FP7 Information & Communication Technologies (ICT)

CONSERN

Deliverable D3.3

Energy-Efficient Cooperative Decision and Control Schemes

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Abstract

CONSERN deliverable D3.3 presents the progress in the cooperation framework of the project regarding mechanisms and studies focusing on energy awareness in wireless networking environments. Such studies cover cellular systems (macro and pico level), ad-hoc networks (WLAN nodes), antenna and relaying systems as well Wireless Sensor Networks. Moreover, initial results are provided, highlighting energy efficiency and gains achieved through the CONSERN cooperative solutions.

Executive Summary

Energy efficiency in networking and communications is currently one of the key requirements for future networks and networked objects and devices. This task is getting more complex when approached within heterogeneous environments featuring multiple requirements and constraints. Energy optimisations are usually coupled with additional requirements which are related to inherent service provision aspects, such as coverage, capacity, communication reliability and robustness. In this sense, different approaches are needed for addressing energy efficiency in different contexts which is also reflected by the different devices forming, each time, a different snapshot of the managed telecommunication environment.

Key objective of the CONSERN project [23] is achieving energy efficiency in cooperative heterogeneous wireless networks and developing solutions for such systems through autonomic and cooperative approaches. Specifically, WP3 targets cooperation and collaboration enablers and mechanisms, cooperative decision and control algorithms, as well as all techniques that optimise the expected gain (e.g. energy, performance) explicitly by utilizing cooperative behaviour.

WP3 workflow and corresponding achievements as captured by WP3 deliverables include:

- Provision and analysis of technical use cases which are also tailored to WP3 scope (from D1.1, [11] , D3.1,[22]),
- State of the art studies regarding the identified technical approach towards addressing WP3 objectives through corresponding working items; outline of proposed mechanisms and considered cooperation enablers (from D3.1, [22]),
- Developing a problem description for selected technical use cases, provision of mathematical and simulation models and formulation, initial description of mechanisms (from D3.2, [9])
- Detailed description of mechanisms (developed algorithms, considered studies), evaluation environment, metrics identification and indicative results (new in D3.3)
- Architectural and semantic considerations and feedback provision to WP4 (new in D3.3).

Moreover, WP3 interactions with the other WPs have been captured during WP3 lifetime by corresponding WP3 milestones:

- Synchronisation with WP1 for use cases and WP4 for architectures and APIs suitable for Self-Growing networks (at M3.1, [24])
- Synchronisation with WP2 on low energy protocols and node/network and system level energy optimisations (at M3.2, [25])
- Synchronisation with WP5 in the selection of algorithms for implementation (in the revised version of D5.1 [31] and in the upcoming D5.2 [32]).

The following enablers, mechanisms and studies compose the WP3 Cooperation framework which is detailed in the Introduction of this deliverable:

- Relay Network Coding Schemes for energy savings in dense home/office short range networks,
- Cooperative power control in ad-hoc networks within a dense home/office environment based on interference mitigation featuring learning capabilities and enhanced situation awareness,
- Cooperative network protocols, specifically, Receiver Defined Transmission for interference minimisation based on dynamic receive channel selection in mesh networks, and resource

sharing between co-located networks following network discovery, negotiation and cooperation,

  - Algorithms and studies for energy savings in Heterogeneous Network (HetNet) environments; different scenarios for energy savings in cellular systems are considered (i.e. dynamic resource activation/de-activation, Distributed Antenna Systems, and cooperative relay (macro) stations), and a set of algorithms have been developed for the scenarios which are under consideration,

- Mechanisms for outlier detection and improved resilience in WSNs developed based on a two-level approach (autonomous and cooperative) exploring different levels of knowledge within and among sensor nodes.

Specifically, D3.3 presents the progress and the outcomes for each of the considered studies and working items which form the scope and the workplan of WP3. Specifically, for each working item (As presented in the previous list) the following are provided:

- Overview of the problem, the developed mechanisms and algorithms, and the corresponding studies and studies,
- Mathematical formulation of models, key parameters and values for each study,
- Identification of the evaluation metrics and the evaluation (e.g. simulation or/and prototyping) environment,
- Description of evaluation studies (scenarios and assumptions), as well as indicative results highlighting performance of the proposed mechanisms and energy gains,
- Mapping of the considered mechanisms onto the CONSERN functional architecture as developed in the context of WP4; this way, WP3 mechanisms and algorithms are presented as addressing the functionalities forming the Self-growing architecture.

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Acronyms

Acronym	Meaning
3GPP	3rd Generation Project Partnership
ACK	Acknowledgement
AODV	Ad hoc On-Demand Distance Vector
AP	Access Point
AS	Antenna Selection
AUC	Autonomic Control
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BLER	Block Error Rate
BS	Base Station
CAS	Centralised Antenna System
CCE	CONSERN Cognitive Engine
CCG	CONSERN Configurable Gateway
CDF	Cumulative Distribution Function
CE	CONSERN Entity
COM	Communication Services
CPM	CONSERN Policy Manager
CQI	Certified Quality Inspector
CR	Cognitive Radio
CSI	Channel State Information
DAS	Distributed Antenna System
DECT	Digital Enhanced Cordless Telecommunications
Donor eNB	The eNB used in 3GPP relay systems
E-AS	Efficient Antenna Selection
ECR	Energy Consumption Ratio
eNB	E-UTRAN Node B
ERG	Energy Reduction Gain
FU	Functional Unit
HetNet	Heterogeneous Network
HVAC	Heating, Ventilation and Air Conditioning
KBO	Knowledge Base Ontology
LLR	Log-Likelihood Ratio
LTE	Long Term Evolution
LTE-A	Long Term Evolution – Advanced
MAC	Medium Access Control
MATLAB	Matrix Laboratory
MCS	Modulation and Coding Scheme
MMSE	Minimum Mean Square Error
MRC	Maximum Ratio Combiner
MT	Mobile Terminal
NACK	Negative Acknowledgement

Acronym	Meaning
NC	Network Collaboration
NLOS	Non Line of Sight
PER	Packet Error Rate
PMI	Precoding Matrix Index
PoC	Proof of Concept
PPT	Packets Per Time
PRB	Physical Resource Block
QPSK	Quadrature Phase Shift Keying
RDT	Receiver Defined Transmission
RRH	Remote Radio Head
RSRP	Reference Signal Receive Power
SFN	Single Frequency Network
SGN	Self-Growing
SINR	Signal to Interference plus Noise Ratio
SIR	Signal to Interference Ratio
SR	Simple Relay
TVWS	TV White Space
UE	User Equipment
UMTS	Universal Mobile Telecommunications System

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1. Introduction

The CONSERN project aims at developing and validating a novel paradigm for dedicated, purpose-driven small-scale wireless networks with special focus on energy-aware self-growing systems. One of the main goals of the project is to develop mechanisms and solutions enabling functionality that improves the dependability, cost and energy efficiency, as well as robustness of (heterogeneous) wireless networks by utilizing reconfigurable nodes and distributed cooperative control functions.

Within the CONSERN project, WP3 targets cooperation and collaboration enablers and mechanisms, cooperative decision and control algorithms, as well as all techniques that maximize the expected gain explicitly by utilizing cooperative behaviour and balancing autonomic capabilities and cooperative decision and control.

WP3 objectives include:

- Obj1: Cooperation and collaboration enablers, introducing techniques for wireless communication between heterogeneous network objects and between network elements and mobile terminals,
- Obj2: Design and develop self-learning methods, including methods for information representation and information fusion,
- Obj3: Introduction of algorithms for cooperation between network elements,
- Obj4: Study the relation/balance between autonomic capabilities and cooperative optimization in order to maximize the energy gains,
- Obj5: Optimisation of fault detection and error correction algorithms in cooperative environments under energy constraints.

Previous work in D3.1 [22] has focused on techniques and technologies enabling cooperation for energy efficiency. D3.2 [9] in consequence chose a number of use cases from D1.1 [11] that are considered suitable to describe cooperative and energy-efficient networking, and focus on a set of specific problems related to cooperative decision and control. These use cases describe the energy-aware networking system models including the assumptions that will be used for analysis and simulation studies, proposing solutions on how to solve the problem in terms of analysis or by means of simulations including algorithms and optimization methods.

This deliverable, , entitled “Energy-Efficient Cooperative Decision and Control Schemes” progress WP3 work at each study and related mechanisms by describing:

- Novel algorithms for each of the studies.
- The evaluation environment (i.e. simulations or prototyping activities), related assumptions and metrics,
- (Indicative) results and performance analysis,
- The mapping of the mechanisms to the CONSERN Self-growing functional architecture, thus describing how the defined architectural blocks are addressed through WP3 mechanisms.

The structure of D3.3 is following the above presented progress and achievements for each of the WP3 mechanisms. Specifically:

- Section 1 describes the Cooperation framework in terms of use cases and attributes, mechanisms and evaluation, reference architectures and WP3 objectives,
- Section 2 provides the progress evaluation considerations and results of the Cooperative Network Coding,

- Section 3 presents the progress and the results for the Cooperative Power Control enhanced by learning capabilities,
- Section 4.1 presents development of algorithms and related experiments for the Cooperative Network Protocols, that is, the Receiver Defined Transmission and the Cooperation between co-located networks,
- Section 5 presents the progress in the three different studies regarding energy savings in Heterogeneous (Cellular) Networks, incorporating resource's selection for activation/de-activation regarding (Macro) BSs, DAS elements and Relay Stations in LTE scenarios,
- Section 6 presents progress and considerations for outlier detection and resilience in wireless sensor nodes,
- Section 0 provides a summary of WP3 considerations at architectural (description of the required/envisaged functionality addressing WP3 work and information elements which are involved in each study) and abstraction (update of WP3 information model providing an common abstraction of the networked elements in WP3 context) levels; these are also provide feedback to WP4 which will be taken into account for further architectural and interfaces specifications,
- Section 0 concludes D3.3 and provides an overview of WP3 next steps and plans.

1.1 CONSERN Cooperation Framework

This section provides a summary view of the CONSERN Cooperation framework in relation to WP3 objectives.

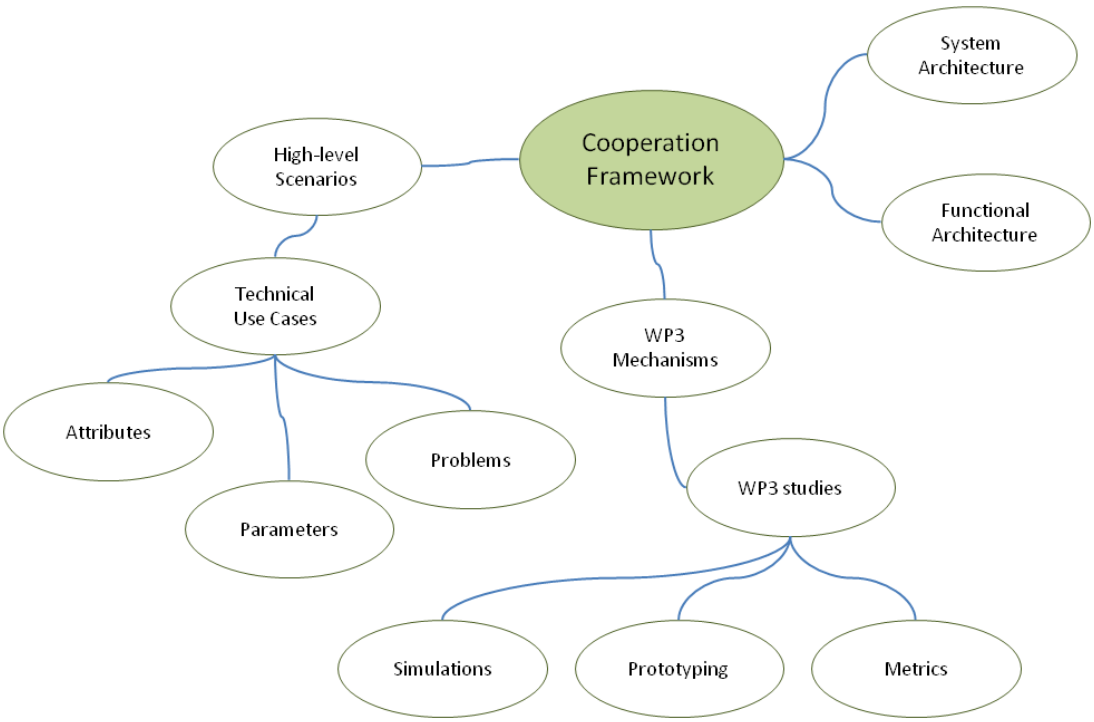


Figure 1-1: WP3 Cooperation Framework.

The following components form the Cooperation Framework:

- Scenarios: one or more of the CONSERN high level system scenarios as defined in D1.1 [11],
- Technical Use Cases as analysed and selected for highlighting WP3 problems,

- Problem(s) describing specific snapshots of the selected use cases and addressed through cooperation enablers and mechanisms as developed within WP3,
- Attributes and parameters providing a more detailed view of the mechanisms application,
- Mechanisms, algorithms and studies composing the core of WP3 work,
- Reference architecture
    - Reference Functional Architecture provides an encapsulation of the provided functionality to network elements and networks and is provided by WP4 for the self-growing aspects of the reference architecture. WP3 mechanisms are mapped to CONSERN functional architecture as presented in D4.2 [14],
    - Reference System Architecture provides a solid view of the networking environment and the deployment of CONSERN functionality to different kinds of networks and network elements and is being developed within WP5 applicable for a proof-of concept. WP3 will provide update plans for integrating WP3 mechanisms to CONSERN integrated PoC.
- Evaluation – Studies include the evaluation framework (e.g. simulation or/and prototyping activities) and identification of corresponding metrics.

1.2 Addressing Cooperation Framework

This section aims at providing a "preposterous" summary of how and in what extent the Cooperation framework is addressed through the work progress and the achievements which have been reported in D3.1, D3.2 and D3.3 – the deliverable at-hand. Initially, the high level scenarios which are under consideration are listed and, on sequence, for each of the Use Cases which have been selected as WP3-related (in D3.2) the identified problems and the mechanisms providing solutions are also presented. For each problem, corresponding attributes are listed and the evaluation framework is also outlined.

In this context the following considerations, progress and achievements apply:

- Scenario(s): Two high level scenarios are being considered within the scope of WP3 Cooperation Framework
    - Scenario 3: Home and Office Environment,
    - Scenario 4: Urban Heterogeneous Environments.
- Use Cases - Problems - Evaluation
    - UC-2/NKUA: Energy Optimization in an Office environment under coverage constraints,
        - Problem1: Energy efficiency and interference mitigation among network elements in a dense environment,
            - Mechanism(s)
                - Cooperative Power control algorithm featuring fuzzy logic reasoning,
                - Enhancement with learning capabilities; both self-learning and learning based on neighbouring nodes are considered.
            - Attributes

        - Energy awareness, Situation awareness, Dependability (Availability).
    - Evaluation
        - Simulation Studies,
        - Proof of Concept component has been developed in the context of WP5,
        - Corresponding mechanisms will be incorporated to the integrated CONSERN PoC based on WP5 work-plan.
    - Metrics
        - Initial set of metrics is presented in the corresponding section of this deliverable,
        - Such metrics will be linked to the overall project's indicators as defined in the Project's DoW,.
    - Reference Architecture
        - Mapping to CONSERN Functional Architecture is presented in the corresponding section of this deliverable,
        - Mapping to generic system architecture will be presented within WP5 in case that the mechanism under consideration is selected for incorporation in the integrated PoC.
- Problem2: Reliability of measurements provided by wireless sensors,
    - Mechanism(s)
        - Outlier detection – autonomous step (node level),
        - Outlier detection – cooperative level (neighboring nodes level).
    - Attributes
        - Energy awareness, Situation awareness, Autonomicity, Dependability (Reliability, Availability).
    - Evaluation
        - Simulation studies,
        - Corresponding mechanisms may be incorporated to the integrated CONSERN PoC based on WP5 work-plan.
    - Metrics
        - Initial set of metrics are presented in the corresponding section of this deliverable,
        - Such metrics will be linked to the overall project's indicators as defined in the Project's DoW.
    - Reference Architecture
        - Mapping to CONSERN Functional Architecture is presented in the corresponding section of this deliverable,
        - Mapping to generic system architecture will be presented within WP5 in case that the mechanism under consideration is selected for incorporation in the integrated PoC.

- UC-5/HWSE: Switch on-off of nodes for Energy Efficiency in Heterogeneous Networks,
    - Problem: Reduce energy consumption in heterogeneous cellular network (HetNet) consisting of sites with different power transmission, coverage and capacity profiles
        - Mechanisms
            - Centralised algorithm for identification of the network resources to be de-activated in order to reduce the overall energy while maintaining QoS levels and corresponding studies; full knowledge model is assumed,
            - Distributed algorithm for the above presented problem; partial knowledge is assumed and the decision logic is distributed to the involved network elements.
        - Attributes
            - Self-growing, Situation awareness, Dependability, Autonomicity, Energy Awareness, Cooperativeness, Reconfigurability.
        - Evaluation
            - Simulation studies have been performed for centralized algorithm which also forms a baseline for the planned simulation studies,
            - Simulation studies have been planned for the distributed environment; comparative studies will follow between the approaches,
            - Proof of Concept Component has been developed in the context of WP5 (mapped to HWDU activities in WP5)
            - Corresponding mechanisms may be incorporated to the integrated CONSERN PoC based on WP5 work-plan,
        - Metrics
            - Initial set of metrics are presented in the corresponding section of this deliverable,
            - Such metrics will be linked to the overall project's indicators as defined in the Project's DoW.
        - Reference Architecture
            - Mapping to CONSERN Functional Architecture is presented in the corresponding section of this deliverable,
            - Mapping to generic system architecture will be presented within WP5 in case that the mechanism under consideration is selected for incorporation in the integrated PoC.
- UC-6/HWSE: Cooperative DAS nodes configuration
    - Problem: Reduce energy consumption in a Distributed Antenna System (DAS) _through selecting which individual antenna nodes to turn off and identifying when it is possible to turn them off.
        - Mechanisms
            - Large-scale fading based antenna selection,
            - Throughput efficiency based antenna selection,

        - Energy aware scheduling.
    - Attributes
        - Energy Awareness, Situation awareness, Cooperativeness, Reconfigurability, Dependability.
    - Evaluation
        - Simulation studies have been performed for Homogeneous topology model,
        - Simulation studies have been performed for Heterogeneous topology model,
        - Comparative studies have been planned,
        - Corresponding mechanisms may be incorporated to the integrated CONSERN PoC based on WP5 work-plan.
    - Metrics
        - Initial set of metrics are presented in the corresponding section of this deliverable,
        - Such metrics will be linked to the overall project's indicators as defined in the Project's DoW.
    - Reference Architecture
        - Mapping to CONSERN Functional Architecture is presented in the corresponding section of this deliverable,
        - Mapping to generic system architecture will be presented within WP5 in case that the mechanism under consideration is selected for incorporation in the integrated PoC.
- UC-7/HWSE: Cooperative relay for Energy Efficiency,
    - Problem: Determine how cooperation between relay nodes and BSs can be achieved in the most energy-efficient way.
        - Mechanisms
            - Algorithm of capacity/throughput analysis,
            - Algorithm of energy saving analysis.
        - Attributes
            - Self-Growing, Energy Awareness, Situation awareness, Cooperativeness, Reconfigurability.
        - Evaluation
            - Simulation
                - Simulation studies have been performed based on three access modes referring to UEs access to central BS (i.e. baseline, simple relay scheme, cooperative relay scheme),
                - Further studies have been planned.
            - Prototyping
                - Incorporation to the integrated PoC is under consideration.
            - Metrics

        - Initial set of metrics are presented in the corresponding section of this deliverable,
        - Such metrics will be linked to the overall project's indicators as defined in the Project's DoW.
    - Reference Architecture
        - Mapping to CONSERN Functional Architecture is presented in the corresponding section of this deliverable,
        - Mapping to generic system architecture will be presented within WP5 in case that the mechanism under consideration is selected for incorporation in the integrated PoC.
- UC-11/IBBT: Energy optimization of co-located wireless networks in a home/office environment
    - Problem1: Noise and interference are local by nature, and therefore when selecting a single channel for the operation of the entire network, some of the nodes may suffer more interference or noise than others.
        - Mechanisms
            - Receiver Defined Transmission (RDT) allowing logical separation of the transmission and quiescent (receive) channels of each node
                - Channel Selection Algorithm,
                - Channel Information Exchange Protocol,
                - Packet formats definition.
        - Attributes
            - Energy Awareness, Spectral Efficiency.
        - Evaluation
            - Experiments have been performed based on three interference scenarios (i.e. no interference/background, emulated interference, and real life interference),
            - Further studies have been planned,
            - Proof of concept component has been developed in the context of WP5,
            - Incorporation to the integrated PoC is under consideration.
        - Metrics
            - Initial set of metrics are presented in the corresponding section of this deliverable,
            - Such metrics will be linked to the overall project's indicators as defined in the Project's DoW.
        - Reference Architecture
            - Mapping to CONSERN Functional Architecture is presented in the corresponding section of this deliverable,
            - Mapping to generic system architecture will be presented within WP5 in case that the mechanism under consideration is selected for incorporation in the integrated PoC.
    - Problem2: Independent networks can benefit from sharing in the form of information, resources and infrastructure. By sharing (network) resources and

optimizing resources across network boundaries, network performance and power consumption can be optimized in a global way.

- Mechanisms
  - Network Collaboration is achieved by exchanging information between networks, and negotiating which network services to activate in each of the networks. It is composed of the following steps
    - Channel Selection Algorithm,
    - Network discovery algorithm,
    - Negotiation algorithm,
    - Optimization algorithms.
- Attributes
  - Energy Awareness, Self-growing, Spectral Efficiency.
- Evaluation
  - Experiments have been performed showcasing Network Collaboration with two networks: temperature monitoring and intrusion detection,
  - Further studies have been planned,
  - Proof of concept component has been developed in the context of WP5,
  - Incorporation to the integrated PoC is under consideration.
- Metrics
  - Initial set of metrics are presented in the corresponding section of this deliverable,
  - Such metrics will be linked to the overall project's indicators as defined in the Project's DoW.
- Reference Architecture
  - Mapping to CONSERN Functional Architecture is presented in the corresponding section of this deliverable,
  - Mapping to generic system architecture will be presented within WP5 in case that the mechanism under consideration is selected for incorporation in the integrated PoC.

- UC-14/TREL Cooperation Enablers in Home Gateway Environments.
  - Problem1: In a dense home/office environment residential users are served by different femto base stations in close proximity to one another and are sharing the same frequency-time resources such that their communications interfere in either uplink or downlink.
    - Mechanisms
      - Cooperative schemes for energy saving in networks that utilise network coding strategies based on a relay.
    - Attributes

    - Energy awareness, Situation awareness, Dependability (Availability, Robustness), Cooperativeness.
- Evaluation
    - Simulation studies have been performed based on a source transmitting to a destination in the presence of a strong interferer given by a second source,
    - Simulation studies with LTE turbo codes,
    - Further studies have been planned.
    - Incorporation to the integrated PoC is under consideration.
- Metrics
    - Initial set of metrics are presented in the corresponding section of this deliverable,
    - Such metrics will be linked to the overall project's indicators as defined in the Project's DoW.
- Reference Architecture
    - Mapping to CONSERN Functional Architecture is presented in the corresponding section of this deliverable,
    - Mapping to generic system architecture will be presented within WP5 in case that the mechanism under consideration is selected for incorporation in the integrated PoC.

2. Cooperative Network Coding

2.1 Relay Network Coding Schemes

In this work we investigate cooperative schemes for energy saving in networks that utilise network coding strategies based on a relay. The use case scenario of reference was described in Section 2.1 of [1]: two interfering femtocell base stations, BS1 and BS2 are communicating with their respective mobile terminals, MT1 and MT2. A listening relay station can communicate on an interference-free control channel with the receivers, e.g. through a WLAN or an Ethernet connection. In case of a downlink transmission from BS1 to MT1 and BS2 to MT2, the relay can broadcast some side information to the mobile terminals, whereas in an uplink configuration, the relay broadcasts the side information to the two base stations.

This use case scenario can be conveniently modelled by an *interference relay channel*, as described in Section 3.1 of [1] and depicted in Figure 2-1.

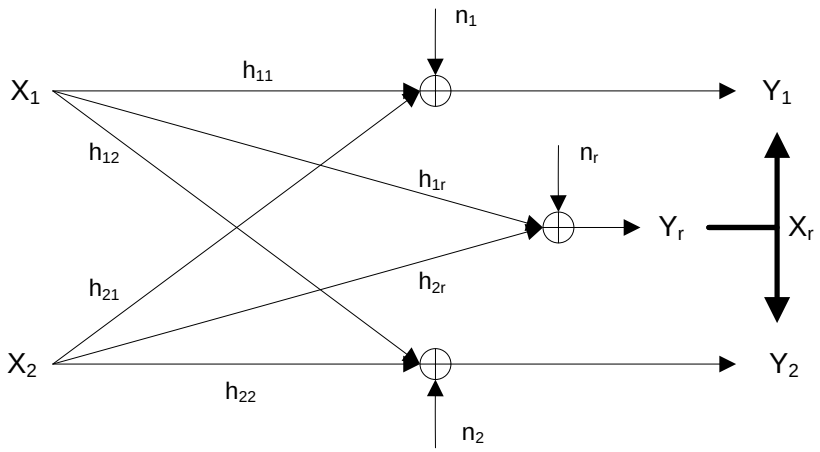


Figure 2-1: Interference relay channel model.

Source node 1 wishes to send a data message, X_1, to destination node 1, while source node 2 wants to communicate message X_2 to destination node 2. The two transmissions are uncoordinated, which causes interference and compromise the ability of the two receivers to decode their respective messages successfully. The relay node listens to the communications between the sores nodes and the destinations and helps to resolve the interference by sending some information about Y_r to both the destination nodes on a separate control channel of rate R_0. Note that the model above is applicable to either a downlink transmission, where the source nodes are interfering small base stations and the destination nodes are user terminals, or an uplink communication where the roles of source and destination nodes are reversed. The symbols h_{ij} denote the baseband channel gains from node i to node j, with i,j=1,2, while h_{ir} indicate the channel gains from source node i to the relay node. The AWGN components are denoted by symbols n_i, for the destination nodes and n_r for the relay node.

The channel outputs for the interfering relay channel model are given by

$$Y_1 = h_{11}X_1 + h_{21}X_2 + n_1$$
$$Y_2 = h_{12}X_1 + h_{22}X_2 + n_2$$
$$Y_r = h_{1r}X_1 + h_{2r}X_2 + n_r$$

The symbol X_r represents a lossy compressed version of the relay observation Y_r.

In [2] Cover and El Gamal first proposed a compress-forward network coding scheme, in which the relay compresses its noisy observation of the source signal and forwards the compressed observation to the destination node. In their original work the compress-forward scheme is applied to a relay channel with a single source and destination and the source and relay signals cooperate coherently to resolve the uncertainty about the transmitted message at the destination. However, the same general scheme is applicable to an interfering relay channel, which can be viewed as the combination of two relay channels sharing the same relay node and relay message. In Cover and El Gamal's work random binning arguments are used as a source coding strategy to prove optimality for some types of channels. However, very few practical compress-forward coding strategies for an interference scenario are available in the literature. One such practical scheme recently appeared in [3] and uses nested lattice codes [4] to map the relay observation Y_r into X_r. In this work we build on this network coding strategy and show how energy saving can be achieved in an interfering relay channel with realistic channel coding (namely, the 3GPP LTE turbo codes).

Let us consider a one dimensional complex lattice $\Lambda = \mathbf{G}\mathbb{Z}[j] \subset \mathbb{Z}[j]$, where $\mathbb{Z}[j]$ denotes the Gaussian integer grid, $\mathbf{G}$ is the lattice generator matrix and the volume of the lattice Λ is $\mathrm{vol}(\Lambda) = \det\mathbf{G} = 2^{R_0}$. Generally, a sublattice $\Lambda \subset \mathbb{Z}[j]$ induces a nested lattice partition, denoted by $\mathbb{Z}[j]/\Lambda$, of the Gaussian integer grid into $\mathrm{vol}(\Lambda)/\mathrm{vol}(\mathbb{Z}[j]) = 2^{R_0}$ cosets. Therefore, we can identify our relay quantisation codebook with these cossets and perform the quantisation operation by finding the cosset representative that is closest in Euclidean distance to the observation Y_r We also introduce a scaling factor $\tau > 0$, such that the final nested lattice construction is given by $\tau\mathbb{Z}[j]/\tau\Lambda$. Say $C = \{0,1,\dots,2^{R_0}\}$ the set of quantisation indices identifying the cosets, and $Q(\cdot)$ the quantisation operation that finds the closest Gaussian integer, and then the relay quantisation operation is defined as follows:

$$Y_r \overset{Q_r}{\rightarrow} X_r \in C \quad : \quad Q(\frac{Y_r}{\tau}) \in \Lambda + X_r$$

By optimising the design of the generator matrix G, it is possible to carry out this quantisation operation without need for a lattice point search, which is generally a computationally complex operation.

In the network coding scheme under study, the index X_r forms part of the massage forwarded by the relay node to the destinations on a separate control channel. The relay message also includes the relay channel state information (CSI) in the form of the channel gains h_{1r} and h_{2r}. These can be provided in practice in a quantised format.

Let us now consider the operations the destination nodes have to perform to use the relay side information to improve the decoding process. Let us look at the destination node 1, bearing in mind that the same arguments apply to the other destination node. The idea is that the joint probability density function (pdf) of the received signal y_1 and the relay message x_r, given the correct transmitted symbol x_1 becomes more "concentrated" than the pdf of y_1 given x_1. In statistical terms, the standard deviation of the two random variable are such that

$$\sigma(y_1, x_r | x_1) < \sigma(y_1 | x_1)$$

Therefore, the reliability on the i-th bit of the transmitted symbol, $b_i(x_1)$, increases if some information about the relay observation is made available to the decoder. This reliability function is commonly expressed in the form of log-likelihood ratio (LLR), which is given by the following expression in the case the receiver is unaware of the constellation of the interfering signal x_2

$$\mathrm{LLR}(b_i) = \log \frac{P[b_i(x_1) = 1|, y_1, x_r]}{P[b_i(x_1) = 0|, y_1, x_r]} = \log \frac{\sum_{x_1 | b_i(x_1)=1} p(y_1, x_r | x_1)}{\sum_{x_1 | b_i(x_1)=0} p(y_1, x_r | x_1)}$$

where the summations are over the constellation symbols from which x_1 is drawn. We can rewrite the pdf in the LLR expression as follows, by using basic properties of the conditional probability

$$p(y_1, x_r | x_1) = p(x_r | x_1, y_1) p(y_1 | x_1)$$

Because, in this case, the receiver has no prior knowledge of the constellation of x_2, it can assume this signal to be circularly symmetric Gaussian, $x_2 \sim \mathcal{NC}(0, P_2)$, where P_2 is the transmit power of the signal from the interfering node. Let the AWGN components be $n_1, n_2, n_r \sim \mathcal{NC}(0,1)$, and P_1 be the transmit power of x_1. Note that because of the noise normalisation, P_1 and P_2 also equal the ratio between the received power of the useful signal and the thermal noise power at destination node 1 and 2, respectively. Therefore y_1 given x_1 is Gaussian with mean and variance

$$m_1 = h_{11} x_1 \quad , \quad \sigma_1^2 = | h_{21} |^2 P_2 + 1$$

such that the second term of the condition pdf above is given by

$$p(y_1 | x_1) = \frac{1}{\pi \sigma_1^2} \exp\left(\frac{| y_1 - m_1 |^2}{\sigma_1^2} \right)$$

With regards to the first term of the conditional pdf, it can be calculated by the following integral over the quantisation region of x_r, $\mathcal{Q}_r^{-1}(x_r)$

$$p(x_r | x_1, y_1) = \int_{y_r \in \mathrm{Q}_r(x_r)} p(y_r | x_1, y_1)$$

The argument of the integral is also Gaussian with mean

$$m_r = h_{1r} x_1 + h_{2r} x_{2,\mathrm{MMSE}}$$

where the last term is the MMSE estimate of x_2 given y_1 and x_1

$$x_{2,\mathrm{MMSE}} = \frac{h_{21}^* P_2}{| h_{21} |^2 P_2 + 1} (y_1 - h_{11} x_1)$$

and variance

$$\sigma_r^2 = \mathrm{E}[(y_r - m_r)^2] = \mathrm{E}[(h_{2r}(x_2 - x_{2,\mathrm{MMSE}}) + n_r)^2] = | h_{2r} |^2 e_{2,\mathrm{MMSE}}^2 + 1$$

where the minimum mean square error is given by

$$e_{\mathrm{MMSE}}^2 = \frac{P_2}{| h_{21} |^2 P_2 + 1}$$

On the other hand, if the receiver knows the constellation of the interfering signal x_2, we can condition the terms in the LLR formula with respect to x_2 and obtain the modified LLR

$$\mathrm{LLR}(b_i) = \log \frac{\sum_{x_2} \sum_{x_1 | b_i(x_1)=1} p(y_1, x_r | x_1, x_2)}{\sum_{x_2} \sum_{x_1 | b_i(x_1)=0} p(y_1, x_r | x_1, x_2)}$$

In this case the conditional pdf reads

$$p(y_1, x_r | x_1, x_2) = p(x_r | y_1, x_1, x_2) p(y_1 | x_1, x_2) = p(x_r | x_1, x_2) p(y_1 | x_1, x_2)$$

where the second equality follows from the fact that $y_1 - h_{11} x_1 - h_{21} x_2 = n_1$ is independent of x_r.

T Therefore $y_1 \mid x_1, x_2$ is Gaussian with mean and variance

$$m_1 = h_{11}x_1 + h_{21}x_2$$
$$\sigma_1^2 = 1$$

while $y_r \mid x_1, x_2$ is also Gaussian with mean and variance

$$m_r = h_{1r}x_1 + h_{2r}x_2$$
$$\sigma_r^2 = 1$$

After calculation, the bit LLR's are fed to the decoder for the decoding of message X_1. A similar procedure is carried out by the destination node 2 to decode message X_2.

2.2 Evaluation Metrics and Evaluation Environment

In this section we present the evaluation framework used to access the performance of the relay-based network coding scheme described in the previous section. In particular, we want to emphasise the energy saving aspect achieved by the scheme in terms of transmit power reduction. The basic simulation scenario consists of a transmitting femtocell base station interfered by another adjacent femtocell, a receiving terminal and a relay node. We assume that an error free control channel is available between the relay node and the destination.

In order to evaluate the transmit power we use the parameters reported in Table 2-1. In particular we use the microcell path loss model for NLOS at 1900 MHz adopted by the 3GPP [5]. We also consider a highly interfered scenario with the power of the interfering signal equal to that of the useful signal (SIR=0 dB). This corresponds to a worst case scenario of a femtocell user located at the cell edge and equidistant from the own and interfering base stations.

Channel model	Independent Rayleigh fading
Thermal noise spectral density (N_0)	-174 dBm/Hz
Carrier frequency	1.9 GHz
Transmit bandwidth (B)	20 MHz
Femtocell range (d)	50m
Path loss model (microcell NLOS)	PL(dB) = 34.53+38*$\log_{10}$(d)
Signal to interference ratio (SIR)	0 dB
Transmitter antenna gain (G_T)	0 dB
Receiver antenna gain (G_R)	-1 dB

Table 2-1. Channel model parameters for evaluation of transmit power.

The received power at the destination node is calculated from the SNR as follows

$$(P_R)_{dBm} = \mathrm{SNR}_{dB} + (N_0)_{dBm} + 10\log_{10}(B)$$

The transmitted power is obtained from the following link budget formula

$$(P_T)_{dBm} = (P_R)_{dBm} - (G_T)_{dB} - (G_R)_{dB} + (PL)_{dB} = \mathrm{SNR}_{dB} + 10*\log_{10}(B) + 38\log_{10}(d) - 140.47$$

2.3 Evaluation

In this section we present some simulation results obtained with the parameters described in the previous section. The basic simulation framework consists of a source transmitting to a destination in the presence of a strong interferer given by a second source. The average transmitted power of the interfering signal is the same as that of the intended source and the signal to interference ratio at the receiving unit is 0dB. Our main evaluation metric is energy saving at the transmitter, therefore we compare the transmit power required to achieve typical error rate values when a relay node operates a compress-forward strategy. We compare results for different relay message sizes. We also assume that the receiving node knows the CSI at the relay node. This information can be provided as part of the control signalling exchanges between the relay and the destination node.

Firstly, we consider an uncoded transmission and compare the performance of the relay based network coding scheme for an increasing number of relay message bits R_0. The modulation is QPSK. We also assume that the receiving node knows the signal constellation of the interfering transmission. In this case we plot the results in terms of SNR versus bit error probability (BER) in Figure 2-2.We note that at meaningful BER one additional bit of side information brings an SNR gain of about 2dB in the range R_0=1 to R_0=4. Besides, at BER=10^{-3}, almost all of the SNR gain is achieved by a relay message of just 4 bits. The curve corresponding to R_0=0 refers to a setup where the receiver only knows the interfering signal constellation and the relay CSI. Note that this information is enough to allow the receiver to decode the message albeit at very high cost in terms of required transmit power. The transmitter energy efficiency is significantly improved by adding very few bits of side information.

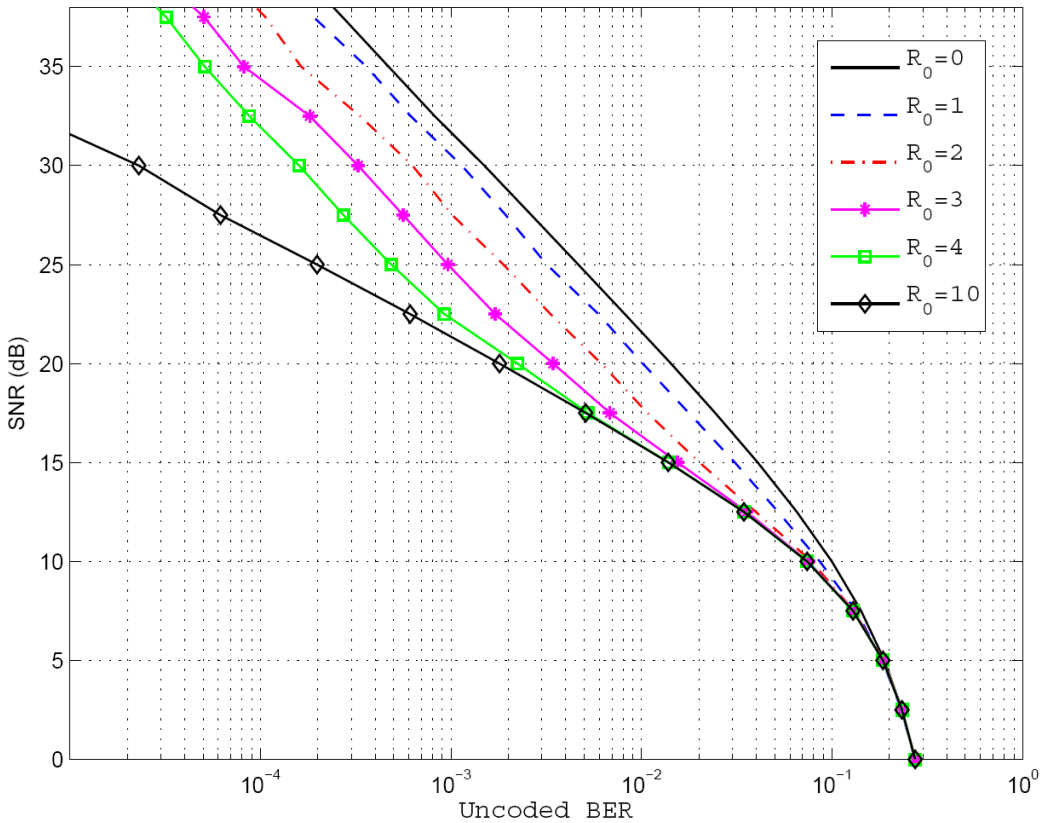


Figure 2-2: Quantise-forward network coding performance for uncoded transmission. The receiver knows the interfering signal constellation.

Next, we tested the scheme with LTE turbo codes. In Figure 2-3, we show the transmit power reduction in mW versus BER for a rate ½ code and QPSK modulation, using the parameters of Table 2-1. In this case we assume that the receiver does not know the interfering signal constellation, hence the information received by the relay consists of the relay CSI and the compressed observation made by the relay. Note that the lack of information about the interfering signal, corresponding to the curve with R_0=0, makes it impossible to successfully decode the message. In this case the relay information is not only helpful in reducing the required transmit power but also essential to decode the message correctly in this highly interfered scenario (SIR=0dB).

