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Deliverable D3.2

Design of Energy-Aware Networking and Cooperation Mechanisms

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Abstract

This deliverable brings forward how cooperation between network nodes and elements can be used for energy-aware cooperative decision and control. It builds on the cooperation enablers which were studied in D3.1 and presents system models which will be used in future research. Along with these models, mechanisms for energy-efficient cooperative designs are presented.

Executive Summary

Low energy communication between one or multiple networked devices is envisioned to be fundamental in future systems. One of the aims of the CONSERN project [1] is to develop solutions for such systems through autonomic and cooperative approaches. Through use cases developed in D1.1 [2] of the project, Work Package 3 (WP3) aims at developing techniques and mechanisms which are tailored to suit these use cases. In the CONSERN framework, WP3 focuses on:

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

In D3.1 [3], a set of enablers for energy-aware cooperation and decision control were identified. The current deliverable extends the ideas and puts these enablers into a context of models for a certain subset of the use cases in [2].

In the deliverable the following use cases are studied and some ideas for their solutions are given:

- In an indoor environment relays can be used to mitigate interference between co-located femto base stations using the same frequency band. Cooperative relay communication and network coding is proposed to be used, based on the information fusion mechanisms, to increase the network performance and reliability.
- A Heterogeneous Network (HetNet) is a network consisting of a mix of network nodes of various types. In such a network environment, relays can be used to save energy by cooperating and thus lower the total number of needed transmissions. Similar results can be obtained by using distributed antenna systems. OPEX is a big cost for network operators and by switching of network nodes at times with low traffic demands energy can be saved. All these HetNet use cases build on the idea to save energy by directing the transmitted energy and utilising nodes that are close to the user.
- In Cognitive Radio using licensed bands, it's of utmost importance that secondary users do not interfere with primary users. Cognitive Radio power control is thus seen as important and will be studied.
- Today, there exist many devices which make use of unlicensed bands for their communication, e.g., WiFi, Bluetooth, ZigBee and DECT. It is anticipated that as the number of devices grow the interference between them will increase. To this end, CONSERN will focus on detection of and cooperation between various co-located network devices.
- Wireless sensor networks can be used to collect environment information and help other networks in their cooperation. However, sensor raw data is often unreliable so ideas information fusion will be used to improve the quality.

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Acronyms

Acronym	Meaning
AI	Artificial Intelligence
BS	Base Station
CDF	Cumulative Distribution Function
COG	Center of Gravity
CSG	Closed Subscriber Group
CSI	Channel State Information
CR	Cognitive Radio
DECT	Digital Enhanced Cordless Telecommunications
DeNB	Donor eNB
eNB	E-UTRAN Node B
E-UTRA	Evolved-UMTS Terrestrial Radio Access
GDAS	Generalised Distributed Antenna System
IoT	Interference over Thermal
ISM	Industrial, Scientific and Medical (Radio Bands)
KPI	Key Performance Indicator
LLR	Log Likehood Ratio
LTE	Long Term Evolution
LTE-A	LTE-Advanced
MDP	Markov Decision Process
MIMO	Multiple-Input and Multiple-Output
MT	Mobile Terminal
PA	Power Amplifier
PCA	Principal Component Analysis
PRB	Physical Resource Block
QoS	Quality of Service
RB	Radio Block
RL	Reinforcement Learning
RN	Relay Node
RU	Resource Utilisation
SINR	Signal to Interference plus Noise Ratio
SIR	Signal to Interference Ratio
SISO	Single Input Single Output (cf. MISO, Multiple Input Single Output or MIMO, Multiple Input Multiple Output)
SNR	Signal to Noise Ratio
SVM	Support Vector Machine
TD	Temporal Difference
TVWS	TV White Space
UE	User Equipment

UMTS	Universal Mobile Telecommunication System
WiFi	Wireless Fidelity
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network

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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. The main goal of the project is to design mechanisms and solutions in order to enable 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.

Previous work in [3] has focused on techniques and technologies enabling energy efficiency. In order to form realistic studies, these enabling technologies were based on a set of use cases which were studied in [2]. This deliverable, D3.2, titled “Design of Energy-Aware Networking and Cooperation Mechanisms”, builds on these earlier deliverables whilst, a number of use cases has been selected from [2] which are considered as suitable for cooperative and energy-efficient networking. The use cases considered cover different aspects of energy-aware cooperation in an office or home residential area. The research for these use cases covers:

- Interference mitigation between femto base stations; cooperative relay will be studied where the relay is used to help the base stations transmissions,
- Energy-efficient power control algorithms for Cognitive Radio systems operating in unlicensed spectrum bands,
- Methods to save energy in an environment where independent networks using the same or different communication technologies,
- How to save energy in heterogeneous cellular networks; algorithms for adaptation of network elements to the most energy efficient pattern utilizing knowledge from previous actions of network nodes.

The deliverable is structured as follows:

Section 2 discusses the selected use cases and motivates why they are seen as suitable for energy-aware cooperative mechanisms. For each of the use cases the problem to be solved is defined and the used methods are outlined. The section also discusses information management in general terms.

Section 3 describes the energy-aware networking system models including the assumptions that will be used for analysis and simulation studies.

Section 4 proposes solutions how to solve the problem in terms of analysis or by means of simulations incl. algorithms and optimization methods.

Section 5 discusses some key issues and trade-offs which will be taken into consideration in the studies.

2. Problem Formulation for Use Case Optimisation and Information Management

CONSERN deals with a wide range of different scenarios to which autonomic and cooperative solutions can be applied. In [2], use cases which are connected to CONSERN scenarios were presented. A specific subset of this list of use cases which is related to cooperation was identified in [3]. This is to filter use cases which are better related to the scope of WP3. In Sections 2.1 - 2.4, the use cases from [3] which will be further studied in the course of WP3 are identified. Problem formulations for energy efficient optimisations are given and for each use case, the system models to be used are developed. In addition, section 2.5 discusses information management and, more specifically information modelling, elements abstraction and information fusion. This topic is not explicitly related to any of the specific use cases but is seen as a general problem occurring in many cases.

The list of use cases which are explored in this document are listed in the following table.

UC ID	Title
UC-2/NKUA	Energy Optimization in an Office environment under coverage constraints,
UC-5/HWSE	Switch on-off of nodes for Energy Efficiency in Heterogeneous Networks,
UC-6/HWSE	Cooperative DAS nodes configuration,
UC-7/HWSE	Cooperative relay for Energy Efficiency,
UC-11/IBBT	Energy optimization of co-located wireless networks in a home/office environment,
UC-14/TREL	Cooperation Enablers in Home Gateway Environments.

Table 2-1: List of use cases.

2.1 Cooperative Network Coding

One distinctive trend in the evolution of mobile network topology is the reduction in cell size in densely populated areas, motivated primarily by the surge in cell phone users and the need to provide broadband services. This simple fact has opened up new challenges and opportunities for both vendors and network operators to meet the ever increasing user expectations in performance and quality of service (peak data rate, latency, mobile speed, spectrum efficiency, coverage, power consumption, cost-per-bit). In fact, very small home-based cells dramatically reduce the distance between transmitters and receivers, which in turn allows reducing the transmit power and increasing the overall energy efficiency. Very small cells also allow a much higher spatial reuse, which translates in higher spectral efficiency end eventually higher throughput.

On the other hand, a large scale deployment of femtocells implies that users may be operating their home-based or office-based base station (BS) deciding whom to grant access to their private cell. Therefore, conventional interference management strategies applied to macro-cells, such as centralised and accurate planning of the cell layout and assignment of users to the best serving BS, e.g., the one experiencing the strongest signal) are no longer possible. Therefore, interference between user-run closed-subscriber group (CSG) femtocells becomes a major obstacle for dense and unregulated deployment of base stations in residential buildings. New techniques have to be devised to deal with this.

This section is focusing on the use-case scenario UC-14/TREL, where 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. The interfering femtocells may be located, for example, in adjacent flats in a residential building. In this case, a relay node can be used to assist the decoders by providing side information to help resolve the interference.

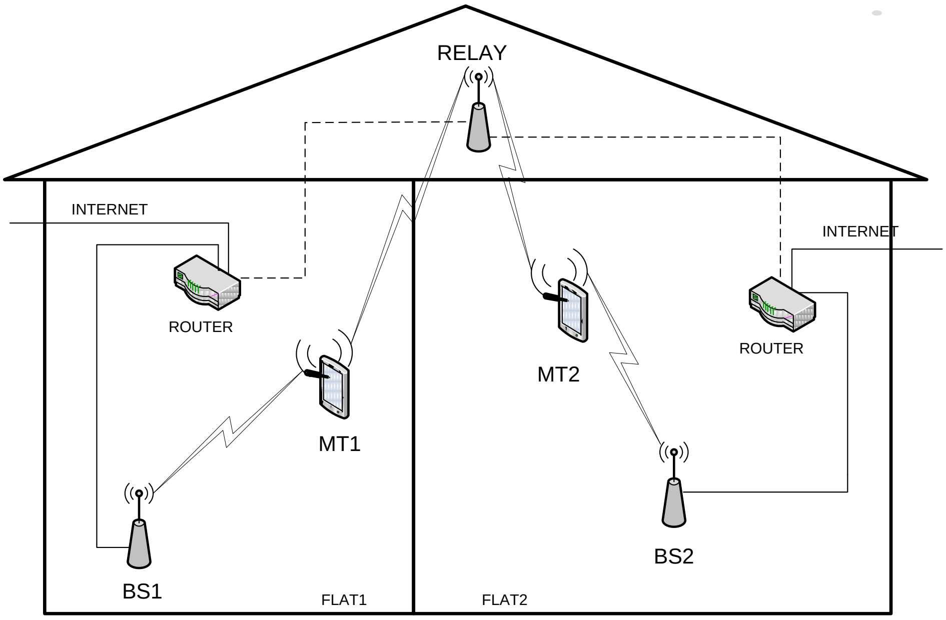


Figure 2-1: Use case scenario where an out-of-band relay node assists two interfering receivers.

In Figure 2-1, the typical use-case scenario is depicted. 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 channel with the receivers: in case of a downlink transmission from BS1 to MT1 and BS2 to MT2, the relay can broadcast some side information wirelessly to the mobile terminals, e.g., through a WLAN; in an uplink configuration, the relay broadcasts the side information to the two base stations, e.g., through an Ethernet connection or a WLAN. The relay listens to the interfering signals transmitted by the BS's in a downlink scenario, or by the terminals in an uplink situation and performs a quantise-and-forward operation on the signal without decoding the data. The side information is forwarded to the decoders on a separate narrowband channel and consists of quantisation index and channel state information (CSI) for the channels between the two transmitters and the relay [35]. The receivers utilise the relay information to improve their data detection.

This strategy can be viewed as an "analogue form" of network coding since the relay does not need to decode the information sent by the transmitters. However, the side information forwarded by the relay is, in general, encoded in a digital message. In other analogue network coding schemes proposed in the literature, for example [36], the relay performs an amplify-and-forward operation, where a scalar relay function is optimised for maximal mutual information between the source and a single destination.

Other network coding strategies encompass a more complicated decode-and-forward operation, whereby the relay decodes the data sent out by two communicating network nodes, performs some digital processing on the symbols, e.g., the well known XOR, and then broadcasts the new message to the destinations, which coincide with the transmitters. This configuration corresponds to the well known "butterfly network" example in digital network coding [34] and it was shown that one (1) bit parity information forwarded by the relay yields two (2) bits increase in throughput. Similarly, it has been recently shown in [35] that one (1) bit relayed under a quantise-and-forward strategy can achieve the same throughput gain of two (2) bits, one for each receiver in the low noise regime.

2.2 Energy Optimization in an Office Environment

The vast proliferation of wireless telecommunication devices has paved the way for anywhere/everywhere communications. At the same time, however, this trend imposes new challenges that are mandatory to address in order to ensure their optimal operation given energy and capacity constraints. Especially in dense environments, such as an office environment, the problem complexity becomes even higher since the coexistence of a plethora of devices results in spectrum scarcity and high interference levels. In turn, this may have a significant negative impact on the quality of service provision realized by the users.

The notion of Cognitive Radio (CR) has emerged as a promising paradigm to resolve the above mentioned impediments by allowing the coexistence of licensed (primary) and unlicensed (secondary) network elements with negligible interference and at the same time provide an efficient telecommunication environment that is able to exploit opportunities through the dynamic utilization of resources.

For Cognitive Radio systems operating in unlicensed spectrum bands where different operators may co-exist, efficient power control mechanisms are required for achieving low energy and addressing “green” aspects. More specifically, power control is needed in order to mitigate interference and provide extended nodes’ battery lifetime, reduced cost and improved long-term reliability. For example, if all nodes transmit at the maximum valid power level then every user is causing significant interference to all the others, which can result in reduced total utility from the network perspective and, finally, poor QoS from the user perspective.

Furthermore, power control mechanisms could also address the self-growing nature of such networks through optimized monitoring and adaptation strategies. This assumes that the power control mechanism is both cooperative and distributive so as to enable network’s scalability. In parallel, such schemes, when combined with efficient decision making capabilities (that consider many different situation awareness elements), constitute an ideal environment with network leveraging capabilities that would benefit both operators and users in terms of capacity and enhanced service realization respectively.

Use case UC02/NKUA looks in this direction and a cooperation power control algorithm for Cognitive Radio systems is proposed that is applicable to a dense office environment. The algorithm promotes cooperative decision making on network nodes and targets optimal configuration and/or operational mode based on information exchange within the neighbouring network elements. Additionally, different network operators are able to identify which is the optimum network configuration regarding the users’ needs in the corresponding area and fuse certain rules and policies so as to further enhance the overall Cognitive Radio system performance.

2.3 Cooperative Network Protocols

With the proliferation of wireless solutions for the home and office environments, the unlicensed ISM band is becoming more and more crowded with collocated systems that operate different wireless technologies in this band, e.g., WiFi, Bluetooth, ZigBee and DECT. Since these technologies do not cooperate, overheard packets from different networks represent obstructive interference. With the installation of an increasing number of wireless devices, the number of interference sources and packet collisions increases drastically, reducing the overall throughput, energy efficiency and reliability [54]. An effective solution to this problem is to create awareness between collocated networks, and as a second step to share resources between those collocated networks.

The approach taken in use case UC-11/IBBT is to enable independent Wireless Sensor Networks (WSN) to cooperate and use each other’s nodes for more optimized and more energy-efficient routing. Nodes can even decide to exchange control-code in view of having more advanced functionality such as, e.g., QoS support functions. Furthermore, in most cases, one or more collocated WiFi access points (APs) will also be present. The WSN can provide interference information to nearby WiFi nodes, giving them a global view on the environment. WiFi nodes can then make appropriate actions to reduce interference. The WiFi nodes in their turn can provide relay services and localization information to the WSN and, hence, reduce the load in bandwidth and energy constrained WSNs. Current solutions do not provide generic mechanisms to detect co-located networks which are operating at different frequencies or different radio modes [55], to adapt transmission parameters and routing strategies in view of merging networks, to define and agree on incentives for accounting the benefits of the cross-network cooperation [56], and to exchange code for enhanced functionalities. Furthermore, no strategies exist for global interference reduction (today interference avoidance is based on local decisions).

Thus, one of the main goals will be to develop intelligent sharing of resources (such as information, services, infrastructure, etc.) between independent networks using the same or different communication technologies.

