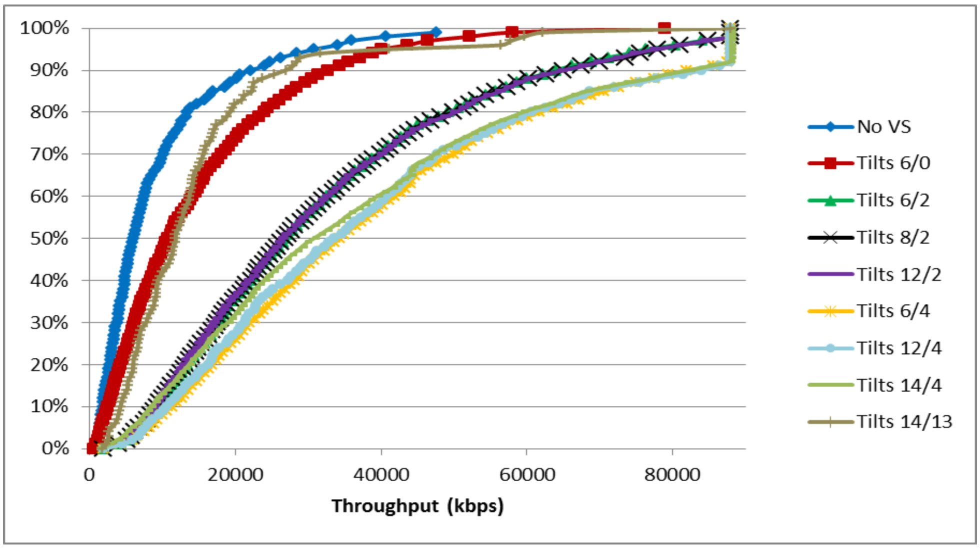


Figure 59: User throughput CDF for the outer sector of cell 13

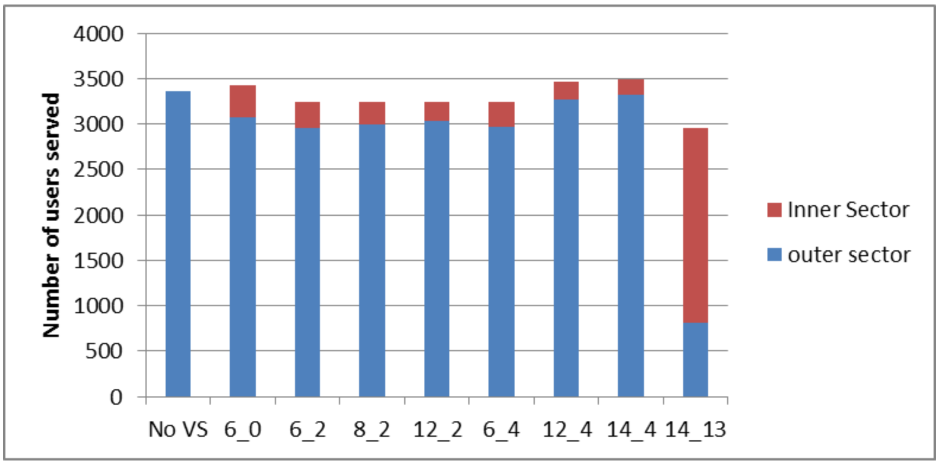


Figure 60: Served users per sector for cell 13

For the purpose of understanding and evaluating the performance of VS, it is better to focus on the cell/sector level statistics and KPIs, since they offer a much better insight, than the network level KPIs. For that purpose, a specific cell, which is heavily loaded, has been chosen for analysis. This cell has the internal Cell ID number 13 and is located at coordinates *x*: 705, *y*: 895, as seen in the RSRP plots in Figure 57. Figure 58 and Figure 59 below depict the user experienced SINR CDF and the user throughput CDF for the outer sector of Cell 13, respectively, while Figure 60 depicts the number of users that were served by both the inner and outer sectors of cell 13 during the simulation.

From Figure 58 above, it can be observed that all the scenarios with VS (except for the extreme tilts scenario ‘Tilts 14 / 13’) give an improved SINR curve, and the curve is similar for scenarios with the same outer tilt. The improvement over the reference scenario comes from the decreased interference from the neighbouring eNBs due to the increased outer tilts. The similarity among results with the same outer tilt comes from the fact that the transmission power and interference patterns remain very similar when only the inner sector tilt changes. The change of the inner sector tilt will only mildly affect the interference pattern between the inner and outer sectors. This can be seen from scenarios “6 / 4” and “12 / 4”, where the latter gives a slightly better SINR curve, due the decreased interference between the inner and outer sectors (the smaller the difference between the tilts of the inner and outer sectors, the larger the interference between them). Finally, as a sanity check, the SINR curve of the extreme tilts scenario (“Tilts 14 / 13”) is depicted, and as expected, it is worse even than the reference scenario SINR curve, due to the extreme interference caused between the inner and outer sectors.

Most of the above observations are also true for the user throughput CDFs that are depicted in Figure 59. The same patterns as before arise for scenarios with the same outer tilt, while the gains in SINR can be translated into smaller or larger gains in throughput, depending on the distribution of users within the cell. From this Figure, the densification gain of VS becomes obvious when applied to a highly loaded cell, since all of the scenarios with VS perform better than the reference scenario. The fact that the throughput seems to increase with increasing outer sector tilt, is also due to the fact that the coverage area of the cell becomes smaller and hence, less users are served (see Figure 60). As a consequence the available resources are divided among fewer users, and the users experience higher throughput. This is also why the extreme tilts scenario seems to perform better than the reference scenario in terms of throughput. By observing Figure 60, it is immediately seen that the outer sector of cell 13, serves much less users for the extreme tilts scenario than for the reference scenario and that is why it appears to have better performance. Moreover, it is observed that for all scenarios, the inner sector serves a small percentage of the total users in the cell, which is explained by the high tilt of the inner sector which means that only a small geographical area is served from it (only the users very close to the eNB are served by the inner sector). Finally, an interesting observation from Figure 60 is that for a specific outer sector tilt, if the inner sector tilt is increased beyond a certain point, e.g. scenario ‘Tilts 14 / 4’, the user throughput of the outer sector deteriorates, since more and more users “migrate” from the inner to the outer cell, and they have to be served with the same amount of resources.

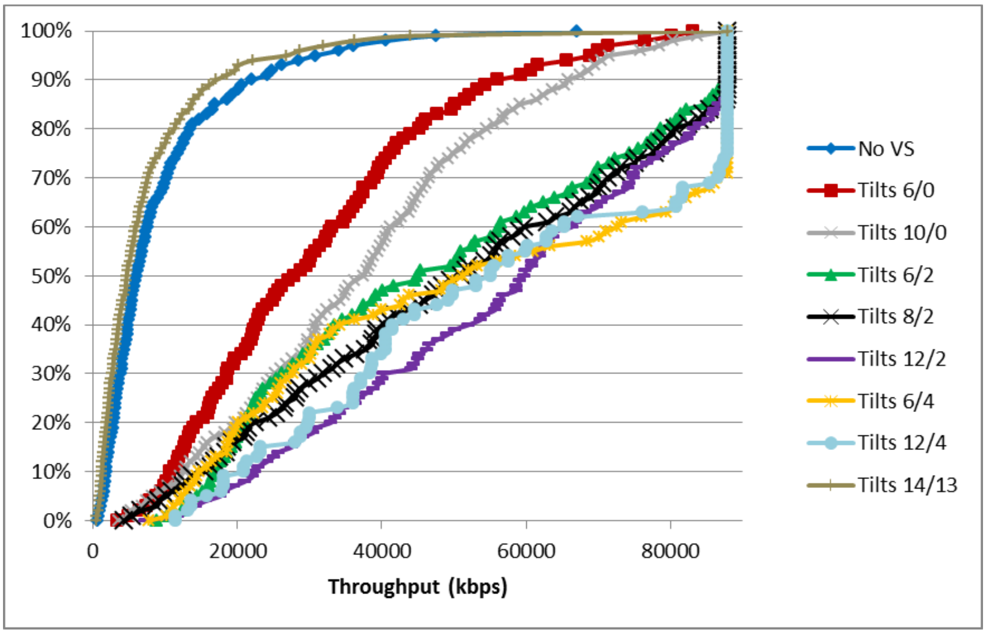


Figure 61: User throughput CDF for the inner sector of cell 13

Apart from the performance of the outer sector, it is also very interesting to see the performance of the inner sector as well. Figure 61 below, depicts the user throughput CDF of the inner sector of cell 13.

From Figure 61, the benefits of VS for the users close to the eNB, can be observed. Obviously a straight forward comparison is not fair, since the inner sector serves about 10 % of the total users that are served from cell 13 in the reference scenario, but the experienced throughput for the users with high SINR is increased significantly. Once more, as the inner sector becomes smaller, with increasing tilt, the throughput improves. It is interesting to note, that during the extreme tilts scenario, the allocation of users per sector is substantially different compared to the other scenarios due to the weird interference phenomena caused by the extremely high tilts and the fact that the inner and outer sectors have almost identical tilts. This fact also results in the deterioration of the experienced user throughput compared to the reference scenario. This interference does not originate from neighbouring cells (since they are all heavily down-tilted) but from the outer sector of cell 13, which has almost the same tilt as the inner sector.

By examining Figure 59, Figure 60 and Figure 61 together, the benefits of VS become obvious. By combining the user throughput CDFs of the inner and outer sector and by comparing them with the throughput CDF of the reference scenario, while keeping in mind the total number of users served, we can observe that about the same number of users are being served (in terms of order of magnitude, since the no coverage percentage remains relatively low) and in all cases where VS is applied (except for the extreme tilts case) their experienced throughput is much better than it was during the reference scenario simulation. However, the percentage of not covered users should also be kept in mind. As the previously presented results indicate, the tilt of the outer sector should remain in relatively small values, in order to provide good coverage for the users of the network.

In order to get an insight of the scale of the improvement that is feasible with VS, the average throughput per pixel is shown below in Figure 62, for the reference scenario and the best VS scenario, "12 / 4", respectively. The number of users / calls per pixel is the same in both cases, but in the case of the reference scenario the average throughput of most pixels is closer to the lower limit of the colour scale, thus making them not visible.