Two bits of relay side information are enough to improve dramatically the decoder performance. Also, by adding one more bit to the relay message from 2 to 3 bits, the transmit power efficiency of the source node is improved by about 8.5mW at BER=10^{-3} or by 69%. A further 10% improvement can be achieved by increasing the relay message from 3 to 4 bits.

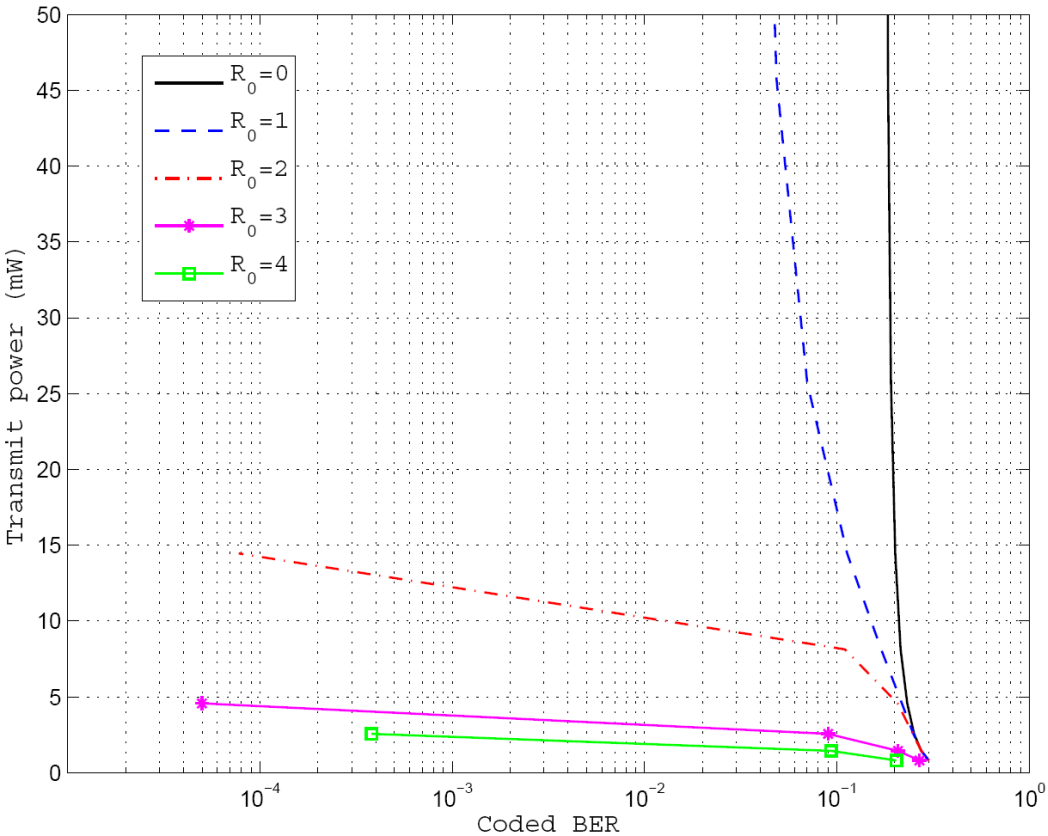


Figure 2-3: Quantise-forward network coding performance for coded transmission (LTE turbo code, rate 1/2). The receiver is unaware of the interfering signal constellation.

2.4 Map on the CONSERN Functional Architecture

We refer to D4.2 [14] where CONSERN entities were formally described. According to the definition, we have identified the CONSERN ENTITIES involved in the relay network coding system as *Type B* CEs.

In our relay network coding system, we have utilised the Cooperation, Execution, Monitoring, and Communication Services functions. Here, we utilise the Cooperation function to coordinate the transmission of the mobile terminals such that the transmissions are synchronised. The Monitoring and Execution functions are used by the relay terminal first to listen to transmissions from mobile terminals, and then to quantise the observed signal to a manageable number of bits.

The Communication Services function acts as a bridge between the relay terminal and the two neighbouring base stations. Through this function, the relay terminal communicates the quantised

observed signal to the two base stations. The quantised observed signal is then used to improve the bit reliability through techniques described in the previous sections.

An illustration of the mapping is shown in

Figure 2-4.

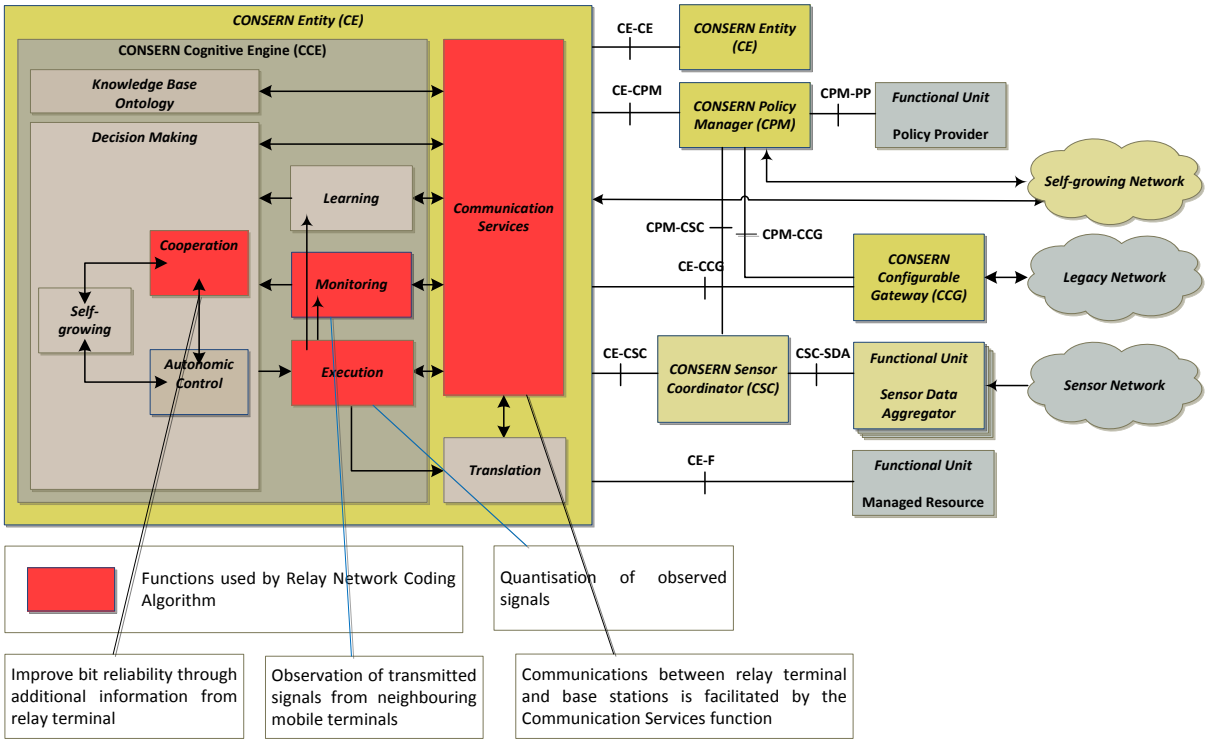


Figure 2-4: Mapping of Relay Network Coding system to CONSERN Entity.

3. Cooperative Power Control Scheme

Cellular networks tend to use as small cells as possible in order to improve their capacity. Towards this direction the exploitation of femto BSs for indoor coverage will be indispensible [8]. The continuous shrinkage of the cell coverage area, will lead to an increase of the number of cells in a given area; such increase, if not carefully considered, will consequently lead to increased interference among femto BSs.

The simultaneous access of incumbent and license-exempt nodes to the spectrum makes the problem even more challenging. Thus, there is an urgent need for power control algorithms that will maximize the overall system performance and mitigate the inter-cell interference. As discussed in [9], these algorithms shall employ cooperative spectrum sharing and at the same time be distributed in order to efficiently exploit the shared spectrum. Moreover, efficient message exchange scheme should be utilized. These features of the system characterize it as a Cognitive Radio (CR) system as it is defined in ITU-R(2009) specifications [26]. Furthermore, it is important to preserve the message exchange scheme as simple and energy efficient as possible, in order to achieve even better system performance. In order to meet the previously mentioned objectives, message retransmission should be avoided and uncertainties regarding the state of the network should be dealt with. Thus, a Cooperative Power Control algorithm for Handling Uncertainties is proposed; such algorithm employs information dissemination via an efficient message exchange scheme and handles uncertainties using fuzzy reasoners. Also learning capabilities are incorporated to the Cooperative Power Control algorithm in order to achieve Enhanced Environment Perception. The following sections provide the description of the aforementioned algorithms as well as simulation results that prove the validity of the proposed solutions. Finally, a mapping to the CONSERN Functional Architecture is provided.

3.1 Cooperative Power Control for Handling Uncertainties

In this section a brief overview of the cooperative power control algorithm is provided. Our approach is based on [10]; the aim of this solution is to maximize overall network utilization taking into account both secondary users needs for Tx power and the presence of interference due to high Tx power levels.

The proposed approach concerns ad-hoc networks and is based on an information exchange scheme towards the identification of the appropriate transmission power levels. The algorithm incorporates a fuzzy reasoner in order to handle uncertainties in the network regarding message exchange. The original algorithm is described in details in [9]. The initial solution is modelled for Cognitive Radio (CR) systems that cooperate in an ad-hoc mode to adjust their Tx power and achieve interference mitigation; however the algorithm model is applicable, to any wireless communication technology that is able to incorporate the notion of cooperativeness. In the proposed solution we modify the initial algorithm so as to operate in femto BSs that operate in TV white spaces (secondary nodes).

As thoroughly described in [9] an objective function that captures the overall network utility is maximized. To achieve this, the selection of transmission power of every license-exempt node should be carefully selected as it is based on a trade-off between the capacity of a network node and the interference caused to the corresponding neighbourhood. The following function captures this balance; thus the selected power value of each node is the one that maximizes this function.

$$u_i\left(\gamma_i\left(p_i^k\right)\right) - a \cdot p_i^k \sum_{j \neq i} \pi_j^k \cdot h_{ji} \tag{3.1-1}$$

The first part indicates a relation to the Shannon capacity for the corresponding user, while the second part captures the negative impact in terms of interference prices that a user causes to its

neighbourhood. The *α* factor is introduced so as to capture uncertainties in the network; these uncertainties are related to the perception each network node has, regarding the interference price it has received from each of its neighbouring nodes. This is related to the fact that once a network element proceeds adjusting its transmission power, it informs its neighbours in an ad-hoc manner. This implies that even though a network element has collected information from all of its neighbours in order to adjust its transmission, the gathered data could be obsolete and, as a consequence, they will not capture the current neighbourhood's state. The obsolescence of the interference prices is related to the update interval (i.e. the periodic update) of each network element.

The algorithm consists of three steps, namely, the initialization, the power update and the interference price update. The former is related to the introduction of initial valid transmission power and interference price values. The second concerns the transmission power update based on the interference prices each node receives from its neighbours. Finally, the latter captures the communication of its interference prices to the neighbourhood, by every network node. The second and the third steps are asynchronously repeated until the algorithm reaches a steady state (i.e. a state where every network element has the same transmission power for two consecutive time iterations).

Due to the nature of the BSs communication (i.e. asynchronous communication), each one might have its locally-set update interval. Thus, it is possible that the femto BSs do not have the current network status (from the messages exchange). This implies that the use of the fuzzy reasoner in order to capture the uncertainties is imperative [10]. The inputs and the inference engine of the fuzzy logic controller of the fuzzy reasoner should be modified in order to adapt to the new application area. More specifically, the number of femto BSs, the number of end-users connected to the femto BSs and the update time interval are used as inputs of the fuzzy reasoner. Table 3-1 provides the rules of the inference part of the fuzzy reasoner. The dominant factor for the decision making process, as it could be noted, is the update interval. This input captures the frequency of the information updates regarding the interference price of a network element to its neighbours.

Rule Number	Num of femto BS	Num of users	Update Interval	Interference price
1	Low	Low	Low	Low
2	Low	Low	Medium	Low
3	Low	Low	High	Medium
4	Low	Medium	Low	Low
5	Low	Medium	Medium	Medium
6	Low	Medium	High	Medium
7	Low	High	Low	Medium
8	Low	High	Medium	Medium
9	Low	High	High	High
10	Medium	Low	Low	Low
11	Medium	Low	Medium	Medium
12	Medium	Low	High	High
13	Medium	Medium	Low	Medium
14	Medium	Medium	Medium	Medium
15	Medium	Medium	High	High
16	Medium	High	Low	Medium
17	Medium	High	Medium	Medium
18	Medium	High	High	High

Rule Number	Num of femto BS	Num of users	Update Interval	Interference price
19	High	Low	Low	Medium
20	High	Low	Medium	Medium
21	High	Low	High	High
22	High	Medium	Low	Medium
23	High	Medium	Medium	Medium
24	High	Medium	High	High
25	High	High	Low	Medium
26	High	High	Medium	High
27	High	High	High	High

Table 3-1: Fuzzy Reasoner's rules.

3.2 Learning-Enhanced Environment Perception for Cooperative Power Control

3.2.1 Background

Fuzzy Logic

As mentioned in D3.2 [9], fuzzy logic is an ideal tool for dealing with complex multi-variable problems. Fuzzy reasoners address uncertainties more efficiently in comparison to Boolean algebra by using a mapping of outputs to a degree of a state,thus tackling the ping-pong effect. Finally, the nature of the fuzzy logic enables the fuzzy reasoners to deal with problems with contradictive inputs. The aforementioned characteristics make fuzzy logic an ideal tool to capture situation perception of a network element (i.e the way a network element perceives its environment).

A fuzzy reasoner consists of three parts, namely, the fuzzifier, the inference engine and the defuzzifier. The fuzzifier undertakes to transform the input values (crisp values) to a degree that these inputs belong to a specific state (low, medium, high, etc) using the input membership functions. The inference part correlates the inputs and the outputs using simple "IF...THEN..." rules. Each rule results to a specific degree of certainty for each output; these degrees then are being aggregated. During the defuzzification the outcome of the abovementioned aggregation is being mapped to the degree of a specific state that the decision maker belongs. Several defuzzification methods exist; the most popular is the centroid calculation, which returns the centre of gravity of the degrees of the outputs, taking into account all the rules, and is calculated using the following mathematical formula:

$$u_{COG} = \frac{\int u_i \mu_F(u_i) du}{\int \mu_F(u_i) du} \tag{3.2-1}$$

k-Means

k-Means is a well known data-mining clustering technique. The core idea of data clustering is to partition a set of N, d-dimensional, observations into groups such that intra-group observations exhibiting minimum distances (for example Euclidean distance) from each other, while inter-group distances are maximized. k-Means [18] tries to minimize the following objective function:

$$J = \sum_{i=1}^{c} J_i = \sum_{i=1}^{c} \left(\sum_{k, x_k \in G_i} \| x_k - c_i \| \right) \tag{3.2-2}$$

where c is the number of clusters, G_i is the *i-th* group, x_k is the kth vector in group J_i and represent the Euclidean distance between x_k and the cluster centre c_i. The partitioned groups are defined by using a membership matrix described by the variable U. Each element U_{ij} of this matrix is equal to 1 if the specific j^{th} data point x_j belongs to cluster i, and 0 otherwise. The element U_{ij} is analyzed as follows:

$$U_{ij} = \begin{cases} 1, \text{ if } \|x_j - c_i\|^2 \le \|x_j - c_k\|^2, \text{ for each } k \ne i \\ 0, \text{ otherwise} \end{cases} \tag{3.2-3}$$

This means that x_j belongs to group i, if c_i is the closest of all centers.

3.2.2 Proposed Learning Algorithm

The proposed learning algorithm consists of three parts, namely, the monitoring/labeling, the classification and the adaptation of the fuzzy reasoner. The purpose of such algorithm is to enable the network element to evolve the way it perceives its environment. More specifically, as thoroughly described in [Section 2.1], the femto BSs use fuzzy reasoners in order to capture the network uncertainties; such uncertainties are related to how correctly each network node has received and compiled information regarding the interference price which should have been available by the node's neighbours and are captured by a factor (Equation (3.1-1)). However, the way a network element interprets its environment for the extraction of *a* is static and is based on expert's knowledge. The aforementioned knowledge is induced in the fuzzy reasoners via the fuzzy reasoners' input membership functions. This implies that all network elements that have the same configuration, have the same situation perception as well, given the fact that each network element models its environment via its input membership functions. Furthermore, it would be a major benefit for the network administrators to enable network elements to evolve the way they interpret their environment; this could be achieved by changing the shape of the input membership functions. In order to tackle the static definition of the situation perception, we propose a feedback based learning scheme that evaluates how the network performed after a transmission power adjustment, in terms of the interference prices.

In the proposed scheme, each femto BS that is part of the network monitors its environment. Every time that the network nodes collaboratively proceed in transmission power adjustment, their interference prices are being compared to the previous ones and the interference factor calculations are being labelled as:

- Beneficiaries: for the decisions that led to reduction to the interference value caused to the neighbouring network elements,
- Neutral: for the decisions that led to similar interference values, thus the decision could not be characterized either as correct or wrong,
- Non Beneficiaries: the decision led to increase in the interference value caused to the neighbouring network elements.

More specifically, periodically, the network elements cooperatively identify the optimum transmission power using the methodology described in Section 3.1; the procedure is iterative, requiring finite steps number (i.e. maximum 30 iterations). Before every periodic transmission power adjustment, the interference value is being compared to the one before the previous transmission power adjustment (Figure 3-1).

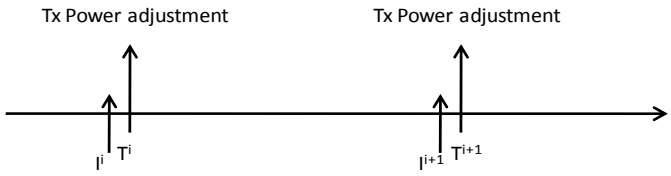


Figure 3-1: Timeline for Interference calculation and transmission power adjustment.

The input vector $Z \rightarrow i$ (i.e. num of femto BSs, num of users, update interval) of each network element is being evaluated against a predefined fuzzy inference system and results to a value which, in conjunction to the interference prices, is used for the calculation of the optimum transmission power. Comparing the interference prices before the initiation of the *i-th* transmission power adjustment and the *(i+1)-th* we label the decision (i.e. Y_i is beneficial, neutral or not beneficial) accordingly. The comparison is done using the Euclidian distance metric. This procedure results to a set (*S*) of labelled decisions that through the afore-described phase is (almost) certain that have been correctly labelled. Table 3-2 presents the key points of monitoring/labelling part of the algorithm.

Step	
Input:	**Approximation Parameter ε, Sample Size N**
Output:	**Set of observations S**
1.	S←0
2.	i=0
3.	while true
3.1	i++
3.2	Retrieve vector $\vec{Z}_i$ and $\vec{IP}_i$
3.3	α_i ← fuzzy logic ({# Femto APs, # Users, Update Interval})
3.4	Calculate Tx power
3.5	Wait for $\vec{Z}_{i+1}$ and $\vec{IP}_{i+1}$
3.6	Calculate I^{factor}_{i+1}
3.7	If ($\|I^{factor}_i - I^{factor}_{i+1}\| < \varepsilon$) → Y_i=Neutral
3.8	Else ($\|I^{factor}_i - I^{factor}_{i+1}\| > \varepsilon$) and ($I^{factor}_i - I^{factor}_{i+1} > 0$) → Y_i = Beneficiary
3.9	Else ($\|I^{factor}_i - I^{factor}_{i+1}\| > \varepsilon$) and ($I^{factor}_i - I^{factor}_{i+1} < 0$) → Y_i = Non Beneficiary
4.	return S

Table 3-2 : Monitoring/Labelling algorithm.

Using the labeled data three (3) clusters are formed to exclude the misclassified data from the previous step; the clustering is performed using k-Means (Table 3-2). Thus, each network element maintains a set of three clusters, one for classifying every decision type. By representing each cluster to a 3D grid we map each cluster to a geometrical object (i.e. sphere $S_{i,}$). Each sphere is centred at $C_j=\Sigma_{i=1}^{|Ci|}S_i/|C_i|$ and has radius $R_j=\max_{i=1}^{|Ci|}||CE_i-S_i||$.

Step	
Input:	**Set of observations S, Cluster Size k**
Output:	**Set of Bounds B**
1.	B←O
2.	$\{C_i, R_i\}$ = k-means(S, k)
3.	B = Geometric_Bounds(C_i, R_i)

4.	return B

Table 3-3 : k-Means and geometric bounds calculation procedures

For each couple of clusters i, j, the cluster centres C_i, C_j define a line ε that interconnects the two points. This line can be described by the following set of equations:

$$p_m = x_m + u\square(y_m - x_m),\ m = 1...d \tag{3.2-4}$$

Line ε intersects with spheres S_i and S_j in four points which can be retrieved by substituting the p_m values into the following hyper sphere equations:

$$D_i \rightarrow \sum_{m=1}^{d} (p_m - x_m)^2 = R_i^2 \tag{3.2-5}$$

$$D_j \rightarrow \sum_{m=1}^{d} (p_m - y_m)^2 = R_j^2 \tag{3.2-6}$$

A simple way of identifying the bounds would be to extract the intersection points that belong to different hyperspheres and exhibit minimum distance from each other [14]. Let A1 and A2 be the intersection points of the beneficial and neutral clusters with line ε and A3 and A4 be the intersection points of the neutral and the non beneficiary clusters with line ε respectively (Figure 3-2).

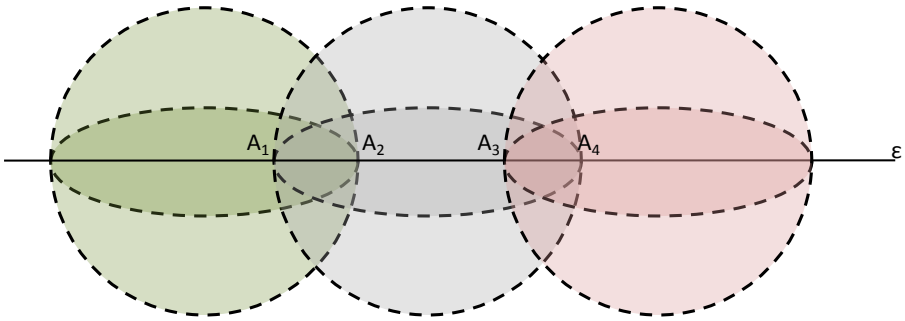


Figure 3-2 : Intersection points identification mechanism.

In a more intuitive analysis, it could be mentioned that the point of a cluster that has the greatest distance from its center, is where the input membership function (and thus the certainty for the rest of the measurements) is zero. Similarly, it could be mentioned that the decision maker has uncertainties in the cluster overlapping regions. The aforementioned approach enables the mapping of the cluster bounds to the input membership functions of the fuzzy reasoner (Figure 3-3). This procedure results to the modification of the environment perception of each network element.

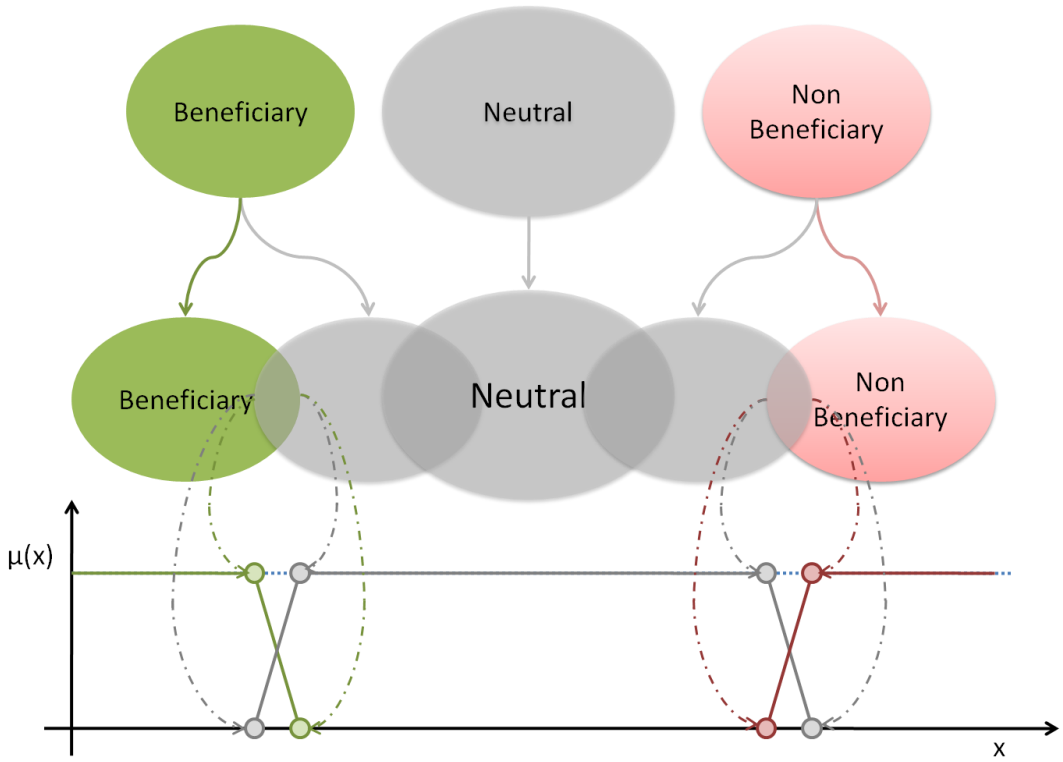


Figure 3-3 : Clustering and membership functions bounds extraction mechanism.

3.3 Evaluation Metrics and Evaluation Environment for Cooperative Power Control mechanism

In CONSERN deliverable D1.1 [11] a series of definitions were given so as to set the directions for WPs further work. Proposed scenarios, use cases and system requirements were defined in detail, in order to be used throughout WPs in conjunction to a set of attributes that capture the targets of the CONSERN project. More specifically, an attribute reflects a certain technical feature; each attribute is evaluated by metrics that act as quantitative measures of the degree to which a process possesses a given attribute (at current case the cooperative power control algorithm).

In the case of cooperative power control between femto BSs, the proposed algorithm in [10] possesses the attributes of energy awareness and cooperativeness. As far as the former is concerned, the specific parameters related to the proposed approachare the available peak power, the node (i.e. femto BS) transmission output power level and the trade-off between power and capacity. As far as the latter is concerned, the amount of the ability to recognize cooperative behavior needs, the number of negotiation steps prior to power level agreement and the adjustment in Tx power are identified as key parameters of this approach.

The metrics used for the evaluation and validation of the proposed solution are moving towards two directions; to capture the benefits from introduction of the cooperative power control (with and without the incorporation of the learning scheme) and to identify how the network elements' situation perception evolves (via the learning scheme). The cooperative power control is being evaluated using the utility function (Equation (3.1-1)) and transmission power. The utility function is related to the cooperative power control algorithm's convergence; it captures the femto cells cooperative behaviour, given the fact that the utility maximization is the objective of the femto cells cooperation. Once the maximum utility is obtained the Tx power levels in which femto BSs transmits is extracted. Finally, a femto cell's transmission power depends on both the Shannon capacity (positive impact) on the one hand and the caused interference to the neighbouring BSs (negative

impact). As far as the evolution of the situation perception, we identify as a key metric how much the way a network element perceives and models its environment is affected. More specifically, the factor a and its sensitivity to the environment changes is the most crucial part of the enhanced situation perception, taking into account that this is the way a femto BS identifies the uncertainties.

For the evaluation of the cooperative power control algorithm, urban environments are considered. The evaluation scheme is based on a topology of 10 femto BSs that communicate asynchronously in order to cooperate and identify their transmission power levels. The distance between neighbouring femto BSs is considered to range from 50 to 550 meters, reflecting real life indoor and office environments [12]. In addition the link gain is defined as:

$$h = d^{-a} \tag{3.3-1}$$

where d is the distance between two femto BSs (a is set to 3 - indoor and urban environments are considered)[16]. As far as the transmission characteristics are concerned, we assume that the femto BSs operate at very low transmission power levels, always radiating less than 0.1 Watts (i.e. less than standard wireless LAN access points) and often operate at transmission power levels fairly below 0.02 Watts [13]. Furthermore, in cases of enterprise Femto BSs the upper bound of power level is set to 0.2 Watts, thus allowing a power range between 10 and 23 dBm.

3.4 Evaluation of Cooperative Power Control Scheme

The performance of the cooperative power control algorithm is evaluated through extensive MATLAB simulations; as basis for the algorithm's evaluation a scheme of maximum power value assignment is considered. The main objective is to evaluate how the proposed solution performs, compared to a simplified scheme of no cooperation between femto BSs and transmission in arbitrary transmission power values (i.e. in this case maximum power levels). The major difference between these two schemes is that in case of cooperation, femto BSs choose their transmission power considering both their needs for capacity but also the interference they cause to neighbouring nodes.

3.4.1 Cooperative Power Control for Handling Uncertainties

In the used simulation scheme 10 femto BSs cooperate in order to identify the optimum transmission power based on the identified utility function (Equation (3.1-1)). The cooperative power control is evaluated using 10 random topologies (in relation to femto BS positions). Figure 3-4 (left side of the figure) provides the average transmission power of the BSs in relation to the 10 randomly selected network topologies. In most of the topologies the proposed algorithm performs better than the baseline solution; in many of them (i.e. topology instances 3, 8, 9, 10) the energy gains are significant. In the occasions where the femto BSs choose same transmission power as in the baseline algorithm (maximum), the randomly selected distances between the BSs allow the transmission power to be set in its maximum value, without causing interference to neighbouring BSs.

Moreover, Figure 3-4 (right side of the figure) provides the average utility, for the 10 different topologies (same as in the previous experiment). As mentioned earlier, the utility is a trade-off between the Shannon capacity on the one hand and the caused interference on the other. The proposed algorithm achieves similar or enhanced performance compared to the baseline algorithm in most of the tests; in none of the experiments the baseline algorithm outperformed the introduced solution.

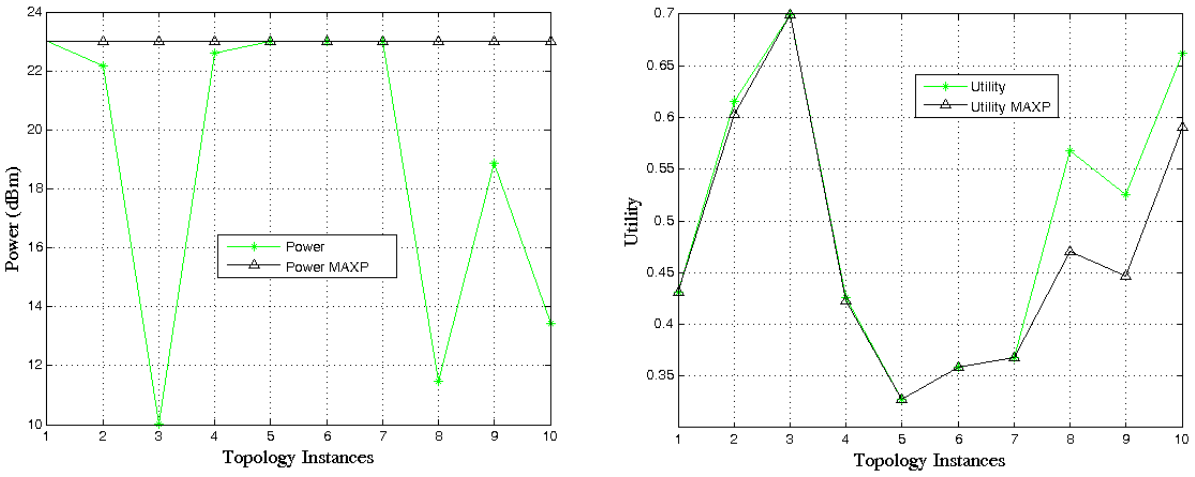
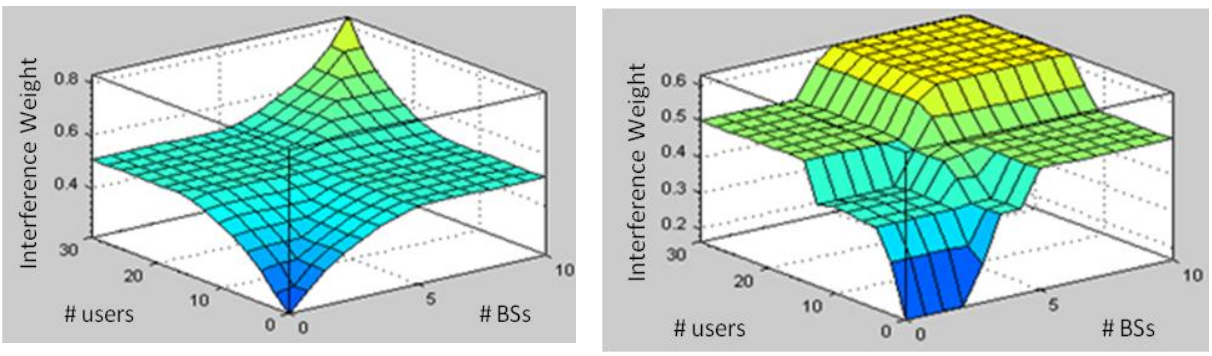


Figure 3-4 : Average Tx Power and Network Utility for 10 different topologies

3.4.2 Learning Enhanced Environment Perception for Cooperative Power Control

For the evaluation of the introduction of learning capabilities in the cooperative power control we have conducted a series of experiments that materialize the benefits of the enhanced environment perception. For the realization of the experiments we have artificially created a dataset consisting of 1000 pseudo-random tuples ({# of BS, # of users, update interval}; normal distribution is used for the generation of the tuples). The dataset reflects network topologies with a relatively small number of BSs, as well as the collocated users.

Figure 3-5 provides the interference weight as a function of the BSs' and the users' number, having as parameter the time interval before (Figure 3-5 (a)) and after (Figure 3-5 (b)) the learning procedure. It is apparent that the weight of the interference part of equation (3.1-1) is significantly affected, based on the feedback from the learning procedure; this implies that the transmission power extraction procedure is affected as well.



(a) (b)

Figure 3-5 : Interference weight as a function of the BSs' and the users' number having as parameter the time interval before (a) and after (b) the learning procedure

For the whole dataset we capture the values of the factor *a*. We then perform a fitting procedure in order to identify the polynomial functions that capture the outputs in the most suitable way. Figure 3-6 provides the 8th polynomial degree functions of the factor *a* before and after the learning procedure. As it is obvious, after the learning procedure, the fuzzy reasoner has become more sensitive to the environment (given the fact that the interference weight is related to the

environment inputs (i.e. # of BSs, # of users, update interval)); this is being captured by the variation of the new *a* values (0.0458) instead of the old ones (0.0091).

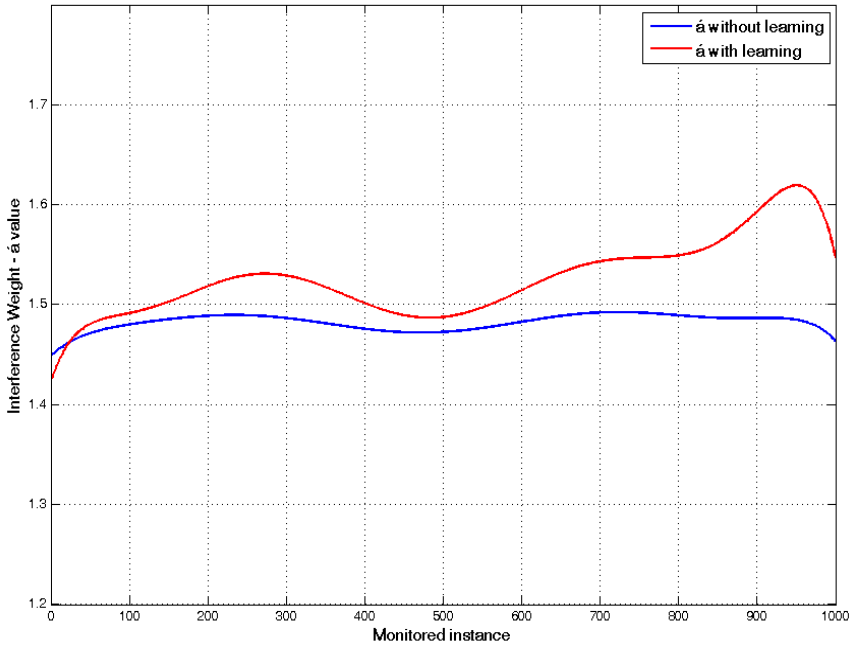


Figure 3-6: Interference weight *a* values before and after the learning procedure.

For a given instance of the dataset, we proceed in identification of the transmission power before and after the learning procedure. More specifically, we follow the approach presented earlier in 3.2. For the identified instance we randomly create a set of experiments (10 different topologies) and evaluate how the algorithm performs. As depicted in Figure 3-7, there are deviations to the final power values when learning procedure is applied. In specific topologies (i.e. topology instances 4, 5, 9, 10) significant energy gains are achieved. In the rest of the topologies the learning framework achieves less significant gains but in no occasion energy waste occurs. Furthermore, the overall utility with the incorporation of the learning framework is significantly improved compared to the one that sets transmission power to the maximum. Also, the network elements after the deployment of the learning algorithm achieve better results in the overall utility, in comparison to the ones with the cooperative power control without learning capabilities.

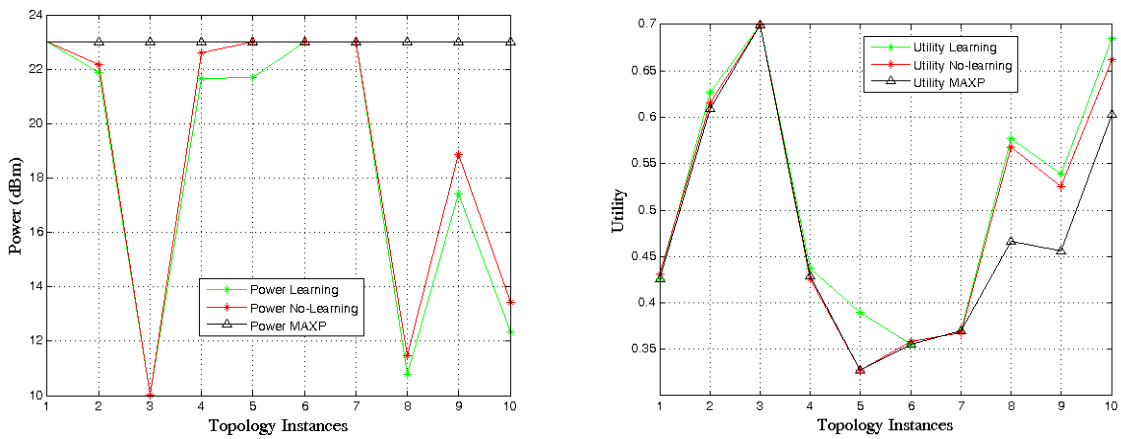


Figure 3-7: Average Tx Power and Network Utility for 10 different topologies with the incorporation of the learning capabilities.

3.5 Map on the CONSERN Functional Architecture

In deliverable D4.2 [14] a formal specification for the functional entities and their relation is provided in order to specify a concise framework for the CONSERN architecture. A dynamic cognitive control architecture that will address changes on the underlying network topology is also specified. Figure 3-8 provides the functions of the CONSERN ENTITY that are materialized in terms of the cooperative power control for handling uncertainties. More specifically, Cooperation, Execution, Translation and Communication Services functionalities are instantiated. In the case of the learning enhanced environment perception for cooperative power control, also the learning block is being instantiated.