2.4 Cooperative Energy-efficient Optimisation in Heterogeneous Environments

2.4.1 General

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 users during peak traffic periods. In particular cellular networks are dimensioned for peak hour traffic, however traffic intensity varies and the peak traffic occurs only during short periods during a day. Also, in Heterogeneous Network (HetNet) environments 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-utilisation of the radio infrastructure and radio resources is a waste of power. Significant power savings could be achieved by, e.g.:

- Reducing the number of active radio access infrastructure by switching off a number of base stations at different tiers (micro, pico, femto etc.),
- Complete switching off cells which are underutilised, while reconfiguring the remaining infrastructure nodes to provide the same radio coverage and the required capacity/QoS,
- Changing other radio resources including carriers, bandwidth, PA, cells etc.,
- Benefiting from the deployment of lower power infrastructure nodes that provide capacity in short range,
- Utilizing state-of-the-art cooperation technology that exploits spatial diversity and cooperative transmission techniques such as network coding or/and coordinated multi-point transmission.

2.4.2 Powering On/Off of Base Stations

The goal of the research is to find design principles for distributed autonomic algorithms which reduces the energy consumption and which later can be refined and implemented. The radio network is a heterogeneous network (HetNet) consisting of sites with different power transmission, coverage and capacity profiles. The main objective in such a scenario is to maintain coverage and a sufficient QoS with a minimum of energy consumption. More specifically, given a heterogeneous environment scenario (UC-05/HWSE) and traffic intensity distribution, the research objectives for energy-efficiency are:

- Which switch on/off solution is the one providing maximum energy savings?
- Which nodes will switch off and how can other nodes compensate?
- How do nodes cooperate in order to converge to this solution?
- What kind of iterative algorithms can be applied or used?
- How fast can the algorithms converge to reach a solution?

In general, a transmission power minimization problem will be defined based on the assumptions of different scenarios. The assumptions of the different scenarios will comprise the system model for further analysis. A general statement for the power consumption minimisation problem is as follows:

- Within 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 to provide coverage to all users and meet relevant Key Performance Parameters (KPIs).

(KPIs are user related QoS such as minimum supportable throughput, or maximum delay etc.)

2.4.3 Cooperative Distributed Antennas

Distributed antenna systems (UC-06/HWSE) have traditionally been used in indoor environment, such as malls, tunnels and buildings, to cover dead spots with the help of spotted unshielded coaxial cable to simulcast signal [4]. Since all antennas transmit the same signals incoherently, simulcast shows limited efficiency in fading and interference reduction. Recently, a Generalized DAS (GDAS) structure has been studied in the framework of macroscopic MIMO, which is based on the fact that distributed antennas are geographically separated and physically connected to a home base station.

In previous studies of DAS, especially in the single cell environment, all distributed antenna nodes are powered on in order to achieve the optimal capacity and coverage of the network. As the antenna nodes are uniformly distributed within the cell, some nodes are far away from users. They contribute less to the capacity, comparing to their power consumption. In a multi-cell environment, these nodes might even degrade the capacity because they cause severe interference to other cells. The research performed within CONSERN will focus on how individual antenna nodes are selected and when it is possible to turn off some of them. The energy-efficient way is to power on those nodes that play a main role in achieving the capacity and power off the others. As the number of active antenna nodes (corresponding to the power consumption) might be different for different user, the energy efficiency can also be introduced in the utility function of multi-user scheduler. Thus, the power consumption of the network can be greatly reduced while there remains the capacity gain of DAS.

2.4.4 Cooperative Relays

The goal of this research is to determine how cooperation between relays and BSs can be achieved in the most energy-efficient way, as described in UC-07/HWSE. Cooperative relay can enhance the system capacity by improving the channel quality between a User Equipment (UE) and a BS especially for the UE at the edge of the cell by means of deploying relay nodes in the cell, cooperative relay can also induce spatial diversity in wireless networks without the need for multiple antennas on a single terminal. In dense wireless networks, there are, typically, many fixed relay nodes deployed in the region between the UE and the BS.

Determining which of the potential relays should be selected for cooperation is a difficult problem. For example, for a specific UE, several possible paths to access BS may exist: either UE is accessing BS directly, or UE is accessing BS via relay node corresponding to the destination BS, or BS combines these two paths by means of diversity combination at BS. The optimal access path will be determined based on the optimal system performance, e.g., maximum cell capacity, or minimum network energy consumption. Research work, in this step, is mainly focusing on how to find out the best solution to select the optimal access path for UE access with energy aware capability to reach the maximum system capacity based on a well designed utility function. Furthermore, cooperative relay with Network Coding, selection criterion based on energy saving or the appropriate trade-off between capacity enhancement and energy saving by developing utility function may be studied in the future.

2.5 Information Modeling and Fusion

In this section, information management issues are presented; more specifically information modelling, and information fusion in cooperative environments. Information modelling provides a managed system abstraction, as well as the information items which are processed and exchanged within the system. This provides an additional step towards the smart elements abstraction (as originally presented in [1]), outlines the scope and enables the development of knowledge models and information fusion mechanisms.

As described in [3] the Information Exchange (collaboration) is one of the three axes for the CONSERN cooperation management and control framework and ranges between "no information exchange" and "full information exchange". In case of "no information exchange", it is assumed that network nodes and elements make their own decisions taking into account contextual information which can be sensed or monitored/measured based on own capabilities and configuration. Although this implies local (partial) knowledge of the environment it is still possible to have nodes cooperating at a certain level, as, for instance, in cases of conflict resolution protocols: nodes sense collisions and reacts by giving the opportunity to other nodes to transmit. It should be pointed out that this is a very simple case of cooperation of independent decisions. On the other hand, in the case of "full information exchange" network elements exchange information such as measurements, sensed data, configurations and decisions in order to make final decisions on complex problems or take advantage of other node's knowledge under their own context, e.g., adaptation to energy profile/pattern, etc.

The collaboration axis of CONSERN cooperative decision and control [3] ranges from independent sensing to information and context exchange; moreover, various network elements and WSN nodes are included in the CONSERN managed system; it can, therefore, be presumed that a large amount of data needs to be processed, delivered/exchanged and evaluated. Information fusion mechanisms address processing of sensed data and measurements coming from various sources by exploiting synergies and correlations among the data. In this way, information fusion techniques can reduce the amount of information which is needed to be exchanged, optimise energy consumption and enable infering regarding the behaviour of the entity which is monitored / sensed. Information fusion can be applied to different nature of information and data. However, the actual information items and their semantics are important also because efficient data processing must be carried out according to the application objectives; as mentioned in [3] conceptual representation incorporates the information requirements that the fusion functionality has to address.

2.5.1 Managed System Abstraction

System abstraction or conceptualisation, and information modelling is identified as an initial step for enabling the development of energy-aware mechanisms which are utilising information and knowledge management techniques; it is expected to incorporate and give semantics to all concepts, information items, parameters, and measurements which are part of the CONSERN cooperation management and control framework. In this way, the corresponding mechanisms will be developed and elaborated in a coordinated way. Collaborations and correlations between mechanisms will be easier to model and develop under the awareness of the information items which are being considered by each mechanism. Moreover, information model will provide an overall abstraction of the smart elements which are included within the CONSERN ecosystem as well as the surrounding physical environment. As a second step, a model for capturing partial knowledge is planned to be developed enabling the formulation of global knowledge model in a modular way.

Heterogeneous wireless networks and network elements may apply different constraints; for example, wireless sensor networks have strong constraints regarding power resources, processing power and computational capabilities. Such network elements may not be able to operate on a full knowledge model; this means that a limited view has to be developed. In this sense, it is required to identify the elements' constraints as well as the needs for specific knowledge representation and sharing within CONSERN use cases and mechanisms which are being developed. Moreover, certain information and management functionality needs to be included in the model in order to impact the interfaces specification for cooperation as well as self-growing architecture which is under development in WP4.

In [3] an initial selection has been performed in order to identify the use cases which are most relevant to WP3 activities. This research is focusing on information fusion mechanisms and development of an information model for the use cases being considered as most relevant to WP3 partners' work (Table 2-1).

The following requirements have been already identified within [3] regarding system conceptualisation:

- Platform-agnostic abstraction model to capture the system entities and interrelations,
- Integrate contextual representation to reflect the different context of each concept,
- Incorporate policies, rules and constraints reflecting different technical and environmental contexts,
- Harmonised and interpretable approach on knowledge representation in order to accommodate for example nodes that have limited capabilities and views of the entire system,
- Adopt and develop an approach to model concepts and rules in a formal, agreed and shared way to enable sharing and reusability,
- Support inference and reasoning on the system concepts and relation,
- Capture local knowledge supporting also dynamic composition of the global knowledge by integrating partial knowledge.

2.5.2 Information Fusion and Fault Identification

Considering dense environments, where several WiFi APs and UMTS femtocells coexist, the use of numerous types of sensors for enabling efficient network control under coverage constraints is of prime importance. Thus, the exploitation of information deriving from several inputs is required so as to feed all the autonomic and cognitive mechanisms for the network control. However, data collected from WSNs are often unreliable, constituting decision making procedures taking place using these inputs, unreliable as well. The low cost and low quality sensor nodes have energy (battery power), memory, computational resources, and communication bandwidth limitations. Such limitations are often resulting in unreliable and inaccurate gathered data [39].

Identifying anomalies-outliers (measurements that significantly deviate from the rest of the observations) in the network measurements suggests a tricky task. At first, it should be pointed out that such anomalies are related to several issues, not only faults in sensors. More specifically, the outliers may be related to errors in measurements, actual events and malicious attacks. The identification of the aforementioned outliers is related to the specific characteristic of each outlier type (related to spatial correlations, probabilistic characteristics etc) [38].

The identification of the faults in the measurements enables the network management system to feed the network elements with reliable data and, consequently, provide to the corresponding decision making mechanisms correct measurements. Such mechanisms should take into account inputs from both network elements and sensors in order to identify the non-realistic data. Finally, the outlier detection mechanism has to be a lightweight solution thus suggesting a minimum overhead in the management system.

2.6 Summary

In this section the WP3 scope has been refined and detailed in order to identify the specific use cases which better reflect the WP3 partners' working items as well as corresponding problems and issues which are being addressed towards fulfilling WP3 objectives.

In this sense, the following technical areas have been described:

- Cooperative network coding,
- Energy optimisation in dense environments,
- Cooperative network protocols,
- Cooperative energy optimisation in heterogeneous networks
- Elements abstraction, information fusion and fault identification.

In the following sections, models and solutions will be outlined for those aspects as presented in the document's introduction.

3. System and Energy-Aware Networking Models

In this section system models to study cooperation enabler as defined in [3] will be developed based also on the problems and use cases identification which were presented in section 2. The models will be built on those use cases where cooperation is intended to be used as the enabling technology. A model would capture the system under study as derived by the assumptions and the specifics of the selected use case. It will include the network elements, the architectural organisation and the functions required for implementing the system.

3.1 System Model for Cooperative Network Coding

The use-case scenario described in Section 2.1 can be conveniently modelled by an interference channel formed by two transmitting nodes X_1, and X_2 and two receiving nodes, Y_1 and Y_2 as, depicted in Figure 3-1. In a downlink configuration of the scenario in Figure 2-1, X_1 and X_2 represent the base stations BS1 and BS2, respectively, while Y_1 and Y_2 symbolise the mobile terminals MT1 and MT2. The role of transmitters and receivers is reversed in an uplink configuration.

Same upper-case symbols are used, X_1, X_2, and Y_1, Y_2, to denote the random processes associated to the transmitted message and received message, respectively. The out-of-band relay node listens to the interfering signals sent out by X_1 and X_2 and, without decoding the symbols; it carries out a coarse quantisation of the received symbol Y_r to generate an index. This forms the message X_r, which is forwarded in broadcast to the destinations Y_1, Y_2 on an error-free channel. Note that the relay message does not interfere with the main transmission of X_1 and X_2.

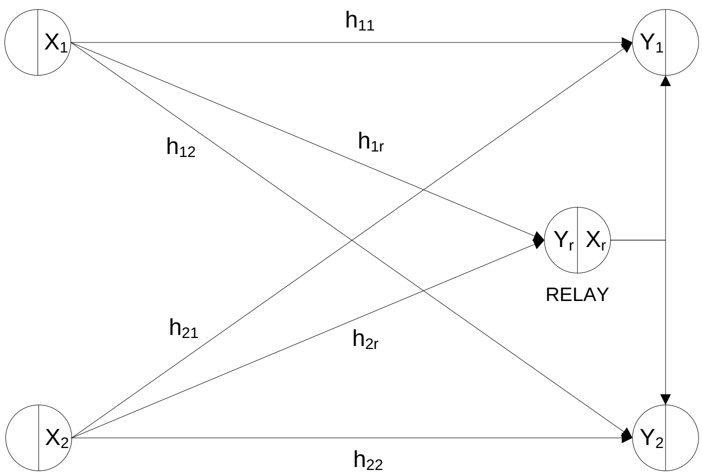


Figure 3-1: System model for the use-case depicted in Figure 2-1.

The transmitters X_1, X_2 and the receivers Y_1, Y_2 form an interference channel. The relay node performs a quantise-and-forward operation of the message X_r, given by a quantisation index. Each receiving node knows its own channel propagation coefficients. The receivers also know the propagation coefficients h_{1r} and h_{2r}. The relay channel to the receivers is out-of-band, i.e. it does not interfere with the transmission of the messages X_1, X_2 and is assumed error free.

It is assumed that the communication links between X_1, X_2 and Y_1, Y_2 and Y_r are modelled by noisy narrow-band channels, whereas the relay message is received error-free. It is also assumed that Y_1 knows the channels h_{11} and h_{21} and similarly, Y_2 knows the channels h_{22} and h_{12}, and the relay knows h_{1r} and h_{2r}. Also, it is assumed that, as part of the relay message, the propagation coefficients h_{1r} and h_{2r} are communicated to the destinations.

The system is described by the following input-output equations

$$\begin{aligned} Y_1 &= h_{11}X_1 + h_{21}X_2 + n_1 \\ Y_2 &= h_{12}X_1 + h_{22}X_2 + n_2 \\ Y_r &= h_{1r}X_1 + h_{2r}X_2 + n_r \\ X_r &= Q(Y_r), \end{aligned} \tag{3.1-1}$$

where n_1, n_2, n_r are AWGN components and Q(.) denotes a quantisation operation.

The side information delivered by the relayed message X_r helps the decoding of messages X_1 and X_2 and by doing so it improves the energy efficiency of the links $X_1 \rightarrow Y_1$ and $X_2 \rightarrow Y_2$. In fact, by incorporating the relay message in the decoding process, the terminals can better resolve the interfering signal, which results in an increase in signal-to-noise plus interference ratio for the same transmit power. Hence, by fixing the target packet error rate, the same average throughput can be achieved for each terminal at a lower transmission power level.

Therefore, the network coding scheme described above can be viewed as a collaborative technique to improve energy efficiency in interfering femtocells. This advantage in terms of energy efficiency is easier to quantify from a theoretical point of view by looking at the increase in mutual information or throughput gain provided by the network coding scheme at high SNR.