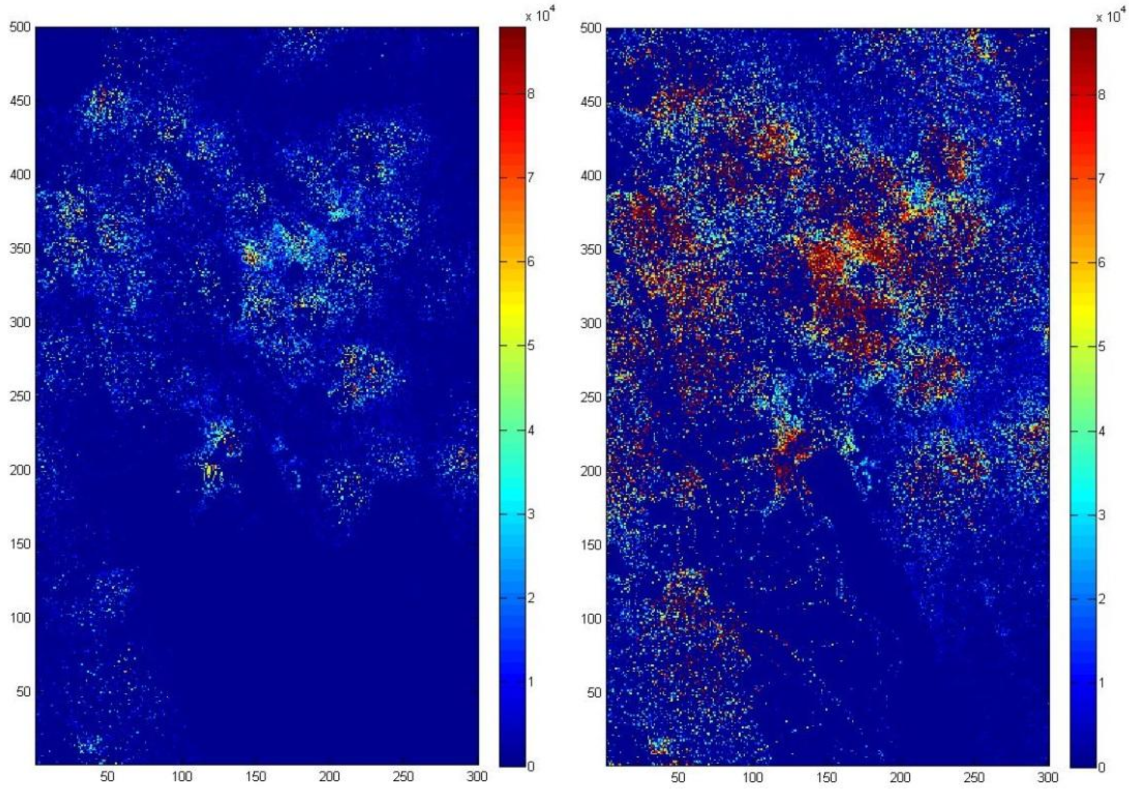


Figure 62: Average Throughput per pixel for in kbps for (a) the reference scenario and (b) the 12/4 scenario

6.7.4.1 Power Per Sector

In this Section, the effect of the transmission power used in each sector of a vertically sectorized cell, will be examined. When VS is applied in a cell, the available transmission power of the antenna of that cell, can be customly split between the two sectors. For the controllability study, the total transmission power of a cell is taken to be 40 Watt (46 dBm). In the previous section, where the effect of the sector tilts was examined, the transmission power was evenly split between the two sectors (20 Watt each). In this section, the effect of providing one sector with more transmission power than the other will be examined. The scenario with tilts 8 / 2 has been selected to be used for this evaluation, as an average VS scenario. It is expected that the use of any other tilt values for the inner and outer sectors would yield similar results in this section, except for the case where extreme (unrealistic) values are used. In the following plots, the various scenarios are denoted “Power *x* / *y*” where *x* is the percentage of the original transmission power (power used by the cell when it was un-sectorized) that is allocated to the inner sector, while *y* is the percentage of the original power allocated to the outer sector.

Figure 61 depicts the user throughput CDF over the entire network. It can be observed that the overall experienced user throughput does not differentiate much for different allocations of transmission power per sector. Nonetheless, a slight improvement of the throughput curve can be observed for the users with the higher throughputs (upper half of the curve) when most of the available power is allocated to the inner sector (scenarios “Power 60 / 40” and “Power 72 / 25”). By allocating most of the transmission power to the inner sector, the performance of the users close to the eNB, i.e. the users belonging to the inner sector, becomes even better. These users were already experiencing a good throughput since they have a good SINR, and were the users that are “populating” the upper half of the throughput curve. On the other hand, the lower half of the throughput curve does not seem to be affected when more power is allocated to the outer sector. The users belonging to the outer sector are the ones “populating” the lower half of the throughput curve, since they are located further away from the eNB and thus experience worse throughput. The lower part of the curve does not improve when more power is allocated to the outer sector because the number of users served by the outer sector is large (much larger than the number of users served by the inner sector), and thus the effect of the extra transmission power is averaged out over all the users. Again, it has to be noted that the user throughput CDF averaged over the entire network is a relative measure, since the vertical sectorization can deteriorate the performance of some cells, while improving the performance of others.

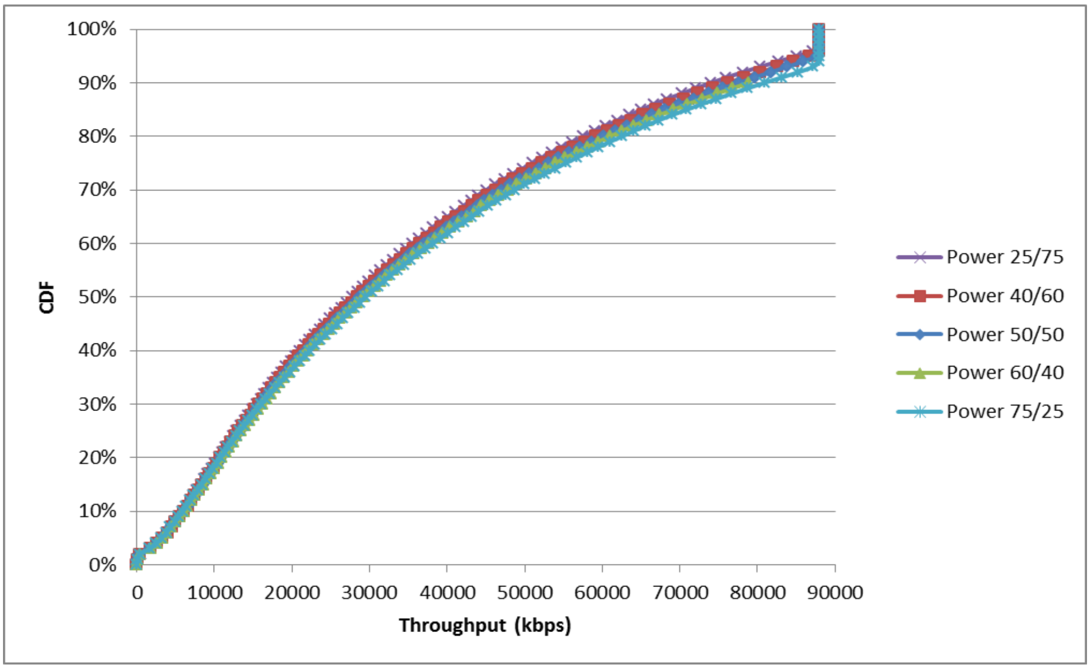


Figure* 63*: User throughput CDF over the entire network with tilts 8/2

As in the case when examining the effect of tilts, also here, it is more interesting to look at the effect of the varying transmission power, on a per sector level and not on a network level. Again, cell 13 is selected to be evaluated as a highly loaded cell. Figure 64 and Figure 65 below, depict the user experienced SINR CDF and the user throughput CDF for the inner sector of cell 13, respectively.

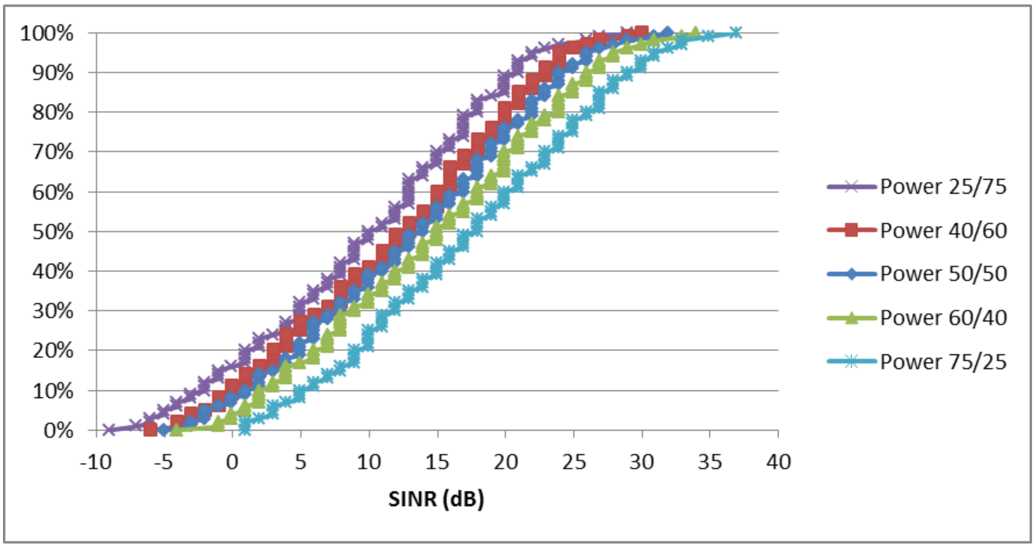


Figure 64: User experienced SINR CDF for the inner sector of cell 13

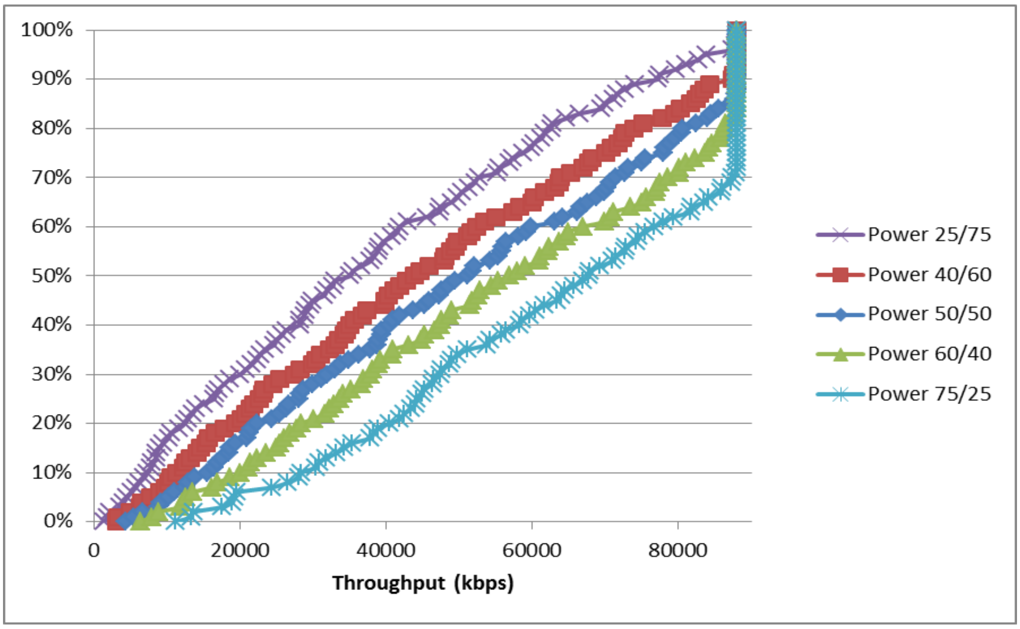


Figure 65: User throughput CDF for the inner sector of cell 13

From Figure 64 it can be observed that when increasing the inner cell transmission power on the expense of the outer cell's power, the user experienced SINR improves, while it deteriorates when reducing the transmission power. This behaviour is, of course, expected and it has a direct impact on the user throughput as can be seen by Figure 65. The effect of the transmission power change, is very obvious for the inner sector, also due to the fact that this sector serves a relatively small number of users (about 10 % of the users of the original un-sectorized cell), hence these users experience a significant change in their performance. On the other hand, the users of the outer sector experience almost no difference due to transmission power changes, because of the large number of users being served by the outer sector, as can be seen from Figure 66 and Figure 67 below, since the user throughput and user experienced SINR CDFs for all scenarios are almost identical. Even when more power is assigned to the outer sector, that power is divided among a large amount of users, which means that each user only gets a small fraction of that extra power, and hence their individual SINR is not significantly improved.