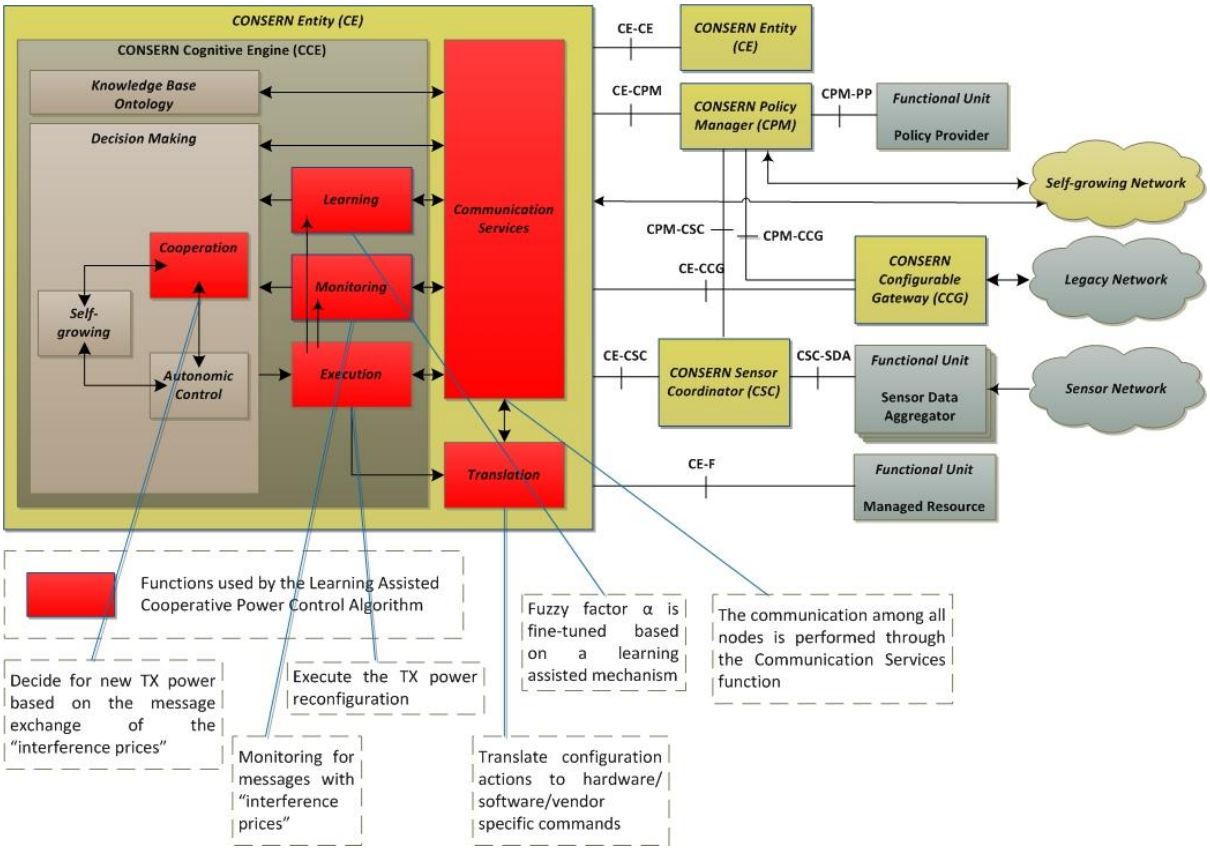


Figure 3-8: Mapping of the Cooperative Power Control Algorithm to the CE.

More specifically, the femto BSs cooperatively decide for their transmission power based on the exchange of their interference prices. After the decision regarding the new Tx power, Decision-Making communicates with the Execution in order to enforce the Tx power reconfiguration. The algorithm uses the Communication Services functions for the information exchange (i.e. interference prices) among nodes. Finally, the translation function provides the mapping between abstract configuration commands generated by the CCE into vendor/hardware specific configurations [15], and although it is not currently supported by the algorithm, it is a potential extension for the future. In the occasion where the learning capabilities are incorporated in the algorithm, the Learning functional block is materialized as well. Based on feedback from the Execution the Learning function updates the decision-making mechanism of the Concern Entity. More specifically, the environment perception of each network element is being adapted according to the effect it an action had to the interference prices.

4. Cooperative Network Protocols

4.1 Receiver Defined Transmission (RDT)

Receiver Defined Transmission (RDT) is a distributed control mechanism for wireless networks in which each node selects autonomously the channel on which it receives traffic. RDT takes advantage of the local nature of noise and interference. By allowing each node to receive in a different channel, lower PER is achieved, which leads to less packet retransmissions and therefore better energy efficiency, but increases spectrum utilization.

When the node is idle, it listens to its quiescent (=receive) channel for incoming messages. To send a packet to this node, any neighbouring node transmits it on the receiver's quiescent channel, as is shown in Figure 4-1. Node A chooses channel 11 as its quiescent channel and node B selects channel 26. When node A wants to send a packet to node B, it sends the packet over channel 26.

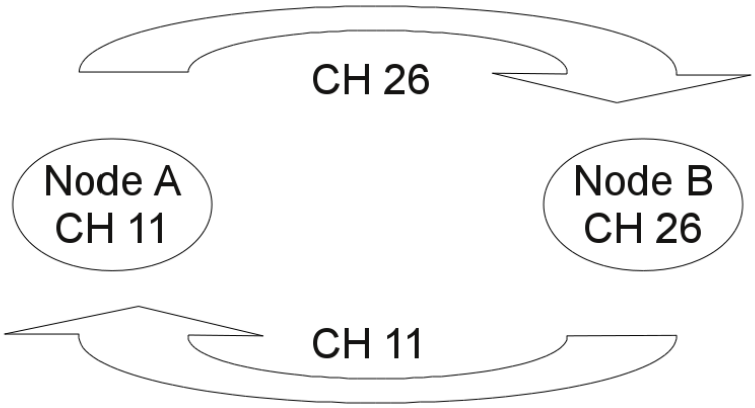


Figure 4-1: Basic Operation Principle of RDT.

4.1.1 Channel Selection Algorithm

We present an implementation of RDT in Zigbee (802.15.4) nodes that operate in the presence of WiFi (802.11) interference. The goal of each Zigbee node is to choose a channel that will minimize PER. Obviously, PER depends only on the Signal to Interference plus Noise Ratio (SINR) at the receiver at the moment it receives a packet.

Figure 4-2 depicts a typical diagram of the energy level received at a Zigbee node within a particular Zigbee channel, when a Wi-Fi client communicates with an access point (AP) in a Wi-Fi channel that completely overlaps this Zigbee channel. The levels at which the Wi-Fi client and AP are received at the node depend on their location relative to the node, and on their transmit powers. They are all relatively constant as we assume users are moving relatively slowly. In this example the Wi-Fi client is received at a lower level than other Zigbee clients, while the Wi-Fi AP is received at a higher level. Therefore, only Zigbee packets that collide with WiFi AP packets will be lost (the last packet in the diagram.) All other Zigbee packets will be received correctly, as the SINR is high enough.

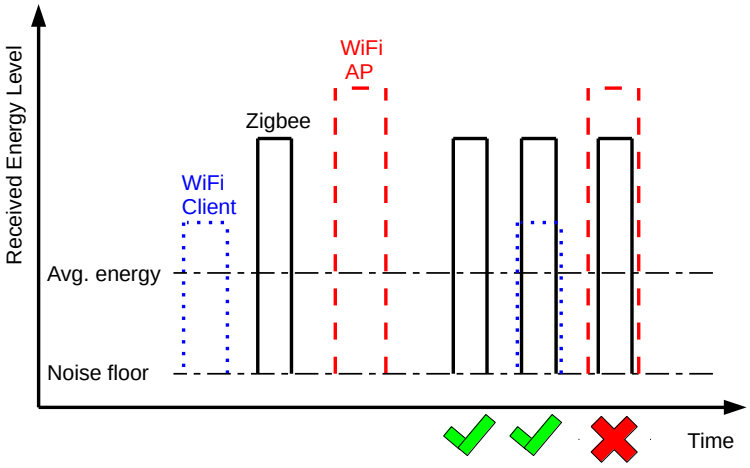


Figure 4-2: Typical received energy.

Current channel selection algorithms usually select the channel with the least amount of average energy measured. However, although a high load on the Wi-Fi client will result in high average measured energy, this load will not necessarily result in any packet-loss. On the other hand, every collision with a packet of the Wi-Fi AP will result in a lost packet. Moreover, the average energy measured is highly dependent on the actual Wi-Fi load during the measurement. As opposed to location and transmit power, Wi-Fi traffic load is not at all regular, but rather quite bursty.

Therefore we prefer to select a channel with lower peak interference, even if it has a higher average interference level at the moment of the measurement.

To select a channel, the node listens for some period of time (5 sec. in our implementation) to each of the Zigbee channels and measures the received energy levels (2000 times per second in our implementation). Then a decision is made in 3 steps:

1. Determine the average energy levels of all channels, and sort the channels according to ascending average energy,
2. Select the first channel in the list where the maximum measured energy is lower than 10dB above the noise floor,
3. If there is no such channel, select the first channel in the list.

If a channel can be selected in step 2, then all Zigbee nodes within a range of about 1/3 of the maximum range of Zigbee from this node will be received at a very low PER independently of the interference.

4.1.2 Channel Information Exchange Protocol

Allowing every node to select its own optimal receive channel allows for a highly adaptive network. However, a packet can be received only if it is transmitted on the correct quiescent channel. One way to achieve this is to transmit it on all channels. However, this method is highly inefficient; it wastes battery power and creates additional interference to other nodes in the network. To avoid these duplicate transmissions it is necessary to inform the transmitter of the quiescent channel of the receiver.

We selected two different mechanisms for distributing quiescent channel information to the surrounding nodes. The first mechanism is to periodically broadcast this information on all channels. This mechanism has the advantage of making sure that all nodes in the area are informed. However, it is costly in terms of power usage, time incurred, and spectral usage. The second mechanism is to piggyback receive channel information on messages that are sent to neighbouring nodes. This

mechanism only costs a few additional bytes inside some of the transmitted packets. When a node decides to switch its receive channel while receiving a stream of packets, it can very quickly notify the sending node by piggybacking its acknowledgments. However, this mechanism cannot guarantee that all surrounding nodes know the quiescent channel.

The combination of both mechanisms overcomes both shortcomings. Slow periodic broadcasts make sure all surrounding nodes know the quiescent channel of the node. At the same time, piggybacking guarantees that neighbouring nodes with which the node actively communicates are updated very quickly.

4.1.3 Implementation

The protocol is implemented in TinyOS 2.1 inside the CC2420 radio stack. It was implemented inside the MAC layer of the stack in order to make it transparent to the higher layers. The architecture of the implementation is shown in Figure 4-3.

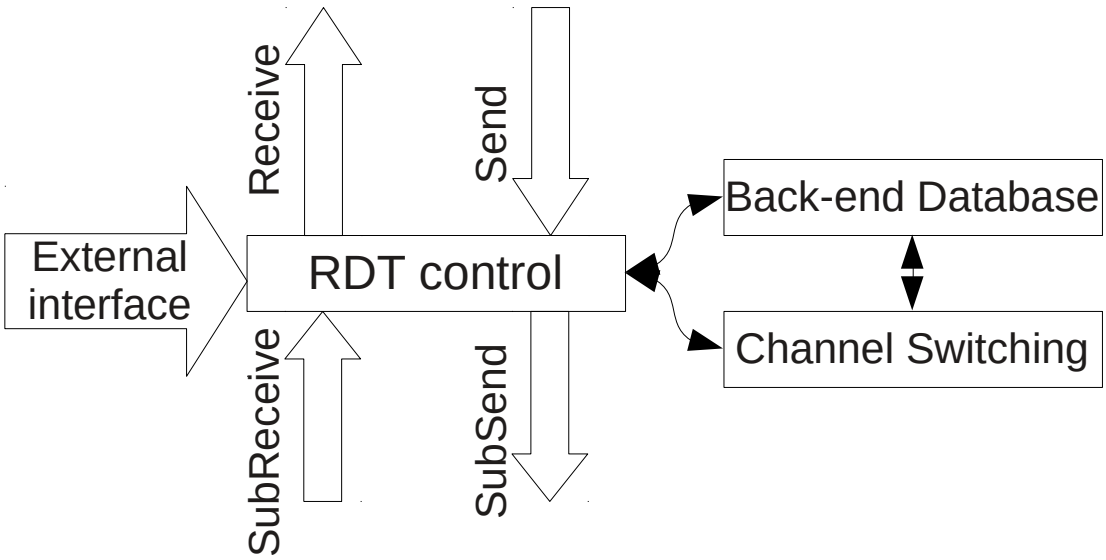


Figure 4-3: RDT implementation diagram.

4.1.3.1 RDT control

The central RDT control module takes care of three tasks: (i) channel switching; (ii) piggybacking of quiescent information; and (iii) periodic broadcasting of quiescent information.

Suppose a packet needs to be transmitted. The RDT control module issues a request to the channel switching module for the channel(s) on which to transmit this packet. It also checks if there is enough space in the packet, and piggybacks the quiescent channel information if possible. Once the transmission of the packet is finished on all necessary channels, the RDT control module requests its own current quiescent channel from the channel switching module, and switches back.

Periodic broadcasting is implemented by sending an empty packet through the application-level active message interface. This results in an empty packet entering the RDT control module through the send interface, which is automatically piggybacked by the RDT control module with the updated information.

4.1.3.2 Channel switching

The channel switching module is responsible for deciding on which channels to transmit each packet, and for selecting the quiescent channel of the node.

To build the list of destination channels towards a specific node, the channel switching module requests the quiescent channel of the destination node from the backend-database module. If the requested quiescent channel is known, it is returned as a single destination channel. Otherwise, the packet needs to be transmitted on all channels that are in use by the system (which can be configured dynamically through the external interface). This design can very easily support multicast, by adding handling of multicast addresses to the channel switching module.

For selecting its own quiescent channel, the channel switching module performs the channel selection algorithm of Section 4.1.1 periodically.

4.1.3.3 Backend database

The backend database module stores information regarding the surrounding nodes. Typical information includes quiescent channel, estimation of path-loss towards the node, PER, time since last packet received/transmitted, etc. This database can also be useful for cross-layer optimisation.

4.1.3.4 Packet formats

As mentioned earlier, quiescent channel information is provided by piggybacking. It is implemented by adding extra trailers to the standard active messages created by TinyOS. When a packet is piggybacked, its AMType is overwritten with the RDT AMType of 255, thus allowing the receiver to distinguish between piggybacked packets and non-piggybacked packets.

Two types of piggyback trailers are specified, one for unicast packets and the other for broadcast packets. The format of the unicast piggyback trailer is depicted in Figure 4-4. The minimal trailer consists of the grey parts. These include to original AMType, the original packet length, the quiescent channel, and the transmit power of the packet. The DataType Definition (DaTD) field defines whether extra information is present in the trailer, e.g. measured path-loss towards a certain node.

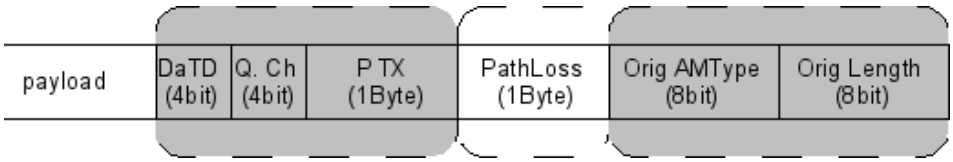


Figure 4-4: Unicast piggyback trailer.

The format of the broadcast piggyback trailer is depicted in Figure 4-5. It consists essentially of the same information; however since it reaches multiple destinations, specific information such as path-loss measurements for different nodes can be placed inside the same packet.

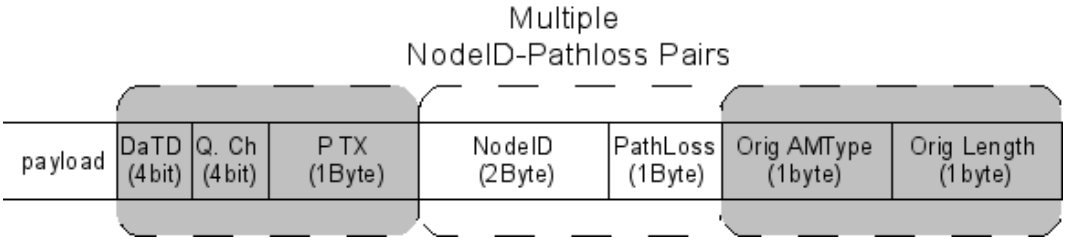


Figure 4-5: Broadcast piggybacking trailer.

4.1.4 Evaluation Environment

Receiver Defined Transmission was implemented and evaluated on the IBBT w-iLab.t test bed. We evaluated the protocol and its implementation on the tmote sky nodes running TinyOS. We selected a subset of nodes in one floor of the building that are aligned along the floor, as depicted inFigure 4-6. This selection achieves a low average PER_Z between all nodes when there is no interference. We

also selected 3 nodes to behave as Wi-Fi interferers on different channels, in order to emulate real-life WiFi network traffic.

The testbed is located in the IBBT office building, where we cannot control the WiFi traffic of the regular office users. However, during night-time the office is empty and then the level of background interference, which is caused by the Wi-Fi beacons, is relatively low.

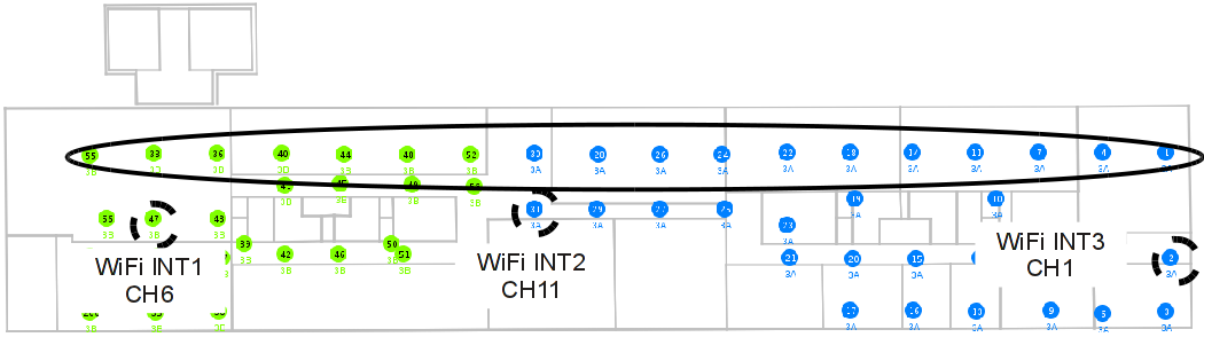


Figure 4-6: The RDT test set-up with Zigbee nodes and WiFi interferers.

Experiments were performed in three different interference scenarios, as follows:

- **No interference / Background:** in this scenario experiments are performed at night-time, and no extra interference is generated.
- **Emulated interference (5.4 – 54Mbps)**: in this scenario experiments are performed at night-time, and extra WiFi traffic is generated by the Wi-Fi interferers in 3 different channels, as shown in Figure 4-6. The 3 Wi-Fi interferers are 802.11g devices that operate at a speed of 54 Mbps. The different scenarios represent different Wi-Fi traffic loads – 10% (5.4 Mbps), 50% (27 Mbps) and 100% (54 Mbps). The transmit power of these devices is 18dBm.
- **Real life interference:** in this scenario experiments are performed at daytime. Real life Wi-Fi traffic is generated by the regular office users and interferes with the Zigbee traffic of the experiment.

4.1.5 Evaluation

4.1.5.1 Experiments

In order to evaluate the advantage of RDT we performed two types of experiments. The first type is intended for measuring the environment. The second type measures the performance of RDT.

At the beginning of each experiment, every Zigbee node measures the interference+noise level at every channel with a sample rate of 1/500µs during 10s. Statistics such as the minimum, average and maximum interference+noise levels per channel are collected. Next, the actual PER_Z experiments start.

In the first type of experiments all nodes tune to the first Zigbee channel, channel 11. One at a time, each node broadcasts 110 packets of 125 bytes at intervals of 12 ms. All nodes report the PER_Z per transmitter to a central database. After all nodes have completed their transmissions, they all switch to the next channel, and the same sequence is repeated. This is done for all Zigbee channels (11-26).

In the second type of experiments the RDT protocol is used. Based on the initial 10s measurement period each node selects its receive channel, and afterwards each node broadcasts 110 packets to all its neighbours.

4.1.5.2 Measurement Results

First we look at measurements of the environment. Figure 4-7 shows interference measurements across the length of the building for all Zigbee channels at night. It is clearly visible that two channels (15 and 20) receive weak interference across the building. Figure 4-8 depicts an identical measurement during daytime. It is apparent that during daytime there is no one channel that is quiet across the building.

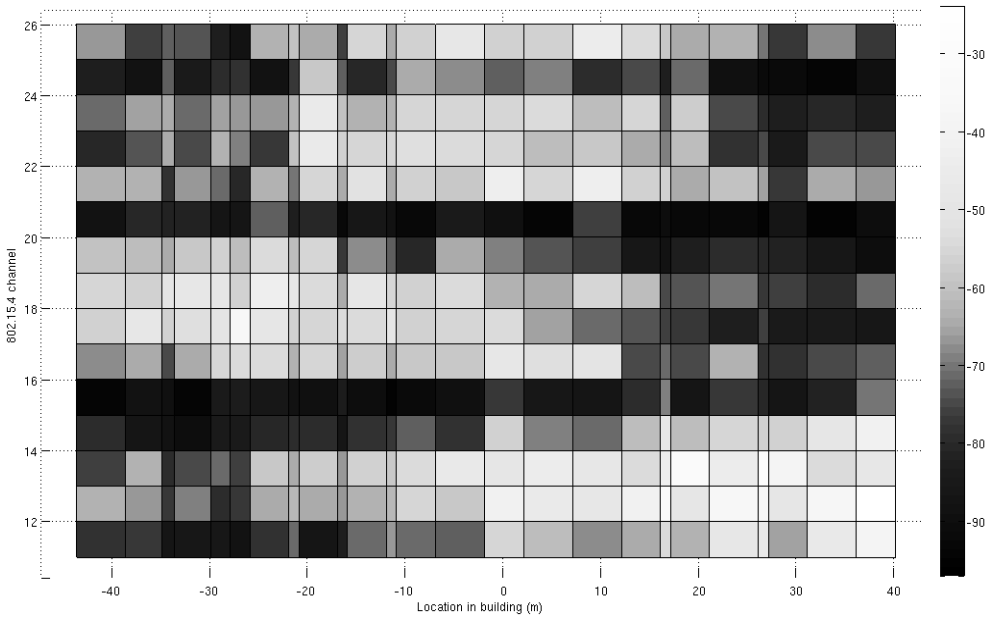


Figure 4-7: Measured maximum interference levels – night-time.

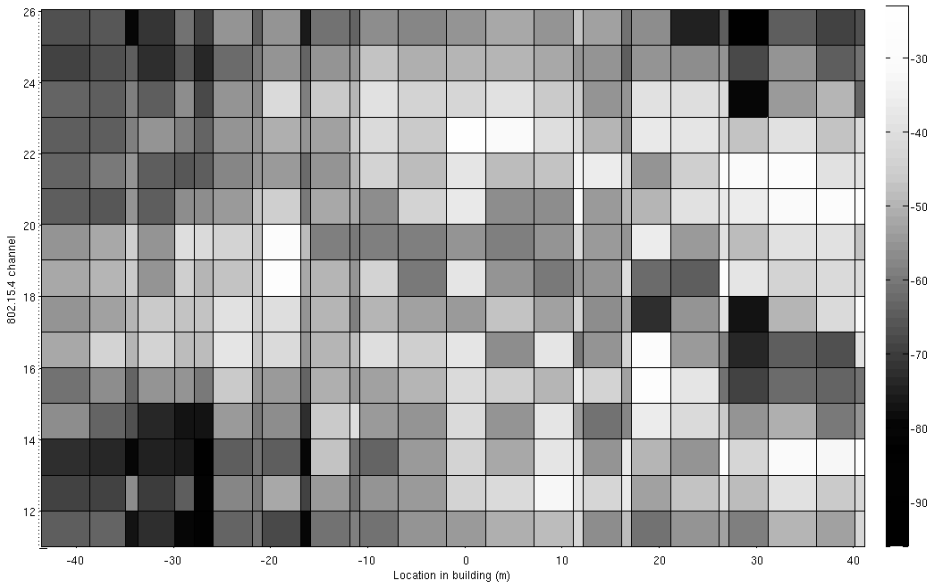


Figure 4-8: Measured maximum interference levels – daytime.

Next, we look at measurements of the performance of RDT, compared to packet error rates that are observed in the different Zigbee channels. Figure 4-9 shows the measured PER at the different Zigbee channels, and compares it to the PER achieved by RDT, during daytime (lighter colours) and at night. The advantage achieved by RDT is apparent in both cases.

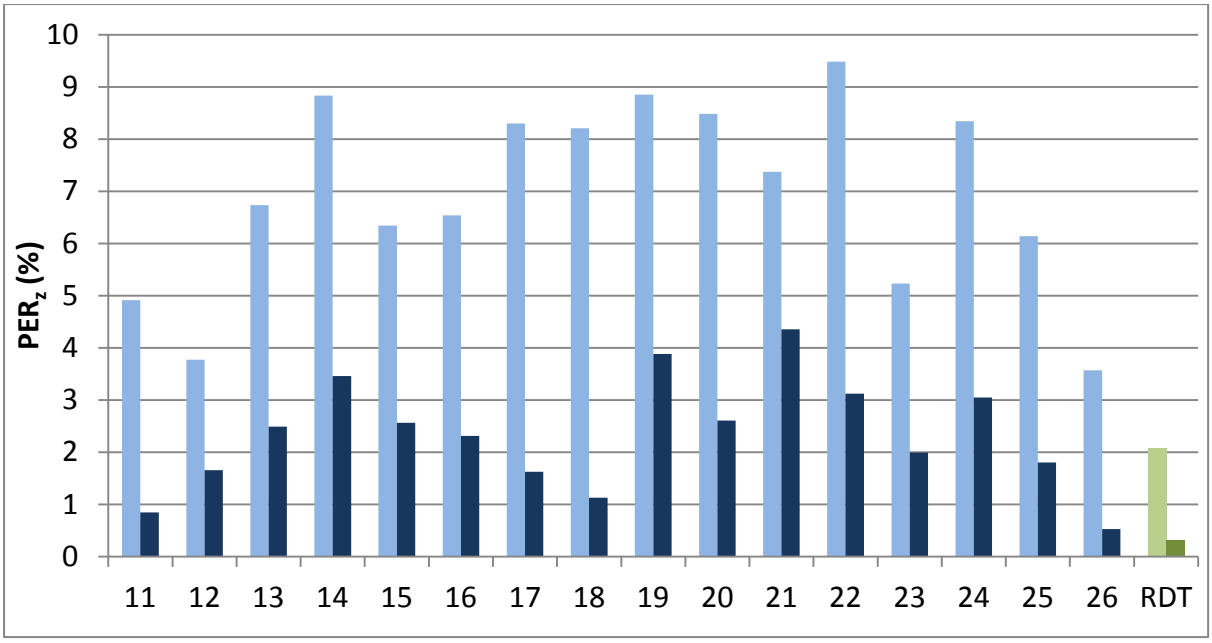


Figure 4-9: Measured PER during daytime and night-time.

4.1.5.3 Comparison of Channel Selection Mechanisms

Now that we have measured statistics of the PER_Z between every pair of nodes in every channel, we can calculate the expected performance of different channel selection protocols. We compare four different alternatives:

- **Random Hopping:** each node uses a pseudo random number generator to choose the next channel to hop to,
- **Best Single Channel:** all nodes operate in the same channel – the one in which performance is the best,
- **Optimal RDT:** the best theoretic performance of RDT, if each node selects the best channel according to *a posteriori* channel information,
- **Implemented RDT:** the RDT as implemented, where channels are selected according to limited background noise measurements, and channel information is exchanged by piggybacking.

The results are summarized in Table 4-1 and compared graphically in Figure 4-10 .

Table 4-1: Comparison between interference avoidance mechanisms.

		Real Life	No int.	5.4Mbps	27Mbps	54Mbps
Pseudo Random Hopping	Average PER_Z	7.04	2.30	3.14	8.53	16.32
	Worst node PER_Z	10.68	6.55	8.50	14.69	36.34
Optimal Single Channel	Average PER_Z	3.57	0.53	2.17	1.65	1.45
	Worst node PER_Z	9.18	2.03	5.15	6.85	8.89
Optimal RDT	Average PER_Z	2.08	0.32	0.52	0.99	0.83
	Worst node PER_Z	3.91	0.70	1.23	1.25	1.37
Implemented RDT	Average PER_Z	2.31	0.34	0.64	1.02	1.41
	Worst node PER_Z	7.26	4.19	4.6	4.83	7.77

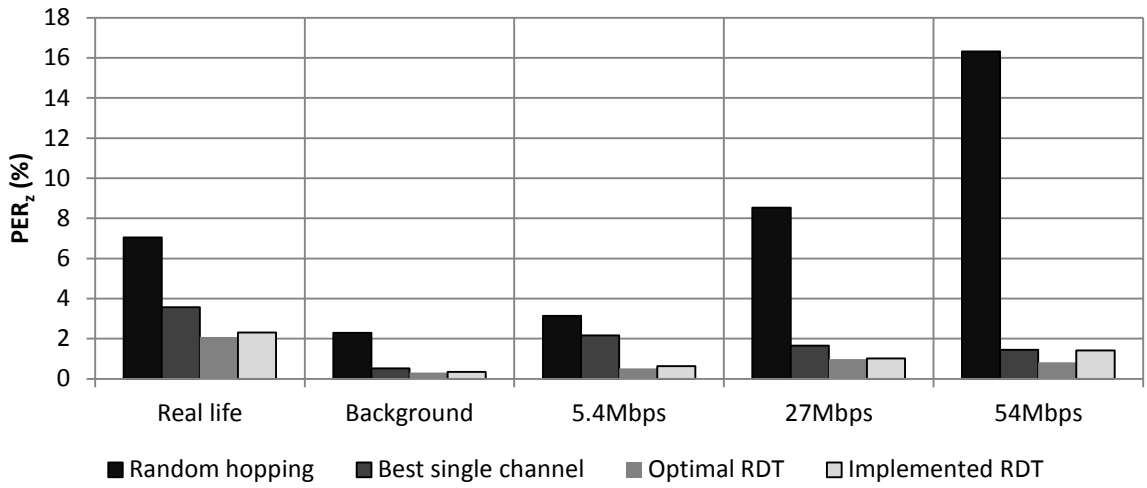


Figure 4-10: Comparison between different interference avoidance mechanisms.

Figure 4-10 clearly shows that random hopping is the worst approach to interference avoidance in all scenarios. The best single channel solution performs reasonably well under most loads. However, in most scenarios RDT outperforms it significantly. In real-life, no interference, 5.4Mbps, 27Mbps and 54Mbps scenarios, there is an improvement of respectively 35%, 35%, 70%, 38% and 3%. Moreover, we reduce PER_Z at the worst node in average with 72.8%. The implemented channel selection, as described in 4.1.1, performs in average 16% worse than the optimal channel selection. This is due to some nodes selecting a less than optimal channel, which is clearly visible when comparing the worst node PER_Z numbers. Albeit this inefficiency, the implemented RDT still outperforms the single channel and pseudo random hopping interference avoidance mechanisms in all interference scenarios.

4.1.6 Map on the CONSERN Functional Architecture

We refer to the generic architecture of a CONSERN enabled network, as specified in Deliverable D4.2 [14]. Figure 4-11 illustrates the functionality of the different CONSERN entities in implementing RDT.

In RDT we utilise the Cooperation, Monitoring, Execution, Communication Services and Translation functions. The Monitoring function maintains an updated view on the status of channels and neighbouring nodes. It listens periodically on all Zigbee channels and measures the receive energy levels, and it stores the receive channels of other nodes. The Cooperation function uses the information collected by Monitoring to decide which channel to use as receive channel, and exchanges this information with neighbouring nodes through the Communications Services function. It also configures the Communication Services and Translation functions through the Execution function to operate on the selected channel. The Translation function piggybacks transmitted packets with receive channel information, and extracts similar information from received packets. The Communication Services function makes sure the node receives on the selected channel, and that every packet is transmitted on the appropriate channels.

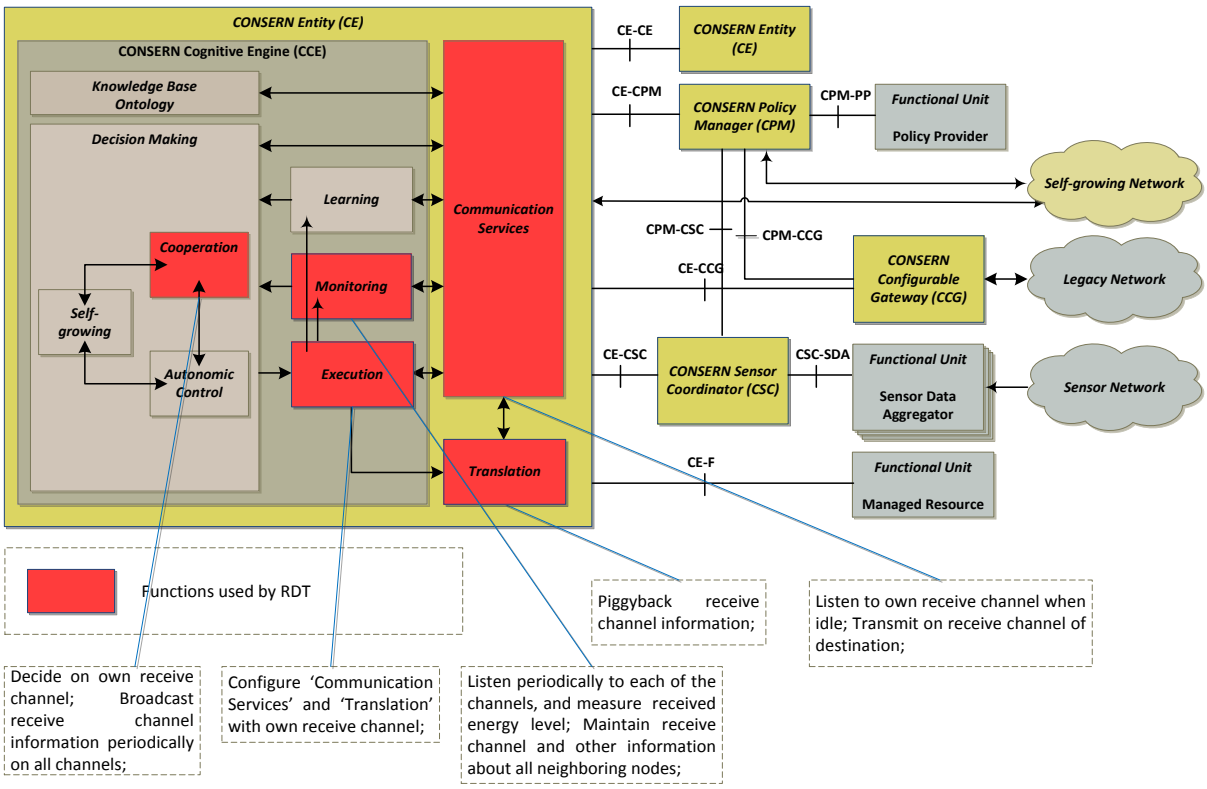


Figure 4-11: Mapping of RDT to the CONSERN Functional Architecture.

4.2 Network Collaboration (NC)

Network Collaboration is a mechanism that allows independent networks to profit from sharing information, resources and infrastructure with each other. By sharing (network) resources and optimizing resources across network boundaries, network performance and power consumption can be optimized in a global way.

Each network has a set of well-defined incentives, or goal, e.g. `minimize battery consumption' or 'maximize throughput'. It also has a set of network services it supports, that can help realize such goals, e.g. 'shared routing' and 'packet aggregation'.

Network Collaboration is achieved by exchanging information between networks, and negotiating which network services to activate in each of the networks. It is composed of the following steps:

- Discovery of co-located networks,
- Negotiation of the selection and configuration of network services,
- Activation of the agreed network services,
- Policy enforcement and network monitoring.

4.2.1 Network discovery algorithm

The first step is for each network to discover if it is co-located with other networks capable of incentive-driven collaboration. To perform discovery, each network selects one or more nodes that are assigned as discovery nodes. These nodes run a discovery algorithm. In the PoC discovery nodes are assigned statically at design time.

As introduced in [9], network discovery can be either passive or active. For the case of sensor networks, which are typically lightly loaded, we choose active discovery for two main reasons:

The time to passively discover a lightly loaded network is expected to be long

While scanning for packets of other networks in other channels, the discovery node is practically disconnected from its own network, and with lightly loaded networks these periods are long

The discovery algorithm is illustrated in Figure 4-12. In this algorithm networks are also referred to as communities. A discovery node A of network C sends out a COMMUNITY_ADVERTISEMENT message every ADVERTISE_INTERVAL time units, transmitting it sequentially on all available radio frequencies F_n. Discovery node B in a neighbouring network D receives the COMMUNITY_ADVERTISEMENT and establishes connection with node A by transmitting an ADVERTISEMENT_REPLY on the radio frequency of network C, as specified in the COMMUNITY_ADVERTISEMENT. A short delay is introduced to allow node A enough time to finish transmitting its advertisements on all frequencies. Once connection is established, the COMMUNITY_PROFILE is exchanged between the discovery nodes.

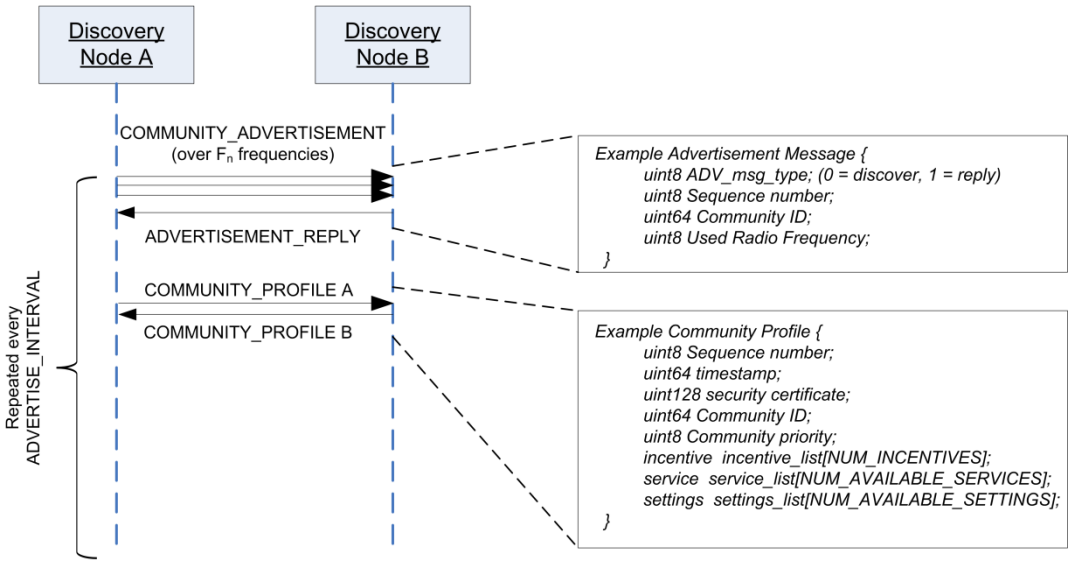


Figure 4-12: Sequence diagram of the network discovery process.

The total number of packets per time unit (PPT) required for the discovery process in community C (i.e. sent by discovery nodes of community C) can be calculated as follows.

$$PPT(Discovery; Community\ C) = (F_n * DN_C + \sum_{j=1}^{DN_C} \sum_{i=1;i\neq C}^{C_j} DN_{i,j}) * \frac{1}{ADV_C} + \sum_{j=1}^{DN_C} \sum_{i=j;i\neq C}^{C_j} \frac{2 * DN_{i,j}}{ADV_i}$$

With

DN_C = The # of discovery nodes in community C
$DN_{i,j}$ = The # of discovery nodes in community i that are within reach of discovery node j
C_j = The # of communities that are in reach of discovery node j
ADV_C = The advertise interval of community C

The formula is composed of three parts. The first part calculates the total number of advertisement messages that are transmitted by the discovery nodes of community C per time unit (F_n* (DN_C / ADV_C)). The second part calculates the number of community profiles that are sent in response to

advertisement replies from neighbouring discovery nodes. The third part expresses that an advertisement reply and a community profile are transmitted in response to each community advertisement that is received from a neighbouring community.

In the experimental implementation the ADVERTISE_INTERVAL is set to 5 minutes, and F_n equals 16 (all available IEEE 802.15.4 channels). With these settings, the discovery overhead is limited to 3.8 packets per minute.