More precisely, as a theoretical example, in [35] it is shown that by using a one-bit quantisation to obtain the relay symbol X_r the rate delivered to the destinations Y_1 and Y_2 increases asymptotically by one bit each in the low noise regime. This is possible under the assumption that the observation Yr made by the relay is not statistically identical to either Y_1 or Y_2, i.e. the relay channel vector $[h_{1r}\ h_{2r}]^T$ is linearly independent from $[h_{11}\ h_{21}]^T$ and $[h_{12}\ h_{22}]^T$. Some insight on where the throughput gain originates can be gained by considering the mutual information $I(X_1;Y_1)$ between the transmitted message X_1 and the pair of signals given by the observation Y_1 and the relayed message X_r. Similar considerations apply to the mutual information between the message X_2 and the observation Y_2. It is assumed that after scaling, the signal Y_r/d is quantised to the binary symbol

$$X_r = \lfloor Y_r / d \rfloor \bmod 2 \tag{3.1-2}$$

By introducing the scaled integer lattice *Z/d={..., -2/d, -1/d, 0, 1/d, 2/d,...},* the operation above can be viewed as a quantisation of *Yr* to a point of a binary nested lattice code, where the code symbol '0' is the coset leader of the lattice translate *{2*Z/d}*, while the code symbol '1' represents the coset leader of the lattice translate *{2*Z/d+1/d}*. The mutual information can be decomposed as follows

$$\begin{aligned} I(X_1;Y_1,X_r) &= I(X_1;Y_1) + I(X_1;X_r \mid Y_1) \\ &= I(X_1;Y_1) + H(X_r \mid Y_1) - H(X_r \mid X_1, Y_1). \end{aligned} \tag{3.1-3}$$

It is not difficult to show that as the noise power of *n1* tends to 0, if X_1 and Y_1 are given, X_r becomes deterministic and the term $H(X_r|X_1,Y_1)$ vanishes. Besides, it can be shown that for vanishing noise power, Y_r/d conditioned on Y_1 tends to have an unbounded variance, which implies that X_r tends to a Bernoulli random variable, such that $H(X_r|Y_1) = 1$.

Therefore, in the assumption of Gaussian codes and minimum-distance decoding, such a simple compress and forward scheme can theoretically provide 3 dB reduction in transmit power at each transmitter to deliver the same throughput to the two terminals.

Higher energy saving is theoretically achievable by using more complex multi-dimensional lattice codes for quantisation, which, however, require a much higher computational complexity.

3.2 System Model for Cooperative Power Control

Mechanisms that employ cooperative spectrum sharing in order to maximize the overall system performance and minimize energy consumption are a key evolutionary step for practical cooperative systems. These schemes need to be distributed in order to be applied efficiently in unlicensed spectrum bands. At the same time, the considered schemes should also be able to employ efficient message exchange schemes in order to maximize the overall system utility therefore the related systems are characterized as cooperative Cognitive Radio (CR) systems.

Power control constitutes a critical aspect for a CR network (as presented in 2.2) since it is necessary not only for decreasing the interference among the secondary nodes, but also for ensuring the interference constraint of the primary nodes. Indeed, when the cognitive (secondary or unlicensed) nodes dynamically access to an authorized spectrum, their transmission power must be strictly controlled so that their operations will not affect the primary (licensed) nodes' behaviour and exceed the interference temperature constraints of the primary nodes.

More specifically, the main challenge for power-efficient opportunistic communication in CR networks lies in striking a balance between the conflicting goals of minimizing the interference to the primary nodes and in parallel maximizing the QoS level, e.g. SINR or capacity, of the secondary nodes. Power control has a strong impact on CR's transmission and interference range.

Controlling the transmission power includes determining a distance, or a function of the distance, between a primary device and the cognitive radio device based on sensing information from a spectrum sensing process. The maximum transmit power of the cognitive radio device is then dynamically controlled based on that distance, while considering a worst case scenario of an underlying cognitive radio model, to guarantee a quality of service requirement of the primary device, e.g. [26], [31].

It is important to note that particularly for systems that target low energy consumption the potential gains from power control should be balanced against the cost of the extra signalling that is required for cooperation. This implies that message exchange schemes utilized for the cooperation should be as economic as possible, avoiding costly acknowledge messages and retransmission. In this context, uncertainties in message exchange should also be taken into consideration because real systems do not usually operate in ideal conditions. Finally, the algorithm for cooperative power control should be able to converge to an optimal solution within a finite number of iterations to be viable for large scale applications but also to cope with heterogeneity of the nodes, specifically regarding the co-existence of cognitive and legacy devices.

3.2.1 System Model Assumptions

Cognitive Radio systems operating in licensed spectrum bands with co-existence of both primary and secondary nodes, e.g., as in the case of the TVWS bands require mechanisms for spectrum sensing and spectrum mobility in order to guarantee no interference in the primary user. However, if multiple secondary systems can co-exist with the primary system, then mechanisms for efficient spectrum decision and spectrum sharing, coupled with power control schemes for interference minimization between these systems are also required.

The main assumptions and definitions for the proposed power control algorithm are the following:

- Focus: cooperative power control between the nodes of different secondary systems, e.g., in the case of different operators in the TVWS bands) in order to maximize network efficiency (in terms of capacity and coverage) and minimize interference,
- L is the number of the assumed cognitive nodes,
- M is the number of spectrum areas with same bandwidth,

- Every node selects its transmission power level trying to maximize a utility function. The latter is defined such that the algorithm converges to a maximum within a finite number of steps,
- Message exchange (“interference prices” [32]) is required for cooperation between the nodes is asynchronous, and,
- Fuzzy logic is utilized to enhance situation awareness by compensating for uncertainties that cause underestimation of the interference.

3.3 System Model for Cooperative Network Protocols

As described in Section 2.3, independent networks can profit from the sharing of resources 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.

Our approach aims to globally optimize network resources through negotiation based cross-layer and cross-network optimizations. The following sections describe (i) the components which will be used to design autonomous optimization solutions and (ii) the sub-problems that need to be solved.

3.3.1 Components

The following components are used in the model for cooperative network protocols.

3.3.1.1 Incentives

Each device will have a number of well-defined incentives that describe the preferred high-level network behaviour. An incentive can either (i) describe behavioural aspects of the network (i.e: `limit the battery consumption'); or (ii) express the need for additional functionality (i.e: `get internet access'); or (iii) give an indication of the expected performance network metrics (i.e: `support video streaming').

Incentives describe the `reasons for cooperation': devices will only engage in cooperation with other devices when this cooperation is beneficial for the incentives of the participating nodes. The incentives of a device are typically set by the application, or configured manually by a network administrator.

3.3.1.2 Community

A community is defined as a set of nodes that have derived common incentives (`network goals'). As such, a community describes a set of co-located nodes that have the same network behaviour and the same network goals: they are similar in terms of capabilities (such as available services) and incentives. All devices of a single community should be able to communicate with each other (either directly, or through intermediate devices that are part of the same community.

As an example, the devices of an office building can be divided into the following three separate communities: (i) Wi-Fi enabled devices that are battery powered; (ii) Wi-Fi enabled devices that are plugged into a power line and (iii) UMTS capable devices.

Devices require a trust relation with all other community members before joining a community. Devices that belong to the same owner are implicitly assumed to trust each other. Otherwise, a trust relationship can be established through the use of certificates which are issued by a (remote) trusted certification authority.

3.3.1.3 Optimization Techniques

An incentive can be realized using a large number of networking techniques. For example, the reliability incentive can be improved by using retransmission schemes, by increasing the transmission power or by using advanced error correction codes. These optimization techniques, that influence one or more of the incentives, are called network services. Thus, whereas incentives indicate network goals, network services are the means to realize these goals.

A network service is not crucial for the correct working of the individual communities, but can be activated or deactivated in a community depending on the required incentives of the communities. For example, activating retransmissions will positively influence the reliability, at the cost of a lower network lifetime.

Example optimization techniques are the following:

- Shared routing. This optimization allows communities to interpret and route packets from co-located communities,
- Interference avoidance. This technique allows communities to cooperate by selecting the transmission frequencies that are least harmful for each other,
- Packet aggregation. This optimization reduces the number of transmissions by combining multiple information exchanges in a single packet.

Based on this definition, the distinction between incentives and network services can be thought of as follows: a network service can be activated or deactivated, whereas an incentive indicates a high-level application or management objective.

3.3.1.4 Negotiation Profiles

To enable negotiation, the characteristics of each community are described in negotiation profiles. A negotiation profile should contain at least the following information:

- A timestamp (time of last update),
- A certificate guaranteeing that the community can be trusted,
- The community ID and priority,
- A list of incentives and their associated importance for the community,
- A list of available network services,
- A description of the configurable settings (transmission frequencies, available packet types, etc).

Negotiation profiles are constructed in a hierarchical manner (Figure 3-2). The incentives of the applications are described in an application profile. If only a single application is deployed on a device, a direct conversion from application incentives to device incentives is possible. However, if multiple applications are deployed on the same device, the application profiles are merged into a device profile. In the case of conflicting incentives, different application priorities can be used to prioritize certain incentives. Similarly, the community profile represents a merged representation of the device profiles of all participating nodes.

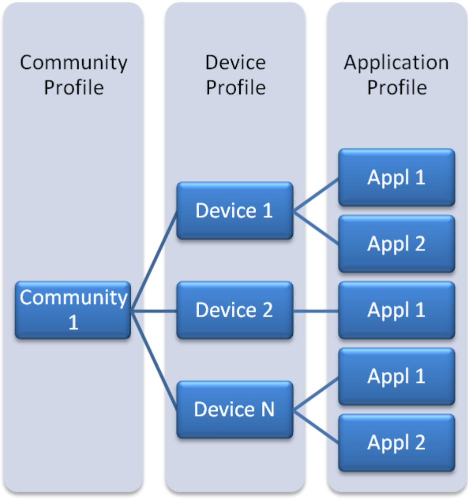


Figure 3-2: Profiles are constructed in a hierarchical manner. One or more application profiles are combined into a single device profile. Similarly, a community profile is generated based on the profiles of all participating devices.

3.3.2 Cooperation Model

By selecting and activating the optimal set of network services in each community, the incentives of each participating community can be optimized. The cooperation model utilizes the components defined in this section to realize a global cross-layer, cross-network optimizations.

The cooperation model is described in Figure 3-3. The model consists of the following five sub-problems [57].

- Creation of communities of similar devices,
- Discovery of co-located communities using heterogeneous communication technologies,
- Negotiation about the selection and configuration of the optimal network optimization techniques,
- Activation of the optimal network optimization techniques,
- Policy enforcement and network monitoring.

The algorithm for each of these sub-problems is described in more detail in Section 4.3.

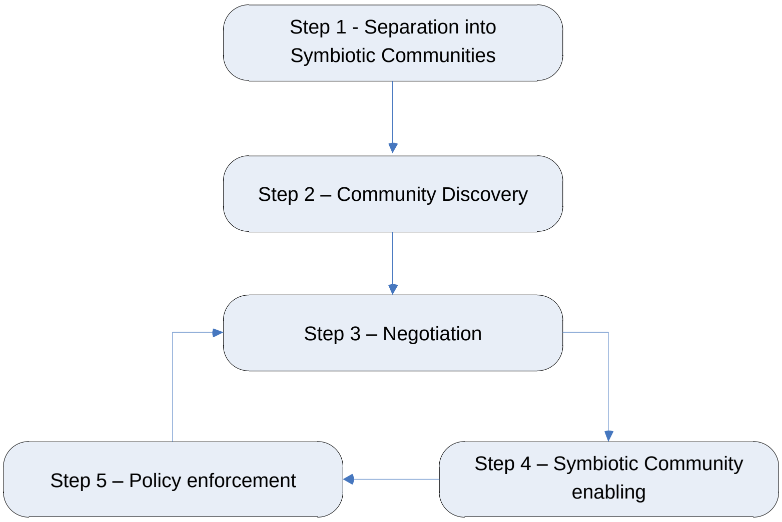


Figure 3-3: The cooperation model of cross-layer cross-network optimization.

3.4 Heterogeneous Network Models

The following three subsections provide models for the three use cases UC-05, UC-06 and UC-07, respectively. The use cases contain the parts which will be used in the studied HetNet scenario. In CONSERN the use cases will be individually studied but as a continuation trade-offs between optimal configurations choices will be of interest in future research.

3.4.1 Power On/Off Energy Consumption Modelling – Macro-Pico Scenario

3.4.1.1 System Model

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 [4]. In 3GPP LTE-A, heterogeneous networks consist of deployments where low power nodes (pico-cells) are placed throughout a macro-cell layout. Figure 3-4 illustrates the network topology scenario that will be used for the simulations.

The network consists of a hexagonal grid of 19 macro base station sites each with 3-sectors with K pico cells are placed within each cell. The pico cells are distributed randomly or clustered according to a distribution typical to a dense user area. Macro and pico cells operate in the same spectrum band. Interference coordination between macro cells is performed. In fact, 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-existed. This assumption will affect the algorithms which are possible in each type of node.

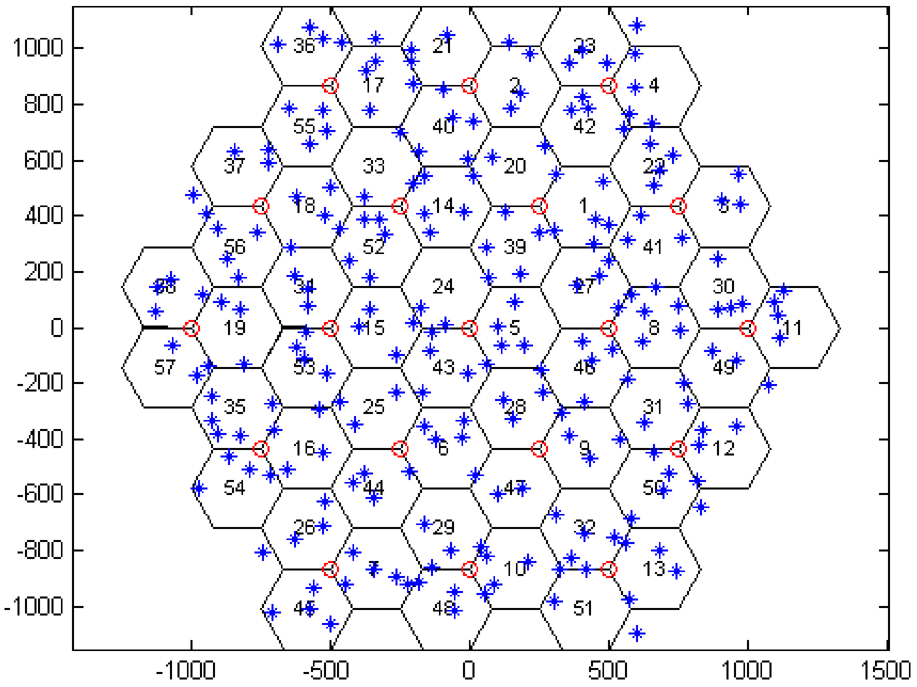


Figure 3-4: Cellular network consisting of 3-sectored macro sites and four pico cells randomly distributed within each macro sector.

Path loss modelling

The total path gain between a UE i and a serving cell j is then obtained with the values calculated as:

$$G_{i,j}\big|_{dB} = G_{distance} + G_{antenna} + G_{shadowing} \tag{3.4-1}$$

The distance path loss $G_{distance}$ is based on a simple formula

$$L_{dB} = L_{const} + \alpha \cdot log\,10(d)$$

with the distance d given in kilometres and $G_{dB} = -L_{dB}$. An example of the path loss as a function of the distance attenuation is depicted in Figure 3-5. The distance path loss models for different UE and cell links are summarized in Table 3-1.