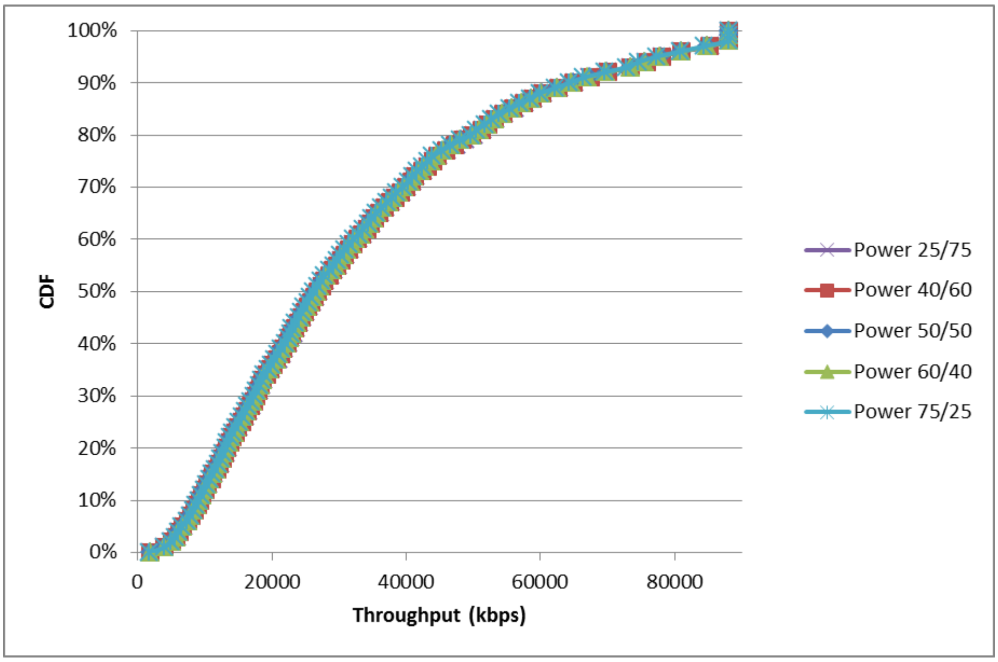


Figure 66: User throughput CDF for the outer sector of cell 13

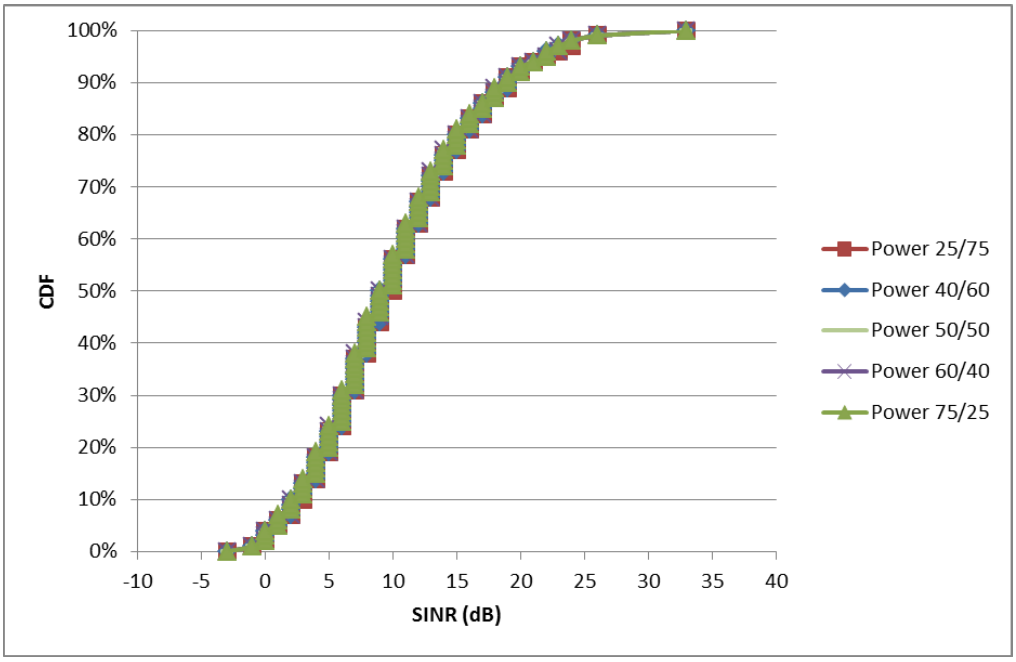


Figure 67: User experienced SINR CDF for the outer sector of cell 13

6.7.5 C&O Analysis Outcome and Way Forward

Based on the results of the controllability study that were presented in the previous Section, a few early conclusions can be drawn, regarding the effectiveness of VS and the performance of this feature in relevance to two control parameters, the sector tilt and the transmission power per sector.

VS is an effective densification approach, since in almost all scenarios there was an improvement of performance compared to the reference scenario. In the scenarios that were examined above, the reference scenario had a very bad performance since the network was extremely loaded and thus, the application of VS always offered improvement due to the doubling of the available resources. The same simulations must also be carried out for scenarios with normal to high and low traffic load, in order to evaluate how VS affects the performance then and when the reference scenario proves better than the scenarios with VS. This will also act as a motivation for having a SON function that adapts to the varying traffic changes.

As far as the tilts of the sectors are concerned, it was shown that the tilt of the outer sector is important with respect to the overall coverage of the network, while the tilt of the inner sector is important for increasing the network performance. The outer sector tilt must be maintained at low values, in order to provide acceptable coverage, even though an increased tilt offers advantages in terms of throughput. The inner tilt affects the experienced throughput of the users close to the eNB. The larger the tilt the bigger the throughput benefits. Nonetheless, it must be kept in reasonable levels in order not to overload the outer sector with large number of users, which would deteriorate their performance. It is also important to maintain a significant difference between the tilts of the two sectors (between 6 and 10 degrees) in order to minimize the inter-sector interference effects.

The transmission power assigned to each sector does not have a big effect on the performance of the users of the outer sector, but it can greatly affect the performance of the users of the inner sector. Depending on the distribution of users between the inner and outer sectors, assigning more power to the inner sector can improve the throughput of the inner sector users, significantly. Again, the division of transmission power between the sectors should be done with caution, in order not to “starve” one of the two sectors.

As a next step for the C&O study, the same simulation scenarios have to be run again, for low, medium and (normal) high load, in order to evaluate the performance of VS in situations where the network is not operating at its capacity limits.

6.8 SON Function

The SON algorithm in AAS use case can be seen at two levels. One aspect of it being the algorithm for activation / de-activation of the VS feature and the other aspect being the algorithm for optimizing the power distribution between inner and outer sectors and also the tilt optimization of the two sectors. During the first phase of the SON algorithm development, the focus is on the first aspect of the algorithm.

The SON functionality maps the network state, defined in terms of Key Performance Indicators (KPIs), into a decision variable, and can be written as follows:

$$D = f\left(KPI_1,\ldots,KPI_N\right) \tag{6-1}$$

where D is the decision variable that can take the values 0 or 1, which correspond to the control action of switching off and on the vertical sectorization, respectively. The function f defines is often denoted as a controller. In the solution considered here, the state of the network is related to the loads of the inner and outer cells.

The requirements for the solution are the following:

(i) Robust operation: avoid ping-pong effects, i.e. frequent switch on and off

(ii) Good reactivity: when traffic conditions are met for activating the VS-AAS, the SON functionality can be activated quickly

(iii) Low complexity: simple algorithm that does not require long computation

6.8.1 SON Algorithms

This Section describes the approach adopted for designing the SON functionality. Details and results will be provided in the subsequent deliverable 4.2, *SON functions for multi-layer LTE and multi-RAT networks (final results)*.

We propose a solution for the VS-AAS SON which follows a design strategy used for Energy Saving SON, namely the sleep mode for base stations, denoted ES SON. The ES SON switches off base stations when traffic level (or load) is below a pre-defined threshold (that can be chosen as zero), and switches it on when traffic level is above a second threshold. When switched off, the traffic of that base station is served by other base stations, of the same or of another technology. In [155], the ES SON is designed using the following steps:

(i) Solve rigorously a small problem (toy model) using a Markov Decision Process (MDP) [155]. The MDP solution provides the form of the controller (policy)

(ii) Parameterize the controller found in step (*i*). In the case of a threshold type of policy, the parameterization is simple

(iii) Adjust the controller parameters using a learning approach, i.e. Policy Gradient Reinforcement Learning.

The design of the VS-AAS SON will follow a similar approach. It is noted that phase (*iii*) can be performed using results from C&O analysis, exhaustive search (if the controller shape is simple), or more sophisticated learning approaches.

At a later stage, an extension of the SON algorithm will be considered, which will take into account the adaptation of tilt values and transmission powers, based on traffic conditions. In other words, the following two steps are envisioned for the development of the SON algorithm:

- Apply a first simple version of the SON algorithm, which makes decisions on which cells to vertically sectorize, with predefined control parameters. This version will only take decisions about activating / de-activating the VS feature.
- Apply an advanced version of the SON algorithm which will activate / de-activate the VS feature and will optimize the tilt and transmission power per sector, based on current traffic conditions.

6.9 Conclusions, Remarks, and Way Forward

The work done so far in this use case and the simulation results presented in this section, depict the benefits of VS as a capacity enhancement measure. The conclusions drawn in Section 6.7.5 reveal the advantages and disadvantages of VS, but it must be noted that these conclusions are also related to the simulation assumptions that were made during the C&O study. The generic behaviour of VS is not expected to change for different assumptions, but some aspects of the system performance might be affected. The possible ways that different assumptions might affect the network performance are elaborated below.

- VS offers densification gains which improve the user performance in both the inner and outer sectors in the case of a highly loaded network. If the network is unloaded (low offered load) the performance of the users of the outer sector could degrade due to the increased interference and the reduced transmission power. The evaluation of VS in an unloaded network is the next step for this use case, as mentioned earlier.
- In these first results that are presented in this chapter, the assumption was made that VS is applied uniformly in the entire network (VS is applied to all the cells with the same tilts and power per sector distribution). This assumption has the following effects:
    - When larger tilts are used for VS (more down-tilted), the region that is served from each sector becomes smaller (and closer to the eNB) which results in higher received signal strength. At the same time, since all the neighbouring cells are also down-tilted further, the inter-cell interference becomes smaller, which increases the user SINR even further and thus their performance increases.
    - When larger transmission power is used for the outer sector, the received signal strength for the users is increased, but at the same time the inter-cell interference is also increased, since all of the neighbouring cells are also using increased transmission power for their outer sectors. That is why there is no change visible in the experienced user SINR in Figure 67.

  The application of VS on a per individual cell basis is one of the most important next steps for this use case, in order to evaluate the performance of VS under more realistic conditions.
- VS is a capacity enhancement measure, but it can also affect the coverage of the network, depending on the tilts used for the outer sector. Two main points arise from our simulation results:

- When the tilt of the outer sector is not changed at all, the coverage of the network remains the same as it was for the un-sectorized case, as can be seen in Figure 56 (scenarios ‘No VS’ and ‘Tilts 6 / 0’). As long as the tilt of the outer sector remains in comparable levels with the un-sectorized case, the coverage of the network should remain in acceptable levels.
- Even though the RSRP values decrease significantly when large tilts are used for the outer sector, as can be seen in Figure 57, the ‘No coverage percentage’ remains very low due to the fact that very few users drop below the -120 dBm RSRP coverage threshold used throughout the simulations. Even though this is a realistic value, it has proven to be unsuitable for this scenario which is densely populated with eNBs.

  It is for further study a more suitable RSRP threshold to be used in this scenario, which will reflect the loss of coverage in a more accurate way.