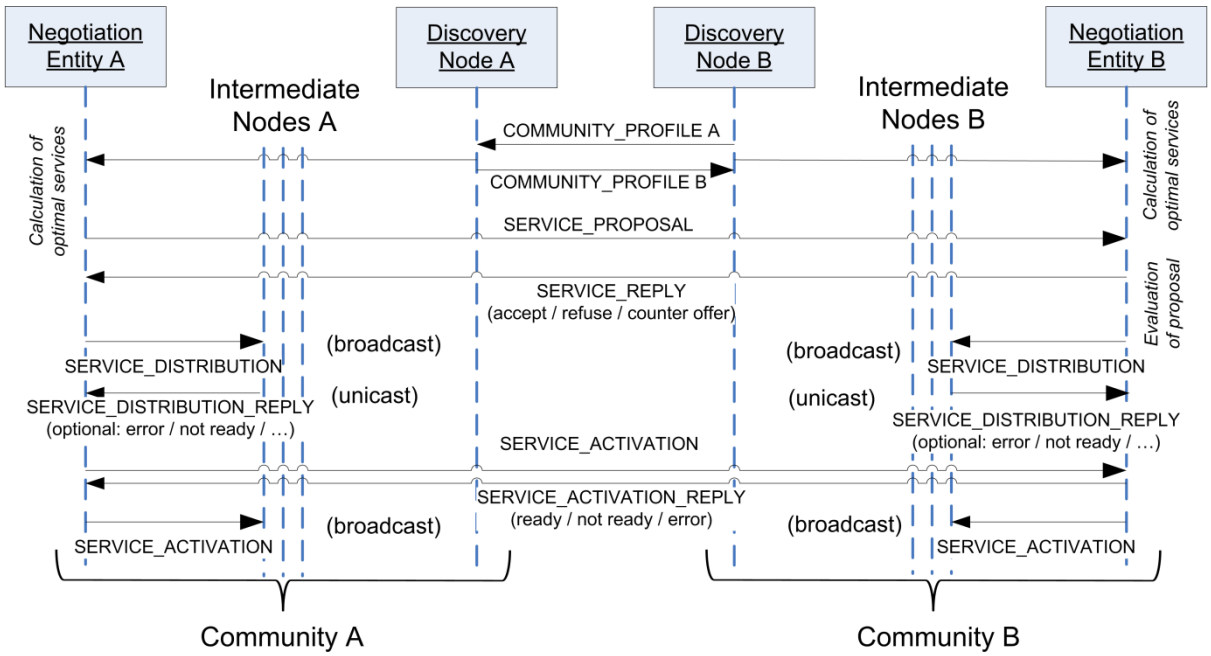
For dynamic networks, the advertisement interval should be set to a low value, whereas energy constrained networks or networks that interact rarely would prefer a much higher value to reduce the energy consumption. In large networks, the overhead of the discovery process can be reduced further by intelligently choosing the location of the discovery devices; or by implementing more intelligent discovery algorithms. For example: a discovery node can choose to send only a single reply message if it is in reach of multiple discovery nodes from the same community.

4.2.2 Negotiation algorithm

By now, the co-located communities have exchanged profiles which describe the incentives of each community. The next steps investigate if cooperation between different co-located communities – in the form of activating cross-network services such as interference avoidance – is beneficial.

To perform negotiation, one negotiation entity is assigned in each network. These entities run a negotiation process. Negotiations are expected to require a relatively high processing capacity, therefore in the PoC it is the sink that is assigned also as the negotiation entity.

The negotiation process is illustrated in Figure 4-13.




```
Example Service Negotiation Message {
        uint8 sequence number;
        uint8 transaction ID;
        uint64 timestamp;
        uint128 negotiation_code; (0 = proposal, 1 = reply, 2 = distribution, 3 = activation)
        uint128 negotiation_option;  (0 = accept, 1 = refuse, 2 = counter offer, etc.)
        service  activated_list[NUM_ACTIVATED_SERVICES];
        settings  activated_list[NUM_ACTIVATED_SETTINGS];
 }
```

Figure 4-13: Sequence diagram of the negotiation process.

Whenever the discovery node receives a new or updated community profile, it forwards this profile to the negotiation entity. The negotiation entity uses an optimization algorithm (see Section 4.2.3) to determine which network services are to be enabled in order to maximize the profit (or utility) of each network, according to its own incentives.

After this calculation, service negotiation messages – in the form of SERVICE_PROPOSALS and SERVICE_REPLIES – are exchanged between the negotiation entities, through the discovery nodes, until a common decision is reached. Each service negotiation message includes a transaction ID to keep track of the negotiation process. The type of negotiation message (proposal, reply, etc.) is indicated by the negotiation code of the negotiation message (see Figure 4-13). Each message type can also include one or more options. For example, a SERVICE_REPLY message can have one of the following options: PROPOSAL_ACCEPTED, PROPOSAL_REFUSED, PROPOSAL_COUNTEROFFER. Finally, the list with services and settings may be omitted from the service negotiation message if they remain unchanged from the previous message with the same transaction ID.

Once the communities reach an agreement on which network services to activate, a SERVICE_DISTRIBUTION message is broadcast by the negotiation entities of each community. These messages inform the individual nodes of each community of the selected set of services and settings. If these settings cannot be activated, a device may respond with a SERVICE_UNAVAILABLE message. If this occurs, the conflict must be solved (by installing the missing service, by removing the device from the community, or by renegotiation) before the SERVICE_ACTIVATION message can be broadcast. Once every intermediate node has received the activation message, the network settings will be changed.

The overhead of the negotiation process (in number of packets) can be calculated as follows.

$$Packets(Negotiation; Community\ C) = 5 * \sum_{j=1}^{DN_C} \sum_{i=1; i \neq C}^{C_j} D_j + 2 * (|C| - 1)$$

With

$D_j =$ The distance (# of hops) from discovery node j to the negotiation entity
$|C| =$ The size (# of nodes) of community C

We assume that discovery nodes are capable of filtering duplicate profiles (for example, if the discovery node is in range of multiple discovery nodes of a neighbouring community). The formula first calculates the number of packet transmissions between the negotiation entity and the discovery nodes of the community, and then adds the service distribution and service activation overhead.

In the PoC implementation $D_a = 2$ and $|a| = 9$. Using the above formulas, the total overhead of a single negotiation round is 26 packets for each community. Re-negotiation occurs whenever (i) a new neighbouring community is discovered; (ii) a neighbouring community is no longer available for cooperation; or (iii) the profile of one of the participating communities changes. To account for failing nodes, the experimental implementation performs a new negotiation process once every hour. As such, the negotiation overhead corresponds to 2.9 packets per hour for each node. In most scenarios, this overhead is negligible when compared to the amount of traffic generated by the application(s).

4.2.3 Optimization algorithms

In our initial implementation in the PoC, we use linear programming for optimization.

Table 4-2: Definition of variables.

Variable Name	Variable Meaning
NP_a	The priority of community (network) a
$profit_a$	The profit function of community a. This objective function should be maximized for each community to optimally profit from Network Collaboration
$IP_{\{i,a\}}$	incentive priority – the priority that is given to incentive i in community a.
$SI_{\{i,a;\ s,b\}}$	the ratio of change of incentive i in community a, when service s is activated in community b.
$SA_{\{s,a\}}$	is a binary variable (0 or 1) that indicates if service s is activated in community a.

Comments:

The priorities (or importance) of communities (NP_a) and of incentives within communities ($IP_{\{i,a\}}$) can be configured by network operators, or adjusted dynamically by applications that run in the communities. To ensure that the incentive priorities from each community are normalized, the sum of all priorities in each community is assumed to be equal to 1 – this can possibly be enforced by an application layer middleware:

$$\sum_{i=0}^{I} IP_{i,a} = 1, \qquad \forall a = 0, \dots, N$$

1. Each incentive i in each community *a* has some numerical value associated with it, that indicates the extent to which this incentive is achieved – to be referred to as 'the value of the incentive'. A higher incentive value indicates better achievement of the incentive. The ratios of change ($SI_{\{i,a;\ s,b\}}$) represent changes in these incentive values. For example, the incentive value associated with the incentive 'maximize network lifetime' in community a could be the average expected lifetime of nodes in this community. Continuing with this example, if activating a sleep scheme (service) in community a increases its average expected node lifetime by 30%, then we write $SI_{\{Maximize\ Lifetime,\ a;\ Sleep\ scheme,\ a\}} = 0.3$. Note that the same service, e.g. sleep scheme, may increase the value of one incentive, e.g. 'maximize network lifetime', and at the same time decrease the value of another incentive, e.g. 'minimize delay'.
2. Initially, in order to be able to use linear programming for approximation, we adopt a naive approach and define the profit function of a community as a linear combination of the ratios of change of the incentives of this community:

$$profit_a = \sum_{i=0}^{I} \left[IP_{i,a} * \left\{ 1 + \sum_{s=0}^{S} \sum_{b=0}^{N} \left(SA_{s,b} * SI_{i,a;s,b} \right) \right\} \right]$$

This definition actually uses the first order approximation of the rate of change of independent incentives, which is

$$\prod_{s=0}^{S}\prod_{b=0}^{N}(1 + SA_{s,b} * SI_{i,a;s,b})$$

When no network services are activated, all $SA_{s\,b}$ equal to 0, and the profit amounts to 1 for each community. When new services are activated, they increase or decrease the values of the profit of all affected communities. Continuing with the previous example, activating the sleep scheme in community a increases its Network Lifetime incentive by 30% (**SI** $_{\{Maximize\ Lifetime,\ a;\ Sleep\ scheme,\ a\}}$ = 0.3) and at the same time it might decrease its Delay incentive by 20% (**SI** $_{\{Minimize\ Delay,\ a;\ Sleep\ scheme,\ a\}}$ = -0.2). Depending on the priorities of these incentives in community a, the resulting profit can increase or decrease.

3. According to our initial naive approach, we define the objective function for maximization as a linear combination of the profit functions of all communities:

$$\sum_{a=0}^{N} NP_a * profit_a$$

The linear program is thus:

Maximize

$$\sum_{a=0}^{N} NP_a * profit_a$$

Subject to:

(i) Services can be activated or deactivated:

$$SA_{s,b} = \begin{cases} 1 & \text{if service } s \text{ is activated in network } b \\ 0 & \text{if service } s \text{ is deactivated in network } b \end{cases}$$

(ii) Incentive priorities are normalized:

$$\sum_{i=0}^{I} IP_{i,a} = 1, \qquad \forall a = 0, \dots, N$$

(iii) No community may have degraded performance:

$$profit_a \geq 1, \qquad \forall a = 0, \dots, N$$

This last condition can be omitted when emergency applications need to be supported.

During negotiation, the linear program is solved and the optimal services are selected such that the combined profit of all communities, as represented by the objective function, is maximized.

It should be noted that network collaboration may dictate that some of the network services are not activated, for example the communities do not share resources, but instead try to avoid hindering each other through the use of interference avoidance mechanisms.

The negotiation entity will use the linear program again, to recalculate new service proposals, only if a new profile is detected, or if the profile information of one of the communities is changed.

4.2.4 Evaluation of Network Collaboration

4.2.4.1 Experimental setup

Network Collaboration was implemented and evaluated on the IBBT w-iLab.t test bed. The experimental configuration consists of two networks, as shown in Figure 4-14. One network represents battery-powered temperature sensing nodes, the other highly reliable intrusion detection security nodes. The transmission power of the sensor nodes is set at -15 dBm, and the Ad hoc On-Demand Distance Vector (AODV) protocol is used for routing. With these settings, packets require up to 4 hops to arrive from one side of the building to the other.

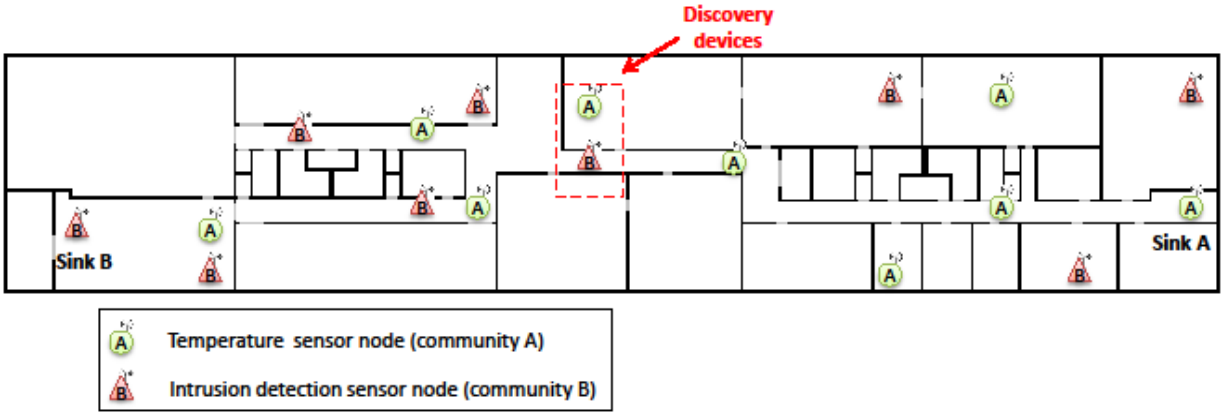


Figure 4-14: Network Collaboration PoC with two networks: temperature monitoring (A) and intrusion detection (B).

The temperature sensors send updates every 10 seconds to the heating, ventilation and air conditioning system (HVAC) control unit (`sink A'). To avoid frequent battery replacements, the main incentive of these nodes is 'maximize network lifetime' ($IP_{ifetime;a}$ = 0.7), with 'maximize reliability' as a secondary incentive ($IP_{eliability;a}$ = 0.3). The intrusion detection sensors send messages every 10 seconds to an alarm system ('sink B'). These messages represent information such as status updates, intrusion alerts or static images from a webcam. To ensure timely reaction in emergency situations, the main incentives of these nodes are 'minimize delay' ($IP_{elay;b}$ = 0.5) and 'maximize reliability' ($IP_{eliability;b}$ = 0.5).

The sensor devices support two collaboration services:

- **Packet Sharing:** when this service is activated in one network, this network also routes packets of the other network towards its own sink,
- **Packet Aggregation:** when this service is activated packet transmissions are reduced by aggregating information from multiple applications and network layers into a single packet.

4.2.4.2 Setting the SI parameters

To set the values of the SI parameters, we measured the influence of the collaboration services on some performance metrics that are directly related to the incentives, and will be used for setting incentive values. As a first iteration, we performed the measurements when each of the services is activated in both networks. This simplification is legitimate in our case, since each of the collaborative services, when activated in a network, has influence on only one network.

Some measurement results are shown below. Figure 4-15 shows the influence of activating packet sharing in both networks, as measured in the testbed. As expected, packet sharing reduces the average number of packet transmissions because (i) nodes can select more optimal paths and (ii) two sinks are now available, thereby reducing the average distance to the sink. However, whereas network B indeed shows a reduction in the number of packet transmissions, network A instead shows a small increase, even though the two networks have very similar topologies. This can be explained, for example, by better link quality of network A, which causes traffic from network B to be off-loaded to network A. The average number of hops, the average end-to-end reliability (defined as the probability of successful end-to-end packet delivery) and the average end-to-end delay are improved in both networks, as expected.

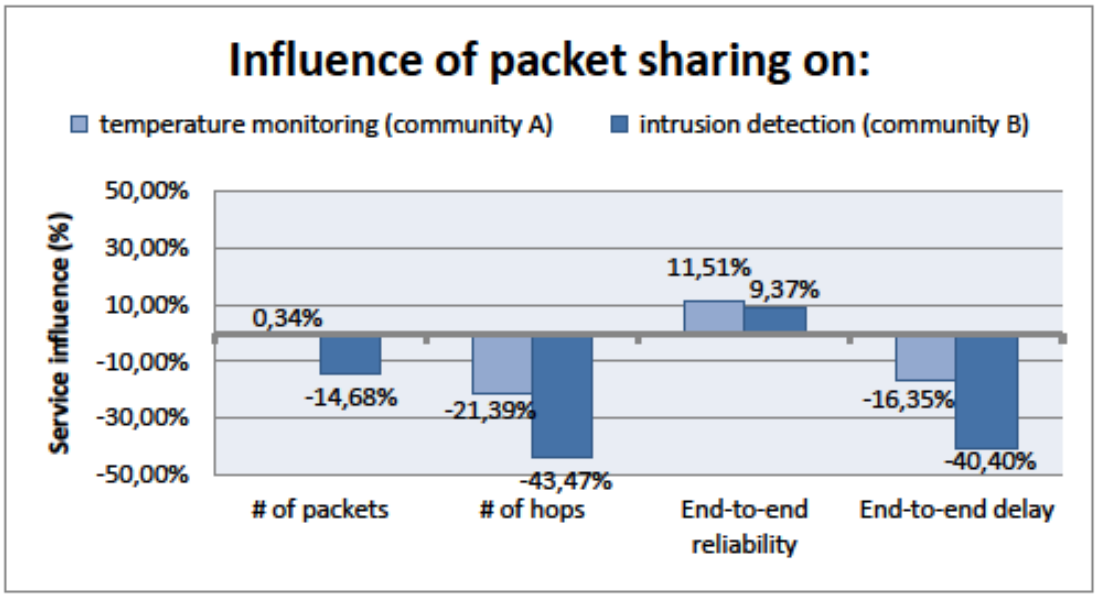


Figure 4-15: Influence of Packet Sharing.

To set the SI values, we define the values of the incentives as follows:

- Battery lifetime is negatively related to the number of packets being transmitted, therefore we define the value of 'maximize lifetime' to be 1/(# of packets),
- We define the value of 'maximize reliability' to be end-to-end reliability,
- We define the value of 'minimize delay' to be 1/(end-to-end delay), as the goal is to minimize, not maximize the delay.

Note that whenever an incentive is directly (positively) related to a measured statistic, we define the value of this incentive as equal to the measured statistic; and whenever they are negatively related, we define the value of the incentive as the reciprocal of the measured statistic. Consequently, in the cases above when the incentive is directly related to some statistic M, and therefore its value is defined as equal to M, the ratio of change SI can be calculated as

$$SI = \frac{M_1}{M_0} - 1 = \frac{M_1 - M_0}{M_0}$$

where M_0 and M_1 are the measured values before and after a service is activated respectively. The resulting formula for SI is positive when $M_1 > M_0$, it is negative when $M_1 < M_0$, and it is always $\geq -100\%$, which are the natural requirements from a ratio of change that is directly related to a statistic.

In the cases above when the incentive value is negatively related to the statistic M, and therefore its value is defined as the reciprocal of M, the ratio of change is

$$SI = \frac{\frac{1}{M_1}}{\frac{1}{M_0}} - 1 = \frac{M_0}{M_1} - 1 = \frac{M_0 - M_1}{M_1}$$

which is positive when $M_1 < M_0$, it is negative when $M_1 > M_0$, and it is always $\geq -100\%$, fulfilling again the natural requirements from a ratio of change, that is in this case negatively related to the statistic.

The resulting SI values in our case are detailed in Table 4-2 below.

Table 4-3: Measured influence of collaboration services on incentives

Incentive	Lifetime		Reliability		Delay	
Network	A	B	A	B	A	B
Packet Sharing	-0.34%	17.2%	11.5%	9.37%	19.5%	67.8%
Packet Aggregation	26.4%	61.6%	-3.6%	-3.1%	-99.4%	-99.3%

As a further simplification for the first iteration of the algorithms, we set the same SI values in both networks, as follows:

Table 4-4: Actual SI values used in the testbed.

Incentive	Lifetime	Reliability	Delay
Packet Sharing	10%	10%	50%
Packet Aggregation	40%	-3%	-99%

Initially, the SI values are configured at design-time. Later on, learning techniques can be used to intelligently monitor and adjust them at run-time.

4.2.4.3 Performance evaluation

When running the linear program of Section 4.2.2 in this setup, the negotiation entities reached the following agreement:

1. Activate packet sharing and aggregation in the temperature monitoring network
2. Activate only packet sharing in the intrusion detection network
3. Use the same radio frequency in both networks

For comparison, we measured the performance of both networks in four different situations:

1. Without cooperation
2. With packet sharing active in both networks
3. With aggregation active in both networks
4. With optimal service selection after negotiation (packet sharing active in A and B, aggregation active in B)

Figure 4-16 shows the average number of hops that are required to reach the sink. This measure is important as it directly influences the number of packet transmissions, the reliability and the delay of

information exchanges, which all influence the incentives. Note that since aggregation does not affect routing, it has no influence on the average number of hops to the sink.

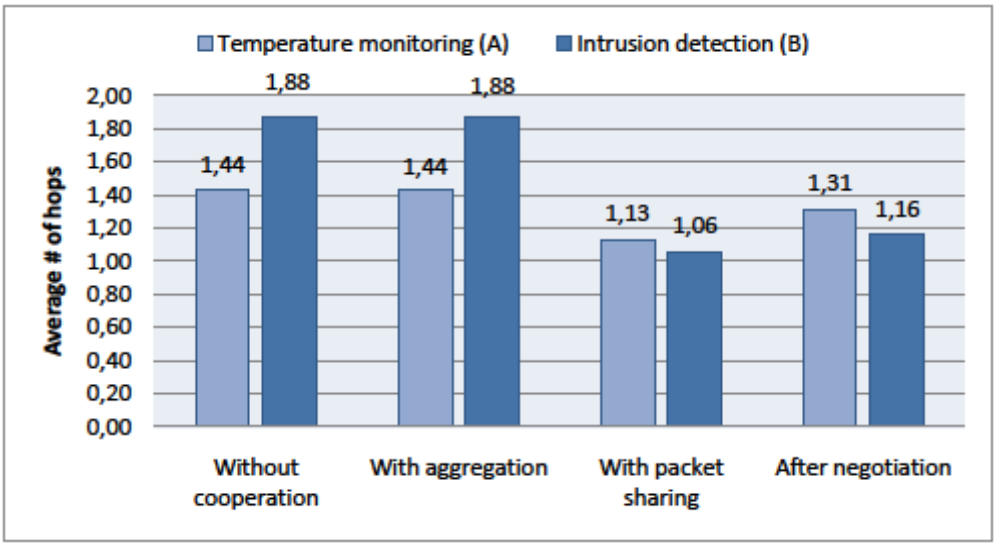


Figure 4-16: Measured Performance: average number of hops.

The average number of packet transmissions is shown in Figure 4-17. It is rather intuitive that packet aggregation has the highest effect, reducing the number of packet transmissions (by 20-40%). Note that although both services decrease the number of packet transmissions, the result after negotiation (when both services are active at the same time in network A) is higher than when aggregation is the only active service. The reason is that the routing paths are shorter, and therefore there are fewer opportunities to aggregate information. We can conclude that in situations where the only incentive is `maximize network lifetime', aggregation should not be activated together with packet sharing.

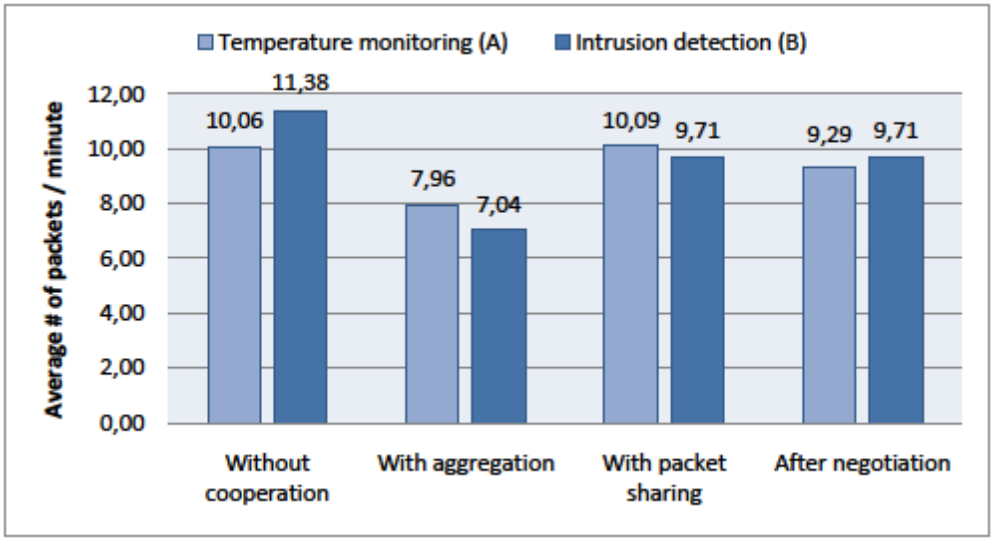


Figure 4-17: Measured Performance: average number of packet transmissions.

The average end-to-end delay is shown in Figure 4-18. The aggregation service temporarily stores information in buffers in order to aggregate it with other information. Consequently, it increases the delay significantly, up to a (pre-configured) value of maximum 10 seconds. For this reason aggregation is not selected for activation in network B, which has low delay as an important incentive. It is interesting that the delay caused by aggregation is longer when packet sharing is also

activated. This is again due to the fact that in this case there are less aggregation opportunities, and therefore stored information needs to wait longer before it can be aggregated.

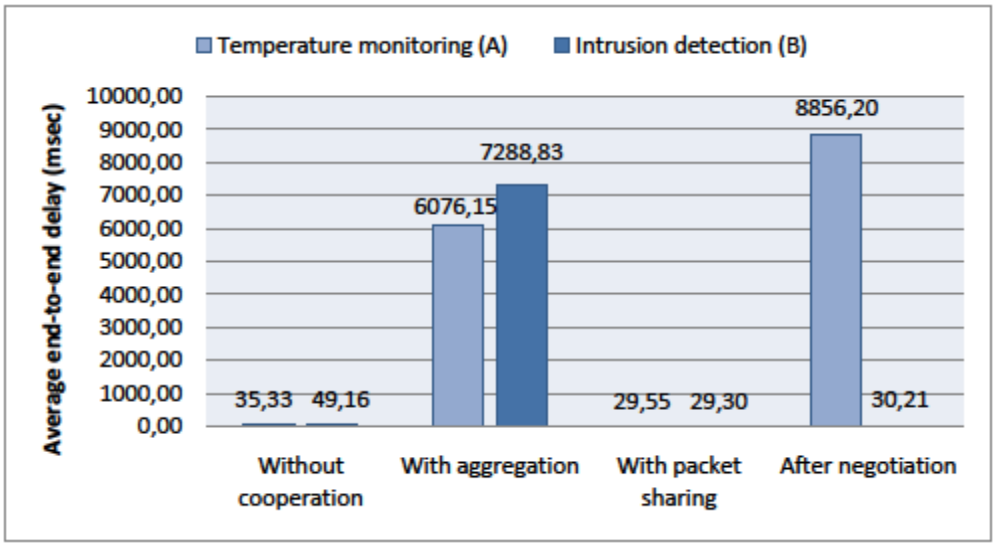


Figure 4-18: Measured Performance: average delay.

Finally, Figure 4-19 shows the average end-to-end reliability. Activating aggregation decreases reliability (by about 3%), since a single lost packet results in the loss of more information. In contrast, packet sharing increases reliability (by almost 10%) since fewer intermediate packet transmissions are necessary. The drop in reliability that results from activating the aggregation service is offset in network A by packet sharing that is activated in both networks after negotiation.

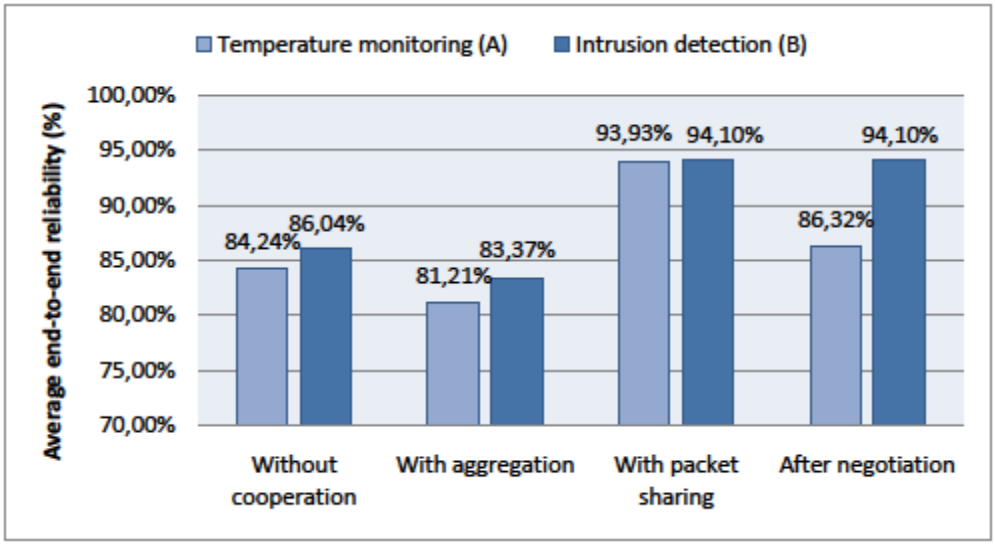


Figure 4-19: Measured Performance: average reliability.

In summary, with network collaboration the incentives of network A (lifetime and reliability) improved by 7.7% and 2.4% respectively, and those of network B (delay and reliability) improved by 14.5% and 11.7% respectively. These improvements correspond quite nicely to the relative priorities of the incentives in each of the networks – in network A lifetime is twice as important as reliability, and in network B delay and reliability are equally important.

We conclude that even when only a small number of network services are available, networks can improve the performance of their incentives by negotiating and cooperating with each other.

4.2.5 Map on the CONSERN Functional Architecture

We refer to the generic architecture of a CONSERN enabled network, as specified in Deliverable D4.2 [14]. Figure 4-20 illustrates the functionality of the different CONSERN entities in implementing Network Collaboration (NC).

In NC we utilise the Cooperation, Monitoring, Execution and Communication Services functions. The Cooperation function controls the complete mechanism. It assigns discovery nodes in the network, receives network profiles of co-located networks, negotiates cooperation with these networks and initiates service activation commands towards the Execution function. Communication with the discovery nodes and the controlling entities of co-located networks is performed through the Communication Services function. Activation of the agreed services is performed by the Execution function. Monitoring for adherence to the agreed cooperation services is performed by the Monitoring function.

NC involves interfacing between CEs. One type of CE that participates in the implementation of NC is co-located with nodes within the network that can be assigned as Discovery nodes. Since these are typically sensor nodes, they have relatively limited capabilities , but still enough to perform the dedicated functions of the discovery operation. The other type of CE that participates in the implementation of NC is co-located with controlling nodes of co-located networks, with which NC negotiations are performed and eventually network cooperation services are activated.

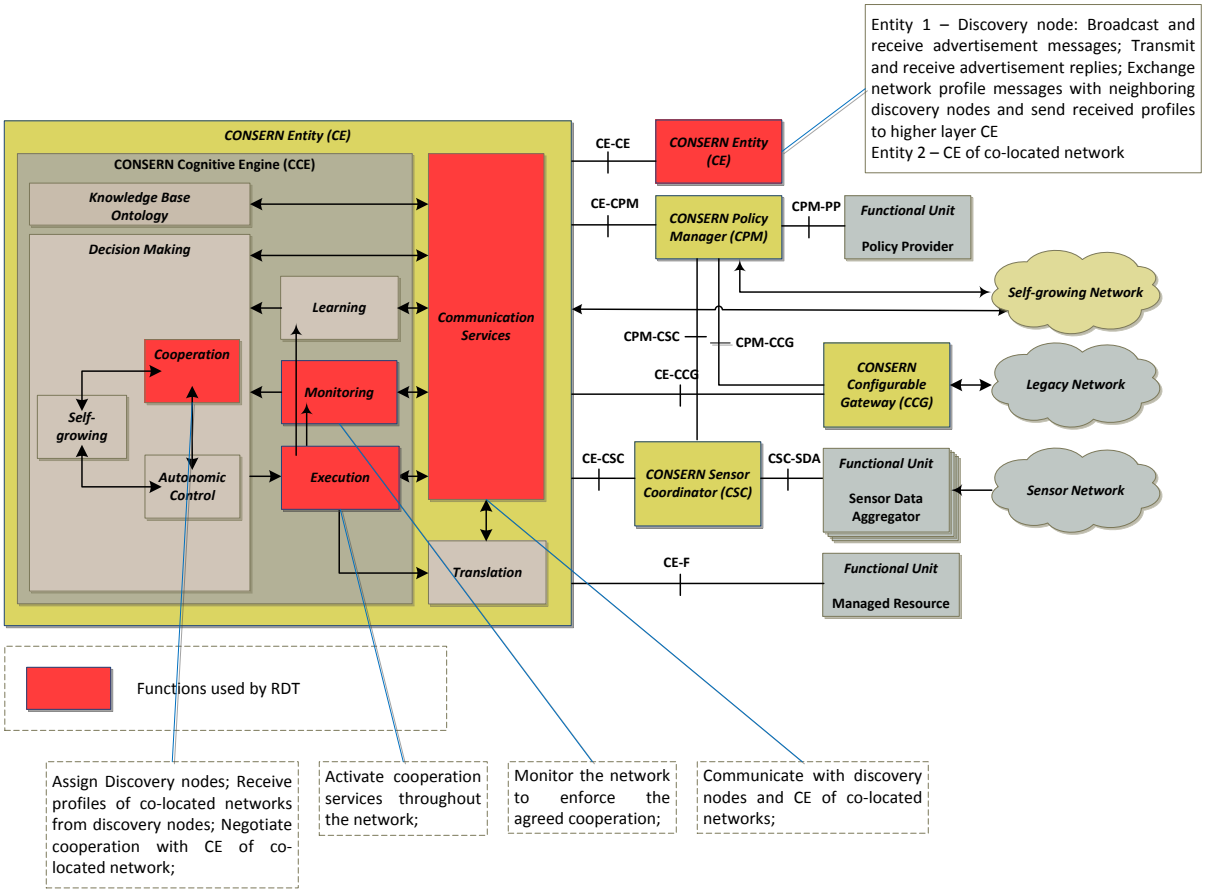


Figure 4-20: Mapping of Network Collaboration to the CONSERN Functional Architecture.

5. Heterogeneous Network Energy Savings

5.1 Cooperative Power On-Off Configurations

The radio network studies are performed in a heterogeneous network consisting of various network radio resources such as macro cells, pico cells, distributed antennas and relays. The studies correspond to three (use case) scenarios defined in D1.1 [11].

The heterogeneous network consists of a cellular layout with macro cells in which small power pico cells are deployed randomly within the macro area. The macro service area may resemble a residential site, working site or a shopping mall. Within some of the macro cells Remote Radio Heads (RRHs) of a Distributed Antenna System (DAS) are dispersed while in some macro cells relays may be located. The resources all have different power transmission, coverage and capacity profiles.

Three studies will be performed. In a first study (UC-5, [11]) criteria and actions for switching on/off a subset of a radio network's resources (sites/cells/sectors/carriers) in order to reduce the energy consumption is addressed. In a second study (UC-6, [11]) RRHs of a Distributed Antenna System (DAS) are dispersed throughout the macro cells in order to increase the network performance and save energy. The Base Stations (BSs) controlling the RRHs may cooperate to find the best possible configuration of RRHs. In a third study (UC-7, [11]) relays are used to enhance the network performance and save energy. In the study, the relays may be using simple decode-forwarding techniques or be used cooperatively. Relays that are not used by any user may be switched off.

5.1.1 Background

A typical characteristic of any cellular system is that it's designed for peak hour traffic despite the fact that the traffic activity in a certain area is high only during short periods of the day. Considering the traffic activity in a residential area it is usually low during daytime when people have left homes for work while it increases in the evenings when people are at home. The opposite pattern prevails for the office area. In a heterogeneous network environment different infrastructures are differently utilised throughout the duration of a day, e.g., macro cells are serving traffic in a residential area during working hours while a vast amount of the traffic is undertaken by pico or femto cells during evenings and late hours. In a working area and office environment the traffic is mainly served by indoor femtocells which are not fully utilised at the end of business days or during evenings and nights. In all cases under-utilization of the radio infrastructure and radio resources is a waste of power and significant power savings could be achieved by reducing the number of radio resources that the network provides in time, space and frequency, e.g., by switching off a number of base stations at different tiers (micro, pico, femto etc.).

One of the simplest approaches to obtain energy efficiency is based on the activation of network resources on demand, thus avoiding to always power on all the resources that are necessary to serve the users during peak traffic periods. In the CONSERN research the decision to gradually add or remove resources (in a switch on/off manner) will be based on cooperative decisions and joint actions between the mobile users and the base stations (BSs) of the network. Depending on the user location, user distribution and topology of the network, switching on/off of certain resources will cause a corresponding adaptation of parameter settings in neighbouring cells, e.g., transmit power, antenna tilt and radiation pattern. Such network reconfiguration might be necessary in order to cope with QoS degradation and coverage and capacity loss.

In order to illustrate the problem under study a heterogeneous network of K cells comprising M macro cells and L low power cells, e.g., pico- or femto cells. The nodes differ in terms of their power transmission levels. The power transmitted from a base station in a macro cell is in the order of 46 dBm allowing an inter-node distance of 500 m up to few kilometres while the corresponding power

emitted in a pico cell is 23 dBm with an inter-node distance of 100 m to 300 m. Higher power levels allows for an increase of the coverage area but in a network of base stations all operating in the same spectrum it results in a lower signal-to-interference (SIR) ratio and hence a lower QoS performance. In addition, power control allows for an efficient distribution of the power among the users in a cell. This is the case for users connected to a macro cell. Pico cell equipment is low cost and is without many of the advanced features used in macro cell equipment. The antennas of pico cells are omni-directional and the nodes are typically without power control functionality. Despite these differences, common to both types is the possibility to set the power on and off. This fact will form the basic assumption for a series of studies that will target power setting solutions in terms of power configurations of a heterogeneous network of cells with no, partial and/or total coverage overlap.

Solving the above problem has been performed by means of simulations. The simulations implement iterative search algorithms that, given a heterogeneous network scenario and traffic intensity distribution, determines which cells will be switched on or off. A general statement for the energy consumption minimisation problem is as follows:

> *With a given a service/geographical area with a set of base stations of different power profiles and a set of users both distributed according to a given scenario, find a set of switched on base stations that maintain required capacity in terms of average supportable user throughput.*

5.1.2 Optimisation Algorithms

All optimisation algorithms attempt to:

$$maximise\ f = \alpha \cdot \frac{T_{5\%_{current}}}{T_{5\%_{baseline}}} + (1-\alpha) \cdot E_{ERG} \qquad 5.1\text{-}1$$

subject to

$$\forall \mathrm{i} \in \mathrm{I}, \min\left(RSRP_{i,current}\right) > \vartheta_{RSRP} \qquad 5.1\text{-}2$$

where

f is the utility or objective function (UTILITY),

$T_{5\%_{current}}$ is the outage (or cell edge) throughput of the current configuration,

$T_{5\%\_baseline}$ is the outage throughput of the baseline configuration,

α is a weight that corresponds to the significance of the utility of the terms $0 \leq \alpha \leq 1$,

I is the set of all users and i is the ith user,

$RSRP_{i,current}$ is the reference signal received power by the ith user,

ϑ_{RSRP} is a threshold value of the received signal strength which is set to -120dBm in our simulations, and

E_{ERG} corresponds to the Energy Reduction Gain which is defined in terms of energy consumption rate ECR (defined in 5.1-4) as follows:

$$E_{ERG} = 1 - \frac{ECR\_current}{ECR\_baseline} \qquad 5.1\text{-}3$$

5.1.2.1 Centralised Algorithms

In the simulation study for the centralised method two search algorithms have been tested, the steepest ascent hill-climbing or gradient search algorithm and the simulated annealing Both of these

algorithms are presented here but since the simulations made led to the same results only the results for the latter one are shown in sections 5.1.3 and 5.1.4.

The basic hill-climbing search algorithm is simply a loop that continuously moves in the direction of increasing value – that is uphill. It terminates when it reaches a peak where no neighbour has a higher value. In its simplest form the algorithm does not maintain a search tree and it doesn't look ahead beyond the immediate neighbours of the current state. In its simplest form hill-climbing generates nearby successor states to the current state based on some knowledge of the problem.

An improvement of the basic hill climbing algorithm is the steepest ascent hill-climbing algorithm which considers all the moves from the current state and picks the best one to replace the current state. This variant is called the steepest ascent hill-climbing or gradient search. As depicted in Figure 5-1 it contrasts with the basic method in which the first state that is better than the current state is selected.

5.1.2.1.1 Algorithm Descriptions

In the algorithms described in Figure 5-1 and Figure 5-2 P denotes a configuration vector; a binary vector of length K= M+L indicating which of the BSs that are turned on or off. The "successor vector" is the configuration vector resulting from one iteration step of the algorithm. The search algorithms differ in their way they produce a successor state.

function STEEPEST ASCENT HILL-CLIMBING(problem)

return a configuration of vector $\bar{P}$ that maximizes the objective function f (UTILITY)

input: network topology of K elements; M macros and L picos, N dropped users

local variables: $\bar{P}_{current}$, vector.