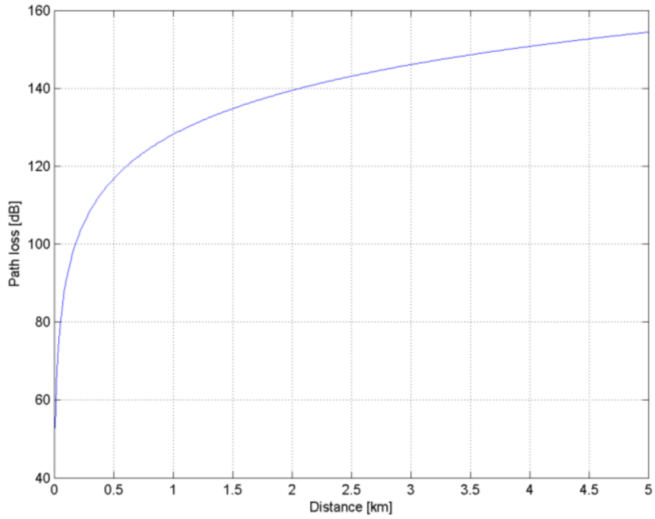


Figure 3-5: Example of the distance dependent attenuation.

Antenna Gains

For the macro sites directed antennas are assumed. The horizontal gain of the antenna directional pattern is given by (3.4.1) and is depicted in Figure 3-6, see [4].

$$A_H(\varphi) = -\min\left(12 \cdot \left(\frac{\varphi}{\varphi_{3dB}}\right)^2, A_{\min}\right), \quad -180° \le \varphi \le 180° \qquad (3.4\text{-}2)$$

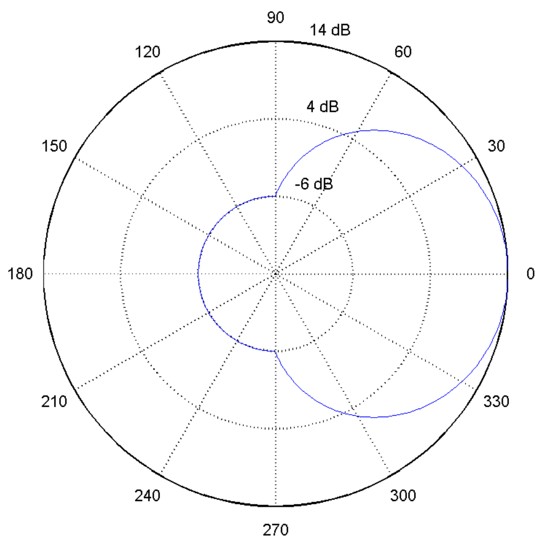


Figure 3-6: Antenna horizontal pattern used in the simulator.

Being low-cost devices, picos have omni-directional antennas with a horizontal antenna pattern gain to any angle given by $A(\phi) = 0$ and an antenna gain of 5 dB as compared to an isotropic antenna. Similarly, UEs are also modelled as using omni-directional antenna with antenna gain 0 dB. The antenna gain is calculated based on the angle of UE's position. The angle is the difference between the main direction of the antenna and the direction between the base station, i.e., the cell node, and the UE as shown in Figure 3-7.

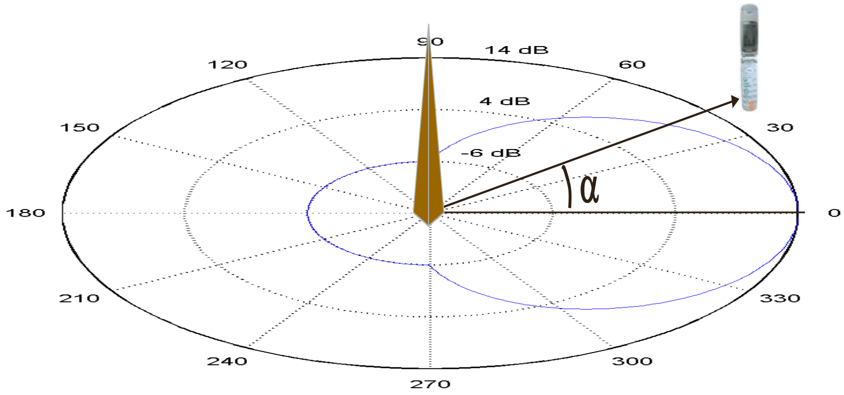


Figure 3-7: Angular antenna gain calculation.

The long-term (log-normal) fading in the logarithmic scale around the mean path loss L dB is characterized by log-normal distribution with zero mean and standard deviation as is given in Table 3-1. Due to the slow fading process versus distance Δx, adjacent fading values are correlated and its normalized autocorrelation function $R(\Delta x)$ can be described with sufficient accuracy by the following function:

$$R(\Delta x) = e^{-\frac{|\Delta x|}{d_{corr}}\ln 2} \qquad (3.4\text{-}3)$$

In this, the de-correlation length d_{corr}, is dependent on the environment. De-correlation length d_{corr} and other simulation assumptions are preliminary specified in Table 3-1.

Parameters		Values and Assumptions	
		Macro Cell	**Pico Cell**
HetNet deployment		Environment: Macro + outdoor/indoor Deployment scenario: Macro + outdoor/indoor hotzone Non-traditional node: outdoor/indoor pico	
Carrier Frequency / Bandwidth		2 GHz / 10 Mhz, FDD	
Inter site distance		500 m (Case1 in [4]), 1732 m (Case3 in [4])	
Macro Cellular layout		Hexagonal grid, 19 sites, 3 sectors per site	
Pico distribution	*Configuration1*	4 Picos / macro cell, uniformly (case 1 in table A.2.1.1.2-4 [4])	
	Configuration2	4 Picos /macro cell, correlated (case 4 in table A.2.1.1.2-4 [4])	
UE distribution	*Configuration1*	25 UEs / macro cell, uniformly (case 1 in table A.2.1.1.2-4 [4])	
	Configuration2	20 UEs/macro cell, 10 UEs/pico cell, clusters (case 4 in table A.2.1.1.2-4 [4])	
Minimum distance		40 m among picos	10m between UE and pico
		75 m between pico and macro	35m between UE and macro eNB
TX power (Ptotal)	*Cell*	46 dBm	30 dBm
	UE	23 dBm	
Antenna gain(horizontal) (For 3-sector cell sites with fixed antenna patterns)		$A_H(\varphi) = -\min\left[12\left(\frac{\varphi}{\varphi_{3dB}}\right)^2, A_m\right]$ $\varphi_{3dB} = 70\ degrees, A_m = 25\ dB$	$A(\phi) = 0$dB (omnidirectional)

Parameters		Values and Assumptions	
		Macro Cell	Pico Cell
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 in [4][1] and $\theta_{etilt} = 6\ degrees$ for 3GPP case 3 in [4]. Antenna height at the base station is set to 32 m. 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	
Channel model		Typical Urban (TU)	
Traffic model		Full buffer	
Scheduler		RR	

Table 3-1: Simulation baseline parameters for the HetNet PowerOn/Off scenario.

Channel model - The channel model does not include fast fading.

Traffic model - Full buffer is assumed.

3.4.1.2 Physical Layer Model

Link-to-system interface - The link level curves for system level simulation has been derived based on link-level SISO simulations.

Interference model - The reuse of frequencies through planned allocation enables a cellular system to increase its capacity with a limited number of channels. The channel matrices for the desired and interfering signals shall be generated according to the path loss, BS antenna gain, and shadowing variations.

Receiver model - Baseline SISO receiver mode for downlink data channel.

Mobility model - Mobility is not simulated.

3.4.1.3 Performance Metrics

The following performance metrics may be used for performance analysis. The study will evaluate the algorithm considering one or more of those metrics. The metrics may be based on a single user or multi user (a group or all). For heterogeneous network performance evaluation, the following performance metrics have the highest priority:

- Data throughput/rate and SINR CDFs are for macro UEs and pico UEs,
- Macro cell area data throughput/rate,
- Fraction of data throughput/rate over low power nodes,
- Macro and low power node serving UE data throughput ratio,
- Interference over Thermal (IoT),
- Capacity, and,
- Outage.

A preliminary description of the metrics is as follows:

1. **SINR CDF.** For downlink simulations, this is defined as the CDF for the SINR observed by each UE on the downlink. This metric allows for a comparison between different reuse scenarios, network loading conditions, resource allocation and power control schemes, etc.
2. **Data throughput (or spectrum efficiency)/Data rate**. Data throughput or spectrum efficiency for full buffer, i.e., there are always packets to transmit in the system.
3. **Outage / “bad QoS”.** It is expected that interference coordination can help to efficiently meet certain QoS criteria for users in bad radio conditions, thus there should be a metric related to non-fulfilment for QoS criteria. The QoS criterion is here defined by a minimum SINR.
4. **Spectrum utilization**. The PRB consumption can be used to evaluate the spectrum utilization.
5. **Resource Utilization** (RU) = Number of RB per cell used by traffic during observation time / Total number of RB per cell available for traffic over observation time.
6. **Capacity**. System capacity is defined as the number of users in the cell when more than 95% of the users are satisfied.
7. **Interference over Thermal (IoT)**. The inter-cell interference is often measured using a quantity called interference over thermal (IoT), which is defined to be the total received interference power at a cell divided by the thermal noise power. IoT consists of thermal noise plus the received power from all neighbour cells transmissions and it is used to evaluate the interference generated by neighbour cells. The value may be based on a single PRB or multi PRBs (a group or all).
8. **Convergence**. The algorithm convergence, i.e., guarantees that the chosen algorithms will not oscillate should be considered. The convergence time should be provided.

3.4.1.4 Energy Efficiency Model for Wireless Access Networks

Site Equipment Power Consumption Model

The Radio Base Station or simply Base Station (BS) is a network node which serving up to three cells. It interfaces the mobile station (through radio air interface) and a wireless network infrastructure (BSC or RNC).BS is a physical component comprising one or more cells [49], [50]. The BS may in each cell serve one or multiple carriers.

The backhaul transmission (a transport function for E1/T1 or similar providing capacity corresponding to the BS capacity) is out of the scope of this model.

The BS consists of several components where the power consumption of each component is a function of the cell load:

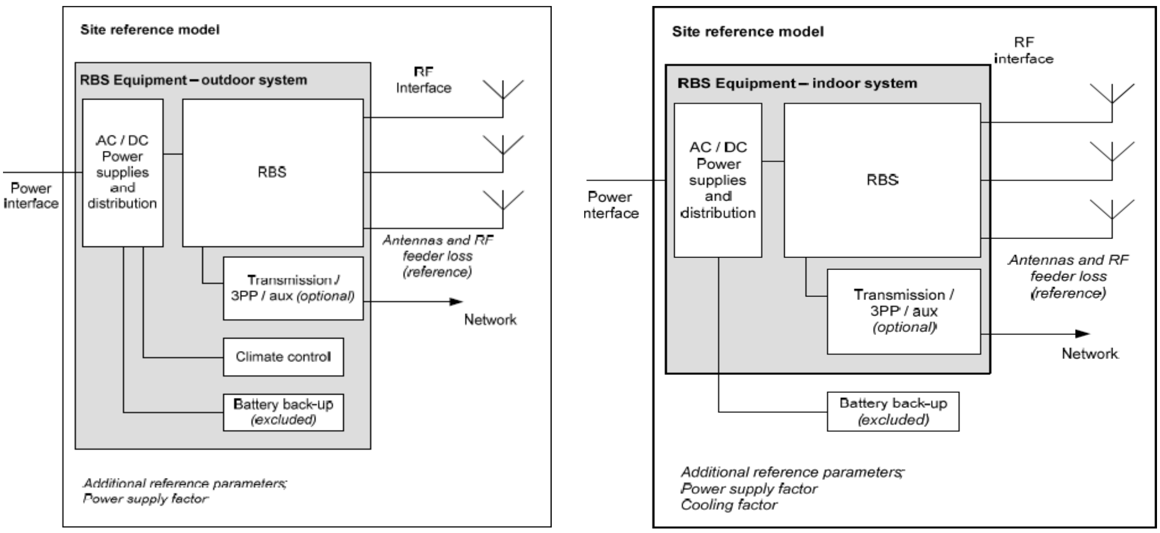
$$P_{total}\,[W] = P_{static}\,[W] + O \cdot P_{dynamic}\,[W] \qquad (3.4\text{-}4)$$

Where O is the cell load as a fraction of the maximum possible load that can be offered, i.e. $O \in [0, 1] \in \mathcal{R}$, P_{static} is the constant power consumed by the cell and $P_{dynamic}$ is the scaling factor of the power consumed per offered load unit. Figure 3-8 shows two examples of reference models for a BS site. The site includes the BS equipment, but may also include different infrastructure support systems and/or auxiliary cabinets. The power consumption and losses of support components needed as a complementary to the site components that are not included in the BS product will be considered by using reference values for those complementary components. Components to be included in the site power consumption value:

- BS equipment and auxiliary cabinets, as defined for the product,
- Rectifiers,
- Climate/conditioning unit,
- Power distribution losses. All power distribution losses between units shall be included for integrated indoor and outdoor BS. For distributed base station the defined model has to be used (extra 5 % considering remote head power consumption),
- Other auxiliary equipment and cabinets.

Functionalities excluded from site reference models are:

- Battery charge power,
- Cooling for batteries (if batteries are integrated part of BS site solution).



(a) Outdoor BS site model (b) Indoor BS site model

Figure 3-8: Reference BS site models [51].

The BS site power consumption is defined for the purpose of making it possible to compare power consumption of the different BS's throughout a network. For this purpose scaling factors are used to scale the BS equipment power consumption compared to a reference site configuration. Scaling takes into account:

- Power output. The power output for reference BS site is 40 W per sector,
- Different cooling solutions. For the reference outdoor BS site corresponding to a macro cell air temperature is +25 °C and +40 °C. For the pico cell no cooling component is included,
- Power supply losses. Power supply reference losses for both rectifier and Radio Remote Head (RRH) in case of a distributed radio antenna BS.

In Figure 3-9 the BS equipment components are depicted for a 3-sectored site. The site average power consumption for this BS is defined as a function of the power consumption of its components and the offered load O.

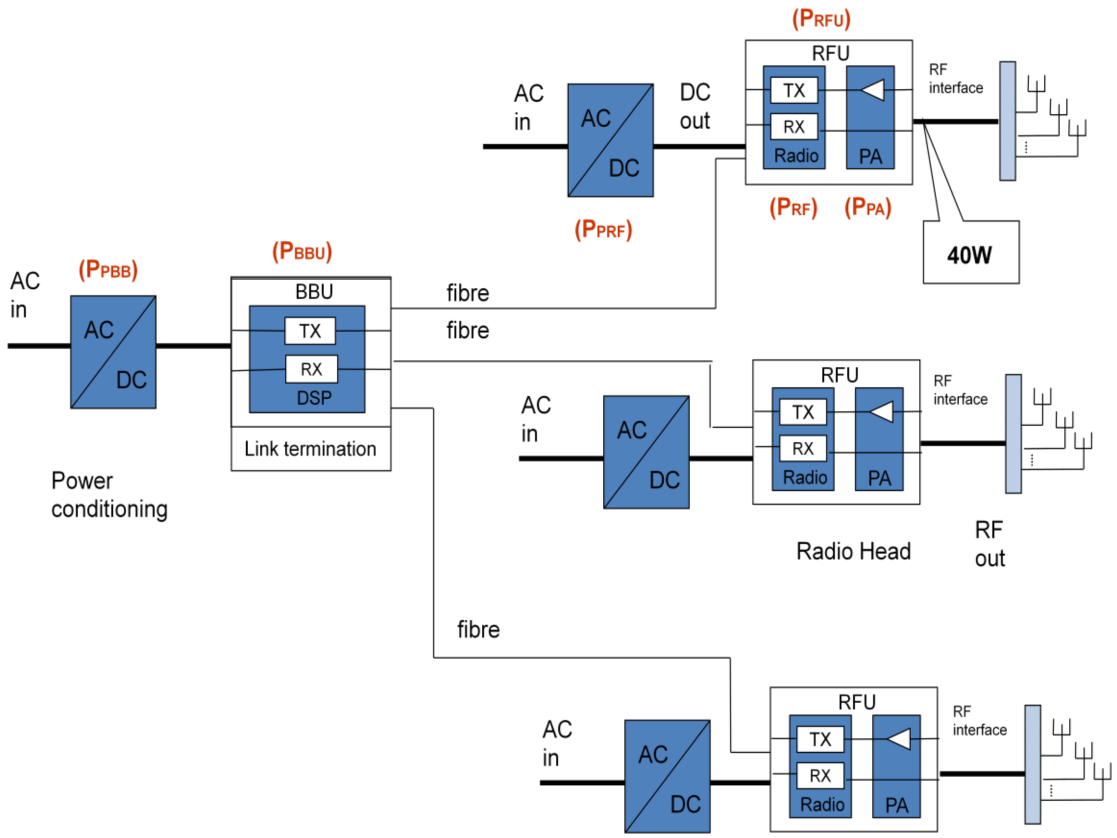


Figure 3-9: BS equipment components.