Based on the insights gained from these first results of the controllability study, the next envisaged steps are:

- Continuation of C&O study: Apply VS on a per individual cell basis. Learning the rules for activating the VS-AAS by correlating inner- and outer-cell loads to performance gains. The performance of the entire network and the cell coverage area will be evaluated. Determining the function for activating the VS-AAS based on load measurements (dynamic thresholds, hysteresis, etc.).
- Continuation of the development of the SON algorithm for activating and deactivating of the VS-AAS feature following the approach described in Section 6.8.
- Study further possible evolutions for the AAS use case: (*i*) SON algorithm incorporating (in addition to activation / de-activation of the VS-AAS feature) tilt and transmission power adaptation per sector, based on current traffic conditions; and (*ii*) SON for RAS for multi radio access technology and multi-layer context.

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7 Conclusions, Remarks, and Way Forward

This deliverable has provided insights of the initial studies about the selected SON functionalities for future networks in the scope of the SEMAFOUR project. Specifically, the investigated use cases are: Dynamic Spectrum Allocation and Interference Management (DSA/IM), Multi-layer LTE/Wi-Fi Traffic Steering (TS), Idle Mode mobility Handling (IMH), Tackling the problem of High Mobility users (HM), and Active/reconfigurable Antenna Systems (AAS). The investigated SON areas address mainly the challenge of network optimization in cases where load unbalance / congestion occur, or more in general, when spatial or temporal traffic variations are detected. Those are important gaps to cover compared to the state-of-the-art and industry solutions and have shown significant potentials in terms of capacity, coverage, and / or user performance improvements. This conclusion is valid except for the IMH use case, where, based on a technical review, only minor advantages are anticipated, and DSA/IM, where further work is necessary before drawing conclusions on the gain level.

In the following, final remarks and the way forward are identified for each individual SON use case.

The ***DSA/IM*** **use case** investigated different network baselines, which represent the extreme case of DSA when a frequency layer is assigned exclusively to all the cells of a network layer or to all possible cells. Based on the results, the following conclusions can be drawn. The current simulation results with and without overlapping spectrum between macro and micro cells give very similar performance. Therefore, it is not directly apparent when to reduce the spectrum usage in the macro cells so that the micro cells can benefit from the reduced interference, and when to add more spectrums in macro layer to satisfy the “hungry users” in spite of causing more interference to other users in micro cells. However, the current simulation results did not consider the load balancing algorithms across different cells which leads to unnecessarily overloaded cells when other cells can share the traffic volume. Therefore, state-of-the-art load balancing and traffic steering algorithms need to be implemented in order to fully investigate the potential of DSA benefits.

The limitations of the current simulations will be addressed in the continued work by using a load balancing algorithm and also by taking ICIC modelling into consideration. The load balancing across frequency layers will be given higher priority as it will also help to understand the multi-RAT use case scenarios, thereby justifying the amount of effort being put in to develop a load balancing algorithm. As further work, macroscopic simulations on a larger scenario area will also be performed, which are necessary for investigations of the macro cell interference when DSA algorithms are applied.

The ***TS use case*** evaluated steering techniques between LTE and Wi-Fi access technologies in a realistic outdoor hot zone scenario with three network layers, i.e. collocated LTE micros and Wi-Fi APs overlaid with LTE macros. Up to two control parameters, i.e. RSS and RSRP thresholds, or two RSRP thresholds have been selected and evaluated by C&O studies and proved as effective in controlling UE network access selection. The C&O outcome provided the basis for the development of two corresponding SON algorithms, RSS-based and RSRP-based, which were evaluated by system level simulations. The behaviour and analysis of the RSS-based and RSRP-based SON algorithms were studied showing balancing load properties between the two access networks. The analysis of the throughput gains was presented for the RSS-based algorithm which showed improved user throughput performance compared to the reference cases of “Wi-Fi if coverage” and fixed RSS threshold TS. The stability and sensitivity of the algorithm was also proved in the evaluated scenario.

A number of topics for future investigation have been identified through the study: a) Better calibration of the simulation tools to allow direct comparison between the performances of the analysed mechanisms and SON algorithms; b) Additional monitoring KPIs that better reflect cell load in both LTE and Wi-Fi has to be added to the SON function to cope with full buffer traffic and improve SON performance; c) Additional monitoring KPIs that better reflect the user performance (experience) such as average and 5th percentile throughput could be studied; and d) The SON functions need to be evaluated and optimized in additional scenarios with, e.g. different network load levels, user mobility, mixed and / or more dynamic traffic, standalone Wi-Fi APs, indoor environments, etc. In order to further improve user and system performance, enhanced and / or additional SON functions need to be considered to be able to provide several SON policy options and strategies to the operator. Examples are steering on-going sessions instead of only selecting a RAT when a session is started and reinforcing controllability by enabling per-UE steering capability and performance metrics (see an example in Appendix A.2). In subsequent SEMAFOUR Deliverable 4.2 (confidential) we will address the topics listed above with the main focus on the in-depth quantitative analysis of the proposed SON mechanisms.

As concerns the ***IMH use case***, while there are a multitude of parameters that could be used to tune cell reselection and extra complexity could be added, it is our belief that, as shown also by recent research papers, idle mode traffic steering alone cannot outperform traffic steering in connected mode. Even an alignment between traffic steering in idle and connected mode will only bring some minor advantages in terms of UE battery consumption and some reduced signalling. In light of the above conclusion, we have decided closing this use case without further investigation.

Regarding the ***HM use case***, in this deliverable we discussed an algorithm to distinguish between users that follow different trajectories through a cell and group users that follow similar trajectories. This algorithm is based on the Dynamic Time Warping (DTW) algorithm that is used in signal processing. The DTW algorithm was adapted such that it is able to find the best match of any suffix of one time series (measurements from a reference user) with any interval of another series (measurements from an active user). The ability of the algorithm to match users that follow similar trajectories was then assessed in an environment where a single user repeatedly follows the same trajectory as a reference user and measurements made by it are compared to earlier measurements collected from the reference user. Afterwards variations in the velocity and trajectory of the active user were introduced. Results show that the modified DTW algorithm is able to identify users that follow the same trajectory even when there are slight variations in their velocities and/or trajectories, and to distinguish between users that follow different trajectories. The developed classification algorithm will serve as an important part of the SON function that will be developed as future work. It will be used to classify users but also to identify new trajectories.

During the first study on handover latency in the Evolved Packet Core, the intra-RAT X2-interface based LTE handover was considered. By theoretically evaluating example signalling message sizes and making estimations for the processing time in the different entities, the total latency in the core network during a handover was estimated. This value is a start for further validation and tweaking by performing experiments on a real test-bed with the OpenEPC platform. Furthermore, the total data traffic overhead during a handover was quantified, to see the impact of a handover in the core network when there is data transmission in progress. These results can be used, for instance, as input for the simulations that are performed in the HM use case for calculating the benefits of reducing handovers.

In the ***AAS* use case**, the Vertical Sectorization (VS) scheme is studied and proved as a capacity enhancement measure. The analysis assumes that VS is applied uniformly in the entire network, i.e. same tilts and power are applied to any sector. VS offers densification gains which improve the user performance in both the inner and outer sectors in the case of highly loaded networks. When larger tilts are used for VS, the region that is served from each sector becomes smaller (and closer to the eNB) which results in higher received signal strength. At the same time, since all the neighbouring cells are also down-tilted further, the inter-cell interference becomes smaller increasing the network performance. However, if the network is unloaded the performance of the users of the outer sector could degrade due to the increased interference and the reduced transmission power. Furthermore, VS affects the coverage of the network as well, depending on the tilts used for the outer sector. As long as those tilts remain in comparable levels with the un-sectorized case, the network coverage should remain in acceptable levels. Even though the RSRP values decrease significantly when large tilts are used for the outer sector, the 'No coverage percentage' remains very low due to the fact that very few users drop below the -120 dBm RSRP minimum coverage threshold. Even though this is a realistic value, it has proven to be unsuitable for this scenario which is densely populated with eNBs.

The next envisaged steps are as follows. First of all, the continuation of the C&O study is targeted. This comprises: a) Applying VS on a per individual cell basis; b) Learning the rules for activating the VS-AAS by correlating inner- and outer-cell loads to performance gains while evaluating the performance of the entire network and the cell coverage area; c) Determining the function for activating the VS-AAS based on load measurements (dynamic thresholds, hysteresis, etc.). The second part is about the continuation of the development of the SON algorithm for activating and deactivating of the VS-AAS feature following the adopted approach in this deliverable.

Appendix A Appendices to Multi-layer LTE / Wi-Fi Traffic Steering

A.1 Extended Academic Publications

This appendix is in relation to the TS use case described in Section 3 and provides a thorough review on individual publications related to the LTE and Wi-Fi TS.

Based on the literature review, a gap between the state-of-the-art and the targets of the use case has been identified. Most multi-RAT TS studies in academia focus on the TS algorithm investigation with homogeneous deployment, i.e. macro cellular cells only, and with a uniform user profile for all simulated users in terms of mobility and / or QoS requirements. So the developments on TS algorithms that take the multi-layer heterogeneity of future LTE networks and the diversity of users into account are needed. Furthermore, very few close-loop SON solutions have been proposed.

The review summarized in this Appendix will be used through the whole project. In the next phase of the study, the publications will be revisited and used to facilitate the extension of the proposed SON solutions in this deliverable and the design of new SON solutions.

The publications are summarized individually. Besides TS algorithms between different RATs, the TS between LTE nodes is also included since the principles may apply to the multi-RAT TS as well.

A.1.1 Publications on Multi-RAT TS

In [41] an experimental comparison is performed between Wi-Fi and 3G. In this performance comparison two users, one that connects through Wi-Fi and one that connects through 3G move along side-by-side either by foot or by car. The Wi-Fi user scans for available or community access points and opportunistically connects to them. The 3G user connects to the AT&T 3G networks. Whenever a user is able to connect, it connects to a server and transfers large random binary data files over HTTP in both the down- and uplink direction. Both users also have a GPS receiver that tracks the position, directions and velocities of the users. Results show that Wi-Fi outperforms 3G in both the up- and downlink direction. In the downlink direction Wi-Fi is for instance able to download 34 Megabytes in 223 seconds while 3G needs 760 seconds to download 55 Megabytes. In the upload direction Wi-Fi even outperforms 3G by a factor 2.6 times due to the poor performance of 3G. Wi-Fi transfers do however mainly take place when the client is stationary. It also is not always the best idea to connect to the access point which has the highest signal strength; instead it is a better idea to connect to access points that just come into range.

[45] studies two types of offload for Wi-Fi: on-the-spot and delayed offloading. On-the-spot offloading makes use of connectivity to Wi-Fi if it is available on the time when a transfer starts. When moving outside the Wi-Fi coverage area, unfinished transfers are continued over 3G. When using delayed offloading on the other hand a deadline is associated with each transfer. Data transfers only take place when Wi-Fi coverage is available, i.e. they are put on hold when users leave the Wi-Fi coverage area and are resumed when the user enters the Wi-Fi coverage area again. If the data transfer does not end before the deadline, the transfer is finished using a cellular network. On-the-spot offloading is commonly implemented in smart phones, delayed offloading is relatively new. The paper performs a quantitative study on the performance of 3G mobile data offloading through Wi-Fi networks using an iPhone application that tracks the Wi-Fi connectivity. Results show that users have Wi-Fi coverage for 70% of the time. On average users are in an area covered by Wi-Fi for 2 hours and once they leave the Wi-Fi coverage area, on average, they stay outside this area for 40 minutes. The results also show that on-the-spot offloading can save 65% of the total traffic load and 55% of energy.