$\bar{P}_{successor}$, highest successor vector

$\bar{P}_{current} \leftarrow$ INITIAL-VECTOR[M,L]

loop do

$\bar{P}_{successor} \leftarrow$ GENERATE_SUCCESSOR($\bar{P}_{current}$), highest

if UTILITY [$\bar{P}_{successor}$] ≤ UTILITY[$\bar{P}_{current}$] **then**

return $\bar{P}_{current}$

$\bar{P}_{current} \leftarrow \bar{P}_{successor}$

Figure 5-1: The steepest ascent hill-climbing algorithm.

Generally, the successor function is where the intelligence lies in hill-climbing search. It has to be sufficiently conservative to preserve significant "good" portions of the current solution and liberal enough to allow the state space to be preserved without degenerating into a random walk.

One specific problem of hill-climbing search is that, depending on its initial state, it can get stuck in a variety of local conditions. It is specifically prone to local maxima (minima). Simulated annealing is a variation of hill climbing, in which at the beginning of the process, the algorithm allows some downhill movements. By doing so the algorithm allows exploration of the whole state space turning the final solution insensitive to the initial state. It can be proven that if T decreases slowly enough, then simulated annealing search will find a global optimum with probability approaching one.

Annealing is based on a metallurgical process metaphor used to temper or harden metals by heating them and the gradually cooling them. To perform the annealing process:

- Start with a temperature set very high and slowly reduce it.
- Run hill-climbing but occasionally replace the current state with a worse state based on the current temperature and evaluate how much worse the new state is.

More formally, the simulated annealing algorithm, as depicted in the figure below, is a version of stochastic hill-climbing where some downhill moves are accepted readily early in the annealing schedule and then less often as time goes on. The value T is defined as a function of time. Specifically, simulated annealing is performed as follows:

- Generate a new successor vector $\overline{\mathrm{P}}_{\mathrm{successor}}$ from current configuration vector, $\overline{\mathrm{P}}_{\mathrm{current}}$.
- If it's better keep it.
- If it's worse, then keep it with some probability proportional to the temperature T.

function SIMULATED-ANNEALING(problem, schedule) **return** a configuration of vector $\bar{P}$ that maximizes the objective function f (UTILITY)

input: network topology of K elements M; macros and L picos, N dropped users

local variables: $\bar{P}_{current}$, vector.

$\bar{P}_{successor}$, highest successor vector

T, the time the algorithm has been running. T controls the probability of a downward step.

$\bar{P}_{current}$ ← INITIAL-VECTOR[M,L]

for t ← 1 to ∞ **do**

T ← SCHEDULE[t]

if T = 0 **then return** $\bar{P}_{current}$

$\bar{P}_{successor}$ ← GENERATE_SUCCESSOR ($\bar{P}_{current}$), highest

ΔE ← UTILITY [$\bar{P}_{successor}$] ≤ UTILITY [$\bar{P}_{current}$]

if ΔE > 0 **the**$\bar{P}_{current}$ **n** ← $\bar{P}_{successor}$

else $\bar{P}_{current}$ ← $\bar{P}_{successor}$ only with probability $e^{-1/T}$

Figure 5-2: The simulated annealing search algorithm.

5.1.2.2 Distributed Algorithms

The centralised algorithms described so far rely on the fact that global knowledge of the network's radio performance is attainable. In distributed versions of the algorithms we move away from the assumption of global network information/knowledge and the optimisation is instead only based on local information/knowledge. In this aspect, local knowledge means that a given BS only has knowledge of some performance parameters of its own cells and possibly its closest neighbour cells but not of cells farther away in the network.

Distributed search algorithms can be divided into autonomous and cooperative search algorithms. In the autonomous algorithms the BSs monitors its radio environment and may also receive information from its neighbours and from this information make decisions whether to switch on/off some of its cells. The cooperative algorithms add the possibility for BSs to improve their decision making by also through information exchange negotiate decisions with its neighbouring nodes.

A distributed cooperative search algorithm has been designed and its performance will be evaluated during the continuation of the project. To make the result comparable to the results obtained for the centralised environment the same utility function will be used. The algorithm is distributed to all the BSs which then run the algorithm and through cooperative decisions decides on which BSs to switch on/off.

5.1.2.2.1 Algorithm description

The network is divided into non-overlapping clusters of neighbouring cells. The initial set of clusters is decided beforehand by the operator but may while running the algorithm be redefined based on certain rules built into the algorithm. In principle, a distributed implementation requires that every BS in the network exchanges the values of their objective (utility) functions' terms with each other but as the network can be very large this is not seen to be a feasible way to go. However, switching on/off a given BS only affects the network's coverage in the proximity of the BS and the change in the network's interference pattern is less pronounced further away from the BS has lead to the idea of introducing cell clusters. The algorithm is distributed to every BS in the network which then sequentially optimises the energy consumption within the cluster, i.e., a certain base station only cooperates and negotiates its parameter settings with cells in its neighbourhood.

The algorithm contains two states, the "Idle state" and the "Execution state". In the Idle state the algorithm runs in a loop where it continuously checks whether any of the criteria to switch on or switch off a cell within the cluster are fulfilled. The criterion to be met is a function of statistics earlier collected for the cell cluster. Once any of the criteria is fulfilled the algorithm enters the Execution state where it finds and decides on the best cell to change the state of. In the Execution state two different processes can be run, i.e. find and switch on or off a cell. When the cell state change has been executed the algorithm returns to the Idle state. Figure 5-3 shows the flow of the algorithm.

In the Execution state the algorithm performs:

- Exchange information with all cells in the cluster. (The information exchanged depends on the utility function),
- Based on the exchanged info, calculate the value of the utility function for each cell in the cluster,
- Based on the exchanged info, each BS calculates the value of the utility function for the whole cluster.

In case a cell shall be switched on

- Consider the cell within the cluster having neighbour(s) with high utility value(s), or,
- Consider the cell within the cluster closest to the cell with the highest load.

In case a cell shall be switched off

- Consider the cell with the smallest utility value within the cluster with the smallest utility value as a "switch off candidate",
- Check whether it's possible to handover the users in the candidate cell to neighbouring cells while still maintaining the required QoS and if so, handover the users to the neighbouring cells and switch off the cell.

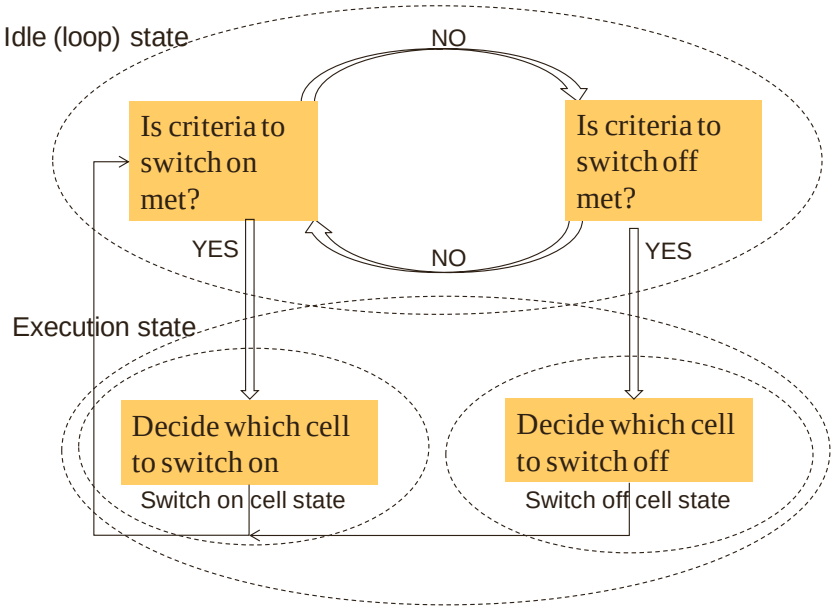


Figure 5-3: Distributed algorithm overview.

5.1.3 Evaluation Metrics and Evaluation Environment

5.1.3.1 Network Topology

Since the heterogeneous scenario has been discussed and defined in 3GPP for LTE-A, the definition follows the HetNet scenario as described in [7]. In 3GPP LTE-A, heterogeneous networks consist of deployments where low power nodes (pico cells) are placed throughout a macro-cell layout. All cells share the same 10 MHz band. Figure 5-4 illustrates the 3GPP LTE-A network topology scenario that will also be used for the simulations in CONSERN. The network consists of a hexagonal grid of *M* macro base station sites each with 3-sectors with *L* pico cells are placed within each cell. The pico cells are distributed randomly according to a distribution typical to a dense user area. The macro and pico cells operate in the same spectrum band and interference coordination between macro cells is performed. It is initially assumed that macro cells are connected and can communicate via the X2-interface while communication between two pico cells and between a pico cell and a macro cell is restricted or non-existing. This assumption will affect the algorithms which are possible in each type of node. In the evaluation described in section 5.1.4.1 the number of macro BSs M= 7 and the number of pico BSs per macro cell is L= 4.

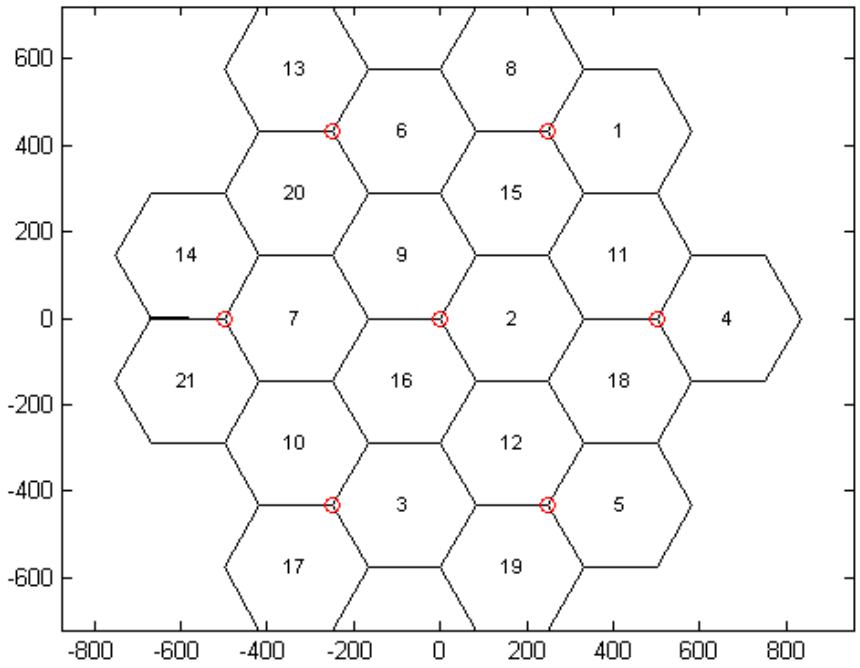


Figure 5-4: Cellular network consisting of M= 7 eNBs with 3 cells per eNB.

5.1.3.2 Basic Simulation Parameters and Assumptions

Table 5-1 below summarises the basic simulation baseline parameters for HetNet PowerOn/Off scenario.

Parameters		Values and Assumptions	
		Macro Cell	**Pico Cell**
HetNet deployment		Environment: Macro + indoor pico	
Carrier Frequency / Bandwidth		2 GHz / 10 MHz, FDD	
Inter site distance		500 m	NA
Macro Cellular layout		Hexagonal grid, 7 sites, 3 sectors per site	
Pico distribution	*Configuration1*	4 Picos / macro cell, uniformly (case 1 in table A.2.1.1.2-4 [7])	
UE distribution	*Configuration1*	25 UEs / macro cell, uniformly (case 1 in table A.2.1.1.2-4 [7])	
	Configuration4	20 UEs/macro cell, 10 UEs/pico cell, clusters (case 4 in table A.2.1.1.2-4 [7])	
Minimum distance		40 m among picos	10 m between UE and pico
		75 m between pico and macro	35 m between UE and macro eNB
TX power (Ptotal)	*Cell*	46 dBm	30 dBm
Antenna gain(horizontal) (For 3-sector cell sites with fixed antenna patterns)		$A_H(\varphi) = -\min\left[12\left(\frac{\varphi}{\varphi_{3dB}}\right)^2, A_m\right]$ $\varphi_{3dB} = 70\ degrees, A_m = 25\ dB$	$A(\phi) = 0dB$ *(omnidirectional)*

Antenna pattern (vertical) *(For 3-sector cell sites with fixed antenna patterns)*		$A_V(\theta) = -\min\left[12\left(\frac{\theta-\theta_{etilt}}{\theta_{3dB}}\right)^2, SLA_V\right]$ $\theta_{3dB} = 10\ degrees, SLA_V = 20\ dB$ The parameter θ_{etilt} is the electrical antenna downtilt. $\theta_{etilt} =$ $15\ degrees$ for 3GPP case 1 and $\theta_{etilt} = 6\ degrees$ for 3GPP case 4 in [7], respectively. The antenna height at the base station is set to 32 m and the . antenna height at the UE is set to 1.5m.	
Combining method in 3D antenna pattern		$A(\varphi,\theta) = -\min\{-[A_H(\varphi)+A_V(\theta)], A_m$	
Antenna gain	*Cell*	14 dBi	5 dBi
	UE	0 dBi	
Noise Figure	*Cell*	5 dB	
	UE	9 dB	
*Distance-dependent path loss for macro to UE*3*		L= 128.1+37.6log10(R) for 2 GHz, R in km	
Distance-dependent path loss for pico to UE		L= 140.7+36.7log10(R) for 2 GHz, R in km	
Lognormal Shadowing with standard deviation		8 dB for eNB to UE	10 dB for pico to UE
Shadowing correlation	*Between sites*	0.5	
	Between sectors	1.0	N/A
Shadowing correlation distance		50 m	
Penetration Loss		20 dB	
Traffic model		Full buffer	
Scheduler		RR (static) – each UE attached to a cell gets an equal share of the 10MHz bandwidth	
Number of optimization iterations		200	
Throughput model		L2S curve with TU channel at 3km/h [19]	

Table 5-1: Simulation baseline parameters for HetNet PowerOn/Off scenario.

In addition to the basic simulation parameters, the following assumptions are adopted for the simulation studies:

- For the studies Monte Carlo simulations are preformed based on a static simulation model that represents the system at a particular point in time by a snapshot. Typically the snapshot is representative of the long term statistics of the system. Keeping the same network topology and the users' position unchanged facilitates the derivation of benchmark scenarios and the comparison of different optimisation methods,
- The simulator drops a number of users (they do not move), determines the serving cell for each user, and then calculates the downlink SINR and downlink throughput for the user. The throughput depends both on the SINR and the number of other users that share the bandwidth of the serving cell,
- UEs with no coverage (RSRP< -120dBm) consume no power and no scheduled PRBs. Those UEs have no throughput,
- If a cell only has UEs with no coverage, it also generates no interference to the neighbouring cells,

- Cells without any UEs are not included in the calculations, e.g., throughput calculation, interference calculation and ECR calculation,
- Cells without any attached UEs are switched off at the end of the optimization to give the final count of cells that are on /off. This makes no difference to the throughput or the energy consumption but makes the state clearer to see. Note that also the cells which have no users attached in the baseline configuration are switched off.

5.1.4 Performance Metrics

Simulations have been made for the downlink and the following performance metrics are used in the analysis.

1) UE mean throughput

The mean throughput observed by each UE. Since the number of UEs is fixed this also gives a direct indication of the total network throughput.

2) Cell mean throughput

The mean throughput observed in each cell.

3) Network throughput

The UE mean throughput times the number of UEs.

4) Energy efficiency

The network level energy efficiency provides a mean to evaluate the energy efficiency of wireless access network at network level thus taking into account not only the BS site energy consumption but also features and properties related to capacity and coverage of the network.

A widely used energy metric is the energy consumption ratio (ECR) such as the required energy per delivered information bit, i.e.,

$$ECR = \frac{E}{M} = \frac{P \cdot T}{M} = \frac{P}{D}\ [Joule/bit], \qquad 5.1\text{-}4$$

where E is the energy required to deliver M bits over time T, P the power consumed and $D = M/T$ is the data rate in bits per seconds.

5.1.4.1 Performance Evaluation

In this section results from the simulation studies of the centralised algorithm are presented and discussed.

5.1.4.1.1 Simulation results (some exemplary figures)

Figure 5-5 shows the baseline configuration for UE configuration 1. Pico cells are marked with red asterisks, and lines indicate the connectivity of each UE.

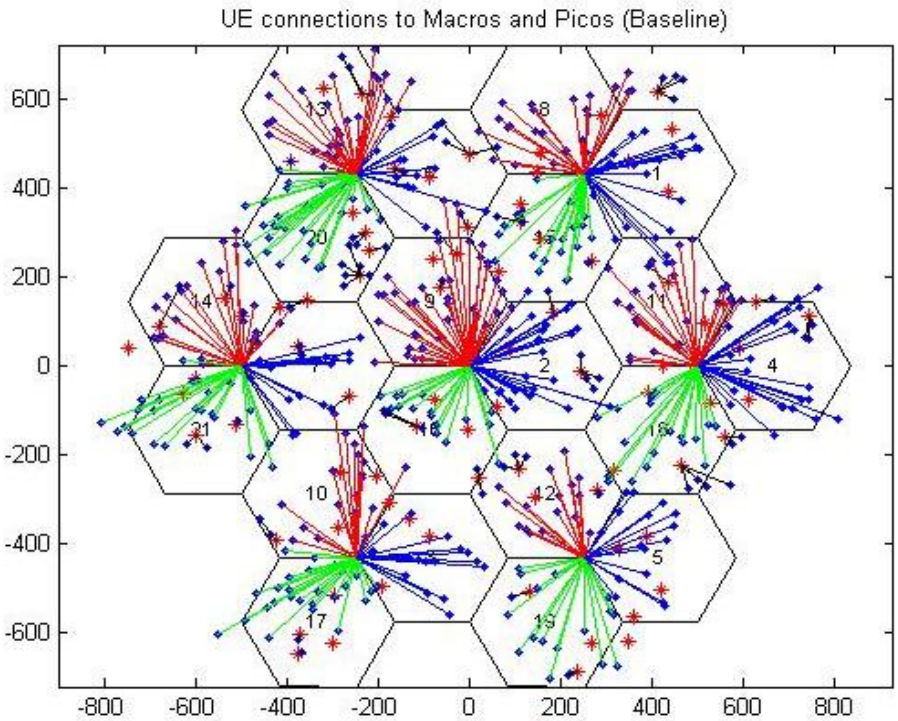


Figure 5-5: UE connections (baseline, UE configuration 1).

Coverage is very good in this configuration and all UEs are in coverage (RSRP > -120dBm).

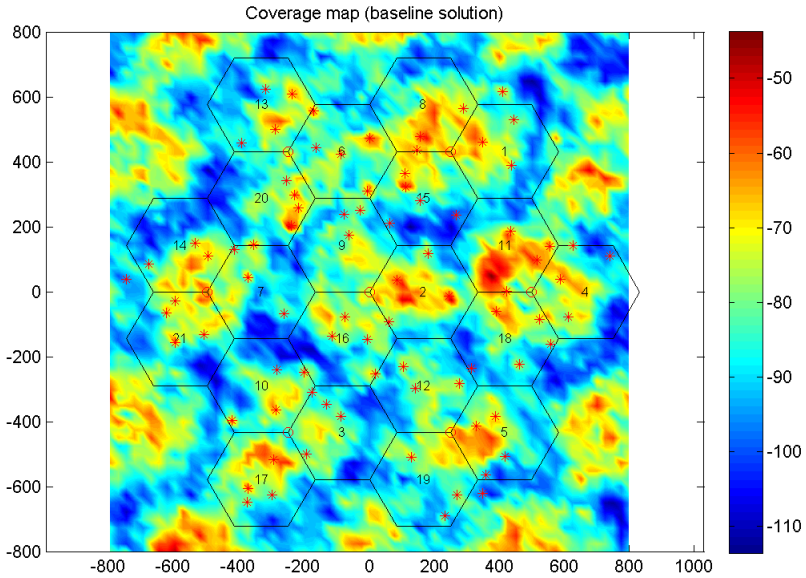


Figure 5-6: RSRP coverage map for baseline (UE configuration 1, all cells are ON except for those with no UEs attached).

When ERG is the only consideration (i.e. when the coefficient is zero) the algorithm switches off many macro cells but switches on a number of pico cells to maintain capacity. In fact, the capacity is greater than in the baseline (the UE mean throughput increases and the number of UEs is fixed). Since minimum RSRP is constrained, four macro cells are not switched off. Note that the blue cross represents pico base station in the last subfigure of Figure 5-7. The red shaded cells are switched off.

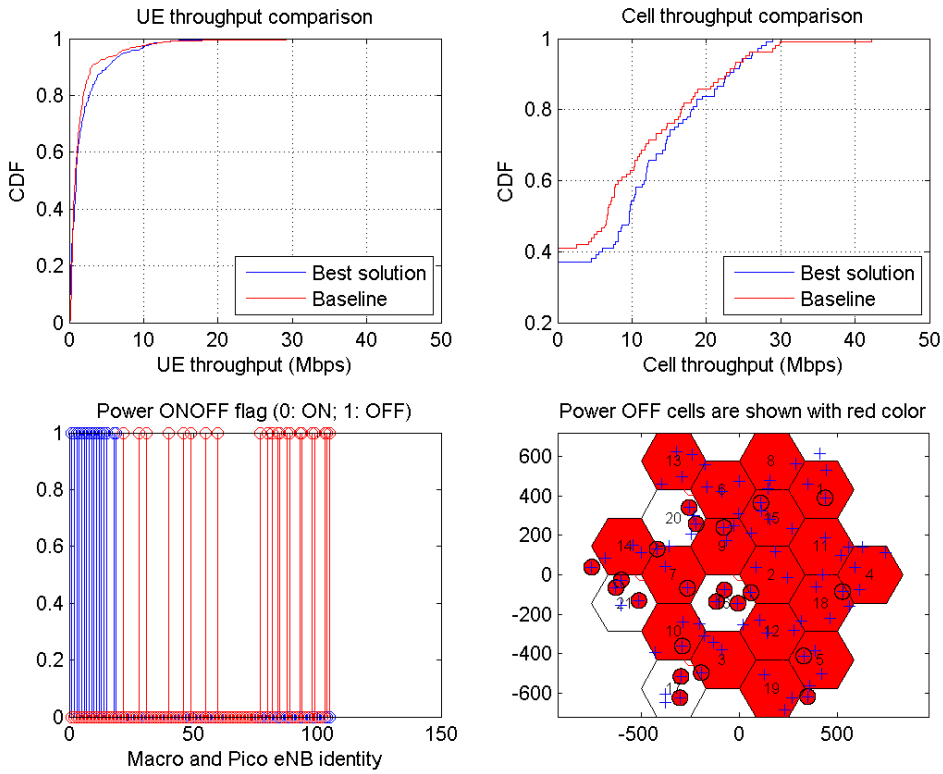


Figure 5-7: Results for optimized network (coefficient= 0.00, UE configuration 1).

Since many macro eNBs are switched off, there are more coverage problematic areas than the baseline case, but these are still rare (coverage > 99%).

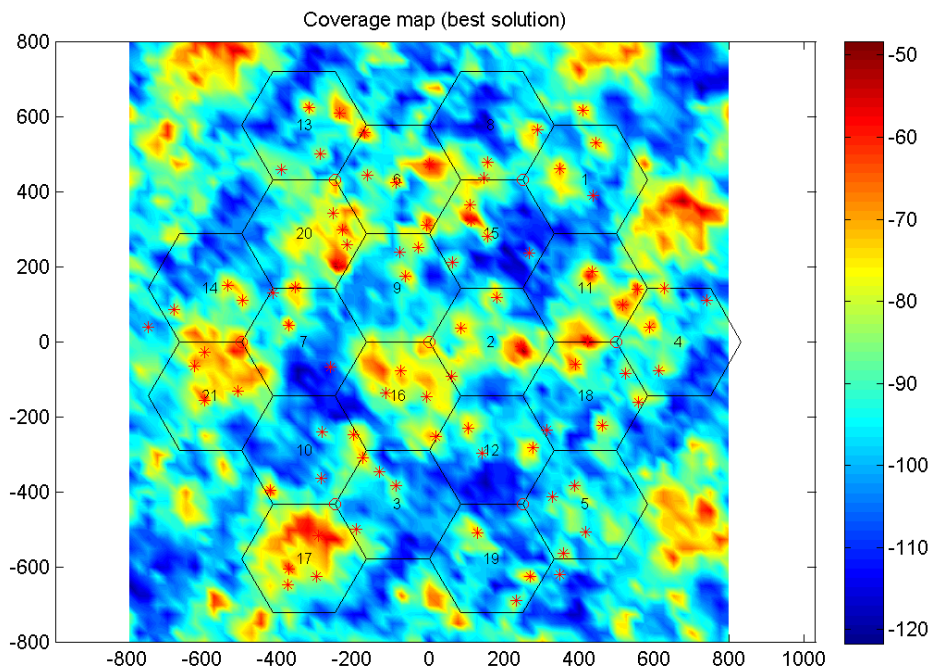


Figure 5-8: RSRP coverage map for optimized network (coefficient= 0.00, UE configuration 1).

The RSRP curve after optimization is shifted to the left. But the minimum RSRP is limited by the optimization (to exceed -120dBm). Thus all UEs have LTE coverage.

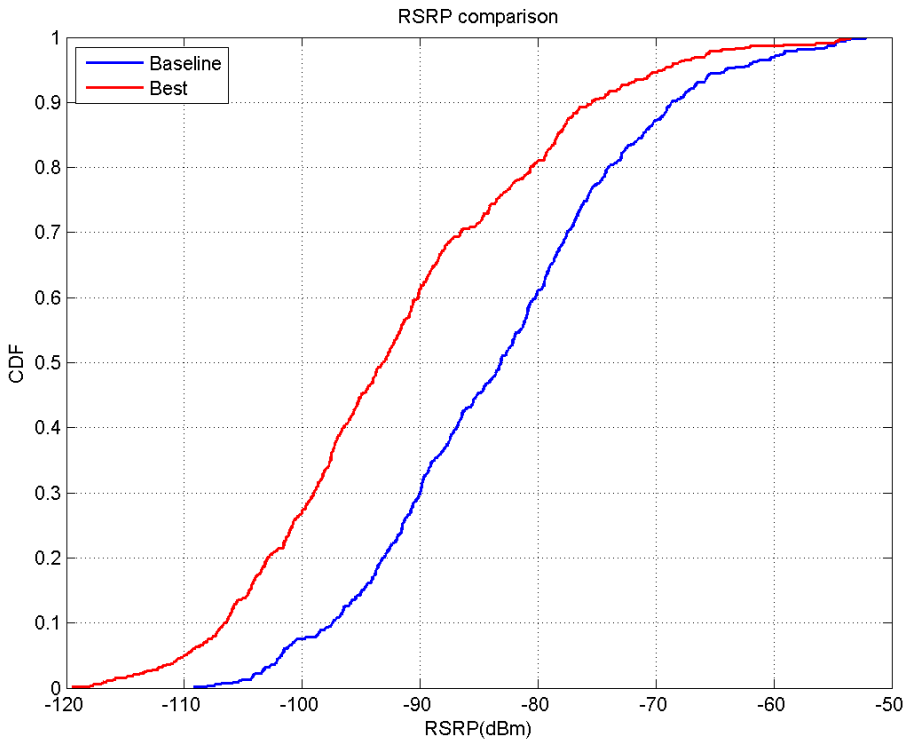


Figure 5-9: RSRP CDF for optimized network (coefficient= 0.00, UE configuration 1).

Some UEs in the pico cell get benefit from the interference reduction from the macro cells and the greater density of pico cells to show better SINR performance in the high SINR range. At the lower SINR range the baseline performs better.

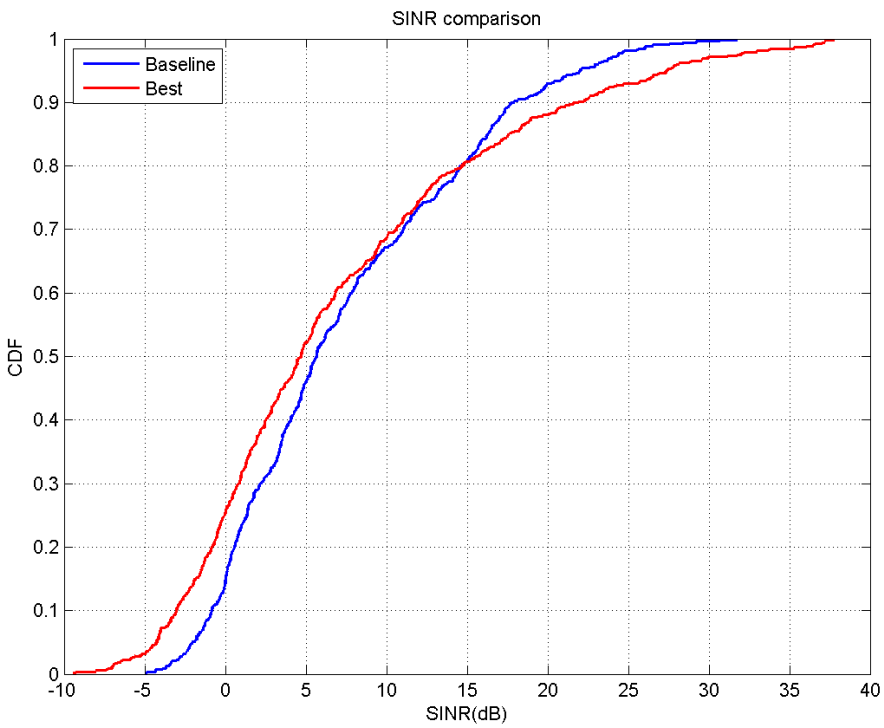


Figure 5-10: SINR CDF for optimized network (coefficient= 0.00, UE configuration 1).

The performance is convergent after about 20-30 iterations. The ERG and utility give the same curve since the first component is missing in the utility function.

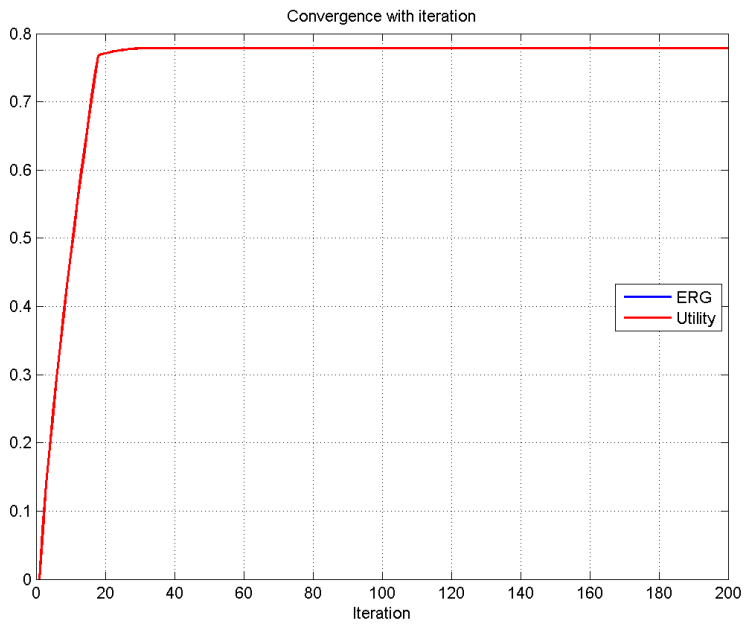


Figure 5-11: Convergence plot for optimized network (coefficient= 0.00, UE configuration 1).

The connections between UE and the serving cells after optimization are shown in Figure 5-12

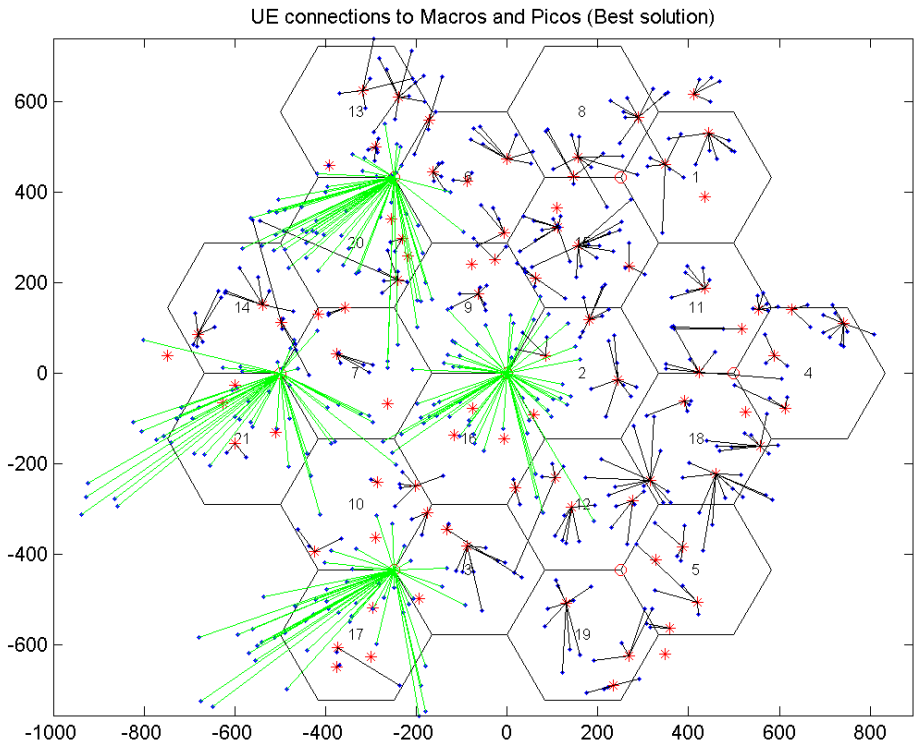


Figure 5-12: Connectivity plot for optimized network (coefficient= 0.00, UE configuration 1).

Looking at the opposite extreme, when we optimize for cell edge throughput (coefficient= 1.00), we find that most macro cells are now enabled. This network is very similar to the baseline.

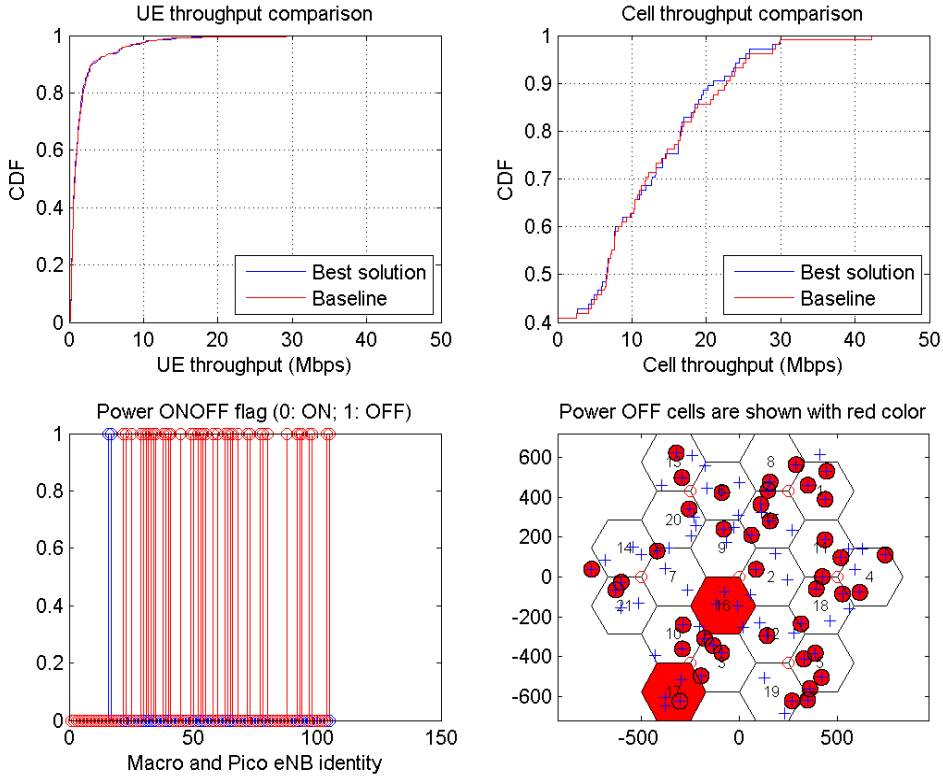


Figure 5-13: Results for optimized network (coefficient= 1.00, UE configuration 1).

Plots for UE configuration 4 are similar to those of configuration 1. The most noticeable difference is the clustering of the UEs around the pico cells. Figure 5-14 shows the connections for the baseline.

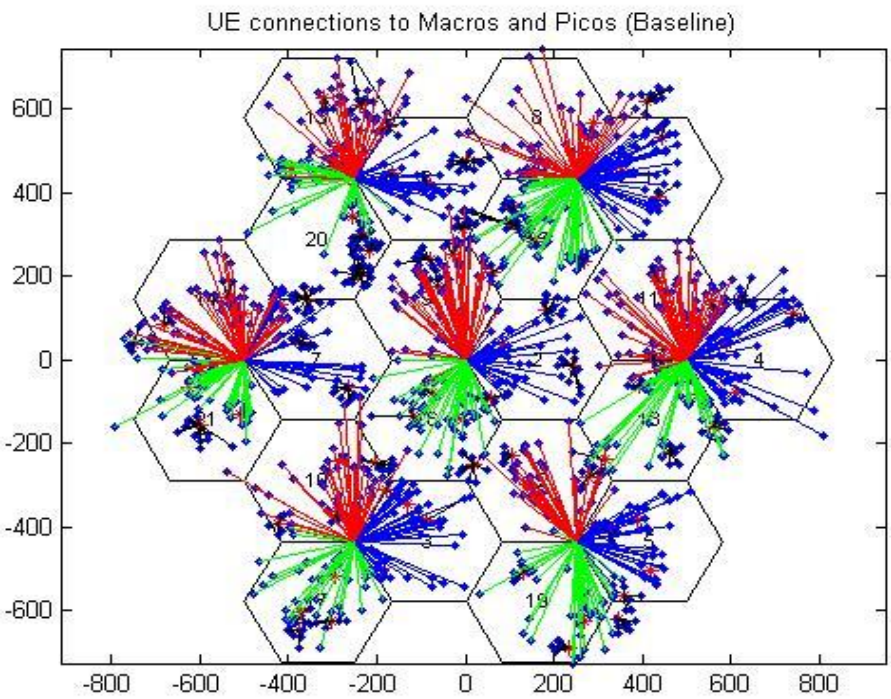


Figure 5-14: UE connections (baseline, UE configuration 4).

5.1.4.1.2 Summary and Future Work

The following results are presented for the centralised algorithm. The comparison is made with a baseline configuration in which all cells are switched on except for those cells which have no users attached.

UE configuration	Coefficient, α	Case	#Mcell ON	#Pcell ON	UE mean throughput (Mbps)	Cell mean throughput (Mbps)	5% UE throughput (Mbps)	ECR (mW/Mbit/s)	Utility value	ERG
1	NA	Baseline	21	41	1.68	14.24	0.22	19.87	0.00	NA
	0.00	Best	4	62	1.91	15.22	0.08	4.40	0.78	0.78
	0.25	Best	5	67	1.80	13.12	0.19	5.63	0.76	0.72
	0.50	Best	14	53	1.85	14.47	0.21	12.59	0.67	0.37
	0.75	Best	19	44	1.70	14.15	0.23	17.96	0.83	0.10
	1.00	Best	19	43	1.65	13.96	0.23	18.47	1.06	0.07
UE configuration	Coefficient	Case	#Mcell ON	#Pcell ON	UE mean throughput (Mbps)	Cell mean throughput (Mbps)	5% UE throughput (Mbps)	ECR (mW/Mbit/s)	Utility value	ERG
4	NA	Baseline	21	64	0.90	13.31	0.12	15.91	0.00	NA
	0.00	Best	2	71	1.10	18.91	0.12	2.18	0.86	0.86
	0.25	Best	2	75	1.11	18.24	0.13	2.20	0.91	0.86
	0.50	Best	3	74	1.08	17.66	0.13	2.85	0.96	0.82
	0.75	Best	13	68	1.00	15.54	0.12	9.31	0.88	0.42
	1.00	Best	18	53	0.83	14.77	0.13	14.68	1.12	0.08

Table 5-2: Results Summary.