For the Radio Frequency Unit (RFU) the power consumption is given by:

$$P_{RFU} = P_{RF} + P_{PA} = \left(P_{RF\_static} + P_{PA\_static}\right) + \mathrm{O} \cdot \left(\eta_{RF} + \eta_{PA}\right) = P_{RFU\_static} + \mathrm{O} \cdot \eta_{RF} \qquad (3.4\text{-}5)$$

where P_{RF_static}, P_{PA_static} are the constant (static) power consumed at 0% offered load by the radio and the power amplifier, respectively and η_{RF}, η_{PA} are the load-dependent dynamic factors of the radio and the power amplifier, respectively.

The power consumption of the RFU (incl. cooling and rectifier) is given by $P_{PRF} = P_{PRF\_static}$ and consequently the total AC power for a radio head RF output power of P_{RFout} can be calculated as follows:

$$P_{ACRF} = \frac{P_{PRF} \cdot \mathrm{O} \cdot \mathrm{P_{RFout}}}{P_{RFU}} = \frac{P_{PRF\_static} \cdot \mathrm{O} \cdot \mathrm{P_{RFout}}}{P_{RFU\_static} + \mathrm{O} \cdot \eta_{RF}} \, W \qquad (3.4\text{-}6)$$

As earlier suggested, a reference value for power output, P_{RFout}, in 2G/3G cellular networks is 40 W.

For the baseband unit (BBU) the power consumption is given by

$$P_{BBU} = P_{DSP} + P_{LT} = (P_{DSP\_static} + P_{LT\_static}) + O \cdot (\eta_{DSP} + \eta_{LT}) \\ = P_{BBU\_static} + O \cdot \eta_{DSP} \quad (3.4\text{-}7)$$

where P_{DSP_static} and P_{LT_static} are the static powers consumed at 0% offered load by the baseband digital signal processing and the baseband link termination respectively and η_{DSP}, η_{LT} are the load-dependent dynamic factors of the baseband DSP and the link termination.

Consequently, if $P_{PBB} = P_{PBB\_static}$ is the power consumed by the baseband unit power supply including rectifier and conditioning, then the total AC power for a 3-sector outdoor BS is given by:

$$P_{AC} = 3 \cdot P_{ACRF} + \frac{P_{BBU}}{P_{PBB}} = 3 \cdot P_{ACRF} + \frac{(P_{BBU\_static} + O \cdot \eta_{DSP})}{P_{PBB\_static}} \quad 3.4\text{-}8$$

Some key figures and value ranges for the computation of the power consumed are given in Table 3-2.

Notation	Description	P_{static} (0% load) or Efficiency Factor	$P_{dynamic}$ or Dynamic Factor η	20% Load Ref. Value	Full Load Ref. Value
P_{PA}	Power consumption of PA [W]	38	96,3	57	134
P_{RF}	Power consumed by radio [W DC]	64W	6,3	65W	70W
P_{PRF}	Efficiency of RRH power supply incl. rectifier and DC/DC cooling	0.85	0	0.85	0.85
P_{ACRF}	Total AC power consumption for a 40W radio head	119	121	143	240
P_{DSP}	Power consumed by baseband [W DC]	74	6,3	75	80
P_{LT}	Power consumed by link termination [W DC]	45	0	45	45
P_{PBB}	Efficiency of baseband unit power supply incl. rectifier and DC/DC cooling	0.91	0	0.91	0.91

Notation	Description	P_{static} (0% load) or Efficiency Factor	$P_{dynamic}$ or Dynamic Factor η	20% Load Ref. Value	Full Load Ref. Value
P_{AC}	Total AC Power [W]	487	370	561	857

Table 3-2: Base station power consumption and efficiency for $P_{\mathrm{RFout}} = 40$ W.

Power Consumption Performance Metrics

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.

For cellular systems performance indicators of interest are mainly associated with voice service (GSM, WCDMA). In rural areas the dominant factor for the dimensioning of a network is the coverage area. The traffic demand is typically smaller than the maximum possible capacity of the BS. Thus, the network utility or the network level performance indicator [km^2/W] for a rural area is defined as:

$$U_{rural} = \frac{A_{coverage}}{P_{site}} \tag{3.4-9}$$

in which $A_{coverage}$ is the BS coverage area [km^2] for rural area and P_{site} is the power consumption of the site. The coverage area is calculated based on both uplink and downlink systems values. The limiting value of uplink and downlink coverage areas is used. Both coverage areas are calculated under low traffic load situation. For downlink calculation the BS signal power level and UE receiver sensitivity and traffic type is used. For uplink calculation the BS receiver sensitivity with UE transmission power and traffic type are used.

In urban areas, the dominant factor for the dimensioning of a network is the capacity of the BS since its capacity is (often) larger than the traffic demand. Thus the network level performance indicator (subscribers/W) for an urban area is defined as:

$$U_{urban} = \frac{N_{BH}}{P_{site}} \tag{3.4-10}$$

in which N_{BH} is the number of subscribers based on the average busy hour traffic demand.

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

$$ECR = \frac{E}{M} = \frac{P \cdot T}{M} = \frac{P}{D}\ [Joule/bit] \tag{3.4-11}$$

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

3.4.2 Cooperative DAS Model – Macro RRH Scenario

3.4.2.1 System Model

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

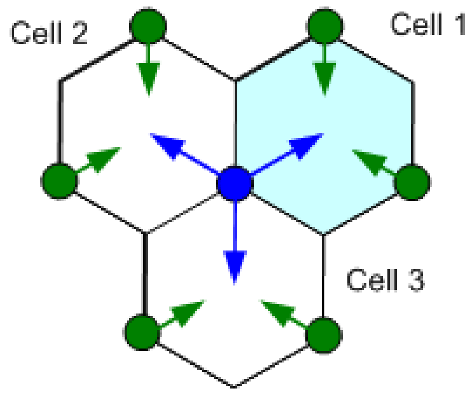


Figure 3-10: Homogeneous Topology Model.

In the homogeneous topology model, 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, as shown in Figure 3-10.

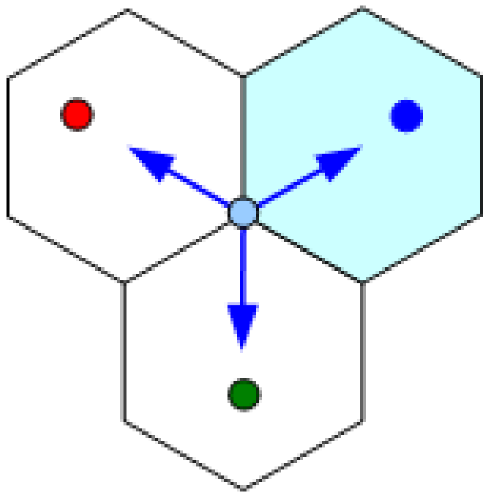


Figure 3-11: Heterogeneous Topology Model.

For the deployment in heterogeneous environments, the cell area of a site is divided into three small hexagonal DAS cell with one omni 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 3-11.

Parameter		Values and Assumptions
Macro Cellular Layout		Hexagonal grid, 19 cell sites, 3 cells per site
Simulation case		3GPP Case 1 [4]
Inter-site distance		500 m
Distance-dependent path loss		L=128.1 + 37.6 $\log_{10}$(.R), R in kilometers
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

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

Table 3-3: Simulation baseline parameters for the DAS scenario.

Channel Model - In the theoretical analysis, Rayleigh flat fading is used to model the fast fading channel. In the detailed system level simulation, spatial channel model (SCM) defined in [52] is used.

Traffic model - Full buffer is assumed.

3.4.2.2 Physical Layer Model

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 [53] 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.

Interference model - 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.

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

$$\mathbf{w} = \frac{\mathbf{h}}{\|\mathbf{h}\|}, \qquad (3.4\text{-}12)$$

where ***h*** is the effective channel coefficient vector after pre-coding.

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

3.4.2.3 Performance Metrics

The following performance metrics will be used for the performance analysis.

- Cell capacity (bps/Hz/cell),
- Cell-edge user throughput (bps/Hz/UE),
- Jain Index (J),
- Dynamic Power consumption (Watt),
- Power radiated from the air-interface.

The Jain Index is used to evaluate the fairness among multiple users and can be written as

$$J = \frac{\overline{T}^2}{\overline{T}^2 + \mathrm{var}[T]} \tag{3.4-13}$$

where $\overline{T}$ is the average throughput of the UE and $\mathrm{var}[T]$ is the variance of UE throughput. If $J = 1$, i.e., $\mathrm{var}[T]$ is zero, the resource assignments to the users are fair because they all have the same throughput. On the contrary, if $J = 0$, i.e., $\mathrm{var}[T]$ is very large, the difference of user throughput is large, which means that the resource assignments to the users are unfair.

3.4.3 Cooperative Relay Network Model – Macro Relay Scenario

3.4.3.1 System Model

Since the relay scenario has been discussed and defined in 3GPP for LTE-A, the definition follows the Relay scenario as described in [4].

E-UTRAN supports relaying by having a Relay Node (RN) wirelessly connecting to an eNB serving the RN, called Donor eNB (DeNB), via a modified version of the E-UTRA radio interface, the modified version being called the *Un* interface.

The RN supports the eNB functionality meaning it, among other things, terminates the radio protocols of the E-UTRA radio interface, and the *S1* and *X2* interfaces. From a specification point of view, functionality defined for eNBs also applies to RNs unless explicitly specified.

In addition to the eNB functionality, the RN also supports a subset of the UE functionality, e.g. physical layer, layer-2, RRC, and NAS functionality, in order to wirelessly connect to the DeNB. The preliminary simulation assumptions are contained in Table 3-4:

Parameter	Values and Assumptions
Network topology	3/7 micro cells, 3 sector per micro cell
Cell radius	200~1000 meters
Maximum UE transmission power	200 mw
Relay transmission power	200 mw-10 w
Relay antenna	UE and Relay: Omni directional antenna SISO/2-2 MIMO Relay and BS: Directional antenna SISO/2-2 MIMO
UE antenna transmission gain	34.53+38*log10(d)
Relay antenna transmission gain	34.53+38*log10(d)
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
Channel model	Urban micro-cell environment: Path loss = 34.53+38*log10(d) Details in 25.996 section 5.3.2
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(-40 deg, 40 deg)
Mean AS at MS	E($\sigma_{AS,MS}$)= 68°
at MS (fixed)	35°

Parameter	Values and Assumptions
Mean total RMS Delay Spread	E( )=0.251 ms (output)
Distribution for path delays	U(0, 1.2 ms)
Lognormal shadowing standard deviation,	NLOS: 10 dB LOS: 4 dB
Pathloss model (dB), d is in meters	NLOS: 34.53 + 38$\log_{10}$(d) LOS: 30.18 + 26*$\log_{10}$(d)

Table 3-4: Simulation baseline parameters for the cooperative relay scenario.

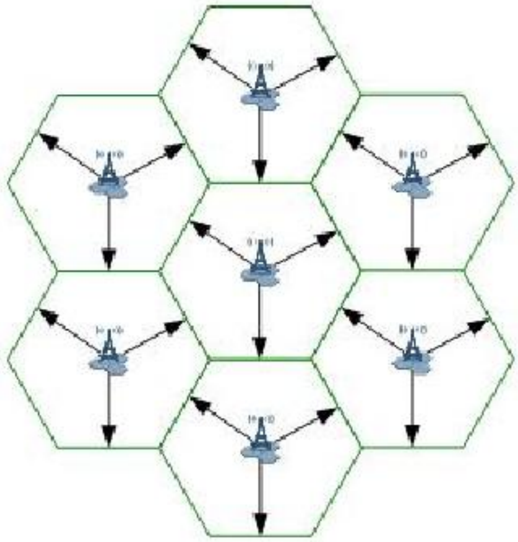


Figure 3-12: The Simulation Baseline.

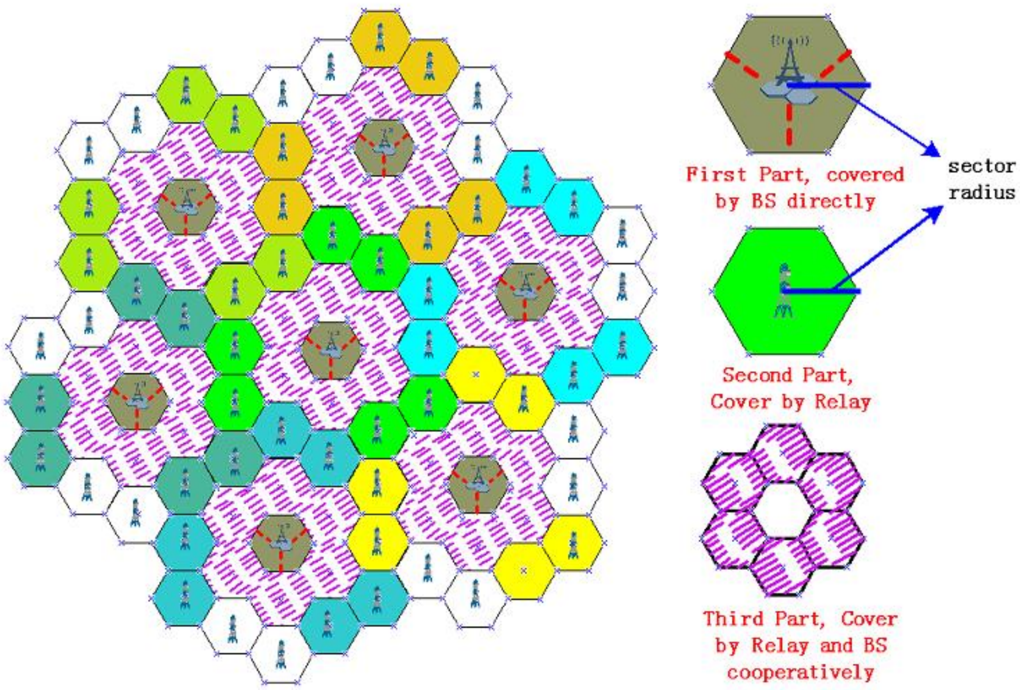


Figure 3-13: The Simulation Scenario.

The simulation models are mainly based on the regular hexagonal cellular structure. One basic regular hexagonal cell area is divided into three parts; the central part is covered by the BS. The central area is further divided into three sectors by means of directional antenna on the central BS. The relay cell is located at the edge of a basic regular hexagonal cell where the edge part is divided into 12 small hexagonal cells with one relay node located in each relay cell, six (6) of which belong to the BS. The middle part is the rest empty part but covered by both the BS and the relay.