In [50] a detailed study of 3G and Wi-Fi access from moving vehicles is performed. The vehicles that are used in the study move around a large geographical area and simultaneously connect to both 3G and Wi-Fi. Results show that Wi-Fi is available 11% of the time while 3G is available 87% of the time. If measured over longer intervals of 10-60s, Wi-Fi coverage rises to 30% and 3G coverage to 98%. On average the throughput of Wi-Fi is half of that of 3G both in the uplink and downlink directions. Using Wi-Fi whenever possible and switching to 3G otherwise is not a good idea as Wi-Fi availability is low which severely limits the fraction of data that can be offloaded. Also, the Wi-Fi loss rate is higher than that of 3G which will degrade the quality of applications that are sensitive to losses like VoIP. Furthermore the paper presents a system, called Wiffler that augments the 3G capacity. This system is based on two ideas: leveraging delay tolerance and fast switching. With leveraging delay tolerance it is meant that the future Wi-Fi throughputs are estimated and transfers are only delayed if 3G usage can be reduced. The Wi-Fi prediction is based on the observation that Wi-Fi access points are encountered in bursts. Fast switching means that if a packet fails to be delivered over Wi-Fi within a delay threshold, it is delivered over 3G. Results show that prediction based offloading reduces 3G usage by 30% while Wi-Fi coverage is only 12% and fast switching reduces 3G usage by 34% while maintaining good voice quality for over 68% of the time.

[38] discusses some fundamental principles and theoretical and practical considerations for the design of TS algorithms for multi-RAT and multi-band cellular communication environments. These include static versus dynamic steering, the fact that newer RATs offer higher data rates and better spectral efficiency, that the offered traffic will consist of a variety of traffic with different characteristics and requirements, that there might be TS constraints based on user priority classes, etc. Further some simple TS algorithms based on coverage or/and load, potentially with a steering policy on top, and the intuition behind them, are briefly described with the view to highlight the strategies that are possible to achieve a superior performance.

[87] investigates downlink performance of indoor deployed Wi-Fi and Femto cells as offloading solution from LTE macro cellular networks. A large-scale dense-urban scenario of a European city is evaluated. The following assumptions are made in the study a) Users are static; b) 558 users are located in the area of 1.27km^2 containing 4 macro sites. The assumed number of users represents a factor 50 increase in number of users compared to typical values from 2010. c) Ratio between indoor/outdoor traffic is set to 70%/30%; d) 50% of the indoor traffic is generated on the ground floor and the remaining 50% is equally divided into the higher floors; e) IEEE 802.11g version of the Wi-Fi has been used throughout the simulations. In this study, the Network Key Performance Indicator (KPI) is defined as: 90% network coverage (maximum 10% network outage) with minimum data rate of 1Mbps in the downlink and 0.25Mbps in the uplink.

In the case of indoor Wi-Fi deployment with Access Point (AP) density of 230AP/km^2 can meet the prescribed KPIs. In case of out-of band LTE Femto cell deployment AP density of 1200AP/km^2 is required to meet the KPIs. In case of in-band Femto cell deployment where Macro and Femto cells share one carrier (2600MHz) shows worse results. High density of Femto cells and their uncoordinated deployment yields strong in-band interference. As a result the defined KPI cannot be achieved even with 1200AP/km^2.

In [88], the author addresses solutions for Wi-Fi offloading in LTE networks in cases when traffic needs exceed the capability of the LTE network. An optimized SNR-threshold based handover for Access Network Discovery and Selection Function (ANDSF) is proposed.

The assumed scenario is as follows: a) dense hotspot areas are considered with hotspot probability of $P_{hotspot}$ = 0.8; b) hotspots have a radius of 50m; c) Hotspot density is 100/km^2; d) subscriber density is 5400/km^2; e) hotspots are located half radius from the base station of its cellular cell; f) UE speed is 3km/h; g) 75% of the traffic is generated in the downlink with minimum data rate of 1Mbps.

Performance of the simulated network and usefulness of traffic offloading towards Wi-Fi strongly depends on the Inter Site Distance (ISD). According to the author it is always better to remain connected to the LTE in case of small ISDs. In addition, for smaller ISDs it is realized that variable SNR-based access network selection yield better user throughput than keeping the Network Discovery distance threshold fixed.

The authors of [61] propose offloading scenarios from LTE to Wi-Fi, which could be used to protect access and core networks against overloading and represent an alternative to femtocell offloading solutions. Two solutions are proposed based on 3GPP standardized schemes (LIPA, SIPTO, and IFOM). In the first solution an extension to the DSMIPv6 mobility signalling to carry routing filters when the UE is connected to multiple accesses simultaneously is proposed. It would not be necessary when GTP is used on the S2a interface, because GTP can already carry Traffic Flow Templates (TFTs), which contain the up- and or downlink packet filters using the Open Mobile Alliance (OMA) Device Management (DM). The second solution builds on the first, traffic from and to the UE would be treated as a service with a low level QoS but, should a higher QoS be required, traffic may be routed either via LTE or Wi-Fi through the EPC and, subsequently, the EPC services are available to the UE. No implementation or simulation results are included.

A.1.2 Publications on Intra-LTE TS

The following papers discuss TS solutions between LTE nodes. Although the goal of this deliverable is to do TS between different RATs, namely LTE and Wi-Fi, the presented solutions can still be useful for TS between multiple RATS in general and LTE and Wi-Fi in particular.

In [39], a distributed mobility load balancing algorithm for an LTE multi-layer network (macro and pico cells) is proposed and analysed. The algorithm dynamically adjusts the cell-pair cell individual offsets with the aim to shift traffic to under-utilised cells, based on load information exchanged over the X2 interface. The assessment of the performance of the algorithm is conducted based on a simulation study that considers different offered load conditions. The analysis focuses on video streaming traffic, and evaluates the UE satisfaction based on measurements at the play out buffer at the UE's side.

The results show that the proposed algorithm can efficiently eliminate potential load imbalances across the different layers, and consequently improves the overall network resource utilisation and user experience. However, at high load and strong interference levels, this occurs at the cost of increased radio link failures. This mobility degradation has minimal effect on video streaming applications due to the robustness provided by the play out buffer, but without additional mobility and interference management optimisations, this degradation might have a critical impact on real-time conversational applications that have stricter delay requirements.

[49] studies femtocells that both operate in licensed and unlicensed bands. In the unlicensed band the femtocell can alternate between operating as access point and LTE femtocell. The paper derives the optional fraction of time (t_f) that the femtocell occupies the unlicensed band for LTE such that a utility function that gives the user satisfaction as a function of the achieved data rate is maximised. Afterwards the developed algorithm is verified using simulations.

In [89] authors investigate the problem of re-distributing traffic demand between LTE femtocells with open access in an enterprise scenario. These scenarios are characterized by a) a 3D structure where neighbour cells are located everywhere around the serving cell; b) a different and more intense user mobility pattern than in a home environment; c) a higher concentration of users varying both in space and time; d) open access instead of closed access; e) the fact that unlike conventional sites, femtocells do not follow a careful planning by the operator.

In order to resolve persistent congestion problems rather than temporary traffic fluctuations of enterprise femtocell networks, network statistics are collected during a longer period (e.g., 1h). Three possible TS principles are evaluated in the paper, in particular:

1. Margin traffic sharing (MTS) – that modifies power budget (PBGT) Handover (HO) margins of adjacent cells.
2. Power traffic sharing (PTS) – that tunes cell transmit power on a per-cell basis to balance the call blocking ratio of a source cell against the average call blocking ratio of its neighbours.
3. Combined traffic sharing (CTS) - that modifies the transmit power of a cell and HO margins of its adjacencies.

The scenario used for the simulations is an office building with femtocells in a larger area of $3x2.6km^2$, comprising a single macrocellular site consisting of 3 tri-sectorized cells. The distance between the macrocellular site and the building is 500 m which gives a constant interference level in the indoor environment. Nevertheless, the macro cell signal is low enough to prevent end users from connecting to a macro cell. A 16 kbps voice over IP service model is studied with an average duration of 100 s.

The algorithms proposed in [89] intend to solve persistent congestion problems by slowly changing parameters based on statistical indicators. The KPIs that are used to evaluate the performance are: a) call blocking ratio (BR), b) outage ratio (OR), and c) HO Ratio (HOR) – the ratio between the number of HOs and the number of carried calls reflecting the network signalling load.

In case individual TS methods are deployed (MTS or PTS) the call blocking can be reduced, but the network connection quality can be significantly deteriorated. Further performance improvements are possible by the deployment of combined TS strategies (e.g., PTS before MTS). As a result (part of) the congestion problems are solved while the quality of the connections is preserved.

In [90] authors propose an automatic network selection (ANS) mechanism that is able to select the best access network existing around a UE. The proposed ANS mechanism takes trade-offs between quality of the connections as well as the preference of the end users and the costs into account. Within this framework a user's requirements can be translated into relative weights that the user assigns to each criterion (price, quality, and mobility). In this fashion the end-user is introduced in the control loop of the system. The scenario considered in [90] accounts for an area fully covered by 3G and partially by Wi-Fi, 802.16 WiMax and LTE. The velocity of the MTs and the number of active users can randomly vary in time. Simulation parameters taken into account during simulations are costs (cents/kb), power consumption (W), data-rate (kbps), network load and Frame Error Rate (FER). The proposed multi-criteria utility function takes user preferences as well as network operator interest into account for efficient and revenue oriented radio resource management.

[51] investigates and compares the downlink performance of different LTE heterogeneous network deployment solutions. The study is conducted for a "Hot-Zone" scenario, i.e. a high-traffic area within a realistic dense urban deployment and the deployment schemes are outdoor pico only, indoor femto-only and joint pico-femto deployments, all combined with an overlay macro layer.

By assuming a traffic growth by a factor of 50, and a minimum required user data rate of 1 Mbps, 43% of the users are found to be in outage for the assumed dual-band macro-only deployment. Furthermore, it is evaluated that 70% of the outage users are located indoor. To effectively decrease the outage level to the target of only 10% of the users in outage, small cells are to be deployed on dedicated channels that are not interfering with the macro layer. A pico-only deployment with 3 outdoor picos per macro sector, or alternatively an indoor femto-only deployment with a density of 400 femtos/km^2, is sufficient to offload 50% of the users and fulfil the outage target. Although the indoor femto-only scenario gives the best performance in terms of average user throughput, the hybrid deployment of outdoor picos and indoor femtos - with each layer transmitting on dedicated frequency resources - gives similar capacity improvements at a lower base station density and 70% offloaded users.

[57] introduces an optimization framework for load balancing in LTE heterogeneous networks (macro and Low Power Nodes, LPNs), by means of cell range adjustment using cell-specific offset. For any given offset setting, the resulting cell load is effectively approximated via the solution of a system of non-linear equations characterizing the load-coupling relation between cells. An effective bounding scheme is developed for solving the load-coupling system.

The theoretical findings, supported by formal proofs, are further demonstrated by simulation results. For a representative scenario of a heterogeneous network deployment, LPN range optimization leads to much more balanced cell load in comparison to the baseline solutions. The results also demonstrate the effectiveness of the proposed optimization procedures.

The following paper presents TS algorithms between multiple RATs, not including Wi-Fi.

In [40], four TS algorithms between HSPA and LTE macro cells in the downlink direction are discussed: two algorithms relying on static network information and two algorithms relying on dynamic information such as SINR and cell load. The performance of the algorithms is assessed by simulations, and also theoretically for the two static algorithms, by considering the 5th percentile and average user throughput as a function of the offered load. Also the impact of the LTE penetration level is considered.