In the above table, UE configuration, as in column 1, refers to the distribution of UEs and is defined in Table 5-1. In general there are two on/off configuration cases (column 3): the baseline, where all cells are powered on, and the best configuration achieved by running the centralised algorithm. The coefficient α (column 2) refers to the weight α as defined in Eq. 5.1-1. Columns 4 and 5 refer to the number of macro cells and pico cells respectively powered on, and columns 6, 7 and 8 list the UE mean throughput, cell mean throughput, and cell edge throughput respectively. Here, cell edge throughput is defined as the 5%-ile of the UE throughput. Finally, columns 9, 10, 11 correspond to the quantities of ECR, value of utility function and ERG as defined in Eq. 5.2-4, Eq. 5.2-1 and Eq. 5.2-3 respectively. From the UE configuration-1 results, the 5% percentile of the UE mean throughput increases as the coefficient increases since the first component in the utility function takes more weight, whilst the ERG falls. If cell edge throughput is not a major concern then the ECR can be significantly reduced using coefficient equal to zero – ERG is 0.78, so ECR is 0.22x that of the baseline. Whilst there is a useful network throughput gain (13%), the power reduction is the main cause of the large ERG. If cell edge throughput is important, setting the coefficient to 0.5 gives a similar 5% throughput value to the baseline whilst achieving an ERG of 0.37 and an increase in network throughput (by 10%).

In the baseline of configuration 4, the majority of pico cells are switched on. This is because many of the UEs are clustered around the pico cells, and there are more UEs in the network. Clearly the freedom to switch off cells diminishes as the network load increases. When the coefficient is set to zero, again, there is a large reduction in ECR, largely through power saving from disabling macro cells. Network throughput increases even though there are 12 fewer cell sites active, and there is no loss in 5% throughput. Increasing the coefficient shows little or no gain in 5% throughput, whilst there is a loss in ECR, especially with coefficients 0.75 and 1.00. Coefficient= 0.00 or coefficient= 0.25 offer clearly the best configuration here.

For both UE configurations, when the coefficient is small (0.00 or 0.25), the optimization prefers to switch off macro cells and use more pico cells to maximize the utility - because macro cell transmission power is 16dB (40 times) larger than in the pico cell there are big reductions in ECR by switching off macro cells. There is degradation in cell edge throughput for UE configuration 1 but not for configuration 4. The network throughput is actually better than the baseline in these small coefficient networks. One risk of switching off more macro cells is that any coverage holes become larger and if there was UE movement then there is greater risk that a UE could move out of coverage. The network-wide coverage has been determined using a grid of 64x64 points, and the coverage in all cases was greater than 99%.

The results obtained from the simulations of the centralised algorithm provide good approximations of optimal solutions and in future work will be used as a benchmark to evaluate the performance of the distributed algorithms.

5.2 Cooperative Distributed Antennas

5.2.1 Background

A Distributed Antenna System (DAS) cell consists of a BS and a set of antenna nodes which are uniformly distributed within the cell and controlled by a central processor. It achieves larger system throughput resulting from the improved spatial multiplex gain as the distributed antenna nodes have low correlation. Also, the energy efficiency can also be greatly improved as the travelling distances of wireless signals in the air are reduced in DAS network.

DAS is typically applied in a dense environment, such as a large office or a hotspot in an urban area, and the area is covered by several independent cells. In order to provide high capacity in an energy efficient way, each antenna in a DAS cell can be switched on or off based on long-term cell-specific statistics and short term terminal-specific information. If a user is close to some antenna nodes, then the other antenna nodes can be switched off to save the transmit power or transmit data for another user to improve the system capacity. PMI (Pre-coding Matrix Index) is used in the MIMO system e.g., LTE, to select the appropriate pre-coding matrix, in the DAS system, each UE can select PMI at the given sub-bands within the whole frequency band to maximize the throughput efficiency and sub-band or wideband pre-coding can be used. DAS nodes located in neighbour cells can also cooperatively negotiate on how to configure their antenna elements through distributed methods.

The system performance of cooperative DAS is investigated in both the homogeneous and heterogeneous topologies. As the baseline, the centralized antenna system with 3GPP case 1 [7] configuration is evaluated. Currently, it is well known that DAS can achieve higher throughput and save more energy than CAS. Besides, we set another baseline as the single frequency network (SFN) mode in which all the transmission nodes send the same signal. One hexagonal area is covered by three set of directional antennas located at the centre, and each antenna set serves a sector. The inter site distance is typically 500 m. In the homogeneous DAS topology model, the hexagonal sector is covered with three directional distributed antennas located at inter-crossed vertices and where each node has a maximum transmit power of 41.23 dBm (one third of the total transmit power). For the deployment in heterogeneous environments, compared with the CAS deployment, the one sector was additionally covered by one omni-directional antenna in the centre of sector. Each node has the transmit power of 43 dBm (half of the transmit power).

5.2.2 Algorithm description

5.2.2.1 Large-scale fading based antenna selection

The path loss L_i (in dB scale) from antenna i due to large-scale fading can be employed as a criterion for antenna selection. This value is related to the free space path loss, the penetration loss and the

shadowing fading. Diagonal matrix $\mathbf{L} = diag(L_0, L_1, \cdots, L_{N-1})$ denotes large-scale fading from each transmit antenna (0, 1, N-1). For each UE, the set defined by

$$\{L_i | L_i < 10 \cdot min\ (L_0, L_1, \cdots, L_i, \cdots, L_{N-1})\} \quad 5.2\text{-}1$$

corresponds to the set of antennas that can be selected for further data transmission.

Initially, UE can transmit at arbitrary power ensuring every RRH can receive the signal, e.g., the maximum power $P_{\mathbf{CMAX}}$. The eNB can estimate large-scale fading based path loss from SRS or PUCCH transmitted in uplink according to the reciprocity of long term channel statistics. If the path loss from the candidate antenna is larger than 10 times of the minimum path loss, then this antenna is not efficient to transmit to the UE and should be powered off. The antenna selection schemes can be defined as a binary diagonal matrix $\mathbf{A} = \mathrm{diag}(a_0, a_1, \cdots, a_{N-1})$, where $a_t = 1$ means that antenna port t is selected.

5.2.2.2 Throughput efficiency based antenna selection

Compared to section 5.2.1, throughput efficiency base antenna selection is more like a small scale fading based way. Here, the throughput efficiency (energy efficiency) η_T can be defined as:

$$\eta_T = \frac{T}{R / R_{total} \cdot P} \quad 5.2\text{-}2$$

where T is the average throughput, R is the number of the active antennas with power on, R_{total} is the total number of antennas, and $P$is the transmission power.

5.2.2.3 Energy aware scheduling

In a proportional fairness (PF) scheduler which is widely used in current wireless system, only the UE throughput and the fairness are taken into account. For a UE to be scheduled in a given time slot, maximization of the following utility function is targeted

$$U = \sum_k \log \bar{R}_k \quad 5.2\text{-}3$$

where $\bar{R}_k$ is the throughput of user k. In order to achieve the maximum, the following decision function is evaluated for each subframe:

$$D_k(f) = \frac{R_k(f)}{\bar{R}_k(f-1)} \quad 5.2\text{-}4$$

where $R_k(f)$ is the instantaneous transmission rate of UE k in subframe f. $\bar{R}_k(f-1)$ is the average throughput of UE k from subframe $(f-1-T)$ to $(f-1)$. The UE for which the decision function is maximised will be scheduled.

When taking power consumption into consideration, we may modify the utility function as follows:

$$U = \frac{\sum_k \log \bar{R}_k}{\sum_k \bar{P}_k} \quad 5.2\text{-}5$$

where $\bar{P}_k$ is the average power consumed by user k. Thus, the scheduler should select the user which maximizes the following energy aware utility function:

$$D_{k'}(f)=\frac{\sum_k \log\left[\left(1-\frac{1}{T}\right)\bar{R}_k(f-1)\right]+\frac{1}{T-1}\frac{R_{k'}(f)}{\bar{R}_{k'}(f-1)}}{\left(1-\frac{1}{T}\right)\sum_k \bar{P}_k(f-1)+\frac{1}{T}P_{k'}(f)} \qquad 5.2\text{-}6$$

where $P_k(f)$ is instantaneous power in subframe f, and $\bar{P}_k(f-1)$ is the average power over the latest T subframes. After the scheduling, the average transmission rate and average power consumption can be updated as:

$$\bar{R}_k(f)=\begin{cases}\left(1-\frac{1}{T}\right)\bar{R}_k(f-1)+\frac{1}{T}R_k(f) & \text{user } k \text{ is scheduled}\\ \left(1-\frac{1}{T}\right)\bar{R}_k(f-1) & \text{user } k \text{ is not scheduled}\end{cases} \qquad 5.2\text{-}7$$

$$\bar{P}_k(f)=\begin{cases}\left(1-\frac{1}{T}\right)\bar{P}_k(f-1)+\frac{1}{T}P_k(f) & \text{user } k \text{ is scheduled}\\ \left(1-\frac{1}{T}\right)\bar{P}_k(f-1) & \text{user } k \text{ is not scheduled}\end{cases} \qquad 5.2\text{-}8$$

Considering the energy aware pre-coding scheme, the power consumption is proportional to the number of active antennas. The ratio between the number of active antennas and total number of antennas R can be used as the energy metric and be introduced in the utility function. The smaller the ratio is, the larger the utility function is. Thus, the UE which requires a smaller transmission power will be assigned a higher scheduling priority. A suboptimal simplification of equation 5.2-5 is as follows

$$U(k)=\frac{R_k(f)}{R\bullet T_k(f-1)} \qquad 5.2\text{-}9$$

where R is the number of the active antennas with power on, $T_k(f)$ is the scheduled times of UE k at subframe f.

5.2.3 System model and Evaluation Metrics

5.2.3.1 System Model

DAS nodes located on regular hexagonal grids are studied in this work package to simplify the performance evaluation.

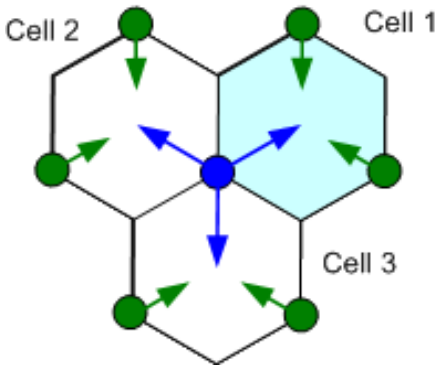


Figure 5-15: Homogeneous Topology Model.

In the homogeneous topology model shown in Figure 5-15, the cell area of a site is divided into three small hexagonal DAS cells with three directional antennas located at inter-crossed vertex of each small cell and distributed antenna nodes are connected with a central controller via high speed backhaul, e.g., fibre.

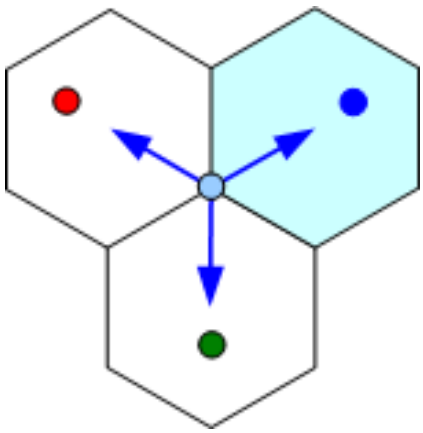


Figure 5-16: Heterogeneous Topology Model.

For the deployment in heterogeneous environments, the cell area of a site is divided into three small hexagonal DAS cell with one omni-directional antenna in the centre of each small DAS cell and distributed antenna nodes are connected with a central controller via high speed backhaul, e.g., fibre, as shown in Figure 5-16. The simulation parameters based on 3GPP Case 1 [7] are shown in Table 5-3.

Parameter		Values and Assumptions
Macro Cellular Layout		Hexagonal grid, 19 cell sites, 3 cells per site
Simulation case		3GPP Case 1 [7]
Inter-site distance		500m
Distance-dependent path loss		L=128.1 + 37.6 $\log_{10}$(.R), R in kilometres
Shadowing standard deviation		8 dB
Shadowing correlation	Between cells	0.5
	Between sectors	1.0
Penetration loss		20 dB
Antenna configuration for eNB		Homogeneous network: 3 directional RRHs per cell Heterogeneous network: 1 directional RRH and 1 omni RRH per cell
Antenna pattern [4] (horizontal) (For 3-sector cell sites with fixed antenna patterns)		$A(\theta) = -\min\left[12\left(\frac{\theta}{\theta_{3dB}}\right)^2, A_m\right]$ θ_{3dB} = 70 degrees, A_m = 25 dB
Antenna gain		eNB: 14 dBi UE: 0 dBi
Carrier frequency / Bandwidth		2 GHz / 10 MHz
UE speeds of interest		3 km/h
Total BS TX power (P_{total})		40 dBm per node
UE power class		23 dBm

Parameter	Values and Assumptions
Noise Figure	eNB: 5 dB UE: 9 dB
Minimum distance between UE and cell	>= 35 meters

Table 5-3: Simulation parameters.

5.2.3.2 Channel and Traffic Models

In the theoretical analysis, Rayleigh flat fading is assumed to model the fast fading channel. In the detail system level simulation, spatial channel model (SCM) defined in [21] is used. For the traffic model full buffer is assumed.

For the Traffic Model, Full buffer is assumed.

5.2.3.3 Physical Layer Model

5.2.3.3.1 Link-to-system interface

In the theoretical analysis, Shannon formula is used to map the received SINR into spectrum efficiency. In the system level simulation, mutual information based quality model [7] is used to map the set of instantaneous SINR on each resource block to the desired indicators of the system, e.g. the BLER which is required to set the ACK/NACK flag, the available payload when selecting pre-coding matrix and the suggested modulation and coding scheme (MCS) for CQI report.

5.2.3.3.2 Interference modelling

In theoretical evaluation, inter cell interference are ideal known without any delay. In system level simulation, the eight strongest interfering cells are completely modelled and weak interference is modelled as AWGN with the same interference power level.

5.2.3.3.3 Receiver modelling

If a user has multiple receive antennas, Maximum Ratio Combiner (MRC) is assumed. The combining vector can be formulated as

$$\mathbf{w} = \frac{\mathbf{h}}{\|\mathbf{h}\|}, \qquad 5.2\text{-}10$$

where $\mathbf{h}$ is the effective channel coefficient vector after pre-coding.

5.2.3.4 Mobility model

The UE has the velocity of 3km/h for Doppler spread, but without any location change.

5.2.4 Evaluation of simulation results

As a baseline, all the transmission antennas transmit data continuously. This is referred to as a Single Frequency Network (SFN). For one comparison, the UE selects the transmission antennas based on the energy aware on/off indicator, i.e., the antenna selection is based on the scheme in section 5.2.2.1. This case is denoted as AS: Antenna Selection. Here, the unselected antennas are powered off or used for other UE(s) transmission in the corresponding time-frequency resource for the sake of energy savings. For another comparison, besides of the setup in the AS case, the ratio between the number of active antennas and total number of antennas R was introduced in the utility function (denoted as E-AS: Efficient Antenna Selection). With this approach, UEs with fewer antennas selected are scheduled with higher priority. The best PMI is chosen in the criterion of the maximum throughput efficiency (energy efficiency) which is mathematically equivalent to the throughput divided by the transmit power. E-AS is the case mentioned in section 5.2.2.2 and 5.2.2.3.

5.2.4.1 Homogenous topology model

The results of a system-level simulation are shown in the table below:

Average	SFN (Baseline)	AS	E-AS
Throughput (bps/Hz)	1.3102	1.2238	1.3243
Energy efficiency (bps/Hz/W)	0.0328	0.0507	0.0553

Table 5-4: The simulated throughput (Mbps) and efficiency (Mbps/W) in the case of SFN (baseline), AS and E-AS.

Energy efficiency is mathematically equivalent to the throughput divided by the average transmit power (equals to total transmit power divided by the average number of active transmit antennas).

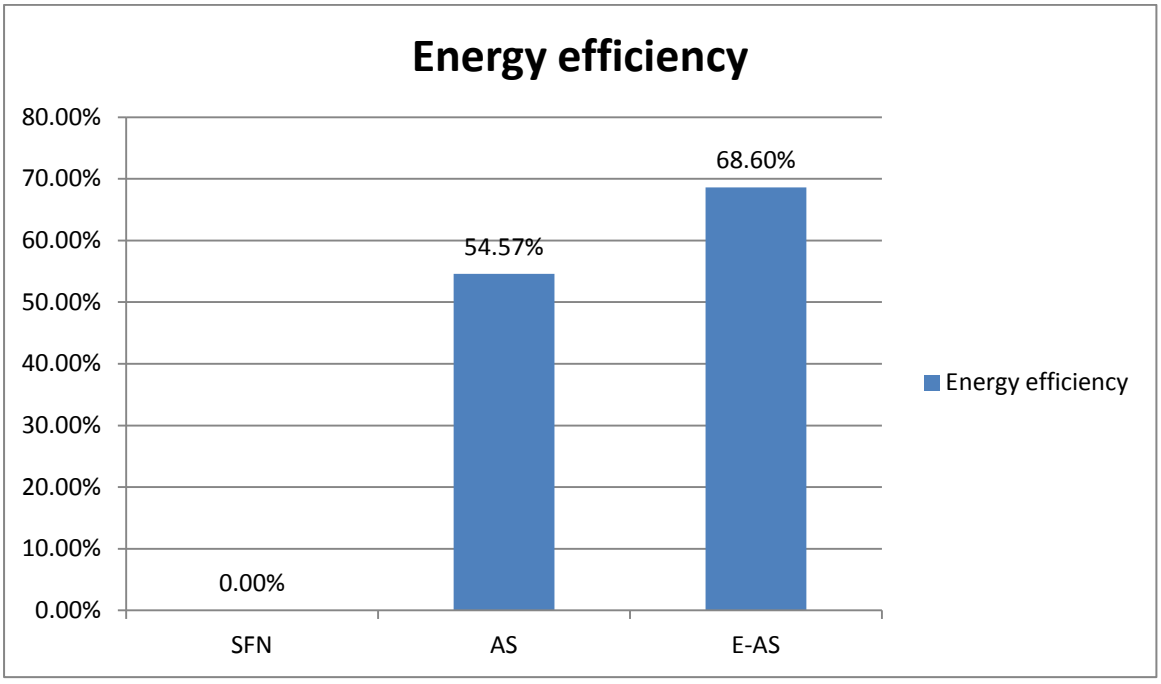


Figure 5-17: The comparison of energy efficiency among SFN (baseline), AS and E-AS for homogeneous topology model.

SFN transmission mode aggregates the most power from all the transmission nodes to the target UE. However, one drawback is that it consumes a lot of energy as compared to the case that some antenna is powered off. The other one is that it introduces more interference to other UEs, although it increases the target UE's received power. From energy efficiency point of view, by switching antennas on or off, as in the AS/E-AS mode, energy efficiency is enhanced. To further improve energy efficiency, the ratio between the number of active antennas and total number of antennas R was introduced in the utility function. As a result, UEs which choose fewer antennas [5.2-1]are scheduled with higher priority since less energy is consumed. Another contribution is from the PMI selection in terms of the maximum throughput efficiency. It finally results in even higher energy efficiency in the E-AS mode.

A comparison between the SFN, AS and E-AS modes is shown in Figure 5-17. The AS and E-AS schemes can achieve around 50-70% gain in terms of energy efficiency compared to the baseline. E-AS mode has also considerable gain compared to the AS mode.

5.2.4.2 Heterogeneous topology model

The results of a system-level simulation are shown in the table below:

Average	CAS	SFN (Baseline)	AS	E-AS
Throughput (bps/Hz)	1.08	1.2315	1.2389	1.2631
Energy efficiency (bps/Hz/W)	0.027	0.0308	0.0463	0.0473

Table 5-5: The simulated throughput (Mbps) and efficiency (Mbps/W) in the case of CAS, SFN (baseline), AS and E-AS.

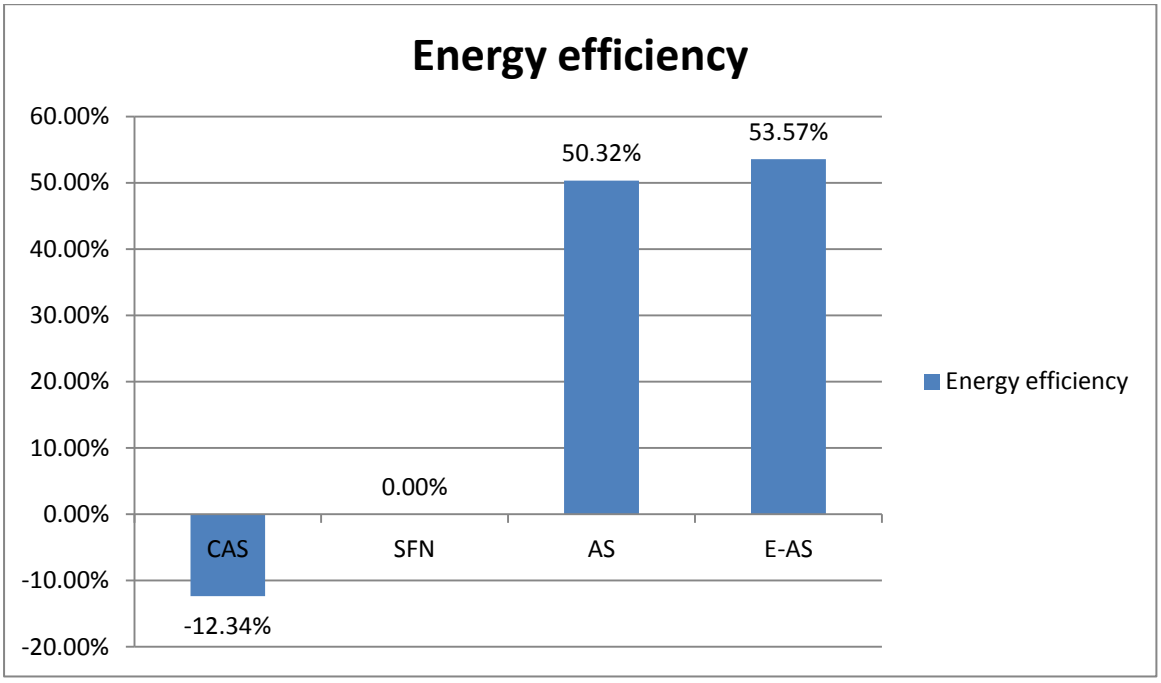


Figure 5-18: The comparison of energy efficiency among CAS, SFN (baseline), AS and E-AS for heterogeneous topology model.

Aligning with the heterogeneous model, the performance of the centralized antenna system (CAS) by locating four antennas in the centre of the cell has been evaluated. It shows that DAS outperforms CAS in terms of throughput. This is consistent with previous academic and industrial evaluation results.

Compared with the homogenous model, there are just two options of antenna selection, say two or four antennas. Naturally, the average number of the selected antennas for transmission is more. Thus, it is probable that the throughput efficiency gain is less than that of the homogenous model. But AS and E-AS modes can still achieve around 50-55% gain compared to the baseline.

According to the simulated result, the heterogeneous model has the similar tendency as the homogenous model, except that AS has a somewhat poorer performance than SFN mode in terms of throughput in the homogenous model. Because all the antennas in the homogenous model are located at the edge of the cell, UEs in the centre area of AS benefit much more than that of SFN transmission.

5.3 Cooperative Relays

5.3.1 Background

The wireless channels inevitably suffer from the influence of path loss and multipath fading, which is a great obstacle for the performance improvement of wireless network. Cooperative relays can enhance the system capacity by improving the channel quality between a UE and a BS especially for a UE at the edge of the cell. By deploying relay nodes in the cell, a cooperative relay can also induce spatial diversity in wireless networks without the need for multiple antennas on a single terminal.

To improve the network performance, there are typically many relay nodes deployed in the region between UE and BS in a dense wireless network. The choice of cooperation scheme for the relay nodes determines the energy consumption and system capacity which is possible to achieve. Determining which of these potential relays should be selected for cooperation and how to cooperate is a difficult problem. For example, for a specific UE there may exist several possible paths to access the BS: the UE accesses BS directly, or the UE accesses the BS via the relay node connected to the destination BS, or the BS combines these two paths by means of diversity combination at BS. The optimal access path is determined based on the optimal system performance, e.g., maximum cell capacity, or minimum network energy consumption.

In order to illustrate the problem above a basic 3/7 network model with 7 hexagonal cells each of which has 3 sectors is developed as a baseline model. Relay nodes are introduced between UE and BS based on the baseline model to validate the performance of cooperative relay scheme in terms of network capacity or energy savings compared to be that of baseline model. In the simulation, the power of relay transmission differs between 200 mW-10 W, and the power of UE also changes under the assumption of maximum transmission power of UE set to 200 mW, the target of the simulation is to determine the optimal transmission power of UEs and relay nodes according to the utility function for network capacity of energy saving.

5.3.2 Algorithm description

The use case and the simulation model of cooperative relay are described in [9] and [11]. The proposed algorithm is mainly designed for the mentioned use case and simulation model.

The general transmission model of relay system is abstracted as following:

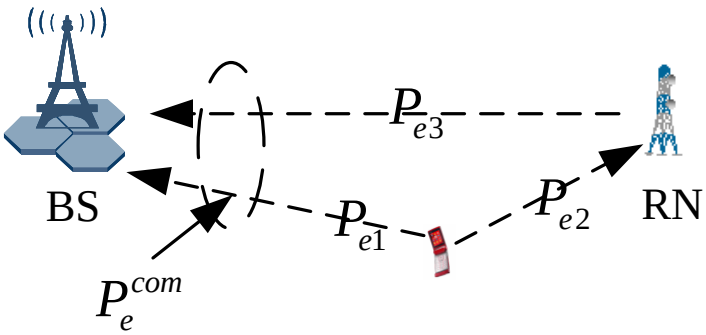


Figure 5-19: The transmission model of relay system.

Three links are introduced in the Relay system: direct link, access link and backhaul link. The direct link is the link between UE and BS, the access link refers to the link between UE and relay node, while the backhaul like is the link between the relay node and the BS.

Where P_{eX} stands for the error rate of signal transmission between two nodes. P_e^{com} denotes the error rate of signal transmission between UE and BS when BS combines the signal received from UE and the signal forwarded by the relay nodes.

The channel model between nodes is defined as:

$$\begin{aligned} r &= h_1 + I_1 + n_1 \\ \hat{r} &= \hat{h}_1 + \hat{I}_1 + \hat{n}_1 \end{aligned} \qquad 5.3\text{-}1$$

where *r* denotes the received signal, h_1 is the channel impulse response, s is the sent signal after demodulation, I_1 is the interference from other neighbour cell and n_1 is the thermal noise. The symbol with acute (^) are the corresponding variables on the backhaul link or access link.

In this cooperative relay scheme, UE may access BS by selecting an optimal path among three candidates, access to BS directly, or access to BS via signal forwarded by relay nodes, or combining the signal received from UE and signal received forwarded by the relay node at BS by diversity combination. The optimal access path is determined by the optimal solution of designed utility function.

5.3.2.1 Algorithm of capacity/throughput analysis

Based on the channel model above, the equivalent noise can be expressed as:

$$\sigma^2 = \frac{\|I_1\|^2 + \|n_1\|^2}{\|h_1\|^2} \qquad 5.3\text{-}2$$

$$P_e = erfc\left(\frac{1}{\sqrt{2}\sigma}\right) * 0.5 \qquad 5.3\text{-}3$$

Where $P_e$is the bit error rate of signal transmission. For the relay forwarding scheme, the UE transmits the signal to relay, and relay node forwards the signal to the BS, if there is no cooperation which means that the central BS only receives its signal from the relay node, then the bit correct receipt rate is given by:

$$P_c = (1 - P_{e3})(1 - P_{e2}) + P_{e2}P_{e3} \qquad 5.3\text{-}4$$

Note: If both the relay node and the BS decode incorrectly, the finally decoded bits are equal to the original bits.

So the signal error rate at the BS is

$$P_e = 1 - P_c = P_{e2} + P_{e3} - 2P_{e2}P_{e3} \qquad 5.3\text{-}5$$

P_{e2} is the error rate between the UE and the relay;

P_{e3} is the error rate between the relay and the central BS;

For the relay cooperation scheme, the BS makes a diversity process by combining the signal received from the UE and the signal received from the relay based on maximum ratio combining (MRC).

We can identify two cases:

Case 1. The signal received by relay is correct:

Take BPSK modulation as an example, the bits before modulation are, $b \in \{0,1\}$the modulated symbol is $s = \mathrm{BPSK(b)} \in \{+1, -1\}$, the signal at the BS can be expressed as :

$$\begin{aligned} r_1 &= h_1 s + I_1 + n_1 \\ r_3 &= h_3 s + I_3 + n_3 \end{aligned} \qquad 5.3\text{-}6$$

Here, r_1 is the signal at the link UE to BS, r_3 is the signal at the link between the relay to the BS, h_k is the channel response, and I_k is the interference, n_k is the noise.

The maximum ratio combining signal is:

$$\hat{r} = (\|h_1\|^2 + \|h_3\|^2)s + (h_1^* I_1 + h_3^* I_3) + (h_1^* n_1 + h_3^* n_3)$$
$$\Downarrow$$
$$\hat{r} = s + \frac{(h_1^* I_1 + h_3^* I_3) + (h_1^* n_1 + h_3^* n_3)}{\|h_1\|^2 + \|h_3\|^2} \qquad 5.3\text{-}7$$

Then, the equivalent noise can be expressed as:

$$\sigma_1^2 = \frac{\|h_1\|^2\|I_1\|^2 + \|h_3\|^2\|I_3\|^2 + \|h_1\|^2\|n_1\|^2 + \|h_3\|^2\|n_3\|^2}{(\|h_1\|^2 + \|h_3\|^2)^2} \qquad 5.3\text{-}8$$

$$P_{com}^{[1]} = erfc\left(\frac{1}{\sqrt{2}\sigma_1}\right) * 0.5 \qquad 5.3\text{-}9$$

When the relay correctly receives the signal from the UE, BS combines the signal from UE and Relay, and the probability of correct decoding is:

$$P_{c2} = (1 - P_{e2})\left(1 - P_{com}^{[1]}\right) \qquad 5.3\text{-}10$$

Case 2. The signal received by relay is incorrect:

When the received signal at relay is in error and it forwards the erroroneous signal to the BS, the signal received at the BS can be expressed as:

$$r_1 = h_1(+s) + I_1 + n_1$$
$$r_3 = h_3(-s) + I_3 + n_3 \qquad 5.3\text{-}11$$

then, the maximum rate combining signal can be expressed as:

$$\hat{r} = (\|h_1\|^2 - \|h_3\|^2)s + (h_1^* I_1 + h_3^* I_3) + (h_1^* n_1 + h_3^* n_3)$$
$$\Downarrow$$
$$\hat{r} = \frac{\|h_1\|^2 - \|h_3\|^2}{\|h_1\|^2 + \|h_3\|^2}s + \frac{(h_1^* I_1 + h_3^* I_3) + (h_1^* n_1 + h_3^* n_3)}{\|h_1\|^2 + \|h_3\|^2} \qquad 5.3\text{-}12$$

The equivalent noise is:

$$\sigma_2^2 = \frac{\|h_1\|^2\|I_1\|^2 + \|h_3\|^2\|I_3\|^2 + \|h_1\|^2\|n_1\|^2 + \|h_3\|^2\|n_3\|^2}{(\|h_1\|^2 - \|h_3\|^2)^2} \qquad 5.3\text{-}13$$

and the related error probability is

$$P_{com}^{[2]} = erfc\left(\frac{1}{\sqrt{2}\sigma_2}\right) * 0.5 \qquad 5.3\text{-}14$$

When the relay incorrectly receive the signal from the UE, the BS combines the signal from the UE and the relay, and the probability of correct decodingis:

$$P_{c1} = P_{e2}\left(1 - P_{com}^{[2]}\right) \qquad 5.3\text{-}15$$

According to formulas 5.3-6 and 5.3-11, we can get the probability of correct BS decoding by combining the signals from the UE and the relay as:

$$P_c = P_{c1} + P_{c2} = (1 - P_{e2})\left(1 - P_{com}^{[1]}\right) + P_{e2}\left(1 - P_{com}^{[2]}\right) \qquad 5.3\text{-}16$$

And the related error rate is: $P_e = 1 - P_c$.

By comparing the bit error rate of direct transmission, relay forwarding and relay cooperation we can choose the best one for maximizing the frequency efficiency.

$$P_e = \begin{cases} P_e^d, & P_e^d \leq P_e^f, P_e^d \leq P_e^c \\ P_e^f, & P_e^f \leq P_e^d, P_e^f < P_e^c \\ P_e^c, & P_e^c < P_e^d, P_e^c < P_e^f \end{cases} \qquad 5.3\text{-}17$$

P_e^d: $Direct\ transmitting\ error\ rate$
P_e^f: $Relay\ forward\ error\ rate$
P_e^c: $Relay\ cooperation\ error\ rate$

Apparently, the smallest bit error rate of the cell is equivalent to the maximum cell capacity.

5.3.2.2 Algorithm of energy saving analysis

Without loss of generality, we take the following macro cell as example.

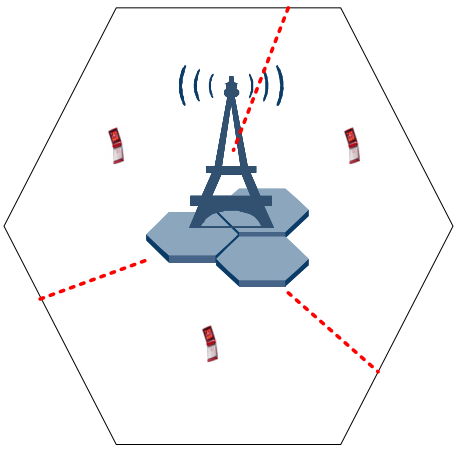


Figure 5-20: Macro cell model.

The central area is split into 3 sectors by BS with 3 antennas. The UEs are uniformly distributed in each sector, the signal received at each antenna of BS is formulated as

$$r_i = \sum_{j=1}^{N} h_{ij}\sqrt{p_j}s_j + n_i \qquad i, j = 1,2,3, \cdots \mathrm{N} \qquad 5.3\text{-}18$$

Where h_{ij} denotes the impulse response of the channel between UE_j and antenna i ; s_j denotes the signal sent by UE_j; n_i denotes the Gaussian noise . p_j is the transmission power of UE_j to send signal s_j.

On one hand, the cell capacity can be improved by increasing the power of signal transmission of UE for the uplink, especially for the UE distributed at the edge of the cell, but it costs more energy. On the other hand, the energy consumption can be decreased by decreasing the power of signal transmission of UE, but it sacrifices the cell capacity, subsequently it will influence UE to access the network.

How to make a best balance between the cell capacity and energy consumption, i.e., the optimal energy efficiency, is the most important issue.

Seeking the optimal energy efficiency is equivalent to find out the minimum energy consumption with the guarantee that the access capacity of each UE reaches to an expected level.

We define the utility function for energy efficiency optimization based on the above analysis as followed:

$$min \sum_{j=1}^{N} p_j$$
$$s.t.\ \ C_i = Blog_2\left(1 + \frac{p_i|h_{ii}|^2}{\sum_{j\neq i,j=1}^{N} p_j\left|h_{ij}\right|^2 + \sigma^2}\right) \geq C_{min}, i = 1,2,3 \cdots N \qquad 5.3\text{-}19$$

Where, B is the access bandwidth. C_{min} is the expected threshold of the capacity for each UE access. N is the number of UE. (Without loss of generality, B is set as 1 for each UE in the simulation.)

Similarly, in the relay system, the signals received at the BS from the UE and relay node are formulated as:

$$r_i = \sum_{j=1}^{N} h_{ij}\sqrt{p_j}s_j + n_i \quad i = 1,2,3, \cdots \mathrm{N} \qquad 5.3\text{-}20$$

$$\hat{r}_i = \sum_{j=1}^{N} \hat{h}_{ij}\sqrt{\hat{p}_j}s_j + \hat{n}_i \quad i = 1,2,3, \cdots \mathrm{N} \qquad 5.3\text{-}21$$

where N is the number of UEs,, h_{ij} denotes the impulse response of the channel between UE_j and antenna i ; s_j denotes the signal sent by UE_j; n_i denotes the Gaussian noise . p_j is the transmission power of UE_j to send signal s_j. The symbol with acute (^) are the corresponding variables on the channel between BS and relay node (backhaul link).

The introduction of relay nodes in the macro cell significantly improves the cell capacity, as well as decreasing the energy consumption of UE by improving the quality of channel between UE and BS, however the relay nodes will also introduce some additional energy consumption, how to make a best balance between the cell capacity and total energy consumption, i.e., the optimal energy efficiency, is the most important issue.

For the relay system, we define the utility function for energy efficiency optimization as followed:

$$min\left\{\sum_{j=1}^{N}(p_j + \hat{p}_j)\right\}$$
$$s.t. C_j \geq C_{min}, \qquad p_j + \hat{p}_j \leq P_{max}, \qquad j = 1,2,3 \cdots N \qquad 5.3\text{-}22$$

Where P_{max} is the total power consumption of the relay nodes and UEs.

The capacity of UE for sending signal C_i^{UE} and the capacity of the relay node for forwarding signal C_i^{RN} on the uplink channel are formulated as followed respectively:

$$C_i^{UE} = Blog_2\left(1 + \frac{p_i|h_{ii}|^2}{\sum_{j\neq i,j=1}^{N} p_j\left|h_{ij}\right|^2 + \sigma^2}\right) \qquad 5.3\text{-}23$$

$$C_i^{RN} = Blog_2\left(1 + \frac{\hat{p}_i|h_{ii}|^2}{\sum_{j\neq i,j=1}^{N}\hat{p}_j\left|\hat{h}_{ij}\right|^2 + \hat{\sigma}^2}\right) \quad 5.3\text{-}24$$

where σ^2 denotes the noise power.

Assume that the total bandwidth allocated for all the UEs and relay nodes is B for uplink, if the bandwidth allocated to the access link is denoted as αB, then the bandwidth allocated to backhaul link is computed as $(1-\alpha)B$, in order to match the capacity of access link and backhaul link, the equation below should be met:

$$\alpha\sum_{i=1}^{N} C_i^{UE} = (1-\alpha)\sum_{i=1}^{N} C_i^{RN} \quad 5.3\text{-}25$$

i.e.

$$\alpha = \frac{\sum_{i=1}^{N} C_i^{RN}}{\sum_{i=1}^{N} C_i^{UE} + \sum_{i=1}^{N} C_i^{RN}} \quad 5.3\text{-}26$$

5.3.3 System model and Evaluation Metrics

5.3.3.1 System model

The simulation models are mainly based on the regular hexagonal cellular structure. The basic simulation environment is consistent with the definition in [7]. In order to analyze the performance gain of the proposed algorithm we introduce the typical 3/7 cell model as the baseline model as shown following:

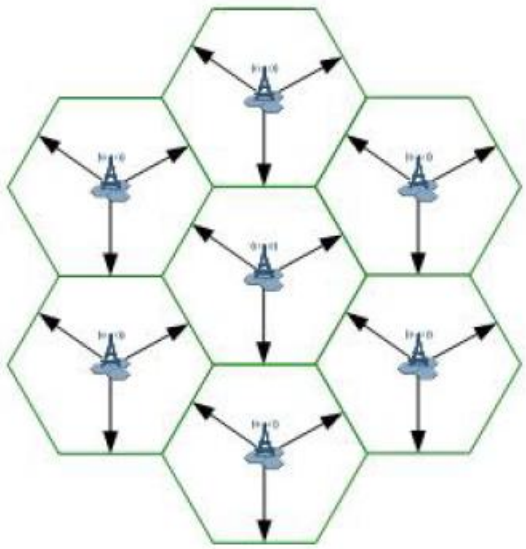


Figure 5-21: The baseline simulation model of cooperative relay.