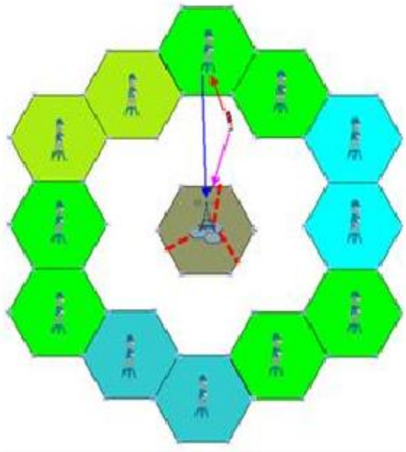


Figure 3-14: Cooperation Model Baseline.

The UEs access the BS via different paths according to the UE distribution:

- UE accesses the BS directly if it is located in the central cell,
- UE accesses the BS via Relay if it is located in the relay cell. Six (6) interspersed relay cells among the 12 relay cells corresponds to one common central BS, and the rest relays corresponds to other neighbour central BS respectively; as shown in Figure 3-14, six relay cells with same green background correspond to the identical central BS,
- For the UE located in the middle cell, three (3) paths are made as candidate access paths: either the UE accesses BS directly, or the UE accesses BS via relay node corresponding to the destination BS, or the BS combine these two path by means diversity combination at the BS. The optimal access path is decided based on the optimal system performance, e.g., maximum cell capacity, or minimum network energy consumption.
- For relay cooperative network coding case, two UEs are located in one cell; these UEs may choose cooperative network coding mode, which means the UEs transmit signals to relay. When both the relay and the BS can receive the signal; then the relay transmits the XOR of the signals from two UEs, the BS combines the signal from the UEs and the relay for data decoding based on joint channel coding and the network coding algorithm.

Channel model - The channel model does not include fast fading.

Traffic model - Full buffer is assumed.

3.4.3.2 Physical Layer Model

Link-to-system interface - The link level curves for system level simulation has been derived based on link-level SISO simulations.

Interference model - The interference model is based on the relay deploy scenarios.

Receiver model - Baseline SISO receiver mode for uplink data channel will have less impact on the terminals.

Mobility model - Mobility is not simulated.

3.4.3.3 Performance Metrics

The following performance metrics may be used for performance analysis. The study will evaluate the algorithm considering one or more of those metrics. The metrics may be based on a single user or multi user (a group or all). For cooperative network performance evaluation, the following performance metrics have the highest priority:

- Data throughput/rate and SINR CDFs are for macro UEs and relay UEs,
- Macro cell area data throughput/rate,
- UE/Relay transmitting power,
- Interference over Thermal (IoT),
- Capacity.

A preliminary description of the metrics is as follows:

1. **SINR CDF**. For uplink simulations, this is defined as the CDF for the SINR observed by each UE on the uplink. This metric allows for a comparison between different reuse scenarios, network loading conditions, resource allocation and power control schemes, etc.
2. **Data throughput (or spectrum efficiency)/Data rate**. Data throughput or spectrum efficiency for full buffer, i.e., there are always packets to transmit in the system.
3. **Spectrum utilization**. The Physical Resource Block (PRB) consumption can be used to evaluate the spectrum utilization.
4. **Resource Utilization** (RU) = Number of Physical Resource Blocks (PRBs) per cell used by traffic during observation time / Total number of RBs per cell available for traffic over observation time.
5. **Capacity**. The system capacity is defined as the number of users in the cell when more than 95% of the users are satisfied.
6. **Interference over Thermal (IoT)**. The inter-cell interference is often measured using a quantity called interference over thermal (IoT), which is defined to be the total received interference power at a cell divided by the thermal noise power. The IoT consists of thermal noise plus the received power from all neighbour cells transmissions and it is used to evaluate the interference generated by neighbour cells. The value may be based on a single PRB or multi PRBs (a group or all).
7. **Spectrum Efficiency**. The metric spectrum efficiency bit/Hz/s may be considered as the improvement of spectrum efficiency can use less spectrum to satisfy the user requirement, which also can save energy.

3.5 Information Management and Fusion in Energy-Aware Cooperative Environments

In section 2.5 issues related to information fusion were presented as well as respective needs for an efficient way of combining the various/multiple sources in order to obtain improved information. Such improvements need to take into account WSN’s constraints as well as the need for different level of accuracy depending on the application and the purpose to serve. Moreover, information modelling was identified as an initial step for the elements’ abstraction and the conceptual representation enabling information processing and knowledge representation.

This section elaborates on the needed functionality and model initiation regarding information processing as well as the information model specification.

3.5.1 Information Fusion Model

In the considered use case (UC-03/NKUA) different types of WSN are required in order to provide measurements and sensed data towards each use case's goal. In a combined view, both use cases are considering coverage and capacity optimisations under energy constraints in a home/office environment where wireless networks (WLAN, UMTS) and WSN have been deployed.

The following procedures are identified regarding WSN measurements provision:

- Sensed data gathering (sensor coordination, CONSERN module),
- Sensed data communication to network elements according to the use case information flow,
- Notification on the existence of "relevant" WSN in the vicinity,
- Evaluation of WSN type of measurements against the considered goals: in this example, additional WSN data is needed in order to assess on congestion problems and fulfil the purpose of the network.

As described in [41], the Intelligence Cycle describes the process of developing sensory information into intelligence, based on the four (4) stages in Figure 3-15a.

- Collection: Raw information is collected from the WSN nodes,
- Collation includes analysis, comparison and correlation of the gathered data; combination or compression may occur at this stage so as for irrelevant and unreliable information to be discarded,
- Evaluation includes information fusion and analysis of the collated information; analysis may identify certain gaps in the intelligence gathering,
- Dissemination means the actual delivery of the fusion results to identified applications/elements/users regarding own actions and objectives.

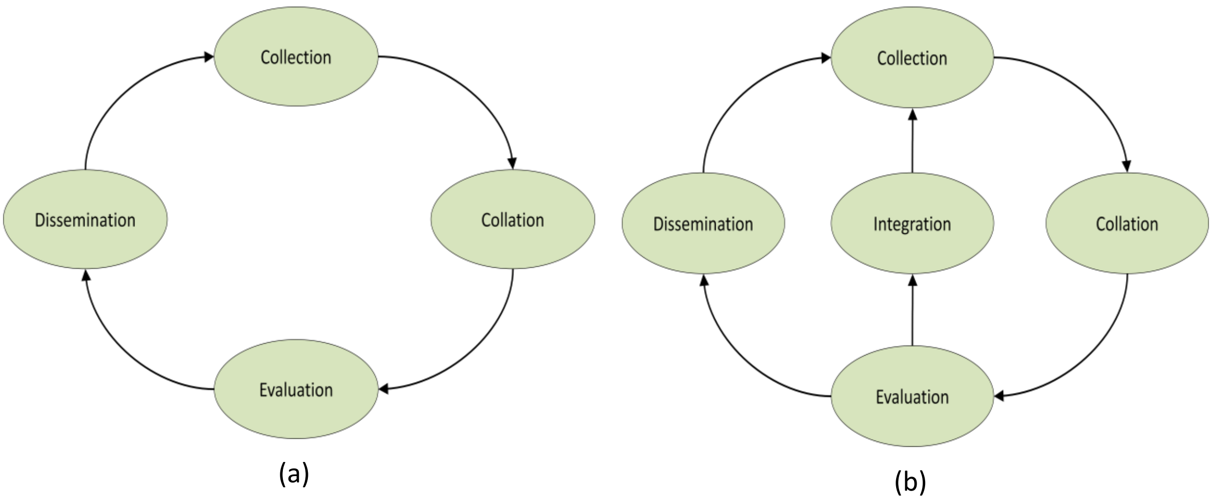


Figure 3-15: (a) The Intelligence Cycle (b) Enhanced.

Under the considered context, evaluation stage includes also the evaluation of the provided data against the "user's" goal; in case integration follows where the specific WSN type is integrated as part of the loop and the provided sensed data as useful (Figure 3-15b).

Several techniques have been used to fuse data based on several criteria (including data type, purpose, and abstraction level). Bayesian inference has been used in the WSN domain to solve the localisation problem [41], identification and/or correction of measurements errors [43] and WSN faults [44]. Fuzzy Logic has been used for controlling the position of sensors [45], support clustering mechanisms [46], as well as optimisation of MAC parameters [47]. Fuzzy Logic is further detailed in following paragraphs highlighting learning capabilities and faults identification.

In [47] an ontology-based approach is presented focusing on how ontologies can be used to support the integration of heterogeneous information sources. Ontologies are used to describe the semantics of the information sources in order to make their content explicit; in this sense, ontology can enable information integration from heterogeneous sources can be addressed at the structural, syntactic or semantic levels as enabling a shared conceptualisation of a system. Ontology has been also described in [3] as enabling knowledge fusion and sharing.

As mentioned, in the various CONSERN use cases, different sources of information has been identified, together with different type of information/data (sensed/measured) as well as requirements for dynamic evaluation and integration of additional information data, based on specific purposes which need to be addressed under each use case's goal. Based on this the following needs to be addressed:

Identification and evaluation of the relevance of the available information sources (WSN, NEs); this is related also to data semantics,

- Reasonable volume of data which needs to be distributed and processed,
- Accuracy and liability of the conveyed data/information,
- Shared understanding in order to enable knowledge and intelligence sharing.

Figure 3-16 provides a high level model of the information fusion; this is also expected to impact the Self-growing architecture which is being developed in WP4.

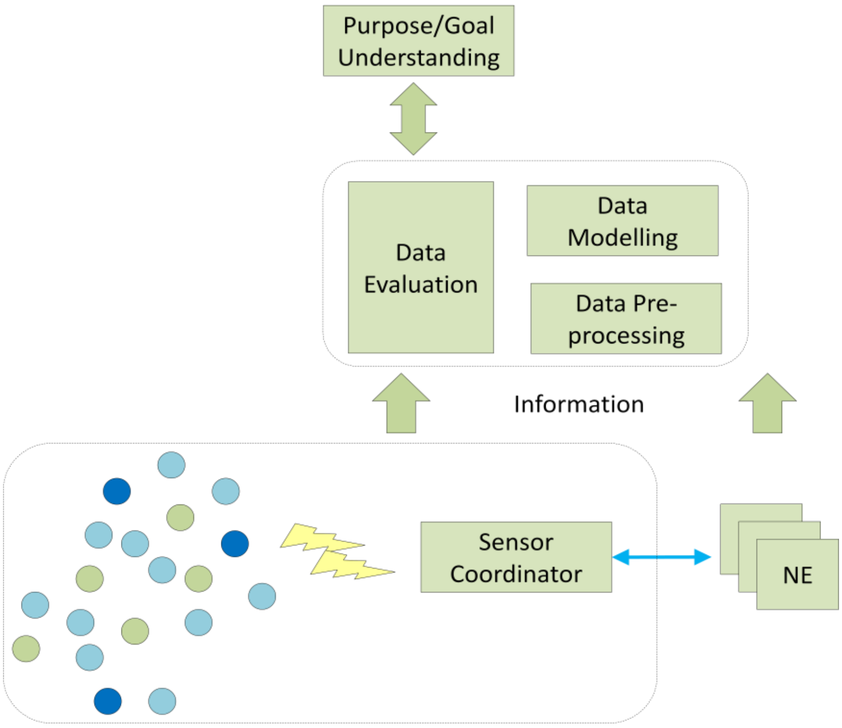


Figure 3-16: Information Fusion - High level model.

- Purpose/goal understanding is related to actual goal which will be served by the provided information. It is important to have semantic-full data and measurements as well as a shared understanding of the purposes which can be served by the available measurements,

- Data Evaluation refers to the actual evaluation of the available measurements regarding the identified goals,
- Data Pre-processing addresses issues related to incomplete, erroneous or noisy data by using statistical techniques in order to fill in missing values, smooth noisy data and remove outliers,
- Data Modelling is used in order to extract the hidden knowledge based on techniques such as regression, decision trees, Bayesian networks, support vector machine, and clustering.

In the following section, a specific information fusion mechanism is presented focusing on fault identification and resiliency aspects.

3.5.2 Resiliency – Fault Identification

CONSERN networks consist of several device types, incorporating sensors as well. The nodes comprising such networks integrate sensing, processing and transceiving capabilities. However, the quality of the gathered data by wireless sensor are often unreliable, due to the low cost and low quality of the sensor nodes and due to several resource constraints such as energy (battery power), memory, computational capacity and communication bandwidth. The unreliable data affect the quality of the collected datasets, thus making their process a difficult procedure. Since actual events, taking place in the real world need to be identified, the events need to be separated from «wrong» measurements. Such procedure is captured by the notion of outlier detection.

In order to identify the proper outlier detection mechanism the actual definition of an outlier is required. Several definitions exist in the literature, concerning the definition of outliers:

a) "An outlier is an observation that deviates so much from other observations as to arouse suspicions that it was generated by different mechanism" [37],
b) "Outliers are measurements that significantly deviate from the normal pattern of sensed data" [38].

The latter is the more suitable to the CONSERN's approach, even though not all inputs used for the decision making and event identification procedures come from WSN but other types of network nodes (routers, APs, femtocells etc) as well.

Furthermore, in order to have a complete understanding of the outlier notion its source should be identified. More specifically, there are three sources of outliers, namely, noise and errors, events and malicious attacks [39]. The former outlier type, concerns malfunctioning equipment and noise in the related measurements; such outliers are likely to be spatially unrelated and mainly occur in a random manner. Events are defined as changes in the real world; these outliers are spatially and timely related. The latter of the outlier types concern malicious events that, due to their nature, are out of topic.

In the following section the main techniques for error and event detection used in the WSNs are going to be briefly described so as to identify the benefits and drawback of each technique. Such approach shall enable the extraction of the requirements of the event identification approach that should be followed.

Outlier detection techniques

In the literature several techniques are being used for outlier detection. This section briefly presents the aforementioned techniques following the taxonomy of Yang et al presented in [39] (other taxonomies exist as well [38], [59]). According to the approach Yang proposes the error detection techniques are being divided into five main categories, namely, statistical-based, nearest neighbour-based, clustering-based, classification-based and spectral decomposition-based.

Statistical Based Approaches

The statistical-based approaches assume a statistical model which captures the data distribution and evaluate the data instances according to this model. Instances with low probability to have been introduced by the identified model are considered anomalies [38]. Based on how the probability distribution model is built, the statistical-based approaches can be further categorized into parametric-based approaches (the underlying data distribution is available) and non parametric ones (every new data instance is evaluated against the statistical model of the measurements) [39]. In [60] a non parametric method is being presented characterizing a measurement as an outlier if it is not in corresponding confidence interval.

Nearest Neighbour-based approaches

Nearest Neighbour-based approaches is based on a well known data mining technique, where a new data instance is analyzed with respect to its distance from its neighbours. Several distance types could be used for the identification of the distance between two instances; the most common is the Euclidean distance. Following this technique, an outlier is a measurement that is located far from its normal (non outlier) neighbours.

Clustering based approaches

Clustering-based approaches are simple and popular techniques for the grouping of data instances with similar behaviour. Similarly to the Nearest Neighbour-based approaches, several distance types could be used for the grouping and the similarity identification between the data, with the Euclidean distance being the more popular one. Data instances are considered as outliers if they do not belong to a cluster, their cluster is identified as a cluster of outliers, or the cluster the instance belongs is significantly smaller to the normal measurements clusters. In [61] a clustering approach is proposed where the measurements not belonging in a cluster (candidate outliers) are evaluated several times in order to ensure the validity of the decision.