Results show that the most adaptive dynamic algorithm significantly outperforms the other algorithms under high load and at 100% LTE penetration level, and that the gain of using this algorithm decreases with decreasing LTE penetration. Based on these results, the paper concludes that when the LTE penetration is low or medium, the best steering strategy is to push all LTE capable UEs to the LTE layer. When the LTE penetration level increases, it becomes beneficial to make use of instantaneous load information, and a more dynamic TS scheme should be used.

Finally, the following papers present algorithms for steering users between LTE and Wi-Fi or between multiple technologies including LTE and Wi-Fi.

[52] discusses load balancing among heterogeneous wireless networks (HWNs), more specifically between RATs (LTE, Wi-Fi, and WiMAX). To this end, a "community" concept is defined, in which radio resources of various RATs are managed together. The load balancing algorithm of the community radio resource management enhances the utilisation of radio resources, reduces the call blocking probability of individual RATs in the community and further enhances the average performance of the whole community.

Information on RATs at the boundary of a community is exchanged between neighbouring communities. The UE is provided with two types of information by the community: elementary and facility information. Elementary information helps UEs to discover available RATs while facility information helps them in the selection of the optimal one. Based on elementary information the UE picks a RAT to attach to. If overloaded, that RAT informs the Community Resource Management function (CRM) and the UE is steered towards a less loaded RAT. The RAT selection can be either FastAccess, used for immediate access without building a candidate RAT list, or OptimalAccess where building a candidate list may require some time. An objective function is calculated for RAT selection.

The simulation of the algorithm shows that it improves utilization of radio resources of RATs in the community and reduces the call blocking probability.

[58] proposes a novel network selection mechanism that takes QoE into consideration for decision making. It is a user-based and network-assisted approach and thus a compromise solution between user and network benefit. The main idea is to use QoE of on-going users in candidate networks as an indicator to select the best network for connection. The UE is equipped with Wi-Fi and 3G interfaces.

For decision making, the authors deploy one of the multi-criteria decision making (MCDM) techniques called Technique of Order Preference by Similarity to Ideal Solution (TOPSIS). In this method, to select the best network (Wi-Fi or 3G), two artificial alternatives are hypothesized: ideal alternative that has the best level for all attributes considered, and negative ideal alternative that has the worst attribute values. TOPSIS selects the alternative that is the closest to the ideal solution and furthest from negative ideal alternative.

Results show that the proposed scheme performs better in terms of guaranteeing both quality of the handover user and on-going users in the target network. The scheme also illustrates a better load balance between the Wi-Fi and UMTS network, because, when bandwidth utilization is high in Wi-Fi, the QoE of users becomes poorer. Users will then select the UMTS network as it has a higher Mean Opinion Score (MOS) at that moment.

[59] presents a load balancing algorithm that aims at minimizing the number of unsatisfied users in a heterogeneous network deployment (LTE macro, Wi-Fi and Femto Access Points) and thus the load balancing algorithm is only active if those are present.

For each time instant, every user in connected state is selecting potential target eNBs (TeNBs), to which it can be transferred in case the serving eNB is overloaded, based on whether their SNR is high enough to maintain the current data rate. Additionally if a user is in a coverage area of a Wi-Fi AP or femto cell, those are also considered as potential target cells. For each eNB with unsatisfied users, the algorithm tries to move the users to different, less loaded eNBs or APs. Users with high PRB usage are considered first in order to minimise the number of handovers and associated signalling overhead. The potential TeNB with the smallest amount of used PRBs is chosen in order to make the PRB load as "flat" as possible across eNBs. However if there are no potential TeNBs, or all potential TeNBs are overloaded, users will be transferred to a Wi-Fi AP, if available, and otherwise to a femto cell, if available.

Simulation results show a clear decrease in the number of unsatisfied users when employing the load balancing algorithm. The performance further improves as coverage of Wi-Fi and Femto APs increase. The network resources are used more extensively with the load balancing algorithm, which means that more users are satisfied with the same available number of PRBs in the network. The number of used PRBs decreases as the Wi-Fi/Femto coverage increases due to the fact that more users are being transferred to Wi-Fi and Femto networks and do not use the EPC PRBs.

In [60] user preference and system conditions are taken into consideration for an efficient vertical handover mechanism (next generation vertical handover decision algorithm (NG-VDA)) design between LTE and Wi-Fi. In this paper handover initiation is taken by measuring RSS and velocity of the UE. The handover decision is taken using a fuzzy logic system that considers bandwidth, battery life, SNR and network load as input parameters. The handover execution is achieved by using Mobile IPv6. The algorithm presented in this paper is just a proposal, no simulation data is provided.

[62] propose a data rate based vertical handover triggering mechanism (DR-HTM) based on the IEEE 802.21 Media Independent Handover (MIH) standard in order to maximise capacity of both Wi-Fi and cellular networks. In DR-HTM, whenever a UE discovers a Wi-Fi network, it obtains information on the achievable data rate of the Wi-Fi network by using remote MIH services. Based on this information, the UE determines the execution of a vertical handover. This method can reflect the traffic load of the Wi-Fi and the cellular network in the triggering decision. Therefore, DR-HTM can help users in receiving their required data rates and help network operators to effectively utilise Wi-Fi networks.

As a result, UEs execute handover only if the candidate Wi-Fi network can provide better data rates than the currently serving eNB and inefficient handovers can be prevented. Moreover, DR-HTM reduces the number of UEs having low frequency efficiency in LTE and increases both the total capacity of LTE and Wi-Fi.

A.2 TS Algorithm Classification and Analysis

This appendix is in relation to the TS use case described in Section 3.

Based on the literature review, the existing TS algorithms are grouped into three categories. The categorization will facilitate the extension of the proposed SON solutions in this deliverable and the design of new SON solutions. One of the potential extensions is to introduce per-UE steering capability to the SON solutions and one such example is described in this section.

A.2.1 Single Criterion TS (SC-TS) Algorithms

Decisions made in SC-TS algorithms are solely based on relative comparison of two quantities at a particular time instant. Examples of such algorithms are:

a. ***Use Wi-Fi if in reach***: Connect to Wi-Fi in case the UE identifies signal from an Access Point (AP), i.e. the measured RSSI is larger than the minimal Wi-Fi RSSI threshold. The criterion becomes:

$$RSSI_{UE} > minTH_{WiFi}$$

Here, $RSSI_{UE}$ is a monitoring KPI, while $minTH_{WiFi}$ acts as a fixed-value control parameter for triggering of the TS decision. In case when SON is applied (see Section 3.9) the RSSI Threshold is dynamically varied.

Pros: The most simple radio access selection criteria.

Cons: Neither the signal quality nor the load (available data rate) of the identified AP are taken into account. In addition, decisions based on observations at a single time instant can make the algorithm behave rather unstable leading to repetitive back and forth handovers ('ping -pong' effect) especially when the UE is located in the cell-edge region of one or more APs.

b. ***RSS*[2] *based TS***: The UE disconnects from the current RAN and connects to the target RAN in case the following criterion is satisfied [67]

$$RSS_{Target} > RSS_{Current}$$

Here TS is triggered by comparing 2 monitoring KPIs also known as "Pure coverage based TS" [38].

Pros: Simplicity as UE easily measures RSS; provides rough estimate of the achievable data rates.

Cons: Measuring solely RSS does not guarantee objective comparison of networks operating in different frequency bands[3]. MCS, bandwidth, transmit power, distribution and density of (active) UEs and type of services might also play a role in determining a system's quality and throughput. Solely RSS based decisions may lead to false alarms [68] and 'Ping-Pong' in cell edge regions. For these reasons purely RSS based TS in heterogeneous networks is considered insufficient.

c. ***Available data rate TS***: Data Rate Handover Triggering Mechanism (DR-HTM) [68] exploits *available data rates* (*R*) as TS criterion. The Media Independent Handover (MIH) protocol of IEEE 802.21 [84][85] is used to calculate R rates based on UE's measurements. The TS criterion becomes:

$R_{candidate} > R_{current}$ (or equivalently $R_{current} > R_{th}$),

where R is a monitoring KPI and R_{th} is a fixed, pre-specified control parameter. $R_{current}/R_{candidate} > k$ ratio may also be used as a control parameter. In SON TS R_{th} or k might be varied to allow for dynamic adaptation of data rate availability among different RANs.

Pros: Improved efficiency over all available RANs [68] due to usage of *R* estimate.

[2] Here, RSS refers to received signal strength in general. In various systems RSS equivalents are differently defined. In case of Wi-Fi this is the RSSI (Received Signal Strength Indicator). In LTE these are RSRP (Reference Signal Received Power).
[3] For this reason even within 3GPP IRAT mobility, the standard does not include any event for relative comparison but only absolute comparison, i.e. the comparison of the individual measurements vs. Absolute thresholds (e.g. B2 event in 3GPP terms, serving < TH2, neigh > TH2).

Cons: Possible instability in case TS decisions made on instantaneous estimates of *R*.

d. ***Load based TS*** criterion is similar to the one described for available data rate based TS, but is instead based on the estimated load per the cell / AP.

Pros: Simple load estimation in a single system. Balanced loads among available RANs [38].

Cons: Conveying load information from different nodes / APs to the decision making entity and the maximum tolerated latency might be challenging. The more frequent the load monitoring the higher the overhead. However, historical[4] daily or weekly load patterns might be used for identification of optimal load balancing among distinct RANs.

Single criterion TS algorithms are in principle easy to implement as the decision is based on the usage of already available or easily computable parameters (network presence, RSS, available data rate, etc.). On the other hand decisions made on the measurements in a single time instant might lead to false alarms and 'Ping-Pong' effects especially in regions of cell edge(s). To cope with these drawbacks taking multiple criteria additional auxiliary parameters in TS decision making might be beneficial. Such scenarios are listed and evaluated in the subsequent section.

A.2.2 Non-weighted Multi-criteria TS (NWMC TS) Algorithms

This section summarizes TS algorithms that use more than one criterion to initiate TS. The aim of such an approach is to acquire improved stability as well as user- and cell-capacity while preserving the low complexity. The following examples are ***RSS*** based [42][43] but are applicable to any other parameter.

a. RSS and Threshold: TS is triggered when the RSS of the target eNB / AP becomes greater than the RSS of the current eNB / AP. An additional criterion is that the current or target level of RSS becomes smaller or larger than a pre-specified threshold (TH), respectively:

$RSS_{Target} > RSS_{Current}\ and\ \ RSS_{Current} < TH,$ or equivalently

$RSS_{Target} > RSS_{Current}\ and\ RSS_{Target} > TH$.

This specific approach combines a comparison of monitored KPIs as well as usage of a predefined threshold as a control parameter.

- *Pros:* The threshold increases the certainty that a desired signal level has been achieved. This approach reduces the number of possible false alarms.
- *Cons:* Comparison based on instantaneous measurements might experience strong variations in the order of 20~30dB [44]. Comparison of different RANs solely on their RSS values might be dubious.

b. RSS and Hysteresis[5]: TS is initiated in case the target RSS becomes greater than the current RSS plus an additional offset, i.e. hysteresis margin H:

$$RSS_{Target} > RSS_{Current} + H$$

- *Pros:* Hysteresis increases system stability and reduces the probability of 'Ping-Pong' effects.
- *Cons:* Same as in bullet a. above.

c. RSS, Hysteresis and Threshold: TS is triggered in case the following condition holds: $RSS_{Target} > RSS_{Current} + H\ \ and\ \ RSS_{Current} < TH$.

- *Pros:* Further reduction of undesired 'Ping-Pong' effects as the UE sticks with the current cell as long as the signal strength level remains better than the given threshold.
- *Cons:* Same as in bullet a. above.