In the cooperative relay scheme some relay nodes are introduced in each macro cell, specifically the introduced relay nodes are deployed at the edge of each macro cell the improve the system performance by cooperative relay schemes. The simulation model for cooperative relay is structured based on the baseline model as shown following:

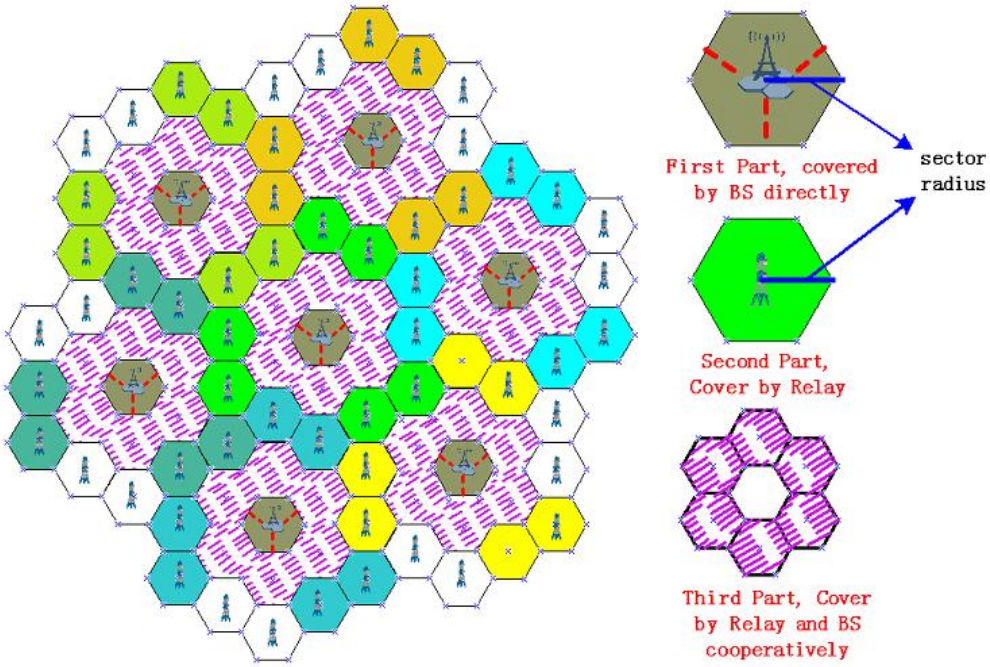


Figure 5-22: The relay simulation model of cooperative relay.

Each macro cell is divided into three areas: central area, middle area and edge area. The central part is covered by the central BS which plays the role of macro BS in the baseline model. The central area is further divided into three sectors by means of directional antenna on the central BS. The edge area is located at the edge of each basic regular hexagonal cell where the edge part is divided into 12 small hexagonal cells with one relay node located in each relay cell. The 12 small relay cells are split into two groups as indicated by same colour, and the dispersed six cells with green colour are controlled by the central BS as shown in Figure 5-23. The middle area is covered by both the BS and the relay. The set of cells constituting the central cell, the six middle cells and the six cells in the outer ring controlled by the central BS is named the “cooperative relay set”.

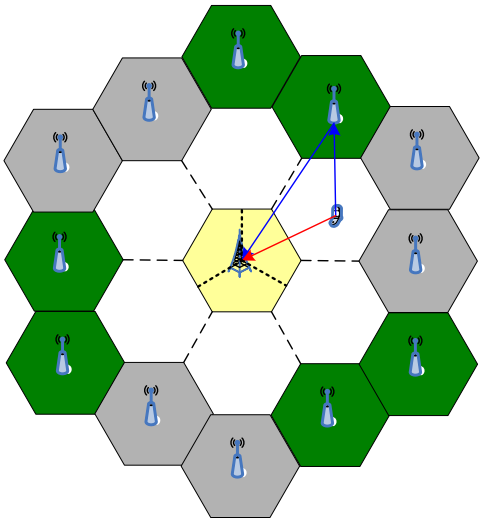


Figure 5-23: Cooperation scheme of a single macro cell; a cooperative relay set.

The UEs may access the central BS via different paths according to the UE distribution due to the introduction of relay nodes. Three access modes are defined in this simulation.

- **Baseline**: all the UEs access the nearest central BS directly without relaying, based on the baseline simulation model.
- **Simple Relay Scheme**: Based on the relay simulation mode, UE accesses the central BS directly if it is located in the central area, while the UE located in the other areas access the central BS via two candidates: access to BS directly, or access to BS via signal forwarded by relay nodes, according to the optimal solution to the utility function in equations 5.3-17 and 5.3-19. How to select the optimal path among the candidates is decided by BS according to the algorithm in Section 5.3.2.
- **Cooperative Relay Scheme**: Based on the relay simulation mode, the UE accesses the central BS directly if it is located in the central area, while a UE located in the other areas access the central BS via 3 candidates, access to BS directly, or access to BS via signal forwarded by relay nodes, or combining the signal received from UE and signal forwarded by relay node at BS by diversity combination. How to select the optimal path among the candidates is decided by BS according to the algorithm in Section 5.3.2.

The UEs are uniformly distributed in each element cell/sector, the element cell/sector, it may be a relay cell, a central BS sector, or an empty cell in the middle area.

The simulation configuration of parameter is mainly based on [5] and [7]. The preliminary simulation assumptions are contained in the following table:

Parameter	Values and Assumptions
Network topology	3/7 macro cells, 3 sector per macro cell for baseline
Cell radius	400 meters, Urban microcell [5]
UE transmission power	20mW-200 mW
Relay transmission power	200 mW-1000mW
Relay antenna	UE and Relay: Omni directional antenna SISO Relay and BS: Directional antenna SISO
UE antenna transmission gain	34.53+38*log10(d)
Relay antenna transmission gain	34.53+38*log10(d)
Antenna pattern[7] (horizontal) (For 3-sector cell sites with fixed antenna patterns)	$A(\theta) = -\min\left[12\left(\frac{\theta}{\theta_{3dB}}\right)^2, A_m\right]$ θ_{3dB} = 70 degrees, A_m = 25 dB
Channel model	Urban micro-cell environment: Path loss = 34.53+38*log10(d)
Number of paths (N)	6
Number of sub-paths (M) per-path	20
Mean AS at BS	NLOS: E( )=190
AS at BS as a lognormal RV	N/A
AS at BS (Fixed)	5 deg (LOS and NLOS)
BS per-path AoD Distribution standard distribution	U(-40deg, 40deg)
Mean AS at MS	E($\sigma_{AS,MS}$)=68°
at MS (fixed)	35°
Mean total RMS Delay Spread	E( )=0.251ms (output)

Parameter	Values and Assumptions
Distribution for path delays	U(0, 1.2ms)
Lognormal shadowing standard deviation,	NLOS: 10dB LOS: 4dB
Path loss model (dB), d is in meters	NLOS: $34.53 + 38\log_{10}(d)$ LOS: $30.18 + 26*\log_{10}(d)$

Table 5-6: Configuration of Simulation parameters.

Additionally, in this simulation fast fading influence is not included, and full buffer mode (users always have data to transmit in their buffers) for traffic model is assumed.

5.3.3.2 Evaluation Metrics

To evaluate the performance of the cooperative relay algorithm compared to that of baseline mode, some metrics are introduced.

- **SINR CDF**: In this simulation only uplink is involved, this is defined as the CDF for the SINR observed by each UE on the uplink,
- **Capacity/Throughput**: defined as the average rate of successful data delivery over a wireless link channel within a basic cell. The capacity/throughput is measured in bits per second (bit/s or bps),
- **Spectrum Efficiency**: defined as the use efficiency of spectrum, which is usually measured in bit/Hz/s,
- **Energy Efficiency**: defined as the efficiency of energy consumption, which is used to evaluate how much system capacity or spectrum efficiency can be reached at the cost of a given energy consumption. In this simulation, the energy efficiency is described in two different ways, either as “cell capacity/energy consumption” or as the “cell capacity/energy consumption” /bandwidth.

5.3.4 Evaluation and analysis of simulation results

In order to evaluate the performance of the proposed algorithm in section 5.3.2 and the cooperative schemes, some simulations based on the above simulation model are made. In the following, the preliminary simulation results are shown.

Figure 5-24 presents the comparison of baseline Scheme, Simple Relay Scheme and Cooperative Relay Scheme in term of CDF curve based on the cell capacity.

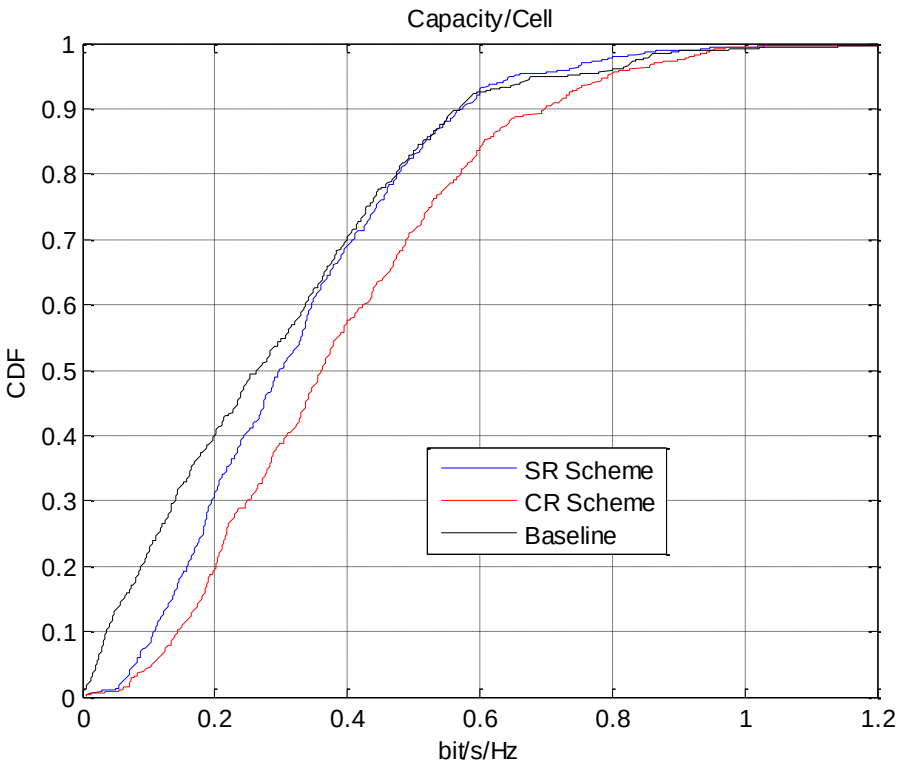


Figure 5-24: Comparison of different schemes for capacity.

Note that the "SR Scheme" in the figure stands for the Simple Relay Scheme and "CR Scheme" stands for the Cooperative Relay Scheme. In this simulation the whole system consists of 7 macro cells with 42 relay cells and 42 middle cells, the maximum transmission power of the relay nodes is set to 1000mW. Without loss of generality, the bandwidth of each macro cell is assumed as 1 in this simulation. The utility function corresponds to the proposed algorithm presented in section 5.3.2.1.

As shown in the Figure 5-24, both the SR Scheme and CR Scheme have made a better performance than the baseline Scheme, the SR Scheme improves about 10% gain compared to the Baseline Scheme on average, and the CR Scheme makes a much better performance than the Baseline Scheme, the improved gain reaches to around 33% on average.

Figure 5-25 presents the comparison of baseline Scheme, Simple Relay Scheme and Cooperative Relay Scheme in term of CDF curve based on the energy efficiency, which is measured in (cell capacity)/(energy consumption).

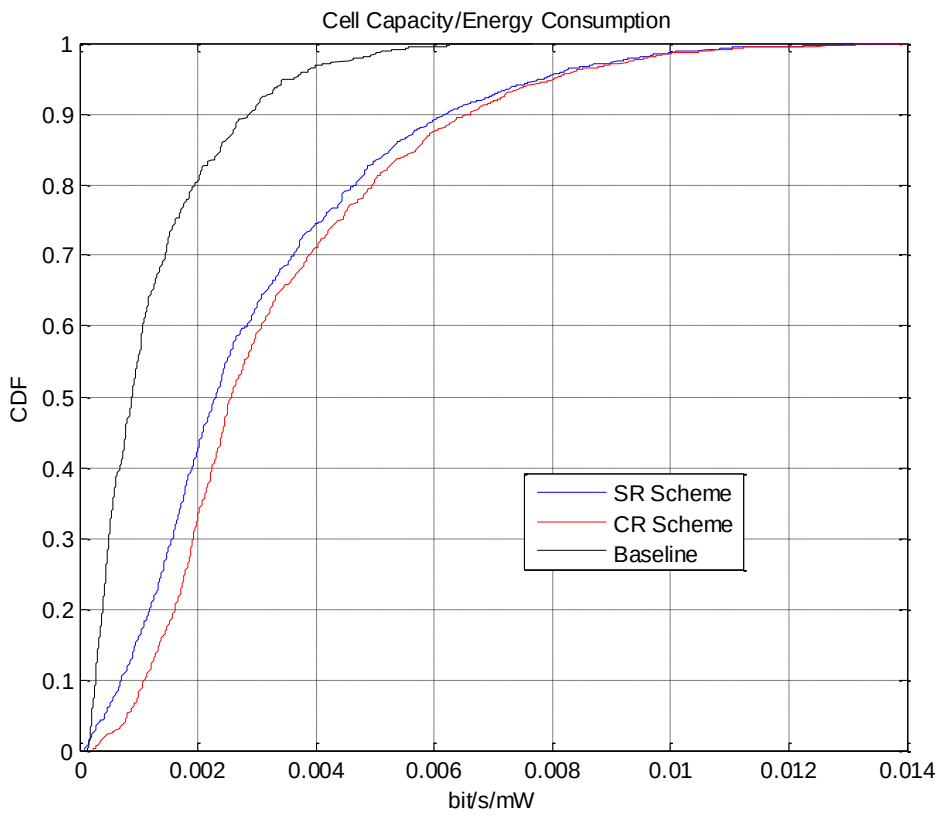


Figure 5-25: Comparison of different schemes for energy efficiency, part 1.

Note that the "SR Scheme" in the Figure 5-25 stands for the Simple Relay Scheme and "CR Scheme" stands for the Cooperative Relay Scheme. In this simulation the whole system consists of three macro cells with 21 relay cells and 21 middle cells, since the utility function for energy efficiency improvement includes many constraints which cause extreme cost when running the simulation. The minimum access capacity C_{min} is set to 0.1 bit/s with the assumption the bandwidth of each macro cell set to 1. The maximum total transmission power of the relay nodes and UEs in a cooperative relay set equals 5000mW. When deriving the (cell capacity)/(energy consumption), the smallest cell capacity is used as "cell capacity" for all schemes allowing for the balance between capacity and fairness. The utility function corresponds to the proposed algorithm presented in section 5.3.2.2.

As shown in Figure 5-25, both the SR Scheme and CR Scheme have made a significant improvement compared to the baseline Scheme, the SR Scheme improves about 160% gain than the Baseline Scheme on average, and the CR Scheme makes a much better performance than the Baseline Mode, the improved gain reaches to around 190% on average.

Figure 5-26 compares baseline Scheme, Simple Relay Scheme and Cooperative Relay Scheme in terms of the CDF of energy efficiency, which is measured in (cell capacity)/bandwidth/(energy consumption).

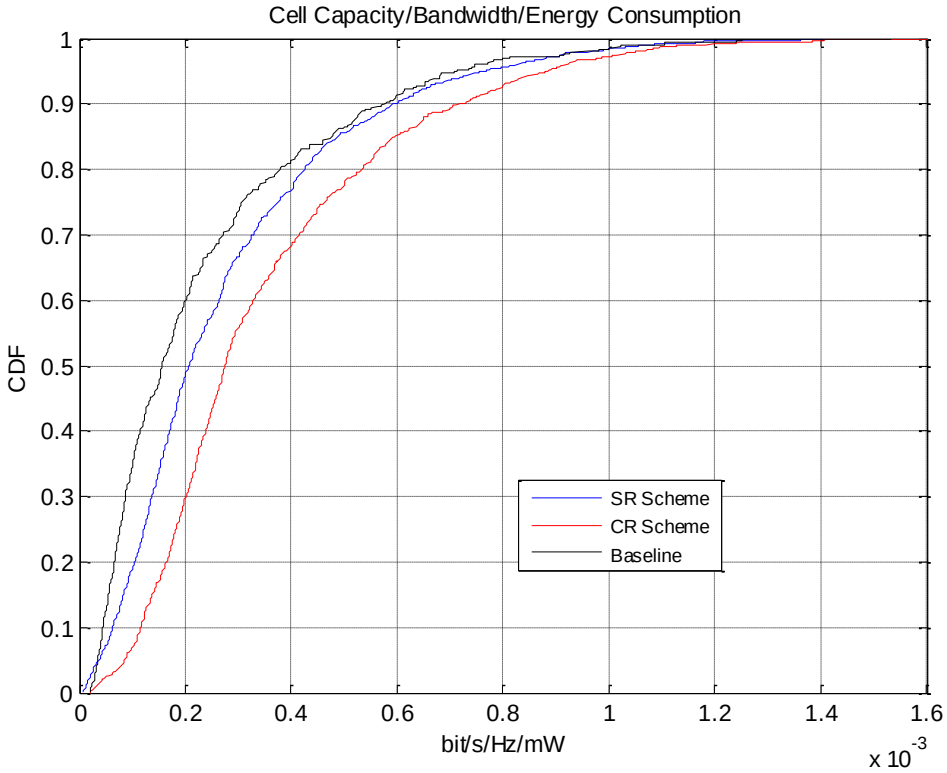


Figure 5-26: Comparison of different scheme for energy efficiency, part 2.

The simulation configuration Figure 5-26 is the same as that of the simulation in Figure 5-25 except that the energy efficiency is defined as (cell capacity)/bandwidth/(energy consumption) instead of (cell capacity)/(energy consumption).

As shown in the figure, both the SR Scheme and CR Scheme perform better than the baseline Scheme, the SR Scheme gives in average gain of about 34% over the Baseline Scheme, while the CR Scheme has a gain of about 76% above average.

5.3.5 Conclusion

Two algorithms are presented in this section for the intention of improving cell capacity and energy efficiency. Meanwhile, two transmission schemes are proposed to validate the performance of the presented algorithms by simulation in the sense that the presented algorithms are embodied in the transmission schemes.

From the simulation results, both the Simple Relay Scheme and the Cooperative Relay Scheme improve the cell capacity when compared to the base line. The CR Scheme is better than the SR Scheme.

When it comes to the energy efficiency defined as cell capacity/energy consumption, both the CR Scheme and the SR Scheme outperform the baseline. The energy efficiency increase for the SRimproved by CR Scheme is more thaneven near to twice than that of the baseline.

Also if the energy efficiency is defined as cell capacity/energy consumption/ bandwidth, both the Simple Relay Scheme and the Cooperative Relay Scheme gets a better performance than the baseline.

5.4 Map of the Cooperative schemes for Heterogeneous Networks

5.4.1 Mapping for the Power On/Off HetNet Use Case

5.4.1.1 The Centralised Scenario

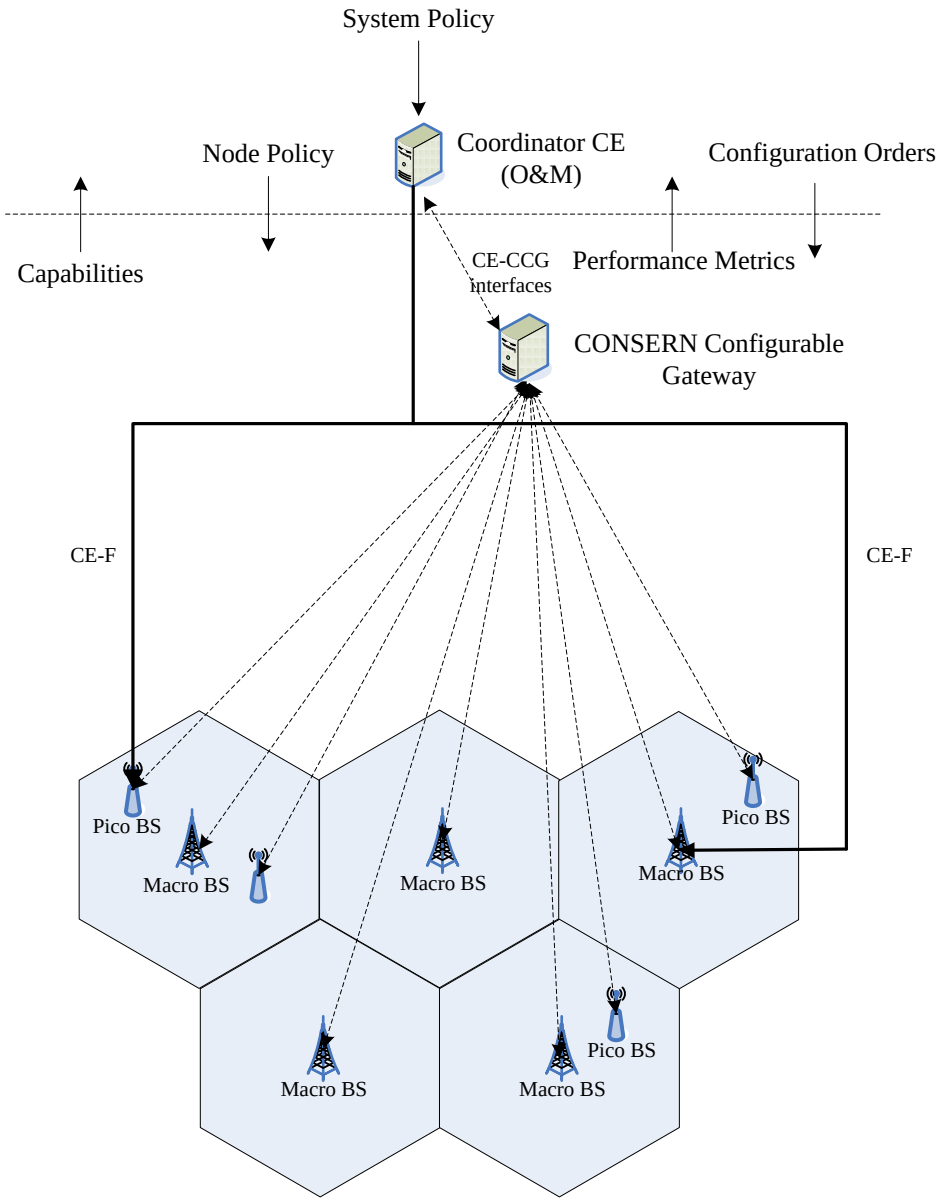


Figure 5-27: The: Mapping for the Power on/off centralised scenario.

This sub-section describes the mapping between the CONSERN entities/functions and the corresponding functionality for the HetNet scenario. The HetNet scenario can be divided into two sub-scenarios, the centralised and the distributed scenario. In the centralised scenario, a Coordinator collects and keeps all the information of the eNBs under its control and whenever needed decides on

actions to reconfigure[1] them in order to save energy. In the distributed scenario, the reconfiguration decisions are autonomously made by the eNBs themselves.

In the centralised scenario, a Coordinator CE resides in the Operation and Maintenance (O&M) system and is built from the logical functions of a full-fledged CONSERN Entity (CE) (except for the Monitoring function) and the CONSERN Policy Manager (CPM). The CPM provides a human-network interface to the network operator to provide high level network policies. Each eNB is in this scenario considered as being a Functional Unit (FU).

In a legacy cellular system monitoring of performance metrics is made by each eNB and reported to the O&M system. In the CONSERN architecture there's a monitoring functionality residing within the CE (CCE) but as this is not needed when implementing CONSERN only this legacy monitoring is considered in the following. The contextual data collected at the eNB is sent to the Communication services (COM) function within the Coordinator CE via the CONSERN Configurable Gateway (CCG). Execution commands to reconfigure eNBs will be sent via the Translation function (TRA).

5.4.1.2 The Distributed Scenario

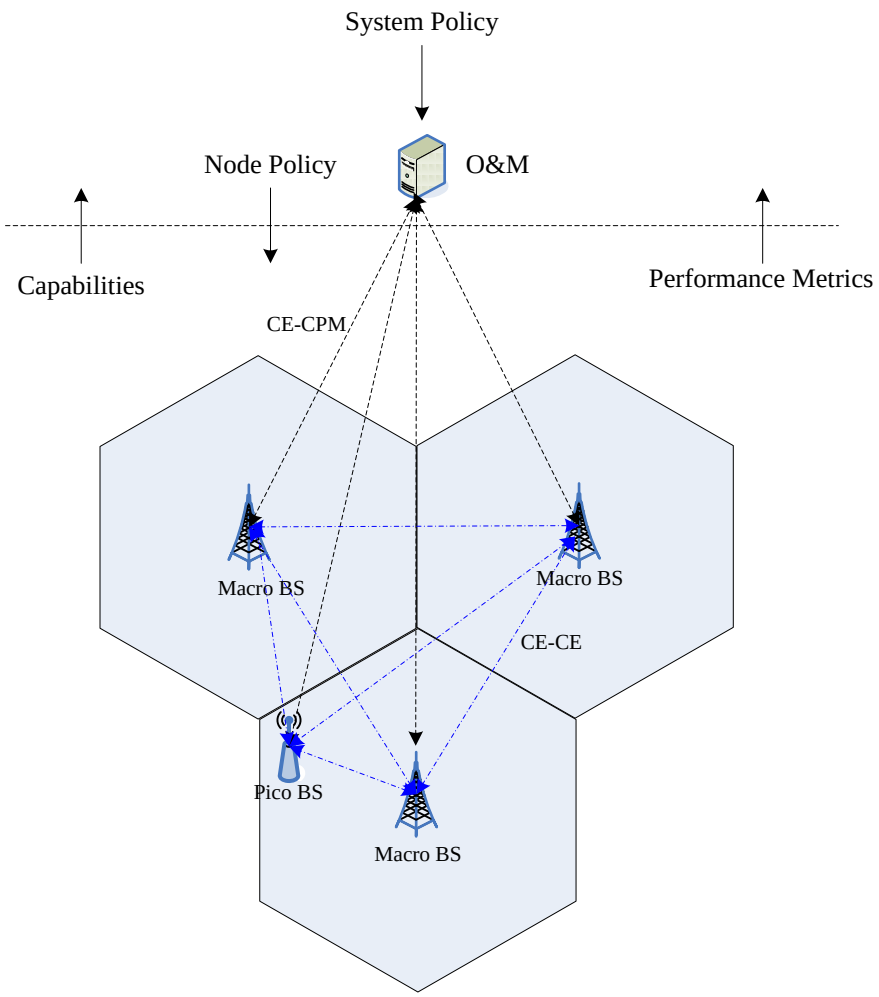


Figure 5-28: The: Mapping for the power on/off distributed scenario.

[1] Note: In the power on/off use case, a configuration is defined as a binary vector where the elements indicate whether an eNB shall be switched on or off.

In the distributed scenario, the Coordinator role is distributed to each eNB and the system policies are downloaded by the operator to each eNB. In this scenario each eNB constitutes a CE by itself. Since in the distributed scenario the CPM still resides within O&M system and the policies has to be distributed to the individual eNBs (the KBO, Knowledge Base Ontology), there is a need for the limited CE-CE interface variant called CE-CPM between each eNB and the CPM.

Similarly to the centralised scenario, monitoring is performed by each eNB. However, the collected contextual data is in case not forwarded to the O&M system but used by the eNBs themselves to decide upon reconfiguration actions. Node reconfigurations are negotiated between the eNBs using the CE-CE interface.

5.4.2 Mapping for the Cooperative Distributed Antenna Use Case

The Cooperative Distributed Antenna use case adopts a distributed model, where the eNB and the connected RRHs (Remote Radio Head) constitute a CE.

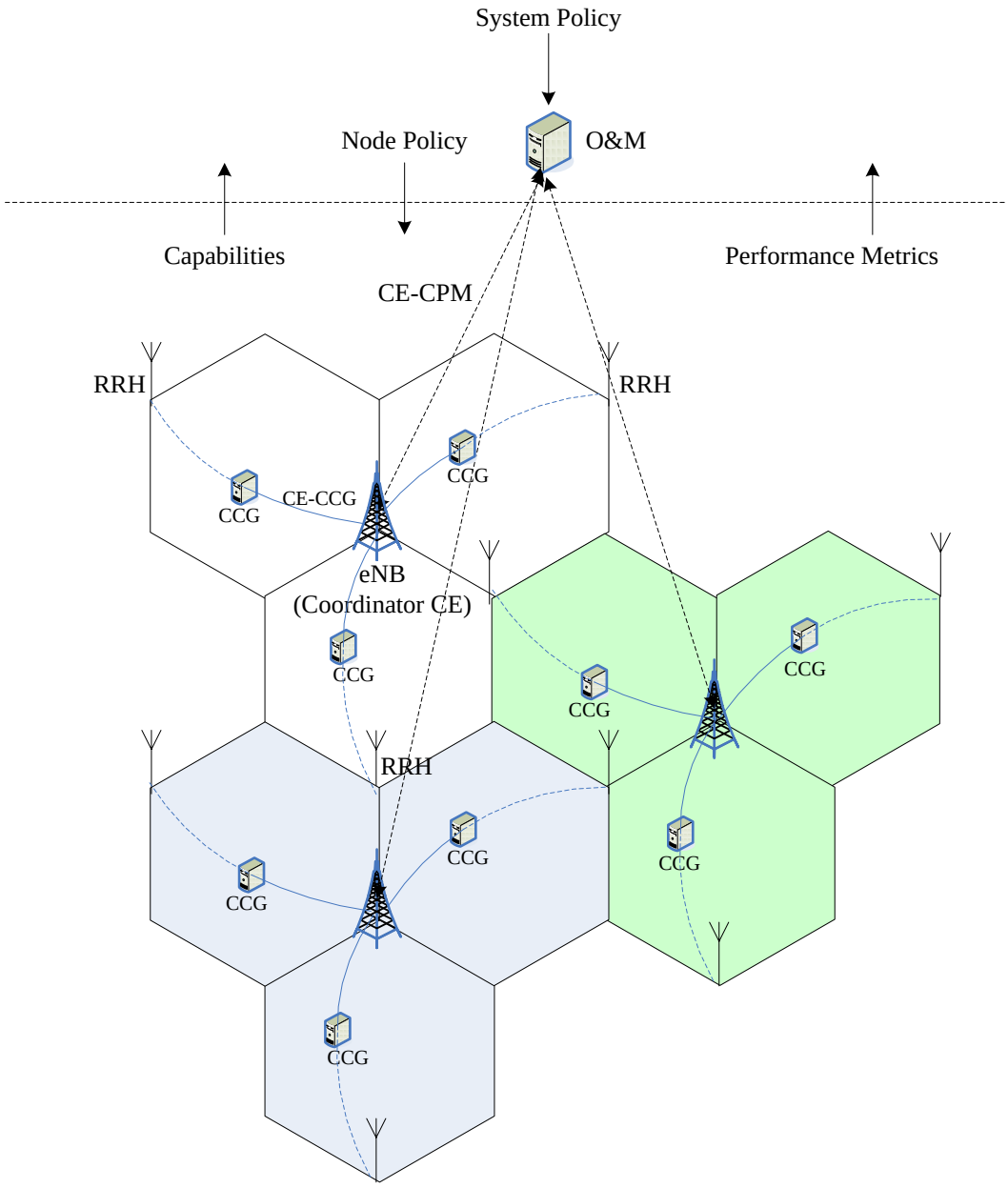


Figure 5-29: Mapping for the Cooperative Distributed Antenna use case.

The Coordinator role is distributed to each eNB and the system policies are downloaded by the operator to each eNB, the reconfiguration decisions are autonomously made by eNBs themselves.

The CPM resides within O&M system and the policies are distributed to the individual eNBs. The interaction between eNB (coordinator CE) and CPM is via the CE-CPM interface.

The monitoring is performed by the RRH. And the collected contextual data is forwarded to the eNB which decides upon reconfiguration actions. The collected contextual data is sent over the CE-CE interface (via the Communication services (COM) function) to the Coordinator CE, i.e., eNB.

5.4.3 Mapping for the Cooperative Relay Use Case

The Cooperative Relay use case adopts a distributed model, where the donor eNB and its related relay nodes constitute a CE.

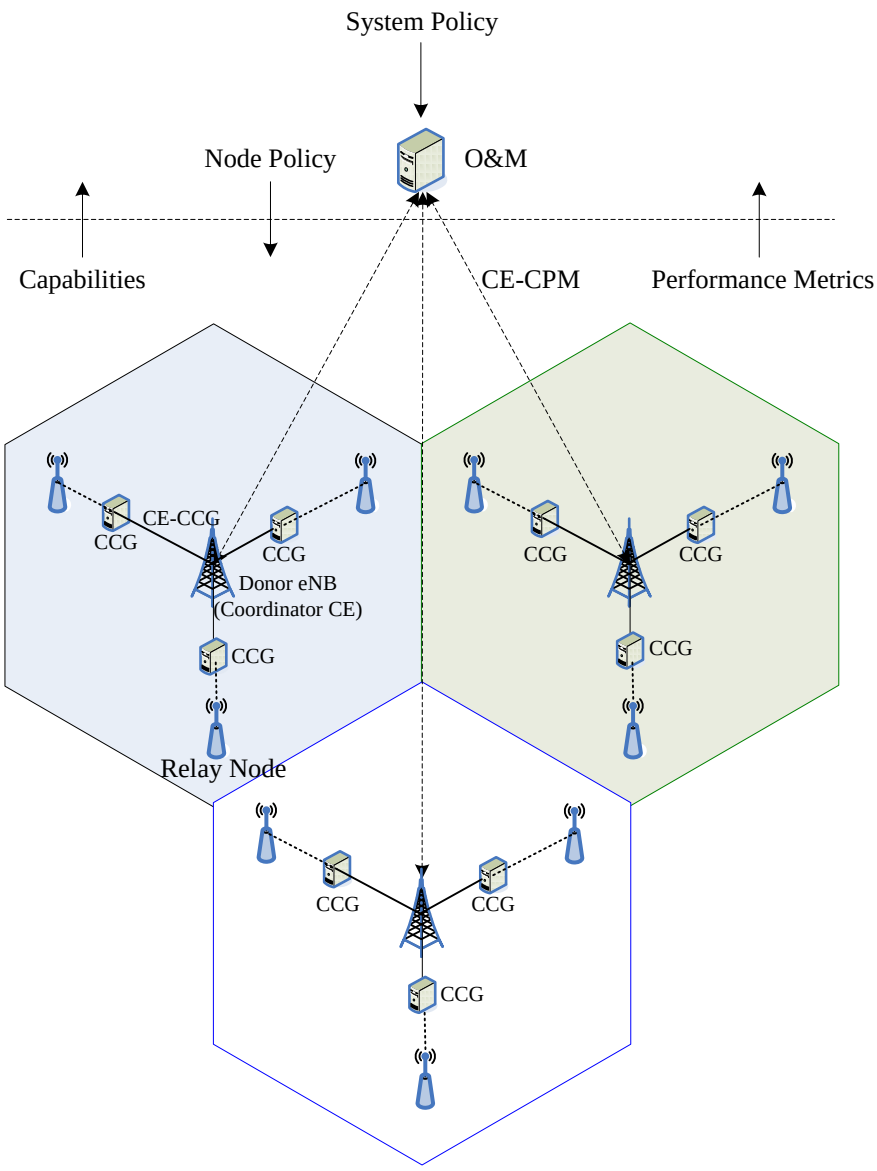


Figure 5-30: Mapping for the Cooperative Relay use case.

The Coordinator role is distributed to each donor eNB and the system policies are downloaded by the operator to each eNB. The reconfiguration decisions are autonomously made by the donor eNBs themselves.

The CPM resides within the O&M system and the policies are distributed to the individual donor eNBs. The interaction between the donor eNB (coordinator CE) and CPM is via the CE-CPM interface.

The monitoring is performed by each relay node and the collected contextual data is forwarded to the donor eNB in order to decide upon reconfiguration actions. The collected contextual data is sent over the CE-CE interface (via the Communication services (COM) function) to the Coordinator CE, i.e., the donor eNB.

5.4.4 CONSERN Entity Mapping to the Heterogeneous Networks

5.4.4.1 The Knowledge Base Ontology (KBO)

The Knowledge Base Ontology (KBO) plays a central role in the system as it in most situations holds information about the past behaviour of the network. The basic information that is kept is related to the policies of the Policy Provider which in our case equals the cellular network operator. Policies are high level rule sets which the network has to comply with in order to fulfil the operator's goals.

The KBO also holds information about the neighbouring nodes' capabilities, used parameter values and possibly also some of the neighbours' rule sets that will often be used by the neighbour in negotiation actions. By keeping this latter information the number of negotiations may be reduced. Examples of capability parameters are among others, frequency range, power transmission profile, and node type e.g., relay, infrastructure node etc.

Another type of information stored in the KBO is the outcomes of executed node configurations. The process to minimise the energy consumption is iterative in the way that starting from an initial network node configuration (power setting) new configurations will be iteratively exploited in order to find an optimal solution. The tested node configurations will be stored in the KBO in order to minimise the need to revisit configurations that have proven to be bad, or to quickly find a configuration that has been proven to work well in a similar situation. The Learning function will to this end cooperate with the Decision function.

5.4.4.2 Decision Making

The Decision Making function is involved when making decisions about future configurations. The decisions are based on the measurements received from the Monitoring function and information stored in the KBO. Once the reconfiguration decisions are determined, they are distributed to the Execution function. In a HetNet scenario it comprises the functions Autonomic Control, Cooperation and Self-growing forming the cognitive loop able to perform decisions. The decisions made are to switch on/off network nodes such as an eNB, RRH or a relay.

The Autonomic Control (AUC) function provides localized decisions in the sense that no information exchange with the environment is needed or performed. In the distributed scenario under study this function plays no role as all decisions are then made through cooperation with neighbouring nodes.

The Cooperation (COP) function makes decisions that require cooperation of nodes but without taking into account the self-growing aspects of the network. It operates in a higher level than the AUC since it takes more complex decisions. It can also control the operation of the AUC. In all the HetNet use cases, except for the centralised scenario, this function decides on the next node configuration in the iterative search towards the optimal configuration. In the centralised scenario under study this function plays no role as all decisions are then autonomously made by the Coordinator CE (O&M). Decisions for the Cooperative Distributed Antenna and the Cooperative Relay use cases are in always made through cooperation between network nodes.

The Self-growing function (SGN) is able to cope with changes in the network topology, i.e., when new network nodes are added or removed from the network.

The Cooperative Distributed Antenna use case and the Cooperative Relay use case, the Decision Making function is collocated with the eNB/donor eNB. The Decision Making function makes decisions based on the performance metrics received from the Monitoring function within the scope of the cell area corresponding to the eNB/donor eNB.

Particularly in the case of Cooperative Relay, the decisions are made at eNB according to the information measured by monitoring function..and in a pace proportional to the time-scales of the measured information reporting.

5.4.4.3 The Monitoring function

The Monitoring function monitors certain performance metrics (e.g. cell load) and when one or more of these metrics reach pre-defined operator thresholds they are reported to the Decision Making function which consequently may act. The reporting may be periodic or be triggered by some events, e.g., the system powering on. In order to make the performance metric measurements as reliable and accurate as possible they shall be made close to the node where the UE is located.

The monitoring function is located in the CE in a CONSERN network. In the power on/off use case, monitoring is performed by each eNB as of today so there's no need for this CONSERN functionality. In the centralised scenario the eNBs regularly report information to the Coordinator that is needed for the CCE to decide upon actions to lower the network's energy consumption. The information may consist of measurements of the cell load, number of users, etc. In the distributed scenario the monitored information is used by the eNB itself to decide upon reconfiguration actions. In the Cooperative Distributed Antenna and Cooperative Relay use cases resides in the RRHs and relays, respectively.

5.4.4.4 The Execution function

The Execution function executes the reconfiguration decisions made by the Decision Making function. The reconfiguration decisions are sent to the eNB/donor eNB or the relay via COM. The function also collects information about the result of reconfiguration actions. It informs the Learning function about the results and also stores them in the KBO for the Learning functions to act upon later.

The Execution Function executes the reconfiguration decision according to the indication from the Decision Functions, e.g., adjusting the transmission power of the relay node/RRH in the use case of Cooperative Relay/Cooperative Distributed Antenna.

5.4.4.5 The Learning function

From the contextual data stored in the KBO (e.g. operator policies, nodes' capabilities and earlier reconfiguration results) the Learning function proactively builds knowledge in order to foresee the result of future configuration changes, thus minimising the signalling between network nodes to save energy. The result of the learning process is stored in the KBO for future use.

5.4.4.6 The Communication Services (COM)

The Communication Services (COM) function is mandatory to implement in all CEs and enables communication with other CEs or Functional units (FU). In the centralised scenario, measurement reports from the eNBs are forwarded by the CCG to the COM function in the Coordinator CE. Configuration orders from the Coordinator are not sent through COM but from TRA, see section 5.4.4.7. In the distributed scenario, because each eNB is a CE by itself, communication between eNBs is done via COM in order to negotiate and agree upon reconfiguration actions.