Classification-Based Approaches

Classification based approaches use models to identify whether an instance as a normal measurement or an outlier. Such approaches consider two distinct phases, the training and the testing. During the former, the classification model which fits to the majority of the training set is being identified. The classification model may need to be updated during the network element's operation in order to capture new instances that are not included in the training set. Support Vector Machines [62] and Bayesian Network [63] classification-based approaches are used for outlier detection.

Spectral decomposition based approaches

Spectral Decomposition-based approaches use principle component analysis (PCA) so as to reduce the dimensionality and conclude to a set of dimensions that capture the behaviour of the data; any data instance that violates the aforementioned structure is considered and outlier [39], [64].

The previously mentioned techniques are mainly used for outlier identification in terms of error detection. Majid et al in [59] attempt to handle outliers as events, using some of the afore-described approaches and achieve very satisfactory success rates. The methods applied are Feed Forward Neural Networks and Naive Bayes, Standard Support Vector Machines (SVM) and their variations. In [66] and [67] fuzzy logic reasoners are used for event detection; in the former network elements locally identify potential errors in using local measurements whereas in the latter a distributed incident identification (i.e. fire) method is developed.

Outlier detection analysis and modelling

The availability of information deriving from several sources (i.e. network elements and sensors of various types) shall enable the network management system to correlate inputs seemingly unrelated. Such system consists of two levels, the monitoring one, where the network elements gather the information and provide the initial evaluation and the brokers that collect information from the monitoring points and correlate the inputs. The brokers exploit their greater network view and their processing capabilities compared to the rest of the networked elements and identify the problematic measurements; such measurements are being dropped from the gathered information. During a second level of evaluation, the network elements that provide problematic inputs are excluded from the from the network's sensing elements in order to assure that these inputs are not going to feed the network management system.

As shown in Figure 3-17, the outlying mechanism is going to be divided into two basic steps:

- Identification of measurements that could be rejected without correlations – this step takes place locally,
- Identification of unrealistic inputs (ex. consumed bandwidth, interference, coverage, motion, etc) based on their correlation; these measurements are going to be removed from the dataset as well.

The first step is going to be take place locally (sensors, network nodes), consuming as less resources as possible, whereas the second one has to take place at more powerful network devices without battery and processing limitations. Then, as mentioned before, the network elements that tend to provide problematic measurements will be excluded from the network, because they are considered unreliable.

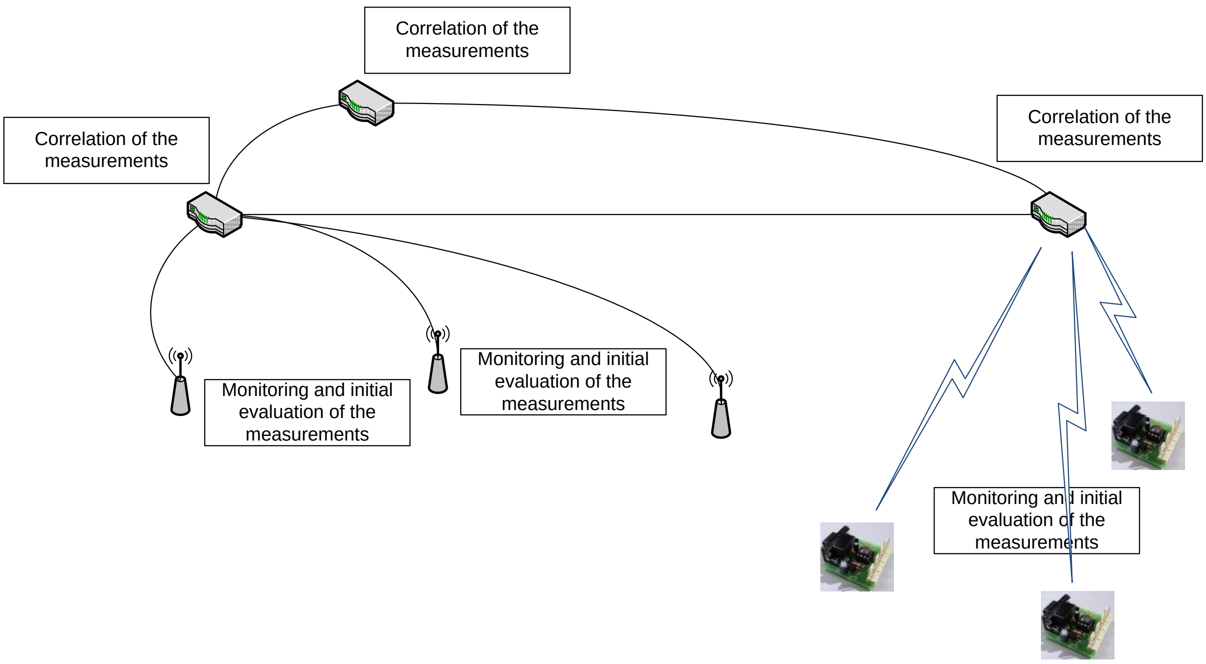


Figure 3-17: Outlier detection mechanism overview.

3.5.3 Information Model

This section describes the process for identifying and classifying the "observed" concepts throughout the CONSERN project scope as it is outlined by the project Use Cases [2] which have been filtered as most relevant to WP3 (as in [3]). This will provide an Information Model under the WP3 context reflecting the cooperativeness view of the project.

The procedure for the initial identification of the involved concepts and entities in the abstraction of the managed system will be based on the complete set of the project use cases. The entities and actors that have been included with specific technical roles will provide the first level of conceptualisation; additionally, material from the system and functional requirements definition will be also utilised for defining the Information Model.

The development of the Information Model for the system conceptualisation and the elements; abstraction under the WP3 viewpoint is based on the following directions:

- Identification of the wireless networks and elements types composing the CONSERN managed system, as they have been defined in the use cases,
- Identification of corresponding parameters for profiles, measurements and policies which detail the information model concepts,
- What types of information and knowledge management functions have been identified in the use cases.

The following information items have been identified:

- The Wireless Network in terms of the different types of wireless networks which form the CONSERN managed system. These includes for example WLAN, UMTS, WSNs, etc,
- The Operator that owns and operates different types of networks,
- The different types of network elements, including, base stations (WLAN access points, UMTS femtocells), WSN nodes (sensing nodes, sensor coordinators, etc),
- The service area (macro and micro cells, etc.),
- The link(s) between the network elements (including cooperation links and relayings),
- Information regarding corresponding profiles, resources, and measurements.

The 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.

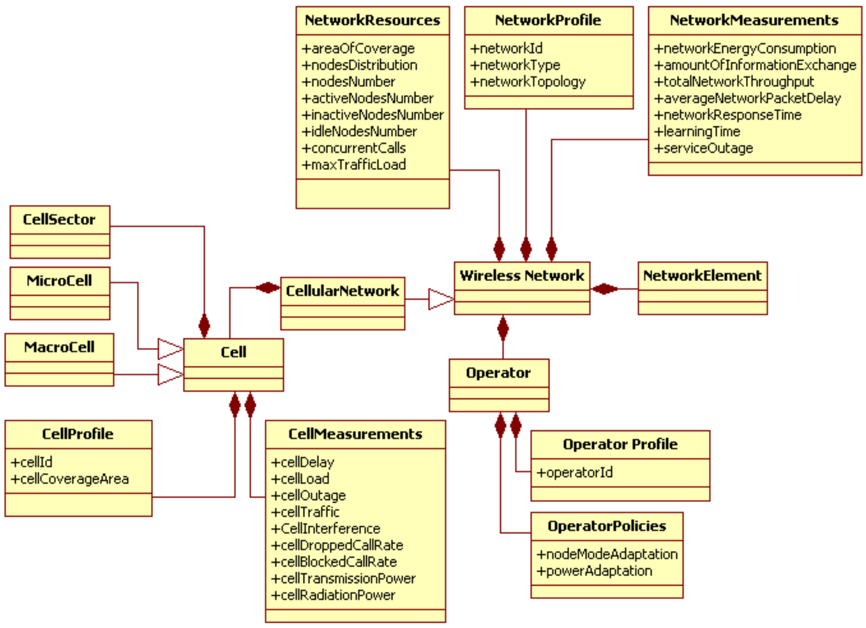


Figure 3-18: UML model for the Wireless Network concepts.

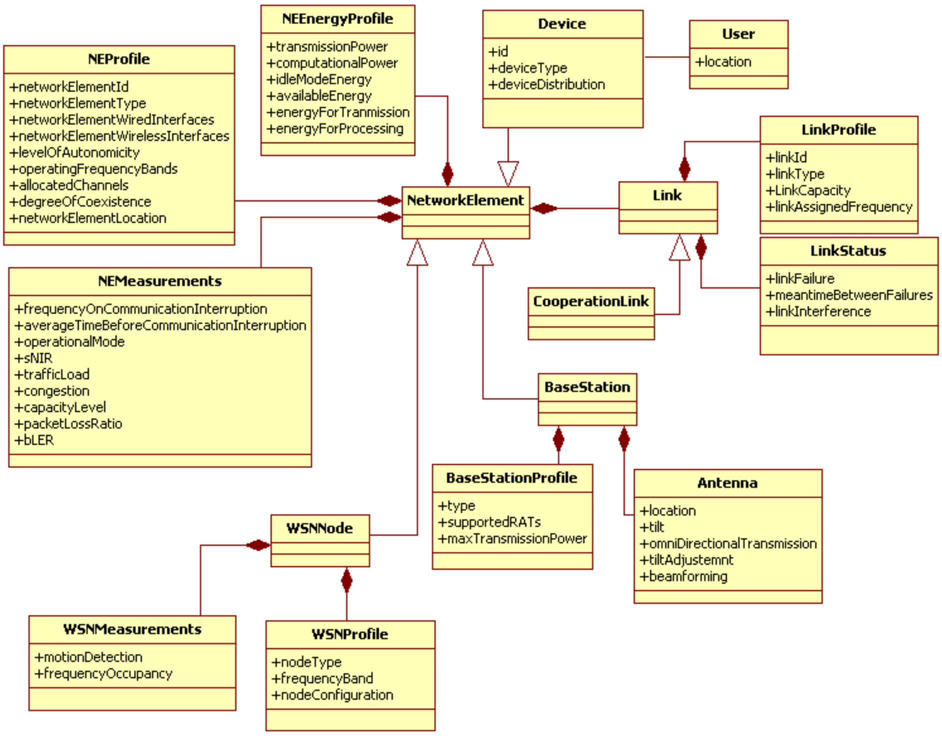


Figure 3-19: UML Model for the Network Element concepts.

4. Energy-Efficient Cooperative Mechanisms Design

4.1 Energy Efficiency by Improved Interference Resolution

The network coding strategy described in previous sections, which is based on an out-of-band relay carrying out a compress-and-forward operation, aims at improving the interference resolution at the two destinations of the interference channel depicted in Figure 3-1. By reducing the impact of interference, energy efficiency can be improved in networks where the cell layout cannot be centrally controlled as in the case of user-controlled femtocell base stations deployed in residential buildings, such as the use-case scenario depicted in Figure 2-1.

Typical metrics that can be used to evaluate the impact on the system performance of this network coding strategy are the system throughput and the user's packet error probability. In particular, in order to evaluate these two quantities by analysis and/or simulations, we need to define the operations the receivers should carry out to use of the relayed information in the decoding process.

The relay information contains an indication of where the observation Y_r by the relay node is located in the signal space. The observation is a linear combination of the messages X_1 and X_2, which is assumed to be statistically different from the observations made by the destination nodes. Therefore, each destination node can use the relayed quantisation index (and the knowledge of the relay channel h_{1r}, h_{2r}) to improve the reliability of bits provided as input to the decoder [35].

Let us assume that the destinations know the constellation used by their own signal as well as the interfering signal and let us consider the decoding of message X_1. Let us call x_1 a generic symbol of the message X_1, M_1 its constellation and b_k the k-th bit of the binary representation of x_1. Similarly let x_2 be the interfering symbol from user 2 and M_2 its constellation. Finally, we indicate with x_r the relayed index. The Log-Likelihood-Ratio (LLR) of the bit b_k is defined by

$$\mathrm{LLR}(b_k) = \frac{\sum_{x_1 \in M_1 | b_k = 1, x_2 \in M_2} p(y_1, x_r \mid x_1, x_2)}{\sum_{x_1 \in M_1 | b_k = 0, x_2 \in M_2} p(y_1, x_r \mid x_1, x_2)} \qquad (4.1\text{-}1)$$

The conditional probability in the above expression can be decomposed as

$$\begin{aligned} p(y_1, x_r \mid x_1, x_2) &= p(y_1 \mid x_1, x_2, x_r)\, p(x_r \mid x_1, x_2) \\ &= p(y_1 \mid x_1, x_2)\, p(x_r \mid x_1, x_2) \\ &= p(y_1 \mid x_1, x_2) \int_{y_r | Q(y_r) = x_r} p(y_r \mid x_1, x_2), \end{aligned} \qquad (4.1\text{-}2)$$

where the second equality follows from the fact that x_r is deterministic if x_1 and x_2 are fixed (the channel is assumed known by the receiver). Both probabilities in the third equation of (4.1-2) are Gaussian distributed as we can easily see from the system equation (4.1-1). We note that the effect of the relay message in the decoding process is dictated by the probability $p(x_r|x_1,x_2)$. Therefore, the quantisation parameters of the relay should be optimised such that this probability should be maximised, or equivalently the entropy $H(X_r|X_1,X_2)$ should be minimised. This is clearly equivalent to minimising the quantisation error.

Once the LLR metric is established, we can evaluate the system performance by simulations for both uncoded data transmission and some practical channel codes, for example the 3GPP turbo codes. We can then characterise the transmit power required by each transmitter to achieve a given throughput and study the energy efficiency gain in terms of reduction of transmit power compared to a scheme without network coding, for a fixed average throughput.

4.2 Cooperative Power Control Based on Fuzzy Logic

Various pricing mechanisms have been proposed for facilitating dynamic allocation of resources in various types of networks, targeting both wired and wireless network topologies, based on different pricing schemes. However, the problem between multiple secondary networks that operate in TVWS bands is different from most of the previous works, since the interference that each node is potentially causing to the rest of the nodes implies that the nodes' utility functions are coupled. This means that in the general case the overall network utility is not concave to the transmission power of each node. We assume a scenario similar to [32], in which the communication is not fixed-rate but the transmission rate can be adaptive ("elastic" data applications) and the goal is to maximize the total utility of the network without guaranteeing interference margins for each node. The proposed algorithm is based on the algorithm in [32] for distributed interference compensation, but incorporates mechanisms for enhancing situation awareness in the case of uncertainties or non ideal message exchange schemes. Specifically, a fuzzy logic reasoner is utilized in order to cope with uncertainties in the message exchange, e.g., from high mobility or a large time interval for the update of interference prices.

According to this algorithm, the nodes exchange information about their interference levels, using for this purpose appropriate message exchange mechanisms. A transmitter sets its power level by considering not only its own SINR information but also the negative impact in utility for other nodes caused from the increased interference that will come as a side effect of the increase in power of that particular node. This serves as a counter-motive that discourages nodes from consistently setting their transmission power to the maximum allowable level. Assuming that there are a total of *L* nodes in a spectrum band with *k* available channels, the SINR of the i*th* node in channel *k* is given by the equation:

$$\gamma_i\left(p_i^{\,k}\right)=\frac{p_i^{\,k}\cdot h_{ii}}{n_0+\sum_{j\neq i} p_j^{\,k}\cdot h_{ji}} \tag{4.2-1}$$

where p_i^k is the transmission power for the node *i* on channel *k,* h_{ii} is the link gain between i*th* receiver and i*th* transmitter, p_j^k is the transmission power for all other nodes on channel *k,* $n_0=10^{-2}$ is the noise level and h_{ji} is the link gain between i*th* receiver and j*th* transmitter. It is important to underline that $h_{ij} \neq h_{ji}$, since the first expresses the gain between i*th* transmitter and j*th* receiver and the second depicts the gain between j*th* transmitter and i*th* receiver.