Algorithm a-c and Time To Trigger (TTT): This approach combines criteria listed above (a.-c.) with a Time-To-Trigger (TTT) parameter. The TTT is specified as the time interval during which the specific criteria for the event needs to be met [76]. In [43] the term "Dwell Timer" is used and it is initialized at the instant the condition in the algorithm becomes true. TS is triggered when the

[4] This would simply mean to run the load estimation over a certain time period and to apply static prioritization accordingly per time of the day and possibly location.

[5] Strictly speaking this approach conducts just a single comparison. However, it is categorized as 'NWMC-TS' due to involution of an additional auxiliary parameter *H*.

condition remains satisfied until the expiry of "dwell timer". *Pros:* Monitoring of parameters over a certain time period improves stability and leads to improved efficiency of the TS triggering mechanisms. Implementation of the TTT is simple and efficient [68].
Cons: The TTT mechanism demands monitoring / measurement of network parameters for a certain time interval. This might lead to an increase in the number of measurements and control sequences.

A.2.3 Proposal of a NWMC Algorithm: 'Available Data Rate Based TS'

In this section an 'Available data rate based' algorithm is proposed that takes advantageous features of the NWMC TS approach into account. Available data rates are estimated for each RAN identified by a UE (in this example these are Wi-Fi, LTE micro and LTE macro).

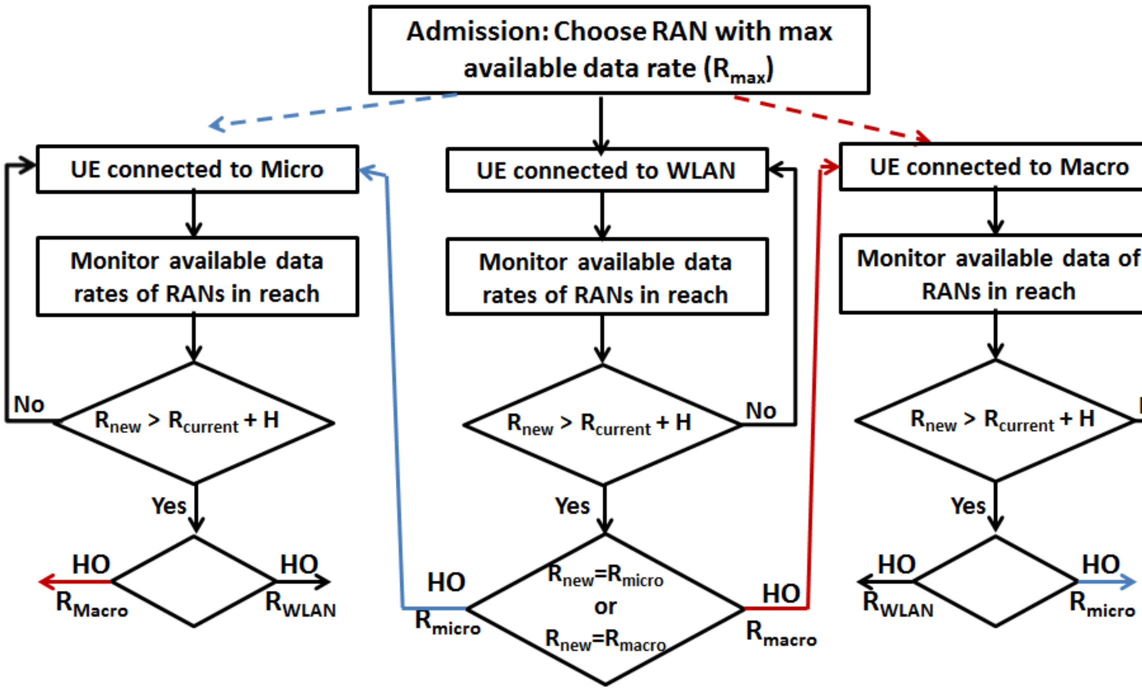

Figure 68: Flow chart of the proposed TS algorithm based on the estimation of the available data rates (R) of each RAN in reach of a UE.

The proposed algorithm is illustrated in Figure 68.

Step 1 - Admission: In the RRC_IDLE mode available data rates (R) of all RANs with which a UE could possibly connect is compared. The UE will connect to the RAN that maximizes the following expression:

$argmax\{R_{WLAN1,..,N}, R_{LTE\_micro1,..,K} R_{LTE\_micro1,..,K}, R_{LTE\_macro1,..,L}\}$ where

a. R_{WLAN} [bps] is estimated Wi-Fi available data rate [68]. N is the number of neighbouring APs for the UE. Several approaches might be followed for the estimation of available data rates in Wi-Fi:

   i. $R_{WLAN} = C_{WLAN} \cdot \frac{MCS_{WLAN}(RSSI_{WLAN})}{\max(MCS_{WLAN})}$ .This calculation exploits the Media Independent Handover IEEE 802.21 standard [84]. $RSSI_{WLAN}$ is the Wi-Fi signal strength measured by the UE. C_{WLAN} [bps] is the average Wi-Fi data rate measured by the AP during $T_{observation}$ or derived from historical data. C_{WLAN} is calculated by the Wi-Fi AP during a beacon interval [68]. $MCS_{WLAN}(RSSI_{WLAN})$ [bps] denotes the throughput for the measured received signal strength level $RSSI_{WLAN}$.

   ii. [44] proposes a passive method for estimation of R_{WLAN} based on IEEE 802.21 [84]. The term *passive* indicates that no probing messages are used yielding reduction of undesired overhead. The approach in [44] is accurate and takes account for possible hidden-exposed terminal problems. The parameters used in the estimation of the available data rates exploit.

iii. In [44] authors provide a comparative analysis of numerous bandwidth estimation schemes based on passive measurements, namely Adaptive Admission Control [54], Improved Available Bandwidth (IAB) estimation [55] and Available Bandwidth Estimation (ABE) [56].

b. $R_{LTE\_micro} = f(PRB_{available_{micro}}, MCS)$; R_{LTE_micro} [bps] stands for the available data rates in an LTE micro cell. The number of neighbouring LTE micro cells for the UE is indicated with *K*. The data rate estimate is calculated as a function of the number of Physical Resource Blocks available for the UE in an LTE cell, $PRB_{available}$, the number of active users in the cell, and a certain adopted packet scheduler approach.

c. $R_{LTE\_macro} = f(PRB_{available_{macro}}, MCS)$; R_{LTE_macro} [bps] represents estimated available data rates in an LTE_macro. *L* is the number of macro neighbouring cells for the observed UE.

Step 2+Step3 – UE connected and monitors available data rates (*R*): At this stage the UE is connected to the RAN that provides largest available data rates. The UE monitors the available data rates of the neighbouring RANs.

Step 4 – HO condition verification: $R_{new}>R_{current}+H$: At this stage it is verified whether any of the neighbouring RANs for the observed UE can provide larger data rates (R_{new}) than provided by the current RAN and increased by a hysteresis H:

$$R_{new}\,(T_{observation}) > R_{currrent}\,(T_{observation}) + Hysteresis,$$

Here, $T_{observation}$ denotes a time interval over which the available data rate is averaged. Hysteresis corresponds to a certain percentage of the $R_{currrent}$. Both observation time and hysteresis are introduced to avoid unnecessary handovers.

Step 5 – TS: In case the condition in step 4 is satisfied the TS mechanism is activated. All subsequent data segments will be conveyed using the RAN that satisfied the specified condition.

This approach can be classified as *UE-assisted network controlled* TS approach, i.e. a network control entity makes TS decisions by exploiting measurements of both the UE and the BS / APs. The proposed algorithm performs optimal distribution of traffic loads and can be used for calculation of "performance upper-bound" in case of load balancing optimization.

Pros: a) Properly balanced load among available RANs; b) Possible usage of historical daily or weekly traffic patterns. In this fashion real time computation burden might be reduced; c) Data rate based TS improves the total capacity of LTE and Wi-Fi compared to solely RSS based TS; d) Good balance between complexity and quality.

- **Cons:** Real time available data rate quantification might be challenging – the more frequent load monitoring the higher the overhead.

A.2.4 Weighted Multi-criteria TS (WMC-TS) Algorithms

WMC-TS algorithms simultaneously evaluate numerous network parameters. Each parameter may be assigned different weights to reflect the importance of each one of them: a utility function is created taking into account parameters such as load, propagation conditions, session QoS requirements, achievable throughput, blocking probability, communication costs, user and provider preferences, etc. For different examples of utility functions, set of parameters and weighting approaches the reader is referred to [45], [46], [47], [48], [52]. The solution to the problem is found by choosing the radio access network that optimizes the created utility function.

- ***Pros:*** Optimization is carried out over numerous parameters / network aspects such that TS decision best meet user and network provider preferences.
- ***Cons:*** Complexity appears to be the biggest disadvantage of the weighted multi-criteria approach.

A.3 On Modelling Assumptions, Scenario Definition and Simulators Calibration

This appendix is in relation to the TS use case described in Section 3. A detailed list of Wi-Fi system modelling assumptions provides interested readers a complete view on the Wi-Fi system simulated in this deliverable. The calibration between the two Wi-Fi simulators used in this deliverable did not give well aligned Wi-Fi user throughput. A detailed analysis on the reasons of the difference is given in this Appendix as well. Efforts have been put in C&O studies to complete the OHZ scenario. The principles and procedures of Wi-Fi channel allocation and total offered traffic settings are detailed in the section.

Furthermore, a modification has been made to the traffic intensity map. The motivation and implementation is described in details.

A.3.1 Wi-Fi System Modelling Assumptions

	Configurations and assumption	**Description**
GI	400 ns	Duration of OFDM symbol guard intervals
Num of data subcarriers	52	Total number of data subcarriers
Slot time	9 µsec	Duration of a slot
CWmin	15 slots (=2^4-1)	Minium contention window size
CWmax	1023 slots (=2^10-1)	Maximum contention window size
MAC Payload Size	Max 1500 Bytes (without frame aggregation)	Payload size of each MAC frame
PHY training header, service, tail	20 µsec + (16 + (N_{LTF}-1)*4) µsec + (16 bit + 6*N_{ES}) @PHY_Rate* N_{LTF}: number of training symbols; N_{ES}: number of encoding streams	Duration of PHY overhead bits * PHY_Rate: the transmission rate of MAC payload decided by LA
MAC header	36 Bytes @PHY_Rate*	MAC header size
ACK	14 Bytes @6 Mbps	MAC acknowledgement frame size
SIFS	10 µsec	Short Inter Frame Space used to separate transmission belong to a single dialog
DIFS	28 µsec	Distributed Inter Frame Space used for a station willing to start a new transmission
CCA threshold	-86 dBm	Clear Channel Assessment used to detect channel usage by other Wi-Fi devices
A-MPDU	Disabled	Aggregation of MAC Protocol Data Unit enabling packing multiple MPDUs together to reduce overheads
Block ACK	Disabled	A 802.11n MAC function enabling one ACK for multiple MPDUs

Table 23: Wi-Fi system modelling configurations and assumption

The Wi-Fi layer modelling is based on the 802.11n PHY / MAC [85] [86] and summarized in Table 23. The 802.11n MAC features of A-MPDU and block ACK [86] are disabled in the first phase of the simulations, presented in this deliverable. These two features can reduce transmission overhead and improve system efficiency and will be enabled in the next phase of the study.

A RSS to MCS mapping table has been extracted from Simulator I (described in Section 3.7.2.1) with which link adaptation (LA) is explicitly implemented. The mapping is shown in Table 24. A subset of all possible MCS is selected for simplicity. The extracted mapping table is imported to Simulator II (described in Section 3.7.2.2) to calibrate the two tools.