Besides the communication services the COM function also provides auto-discovery of changes in the network topology, i.e., addition or removal of eNBs. The function monitors the state of the node and its environment. In case a node's environment change (e.g. a node is added or removed from the network) the function informs the SGN (within the Decision Making function) which may then take appropriate actions to reconfigure the network.

The COM function also plays an important role in the CONSERN architecture as it provides bootstrapping mechanisms.

5.4.4.7 The Translation function (TRA)

In the CONSERN architecture, the Translation function (TRA) communicates with non-CONSERN enabled network nodes, so called Functional Units (FUs). It translates the commands made by the Execution function into commands understandable by the FUs. In the centralised scenario, configuration orders are sent from the Coordinator to each eNB by TRA. In the distributed scenario, the configuration orders are sent from COM, see section 5.4.4.6

5.4.4.8 The CONSERN Policy Manager (CPM)

The CONSERN Policy Manager (CPM) is a CE which provides the interface to the network operator and it holds the policies defined by the operator to control the network's high level behaviour. The policies are defined at network initiation but can be changed at any time during the network's run-time. In both the centralised and distributed scenarios the CPM is internal to the O&M system so the CE-CPM interface does not have to be specified. Examples of operator defined policies are:

- Energy optimisation algorithm to be used,
- Prioritise to keep macro eNBs switched on before micro eNBs (or vs. versa),
- Daytime, night time policy.

5.4.4.9 The CONSERN Configurable Gateway (CCG)

The CONSERN Configurable Gateway (CCG) is a CE which provides an interface making it possible to communicate with legacy (non-CONSERN enabled) network nodes. In the power on/off use case the gateway translates and forwards measurement messages from the eNB to the Coordinator CE and legacy eNBs. Since in the distributed scenario also the eNBs are CEs, there's no need for any CCG.

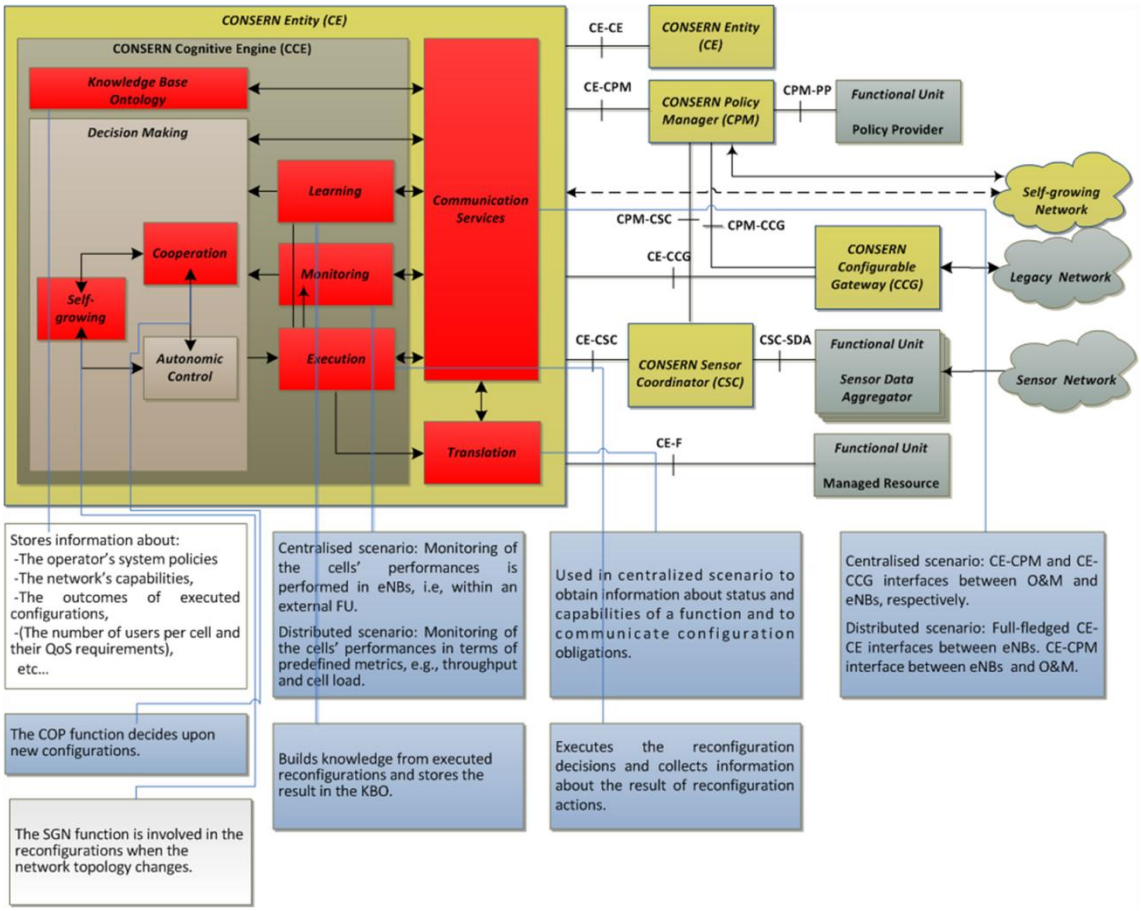


Figure 5-31: The Coordinator CE Functional architecture mapping.

CONSERN Entity (CE)	
CONSERN Cognitive Engine (CCE)	
Knowledge Base Ontology (KBO)	Stores information about: The operator's system policies The network's capabilities, The outcomes of executed configurations, (The number of users per cell and their QoS requirements), etc…
Decision Making	The COP function decides upon new configurations. The SGN function is involved in the reconfigurations when the network topology changes.
Learning	Builds knowledge from executed reconfigurations and stores the result in the KBO.
Monitoring	Centralised scenario: Monitoring of the cells' performances is performed in eNBs, i.e, within an external FU.

CONSERN Entity (CE)	
	Distributed scenario: Monitoring of the cells' performances in terms of predefined metrics, e.g., throughput and cell load.
Execution	Executes the reconfiguration decisions and collects information about the result of reconfiguration actions.
Communication Services (COM)	Centralised scenario: CE-CPM and CE-CCG interfaces between O&M and eNBs, respectively. Distributed scenario: Full-fledged CE-CE interfaces between eNBs. CE-CPM interface between eNBs and O&M.
Translation (TRA)	Function not used in HetNet

Table 5-7: The Coordinator CE functional architecture mapping.

6. Resiliency – Fault Identification

As described in D1.1 [11] we consider that the CONSERN network consists of several network elements with diverse capabilities. More specifically, in the identified use cases the presence of WiFi APs, UMTS femto cells, sensors of several types etc, is assumed. Thus, information fusion and resiliency schemes that assure the efficient information fusion as well as the validity of the available data are needed. Towards this direction, we propose the introduction of an outlier detection scheme that will enhance the CONSERN's network with the attributes of resiliency and efficient information fusion.

The proposed solution is based on a two level approach. Initially, each network element evaluates the gathered information in an autonomous manner. Then, the measurements are being evaluated in conjunction to information from neighbouring network elements of the same or different types. The neighbourhood information is being disseminated to the network via an efficient information fusion scheme. In the following subsections the outlier detection scheme is described in detail.

6.1 Outlier detection analysis and modelling

6.1.1 Autonomous level

As mentioned afore, the proposed outlying detection technique consists of two separate phases. In the initial phase, each network element evaluates each measurement against the rest of the gathered data. More specifically, we propose the use of a non parametric statistical scheme [27] [28] based on the confidence interval. The basis of the proposed solution is Chebychev inequality [29].

Theorem 1:

If the random variable X has a mean μ and variance σ^2, then for every k:

$$P(|X-\mu| \geq k\sigma) \leq \frac{1}{k^2} \qquad 6.1\text{-}1$$

In words, Chebychev inequality states that the probability that X differs from the mean value of the observations at least k standard deviations is less or equal to $1/k^2$.

$$P(|X-\mu| < k\sigma) > 1-\frac{1}{k^2} \qquad 6.1\text{-}2$$

And if we set $\varepsilon = k\sigma$:

$$P(|X-\mu| < \varepsilon) > 1-\frac{\sigma^2}{\varepsilon^2} \qquad 6.1\text{-}3$$

This description enables the set of bounds of a certain probability for the identification of outliers. More specifically, once a new measurement is gathered, each network element evaluates it against the rest of the collected data and decides whether such measurement is likely to be related to the rest of the dataset. The main benefit of the use of the Chebychev inequality is related to the fact that it enables the identification of the probability bounds that a measurement belongs to a specific set of data, without having underlying knowledge about the distribution of the inputs.

6.1.2 Collaborative level

It is of prime importance to evaluate each measurement against the rest of the dataset of the network elements located in the neighbourhood. Such evaluation is also crucial not to create communication overhead, given the fact that for a large number of nodes the message exchange will create significant load. Thus, we propose an efficient voting scheme which correlates the measurements of the monitoring point with inputs from other nodes of the same type and other type of nodes as well.

We propose the use of fuzzy reasoners in order to exploit the merits of fuzzy sets and fuzzy logic in both the information fusion and reasoning procedures for the evaluation of the measurements. Fuzzy logic enables the non-linear mapping of the inputs with the outputs, using the degree of which an input belongs to a specific state. Furthermore, the use of simple "If – Then" rules enables the incorporation of experts' knowledge in the reasoning procedure. Finally, compared to Boolean logic it addresses uncertainties more efficiently; this tackles the ping pong effect as well.

Error! Reference source not found. presents the generic architecture of the proposed scheme, as well as the information fusion scheme between the sensing network elements and the outlier detection points. As depicted, we identify three information flows, one from the network element which is the outlying detection point, one from the neighbouring network elements of the same type and one more from different sensing type points. At this point it should be underlined that several flows of different type sensing elements could be available; for each of these sensing elements a different information flow should be incorporated in the outlier detection/information fusion scheme.

The decision scheme is based on five main operations, namely, the fuzzification of the inputs either of the outlier detection point, or the neighbourhood measurements, the communication of the fuzzified values, the quantification of the neighbourhood observations, the inference process, and the defuzzification.

1. Fuzzification of the inputs either of the outlier detection point, or the neighbourhood measurements. Each network element obtains the readings from a specific interface; these readings are being fuzzified through predefined membership functions. These membership functions map the reading to a degree of truth (ex. X low and Y medium).
2. Communication of the fuzzified values. The fuzzified values are being communicated to the information broker. The information broker gathers information from all types of sensing devices. The main reason for such process is to limit the communication overhead to the network, given the fact that the information broker is going to gather data from all the underlying sensing points and it will provide them back processed data.
3. Quantification of the neighbourhood observations. Once the information broker has received information from the neighbourhood, proceeds in the quantification of the received observations in order to materialize the neighbourhood view. Several methods have been proposed for such quantification [30]; sigma-count factor is used in the proposed scheme:

$$\sum Count(F) = \sum_i \mu_F(x_i) \qquad 6.1\text{-}4$$

   Where X = $\{x_1, ...,x_n\}$ is the set of neighbourhoods and F is a the property of interest (i.e. load, motion etc).
   Then, the neighbourhood observations are being characterized using a fuzzy majority quantifier for the deducing about the neighbourhood's state. The key idea is to identify a statement/solution that "is an option (or a set of options) which is 'best' acceptable by the group" of the observers. Several majority quantifiers exist in the literature, most quantifier is used in the identified scheme:

$$\mu_{most}\left(\frac{\sum Count(F)}{|X|}\right) = \mu_{most}\left(\frac{\sum_i \mu_F(x_i)}{n}\right) \qquad 6.1\text{-}5$$

Where

$$\mu_{most} = \begin{cases} 1 & for\ \ x \geq 0.8, \\ 2x - 0.6 & for\ \ 0.3 < x < 0.8 \\ 0 & for\ \ x \leq 0.3 \end{cases} \qquad 6.1\text{-}6$$

4. The inference process. The inference process is based on the individual measurements as well as the in the quantified neighbourhood observations (i.e. the quantified neighbourhood observations are available in the information broker and are communicated to the monitoring points). Fuzzy logic inference engine is based on rules of the following structure:

   IF s_1 IS F_{i1} AND s_2 IS F_{i2} AND .... s_p IS F_{ip} AND
   Q_{n1} IS F_{j1} AND Q_{n2} IS F_{j2} AND .... Q_{nq} IS F_{jq} AND
   THEN o_1 IS A, o_2 IS B;

   Where
   - s_i is the fuzzified sensor value,
   - Q_{nj} is the quantified neighbourhood observations,
   - F_{ik}, F_{jl}, are the input fuzzy sets,
   - o_1, o_2 are the outputs,
   - A, B are the output fuzzy sets.
5. The defuzzification. The defuzzification procedure provides the final evaluation of the input. The degrees of truth of each of the aforementioned rules are being aggregated and based on this aggregation, a measurement's validity is being evaluated. Several methods are being proposed in the literature as regards the defuzzification, the centroid, the maxima etc. In our approach, the centroid defuzzification method is being used (See Section 3.2.1).

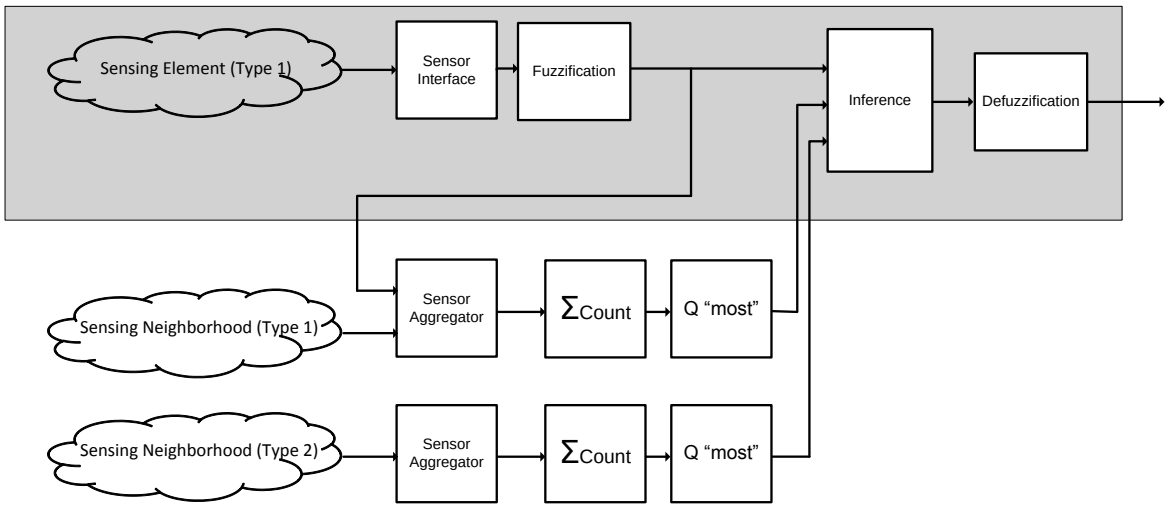


Figure 6-1: schematic representation of the resilience scheme.

6.2 Evaluation Metrics and Evaluation Environment

CONSERN evaluation follows the roadmap posed in D1.1 [11]; in this deliverable, the scenarios, use cases and system requirements were defined in detail. Furthermore, a set of attributes capturing the main characteristic of CONSERN networks are described. Figure 2-1 of D1.1 provides the links between the aforementioned notions (i.e. scenarios, use cases, system requirements and attributes).

The means for the evaluation of the attributes are the metrics that are a quantitative measure of the degree to which a process possesses a given attribute.

In the case of the proposed fault identification mechanism, the main idea is to identify errors in the measurements following a two direction approach; initially the measurements are going to be evaluated in an autonomous manner and then in a collaborative way, so as to identify inconsistencies in the measurements of the monitoring points' datasets in a short timescale, and then proceed in combination of inputs from several inputs. Thus, the identified attributes of the fault identification algorithm are the situation awareness, the cooperativeness and the dependability. As far as the former is concerned, we change in the available systems in the network, the data collected from the sensors and WSN measurements are considered of prime importance parameters. Furthermore, given the fact that the proposed scheme has a cooperative phase, apart from the autonomous one, we need to identify the effect of our solution to both the control signalling and the overall information exchange, in order to materialize the negative impact of the fault identification algorithm for providing resilience to the CONSERN network. Last but not least are the parameters belonging in the dependability attribute, namely, the mean time between failures and the number of service/purpose failures; such parameters could capture the ability of the sensing points to provide reliable information.

The main benefit of the proposed solution is the validation of the measurements by trying to identify inconsistencies between the inputs from several monitoring points. Thus, the key point of this approach is to have measurements from several input points in a single area that will enable the aforementioned cross-checks. A potential scenario for the evaluation of the proposed solution could be the validity check of the measurements deriving from WiFi APs, UMTS femto cells and motion sensors, located in a specific neighbourhood. The fault identification mechanism model the neighborhood measurements for the load and motion inputs; then each network element is going to evaluate the available information/measurements with the neighbourhood inputs (via the quantification of the neighbourhood observations procedure). The main metrics for the evaluation of a resilience scheme, as the one proposed in this section, could be the success rate in the identification of errors on the one hand and the message exchange in the other; these two metrics will capture the benefits (identification of errors) and drawbacks (communication overhead) of the introduction of the proposed method.

6.3 Map on the CONSERN Functional Architecture

Deliverable D4.2 [14] presents the CONSERN's functional entities and their relation in order to provide a solid background for CONSERN's architecture. Figure 6-2 provides the CONSERN entity's functions of the fault identification mechanism. More specifically, Monitoring, Cooperation, Autonomic Control of the CONSERN entity's functions are being materialized, as well as the presence of the CONSERN's Sensor Coordinator and the Sensor Data Aggregator is assumed, in conjunction to their enhancement with new capabilities.

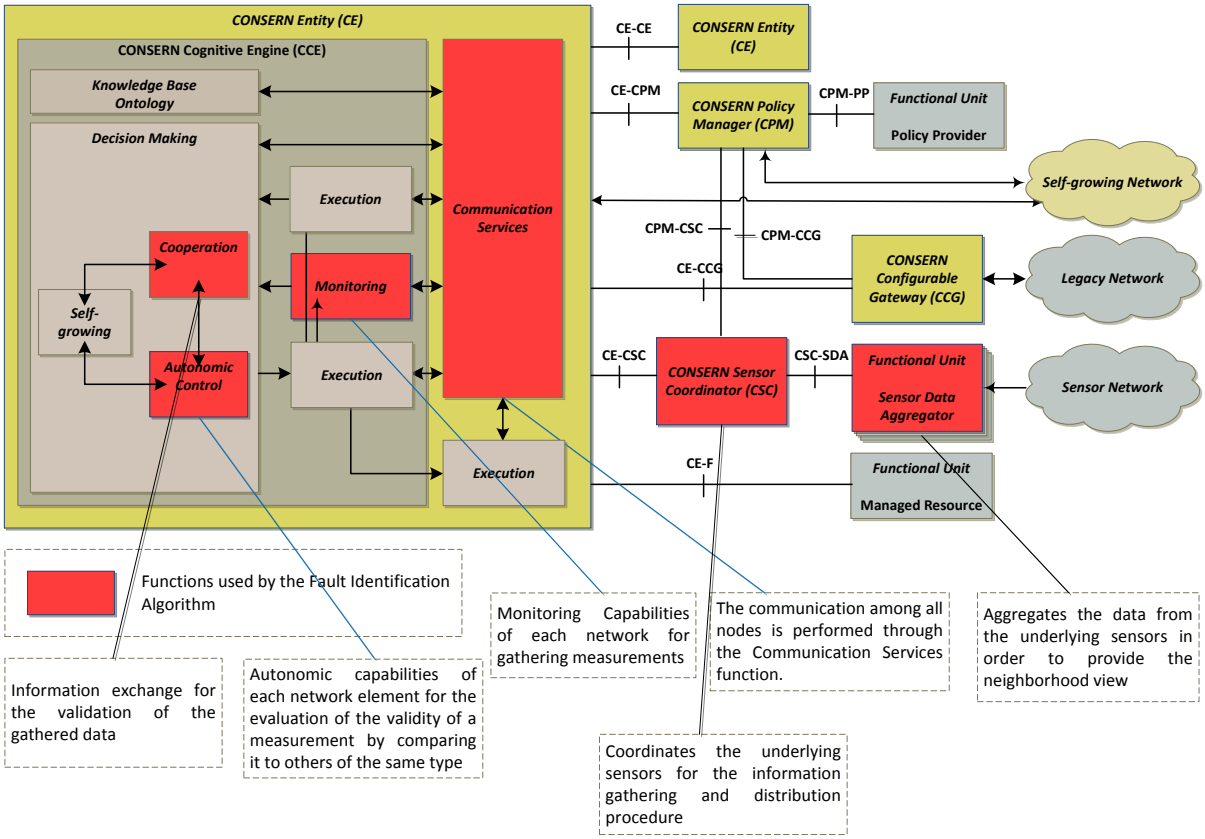


Figure 6-2: Mapping of the outlier detection scheme to the CONSERN functional architecture.

As captured by Figure 6-2 a set of functions need to be instantiated; also cooperation with network elements of other types need to be materialized, namely the Sensor Coordinator and the Sensor Data Aggregator. More specifically, we assume that each network element monitors its environment (i.e. Monitoring function). The monitored data are being evaluated/compared with other measurements of the same type, gathered by the network element (Autonomic Control function) in order to prove their validity. Then, via the Cooperation and the Communication Services functionalities, the network element provides to the neighbouring ones the measurements that, according to its decision engine, have proven to be valid. This information is being gathered by the CONSERN Sensor Coordinator and the Sensor Data Aggregator and is being processed so as to quantify the neighbourhood observations. Then, once again this information is being distributed to the network elements where the cooperative evaluation of the measurements takes place. Thus, a measurement is being evaluated in two phases, the autonomous, where the network element uses its standalone decision engine and one requiring cooperation with the rest of the network elements in located in the neighbourhood.

7. Feedback to CONSERN Functional Architecture

This section summarises the mapping of the mechanisms and studies that are part of the WP3 Cooperation Framework to the first version of the CONSERN Self-growing architecture as defined in D4.2 [14]. It intends to provide a clear view of the WP3 considerations regarding the CONSERN architectural developments and puts together the architectural mappings that have been presented in the preceding sections. This way WP3 communicates how and at what level the architectural functional blocks are addressed through mechanisms and methods being developed and evaluated within WP3.

Moreover, this section presents an updated version of the Information Model that has been initiated by D3.2 [9]. This information model provides an overall abstraction of the CONSERN environment and its enclosed network elements.

7.1 Inside CONSERN Functional Entities – WP3 viewpoint

This section provides a summary of the mapping between the functional architecture as developed within WP4 and the WP3 mechanisms. The objective of this mapping mainly to highlight how the identified functionality is addressed through specific mechanisms which have been developed within WP3; this means that the functional architecture has been challenged against WP3 purposes which include cooperative control and energy optimisations.

In this context for each of the considered functional entities the following information is provided:

- Short description of the CONSERN functional block (from D4.2 [14]),
- Functions and functionalities (from WP3),
- The type of information that is managed by the identified WP3 functions.

Architectural Entity: Knowledge Base Ontology

- Short description: contains information about the state of the network and can be conceptually divided as incorporating knowledge about User, Service, Node, Policies, Events and Actions.
- Information/knowledge elements
    - Network negotiation profile - Incentives: incorporates information regarding the incentives for cooperation for a specific network,
    - Network negotiation profile,- Network Services: incorporates information about the available network services (network capabilities) which are to address/fulfil corresponding incentives for network cooperation.
    - Network cooperation profile: Mapping between incentives and services: this provides knowledge on the network services fulfilling specific incentives for collaboration.
    - Operator’s system policies: policies as defined by the operator reflecting resource management and reconfiguration (e.g. macro-cell, pico-cell, DAS elements, network nodes) targeting energy efficiency in cellular systems,
    - Network Capabilities capturing configurations regarding, for example, assigned frequency ranges, transmission power etc.,
    - Knowledge about previous actions producing outcomes of the executed (re) configurations such as, for example, the (change) in the number of users per cell and their QoS requirements.

Architectural Entity: Cooperation (inside Decision Making)

- Short description: The Cooperation (COP) function carries out cooperative decision making at network node level without taking into account the self-growing aspects of the network.
- WP3 Functionalities
    - Improve data reliability through additional information from relay terminal
        - Decision on reliability levels,
        - Decision on received signal coherency.
    - Decide on new Tx Power based on the message exchange of the interference prices
        - Tx Power set-up (decision).
    - Decide on own receive channel; broadcast receive channel information periodically on all channels
        - Channel reconfiguration (decision),
        - Decision on Receive channel information exchange,
    - Assign discovery nodes; receive profiles of co-located networks from discovery nodes; negotiate cooperation with CE of co-located networks
        - Decision on discovery node identification,
        - Decision on negotiation with co-located networks,
        - Negotiation profiles exchange
    - The COP function decides upon configurations
        - Cooperative decision making on (cellular) nodes configuration – resources activation/de-activation
            - Macro-cell Base Station,
            - Pico-cell base station,
            - Distributed Antenna System element,
            - LTE relay node.
    - Information exchange for the validation of the gathered data
        - Decision on thresholds setting,
        - Decision on data validation and information exchange.
- Information elements
    - Relay messages: user traffic in a relay interference scenario,
    - Channel state information,
    - Interference prices as calculated by each network element taking into account the interference caused to neighbouring elements,
    - Receive channel identifier as decided by each network node,
    - Negotiation profiles as already described,
    - Cellular network node's resources measurements and states (i.e. activated, deactivated, idle, etc.),

- WSN measurements.

Architectural Entity: Self-growing

- Short Description: The Self-growing (SGN) function realizes the self-growing paradigm and provides verification/validation of the self-growing configuration actions executed in the past.
- WP3 functionalities
  - Decision making Cellular system resources reconfiguration in cases of changes in network topology; resources include:
- Information Element
  - Cellular network node's resources measurements and states,
  - Network topology.

Architectural Entity: Learning

- Short description: The Learning function integrates learning capabilities and builds knowledge based on data, policies, events, actions and results.
- WP3 functionalities
  - Fuzzy factor *α* is fine-tuned based on a learning assisted mechanism
    - Parameter(s) configuration based on knowledge of interference prices,
  - Builds knowledge from executed reconfigurations and stores the results in the KBO
    - Knowledge building,
    - Knowledge base update.
- Information elements
  - Interference prices as calculated by each network element,
  - (radio) resources and cellular systems performance parameters,
  - Energy measurements.

Architectural Entity: Monitoring

- Short description: The Monitoring block provides to the Decision Making information related to the state of the node and/or the environment as well as events notification; it, moreover, communicates through Communication Services with the Knowledge Base Ontology for data and information storing.
- WP3 functionalities
  - Observation of transmitted signals from neighbouring mobile terminals,
  - Listen periodically to each of the channels and perform corresponding measurements,
  - Maintain nodes' profile(s),
  - Network monitoring and measurements gathering,
  - Cell performance monitoring.
- Information elements
  - Relay signals (Scenario specific): user traffic in an relay interference scenario,

- Received energy level (per channel),
- Receive channel identifier(s) as decide by each network node,
- Neighbouring nodes profiles (scenario specific),
- Cooperation policies addressing, for example, the actual matching between incentives and network capabilities and driving the decision making regarding collaboration between co-located networks,
- Cell performance metrics (scenario specific),
- Node measurements (scenario specific).

Architectural Entity: Execution

- Short description: performs the execution of the decisions made inside Decision Making entity and communicates with the Translation and the Learning entities.
- WP3 functionalities
  - Signal quantisation in the relay scenario,
  - Configuration action based on the cooperative decision making regarding network elements power set,
  - Receive channel set and services configuration,
  - Cooperation services activation following decision making on cooperation between co-located networks,
  - Reconfiguration execution following, for example cooperative decision making regarding resources activation/de-activation in a cellular scenario.
- Information Elements
  - Relayed signal conveying user and control data,
  - Tx Power values,
  - Receive Channel identifier,
  - Services configuration,
  - Cooperation services profile,
  - Recourses profile.

Architectural Entity: Communication Services

- Short description: The Communication Services (COM) function enables a Cognitive Engine to communicate with Functional Unitss or with other types of Cognitive Engines.
- WP3 functionalities
  - Facilitation of communication between relay terminal and base stations,
  - Exchange of interference prices between network elements and provision of this information to Cooperation functional block, mainly in cases that the network elements participating in the cooperation scenario deploy different types of Cognitive Engines,
  - Exchange of node (energy) measurements and (receive) channel information (RDT),
  - Communication between nodes for discovery and negotiation,

  - Communication of Base Stations (e.g. eNBs) with Policy Manager,
  - Communication of Base Stations (e.g. eNBs) with Configurable Gateway,
- Information elements
  - User and control data (relaying),
  - Interference prices,
  - Node measurements (scenario specific),
  - Discovery and negotiation profiles,
  - Network capabilities and services,
  - Energy measurements,
  - Metrics and KPIs,
  - Energy Policies,
  - Node measurements.

WP3 Architectural Entity: Sensor Data Aggregator

- Short description: Sensor Data Aggregator collects information from a set of sensors and makes it available to other functional entities.
- WP3 functionalities
  - Information gathering from considered sensing nodes,
  - Information distribution,
  - Data pre-processing – data aggregation,
- Information elements
  - Sensors' profile,
  - Sensed data (scenario specific).

Summarising it is worth noting the following:

- The technical work which is ongoing within WP3 has been mapped to the CONSERN Self-Growing Functional Architecture. This way, a clear link is provided between architectural and functional considerations which have been developed around the Self-growing paradigm (as part WP4 work) and specific mechanisms for cooperation problem solving (as core of WP3 work),
- Based on the presented mapping a preliminary evaluation of the CONSERN functional architecture has been elaborated highlighting that the first version of the functional architecture captures and covers the technical work of WP3,
- This also reflects that cooperation key aspects (i.e. network and node discovery, negotiation, cooperative problem solving and information exchange) are also of crucial role for deploying self-growing capabilities at node and network level,
- WP3 mechanisms address most of the architectural entities; in this way a "breaking down" of the architectural blocks is initiated which is expected to be taken into account by WP4 in the context of the architecture elaboration, based on WP4 work plan,
- Additionally to functional mapping, the main information elements have been identified, which are managed within each architectural block or exchanged between functional

entities; such work is completed in the next section where the updated information model is presented thus completing WP3 inputs to WP4 at architectural and semantic level.

7.2 Information Model Elaboration

In this section an updated version of the information model which is being considered within WP3 is presented. WP3 employs a number of cooperative enablers and mechanisms which consider specific viewpoints of deployed network(s) and network nodes featuring certain capabilities, measurements and information exchanges. For such an extensible approach, in the sense that for each mechanism different algorithms have been developed and different studies have been defined a common semantic reference is needed which also provides an abstraction of the managed environment, the smart elements and the managed resources. Moreover, this information model will be communicated to WP4 in order to be taken into account for the elaboration of the CONSERN self-growing architecture focusing on the specification of interfaces.

Elaborating on the procedure that has been presented in D3.2 [9] this updated version of the information model is based on the following concepts types (following the modelling approach of the IEEE P1900.4 information model as overviewed in [22]):

- Concept Identifier: a unique identification of a managed entity, e.g. a network, a network resource, a network element, etc,
- Concept profile: usually, a profile incorporates information types which either don't change or change at large time intervals, i.e. static information; this includes, for example, identification of the resource type(s), related capabilities and general (supported) configurations,
- Concept measurements (if applicable): this includes certain measurements which can be performed within the context of a managed resource. For example, measurements may include observed parameters related to energy, performance, delays, etc.

In this context the information model provides a conceptualised view of the CONSERN cooperation environment through the following abstract entities:

- Network
    - Network Profile,
    - Network Measurements,
    - Network Cooperation Profile,
    - Network Incentive(s),
    - Network Capabilities.
- Network Operator
    - Network Operator Profile,
    - Network Operator Policies.
- Cell
    - Cell Profile,
    - Cell Measurements.
- Network Element
    - Network Element Profile,

- Network Element Measurements,
- Network Element Energy Profile,
- Wireless Sensor Network Element
  - WSN Profile,
  - WSN Measurement.
- Base Station (Cellular Systems)
  - Base Station Profile,
  - Antenna.
- Link
  - Link Profile,
  - Link Status.
- User,
- User Device .

The updated information model concepts and parameters are presented in the following UML models which abstract the Wireless Network as composed of Network Elements and featuring various types of measurements and capabilities.

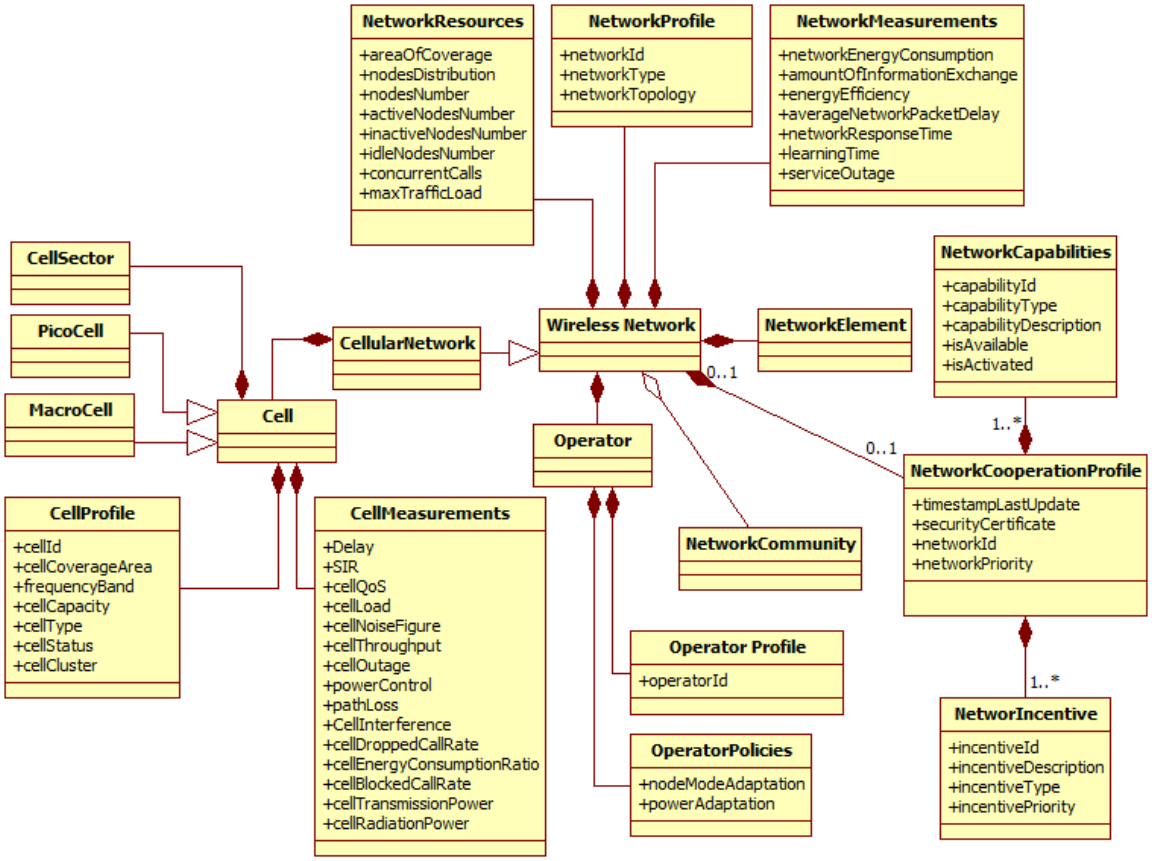


Figure 7-1: UML model for the Wireless Network concepts.

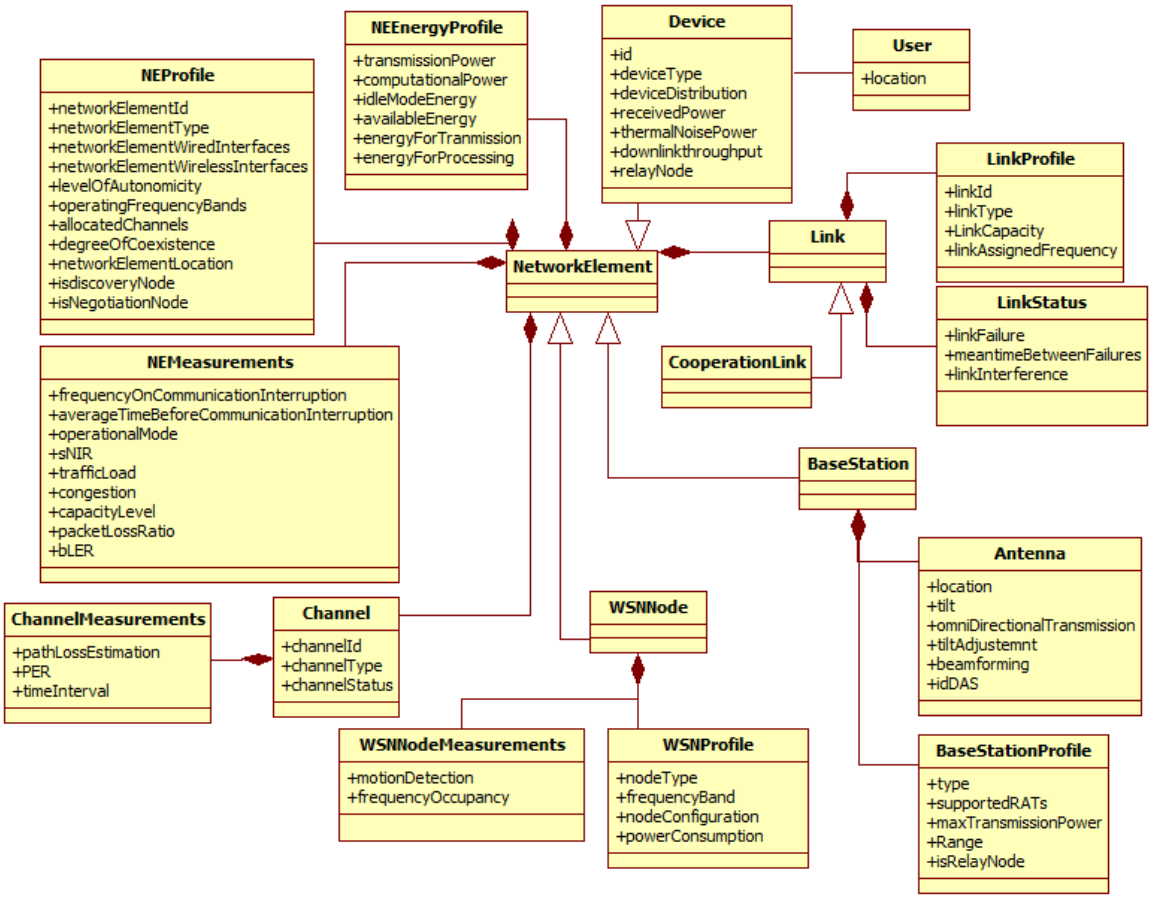


Figure 7-2: UML Model for the Network Element concepts.

8. Conclusion

CONSERN D3.3 has provided progress achieved in the context of the CONSERN cooperation framework by different working items and studies which have been elaborated by the WP3 partners.

More specifically, the Cooperation Framework was presented and the different framework components for each of the WP3 working items and solutions were also described.

CONSERN cooperative studies cover a wide range of deployment scenarios focusing on energy awareness and efficiency. In this context, the following studies have been described:

- Energy savings in Cellular Systems
    - Macro and pico level within LTE environments,
    - Distributed antenna systems (DAS) in LTE environments,
    - Cooperative relaying featuring Relay nodes in LTE environments
- Cooperative power control in ad-hoc communicating nodes applicable to
    - eNodeBs
    - WLAN access points
- Physical Layer studies for Energy savings in Home Environment
- MAC Layer studies for Energy savings in Office Environment
- Energy gains in Wireless Sensor Networks
    - Discovery, negotiation and collaboration
    - Featuring difffernet network capabilities and focusing on traffic sharing between WSNs and WSN nodes

The above presented studies have been elaborated based on the SOTA studies and use cases' analysis (provided in D3.1 [22]), and the problems definition as extracted by the considered use cases, the system models and the formulations (provided in D3.2 [9]). Such elaboration includes:

- Presentation of developed algorithms for the mentioned studies,
- Presentation of the evaluation framework (simulation, prototyping and evaluation metrics),
- Presentation of cooperative optimisations related to energy efficiency,
- Presentation of energy-gains results,
- Mapping to the Functional Architecture as developed within the context of D4.2 [14],
- Identification of the way forward towards completing the described studies.

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