MCS:	**0**	**1**	**2**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
PHY Rate [Mbps]	7.2	14.4	21.7	28.9	43.2	57.8	86.7	115.6	130.0	144.4
RSS [dBm]	-92	-89	-86	-83	-80	-78	-72	-68	-66	-63

Table 24: Mapping between RSS and MCS

A.3.2 Analysis of User Throughput Difference in Wi-Fi Simulator Calibration

A calibration has been carried out between the two simulators described in Section 3.7.2. The two simulators are different in the level of modelling abstraction. While Simulator I explicitly models the Wi-Fi MAC functionalities, Simulator II uses higher level modelling as described in [63]-[65].

The calibration shows a good level of alignment two simulators for isolated APs, i.e. with no other co-channel APs, and in homogeneous scenarios, i.e. all co-channel APs can hear each other. In these cases, the difference in user throughput is less than 20%.

However, more than 50% difference is observed in a more complex scenario as described in Figure 69. In the depicted scenario, AP1 can sense AP2 and AP3, but AP2 and AP3 can only sense AP1 but not each other. In this case, Simulation II modelling assumes the channel accessibility of AP1, AP2 and AP3 is 33%, 50% and 50% respectively. In practice, AP2 and AP3 have more than 50% channel access, since AP1 won't transmit when either AP2 or AP3 transmits. Effectively, AP1 gets less than 33% channel accessibility and AP2 and AP3 have more than 50%. This aspect is reflected in Simulator I since the carrier sensing is modelled explicitly.

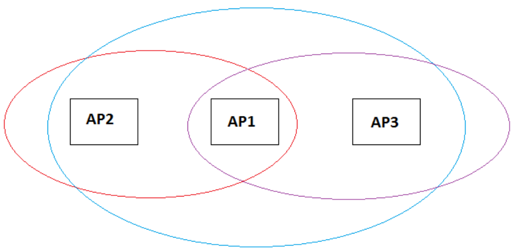

Figure 69: An inhomogeneous AP sensing scenario

It should be noticed that the difference is only observed in the described inhomogeneous co-channel scenario. For APs operating at 5 GHz where much more number of channels is available, the difference will be significantly reduced or eliminated.

A.3.3 Traffic Intensity Map Modification

In the OHZ scenario, new network nodes (LTE micros and Wi-Fi APs) and an additional hotspot have been introduced to the scenario area. Based on the C&O studies, it's identified that the traffic intensity in the north and east parts of the scenario area is too high due to the lack of micros and APs network nodes. Hence the macro cells serving these areas become congested while other cells are still slightly loaded when the offered traffic increases. Therefore the traffic intensity map is modified by decreasing the intensity of traffic in the north and east parts of the scenario area as shown in Figure 70.

A.3.4 DL Traffic Settings

In the OHZ scenario, FTP download with fixed file size has been defined as the offered traffic. Network load is determined by the file size and user arrival rate. For the TS study, the target is to have a scenario in a high load regime. After simulations with different file sizes and user arrival rates, a file size of 5 MB and a user arrival rate of 16 arrivals per second are selected. Given these settings, the most loaded cells start getting congested without the TS SON algorithm. The effectiveness of the SON algorithm on congestion avoidance and load balancing can be tested in this scenario.

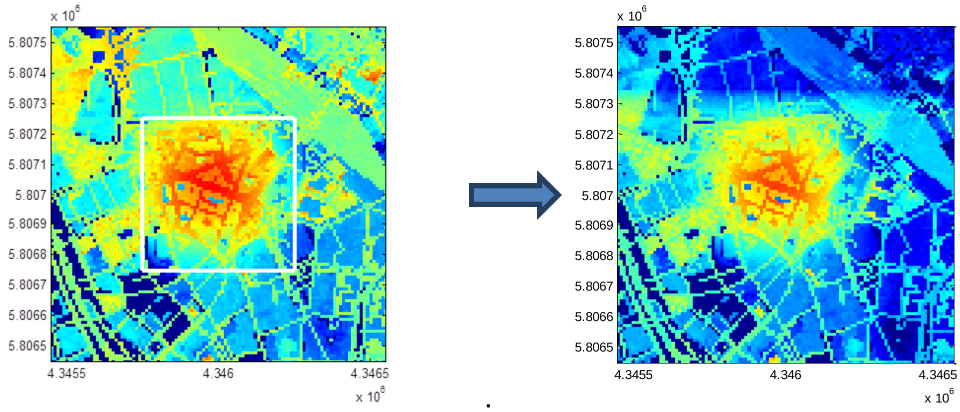

Figure 70: Traffic intensity map modification (Red: high traffic density, Blue: low traffic density) Left: before modification; Right: after modification

A.3.5 UL Traffic Assumption

To make the scenario more realistic, simultaneous uplink traffic in addition to the FTP download is added to the users. The ratio of downlink and uplink offered traffic is configured as 6 to 1 based on typical network usage today. In Simulator I (described in Section 3.7.2.1), simulation results show that 20% of the channel time is taken by the uplink traffic with explicit uplink traffic modelling. Then, the 20% is imported to Simulator II (described in Section 3.7.2.2) as an abstracted parameter to account for the uplink traffic. In the first phase of the algorithm evaluation, presented in this deliverable, only downlink KPIs are analysed.

A.3.6 AP Channel Assignment

Since the outdoor APs in the OHZ scenario are assumed to be deployed by operators, a planned channel assignment achieving a good channel reuse for the carrier Wi-Fi is assumed. A graph colouring algorithm [91] is applied to the channel assignment. In the algorithm implementation, APs are modelled as vertices and APs with minimum path loss between each other are considered as neighbours and modelled as sharing an edge. The algorithm is capable of assigning different colours, i.e. channels, to neighbour APs. The result of the channel assignment is shown in Figure 71 where three channels at 2.4 GHz are colour coded and identified neighbours are connected with red lines. No neighbour APs share the same channel after the assignment.

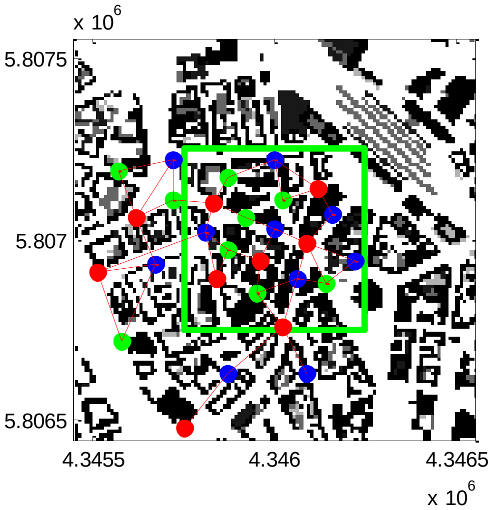

Figure 71: AP channel assignment at 2.4 GHz

Appendix B Appendices to Tackling the Problem of High Mobility Users

B.1 Step-by-step Example of the DTW Algorithm

In this appendix we will give an example of how the ordinary Dynamic Time Warping algorithm works. The measurement series in this example are strings of letters. The distance function $c(x_m, y_n)$ between two elements of the series (i.e. letters) is defined as follows: if two letters are the same and have the same casing, the cost is 0. If they are the same but have a different casing the cost is 0.25. If they are different but have the same casing the cost is 0.75 and if they are different and have a different casing the cost is 1. An example of the distances between two letters is given Table 25.

First element	Second element	Cost
a	a	0
a	A	0.25
a	b	0.75
a	B	1

Table 25: Example of the distances between letters.

We will compute the distance between the strings 'aB' and 'abc'. The distance matrix of these two strings is shown in Table 26.

	a	**b**	**c**
a	0	0.75	0.75
B	1	0.25	1

Table 26: The cost matrix c for the two strings.

When performing the DTW algorithm we start with a matrix that looks as follows:

0	∞	∞	∞
∞			
∞			

I.e., the matrix is extended with a row and a column that contains infinities. The element in the upper left corner is set to 0. By doing this we can compute the values of all remaining elements of the matrix in the same way, i.e. by using the values of the cells to the left, top and top left without having to treat the cells on the first row and column differently.

We then start filling this matrix starting from the upper left corner and working our way down to the lower right corner. It does not matter if we first fill the rows or the columns, in this example we start by filling the rows.

The value of the upper left element is given by $0 + \min(\infty,\infty, 0) = 0$, the matrix thus becomes.

0	∞	∞	∞
∞	0		
∞			

The value of the second element of the first row is computed based on this newly computed value as $0.75 + \min(\infty, 0, \infty) = 0.75$:

0	∞	∞	∞
∞	0	0.75	
∞			

The third value of the first row is computed likewise. The first value of the second row is calculated based on the value of the $1 + \min(0, \infty, \infty) = 1$:

0	∞	∞	∞
∞	0	0.75	1.5

∞	1		

The second element of the second row is the first element whose value is based on three previous computed values: 0.25 + min(0.75, 1, 0) = 0.25:

0	∞	∞	∞
∞	0	0.75	1.5
∞	1	0.25	

The value in the lower right corner is calculated likewise:

0	∞	∞	∞
∞	0	0.75	1.5
∞	1	0.25	**1.25**

The value in the lower right corner of the matrix is the minimum warping distance of the strings 'aB' and 'abc'.

Below a more elaborate example is given for the strings 'aBcCbabbC' and 'ABCACaBbbcC'. The distance matrix, expressing the distances between the individual characters for these strings is:

	A	**B**	**C**	**A**	**C**	**a**	**B**	**b**	**b**	**c**	**C**
a	0.25	1.0	1.0	0.25	1.0	0	1.0	0.75	0.75	0.75	1.0
B	0.75	0	0.75	0.75	0.75	1.0	0	0.25	0.25	1.0	0.75
c	1.0	1.0	0.25	1.0	0.25	0.75	1.0	0.75	0.75	0	0.25
C	0.75	0.75	0	0.75	0	1.0	0.75	1.0	1.0	0.25	0
b	1.0	0.25	1.0	1.0	1.0	0.75	0.25	0	0	0.75	1.0
a	0.25	1.0	1.0	0.25	1.0	0	1.0	0.75	0.75	0.75	1.0
b	1.0	0.25	1.0	1.0	1.0	0.75	0.25	0	0	0.75	1.0
b	1.0	0.25	1.0	1.0	1.0	0.75	0.25	0	0	0.75	1.0
C	0.75	0.75	0	0.75	0	1.0	0.75	1.0	1.0	0.25	0

The constructed warping distance matrix, containing the values to match two prefixes up to a certain point becomes:

	A	**B**	**C**	**A**	**C**	**a**	**B**	**b**	**b**	**c**	**C**
a	0.25	1.25	2.25	2.5	3.5	3.5	4.5	5.25	6.0	6.75	7.75
B	1.0	0.25	1.0	1.75	2.5	3.5	3.5	3.75	4.0	5.0	5.75
c	2.0	1.25	0.5	1.5	1.75	2.5	3.5	4.25	4.5	4.0	4.25
C	2.75	2.0	0.5	1.25	1.25	2.25	3.0	4.0	5.0	4.25	4.0
b	3.75	2.25	1.5	1.5	2.25	2.0	2.25	2.25	2.25	3.0	4.0
a	4.0	3.25	2.5	1.75	2.5	2.0	3.0	3.0	3.0	3.0	4.0
b	5.0	3.5	3.5	2.75	2.75	2.75	2.25	2.25	2.25	3.0	4.0
b	6.0	3.75	4.5	3.75	3.75	3.5	2.5	2.25	2.25	3.0	4.0
C	6.75	4.5	3.75	4.5	3.75	4.5	3.25	3.25	3.25	2.5	**2.5**

Yielding a minimum warping distance of 2.5. The optimal warping path is indicated by a grey shade.