In the following analysis we assume that the environment causes average to high propagation loss and as a consequence the path loss exponent is three (3) [40], therefore the channel gain can be expressed as $h_{ji} = d_{ji}^{-3}$, where variable *d* denotes the distance between the j*th* transmitter and i*th* receiver. The coherence bandwidth defines the separation in frequency after which two signals are uncorrelated. Specifically, in the case of frequency-selective fading, the coherence bandwidth of the channel is smaller than the bandwidth of the signal. Thus, different frequency components of the signal experience uncorrelated fading. On the other hand, in the case of flat fading, the coherence bandwidth of the channel is larger than the bandwidth of the signal. Therefore, all frequency components of the signal will experience the same magnitude of fading. In our case we assume a flat-faded channel without shadowing effects. For a flat-faded channel there is no frequency selectivity and no delay spread, as elaborated previously. This implies that a single path-loss coefficient is used for channel attenuation. The described channel is static, thus the coefficient is fixed, and therefore the path loss is the only attenuation affecting it. Consequently, in this particular case *h* is strictly the channel gain or attenuation. In order to model the impact in utility for node *i* caused by the transmission of all other nodes, we adopt from [32] the notion of interference price. Interference price is defined as:

$$\pi_i^k = \frac{\partial u_i\left(\gamma_i\left(p_i^k\right)\right)}{\partial\left(\sum_{j\neq i} p_j^k \cdot h_{ji}\right)} \tag{4.2-2}$$

It is clear that the interference price expresses the marginal loss in utility due to a marginal increase in sustained interference. Interference prices are exchanged between the nodes in a completely asynchronous way. Furthermore, not only the updates of interference price between users are asynchronous, but also every node can proceed to update at different times its own price and power level values. Each node, subsequently, selects an appropriate level for its transmission power in order to maximize the difference between the increase in its own utility minus the reduction in utility of other nodes caused by the increased interference as expressed by the interference price. Specifically, the mathematical formula that [32] is trying to maximize is:

$$u_i\left(\gamma_i\left(p_i^k\right)\right) - p_i^k \sum_{j\neq i} \pi_j^k \cdot h_{ji} \tag{4.2-3}$$

The first part of the last equation is related to the Shannon capacity for node *i* (the constant term is omitted in order to have a form that can be proved to converge in all cases) and by increasing that part it translates to a direct increase in the maximum bit rate. However, since the transmission of every node is potentially seen as noise by the other nodes in the secondary system, the second term expresses what the other users will lose if node *i* increases its transmission power level. The algorithm consists of the following three steps:

- Initialization: For each node $i \in L$ that is transmitting in channel *k* select a valid transmission power level p_i^k and a positive value for the interference price π_i^k,
- Power Update: For every node *i* update its transmission power level p_i^k trying to maximize the surplus in equation (4.2-3), after a time interval $t_{ai} \in T_i$, where T_i is a set of positive time instances in which the user *i* will update its transmission power level and $t_{a1} \neq t_{a2} \neq \ldots \neq t_{ai}$, and
- Interference Price Update: For every node *i* calculate and announce the updated interference price π_i^k and notify the rest of the users about the updated value, after a time interval $t_{bi} \in T'_i$, where T'_i is a set of positive time instances in which the user *i* will update its interference price and $t_{b1} \neq t_{b2} \neq \ldots \neq t_{bi}$.

The last two steps are asynchronously repeated for all the nodes until the algorithm converges to its final steady state. Due to the nature of equation (4.2-3) it can be proved that the algorithm will converge within a finite number of steps, provided that no external parameters disturb the system. Moreover, if the problem is partitioned so that all users operate in the same spectrum or if the algorithm is executed only for subgroups selecting the same spectrum *M,* then it can be proved that the algorithm converges to a global maximum under arbitrary asynchronous updates [32].

In order to perform the power update in step 2, users select p_i^k from the set *TP* of the allowable transmission power levels, so that the surplus of equation (4.2-3) is maximized. Provided that the allowable power levels are equidistant values (meaning that they can be derived from the previous value by adding a constant increment) then the algorithm will converge, as long as the increment is sufficiently small. In order to execute the algorithm, every user in the network requires knowledge of its own SINR and channel gain, as well as the channel gains and the interference prices announced by other users. The SINR and the channel gain between a user pair can be calculated at the receiver and forwarded back to the transmitter. The channel gains between users can be calculated if receivers periodically broadcast a beacon [32]. This information can also be provided on demand through a specially defined message sent from the receiver. Thus, in case the transmitter requires channel gain information before the reception of the next scheduled beacon, it can request this information from the receiver who will respond with the relative measurements. Finally, interference price values can be also conveyed in the same manner. Every user announces a single interference price, therefore the delay that is introduced by the algorithm scales linearly with the number of users.

However, in the original version of the algorithm from [32], without the coefficient α in (4.2-3), an underestimation of interference prices is likely in some cases, e.g., due to problems in message exchange or increased update time intervals for the interference prices, and the effect of the underestimation is the convergence of the algorithm in a non optimal solution, i.e., the exact transmission power level of all nodes are not the optimal one. Therefore, coefficient α is introduced in our work in order to improve situation aware decision making in the presence of uncertainties such as large update time intervals from the previous interference price update (considering that updates are asynchronous for all users) and potential problems in message exchange due to high mobility. In such cases the relative impact of the subtracted term should be enhanced, otherwise the first term usually dominates and this results to all users selecting the maximum valid power level. In both cases there is a danger that the impact of the interference to others due to the increase in transmission power will be underestimated as explained above, thus factor α needs to avert this scenario by increasing the weight of the second term. In such cases factor α compensates for the underestimation of interference and if it is defined appropriately it can result in a system that approximates the case of “perfect” message exchange. Fuzzy logic is well suited for this since it can handle vague and unclear requirements efficiently and the system can be easily fine-tuned to exhibit the desirable behaviour. Therefore, if coefficient α is included as a “weight” factor that is multiplied with the subtracted interference term then we derive the following equation that is the objective we are trying to maximize:

$$u_i\left(\gamma_i\left(p_i^k\right)\right) - a \cdot p_i^k \sum_{j \neq i} \pi_j^k \cdot h_{ji} \qquad (4.2\text{-}4)$$

4.2.1 Fuzzy Logic Reasoner

The coefficient *α* sets the weight of the subtracted interference-related term in equation (4.2-3) and is determined before the initiation of the optimization phase by executing a Fuzzy Logic reasoner. Specifically, *α* is defined as 1/500 of the Interference Weight derived after defuzzification.

The Fuzzy Logic reasoner which is used is of type “Mamdani”, because this type of reasoner is intuitive, well suited for human input, flexible and widely accepted. It receives three inputs (number of users, mobility level and update time interval for the interference prices) and one output (the Interference Weight). The membership functions mf1 – mf5 are given the labels “very low”, “low”, “moderate”, “high” and “very high respectively”. The rule base for the fuzzy reasoner is presented in Table 4-1.

Rule Number	# of Nodes	Update Interval	Mobility Level	Consequent
1	Low	Low	Low	Very Low
2	Low	Low	Moderate	Very Low
3	Low	Low	High	Low
4	Low	Moderate	Low	Low
5	Low	Moderate	Moderate	Low
6	Low	Moderate	High	Low
7	Low	High	Low	Low
8	Low	High	Moderate	Low
9	Low	High	High	Moderate
10	Moderate	Low	Low	Low

Rule Number	# of Nodes	Update Interval	Mobility Level	Consequent
11	Moderate	Low	Moderate	Low
12	Moderate	Low	High	Moderate
13	Moderate	Moderate	Low	Moderate
14	Moderate	Moderate	Moderate	Moderate
15	Moderate	Moderate	High	High
16	Moderate	High	Low	Moderate
17	Moderate	High	Moderate	High
18	Moderate	High	High	High
19	High	Low	Low	High
20	High	Low	Moderate	High
21	High	Low	High	High
22	High	Moderate	Low	High
23	High	Moderate	Moderate	High
24	High	Moderate	High	Very High
25	High	High	Low	High
26	High	High	Moderate	Very High
27	High	High	High	Very High

Table 4-1: Fuzzy Reasoner Rule Base

As presented the number of nodes have been selected to be the dominant factor, since it has the greatest effect in the final outcome. This is because if the number of nodes is large, even a small increase in the transmission power of a node has the potential to cause increased interference and reduce the QoS to a large number of other nodes.

The update time interval and the mobility level have similar weights but different behaviour. The first is having a uniform effect over the entire valid range of update times, while the latter starts to affect the outcome only after a relatively high level; after that point it increases sharply, because only after a relatively high level of mobility users are likely to underestimate the interference they will cause to others (due to problems in message exchange, etc).

The defuzzification method for generating the final crisp value is “Centroid”, also known as “Center of Gravity - COG”. This method determines the centre of the area below the combined membership function; therefore the final output uCOG is given from the following equation, where u_i are the centres of the membership functions *μF(u)*:

$$u_{COG} = \frac{\sum_{1}^{27} u_i \cdot \mu_F(u_i)\ du}{\sum_{1}^{27} \mu_F(u_i)\ du} \quad (4.2\text{-}5)$$

4.2.2 Methodology for Cooperative Power Control Decision Making

The overall methodology for the derivation of the optimal transmission power of every node is depicted in Figure 4-1. The methodology consists of three main phases, namely:

- The Fuzzy Logic Reasoner phase,
- The Power Computation phase, and
- The Steady State phase.

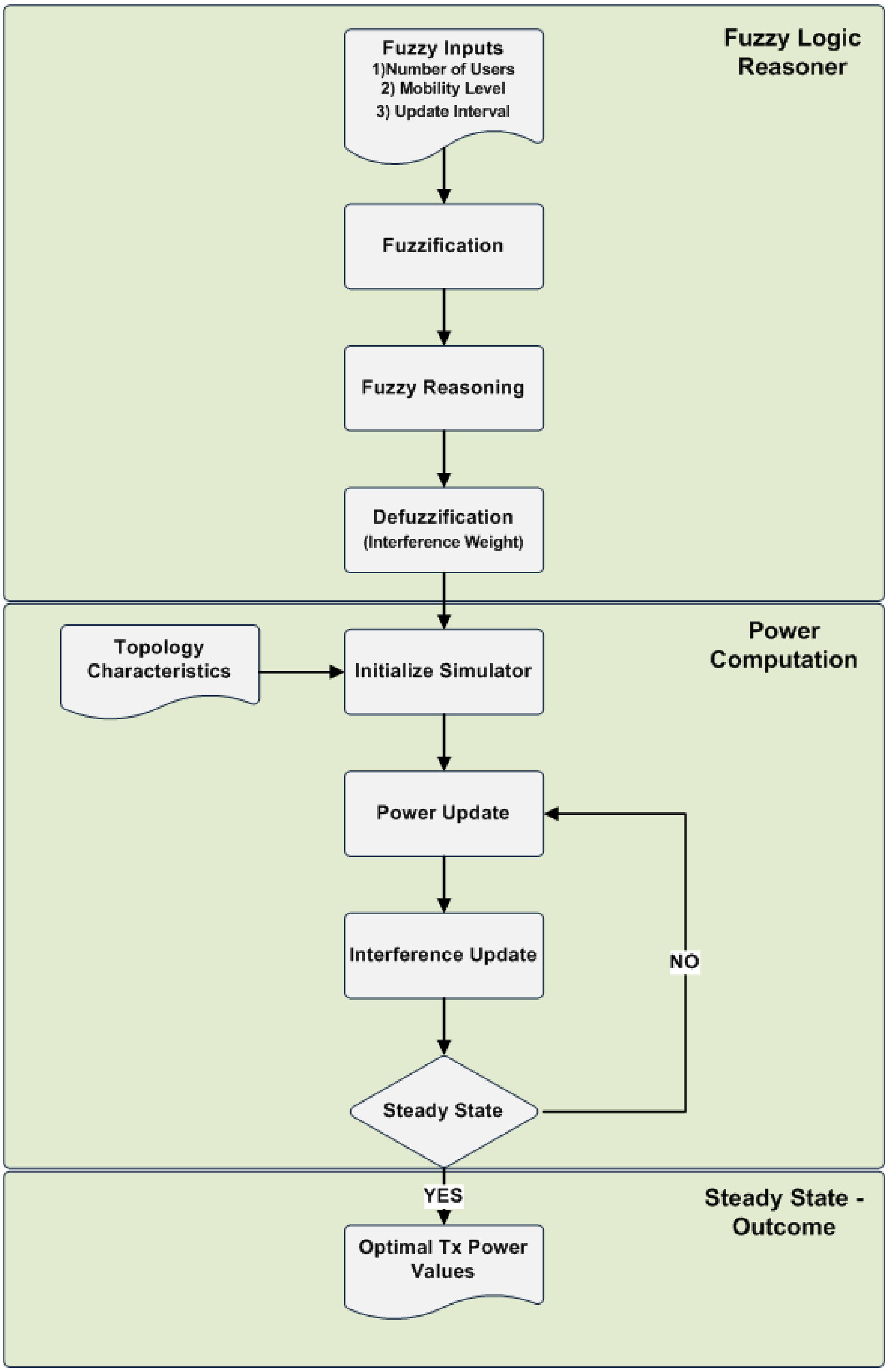


Figure 4-1: Overall Cooperative Decision making Methodology.

Initially, at the Fuzzy Logic Reasoner phase, the fuzzy inputs, which in the considered case are the number of nodes, the mobility level and the update time interval for the interference prices, are provided in order to appropriately compute the Interference Weight. As a next step, fuzzification of the values takes place in order to prepare them for elaboration in a fuzzy logic context. Following the fuzzification process, fuzzy reasoning is applied based on a set of predefined rules (Table 4-1). As previously referred, these rules describe the desired behaviour of the system and define the impact of the input parameters (number of nodes, mobility level and update time interval) in the value of the Interference Weight. After fuzzy reasoning has been completed, the result is defuzzified to numerical, giving the crisp value of the Interference Weight.

The topology characteristics are used to initialize the simulator and every node selects a valid initial value for the transmission power level p_{ik} and the interference price π_{ik}. Finally, the nodes proceed to update their transmission power levels and interference prices asynchronously in order to maximize the utility function. The process is completed when the system reaches a steady point in which no node is requesting to modify its transmission level.

4.2.3 Machine Learning Schemes

Machine Learning is a branch of Artificial Intelligence (AI) related to the design and development of algorithms that manage to infuse knowledge on computers. Such algorithms are fed with empirical data, which are translated to specific behaviours, in order to produce intelligent decisions. Due to the huge amount of input data, as well as their high complexity, the set of the possible behaviours is also very large, so a Learning entity is needed to filter/process a representative set of examples (training data); in this way, Learning entity captures its most important characteristics and consequently benefit the decision making mechanism (output).

Several Machine Learning approaches are developed and according to their specific characteristics are classified to the following categories:

- Supervised Learning,
- Unsupervised Learning,
- Semi-Supervised Learning,
- Reinforcement Learning.

A more detailed description of each approach will be presented in the following subsections.

4.2.3.1 Supervised Learning

Supervised Machine Learning approach states that, for any given set of training examples consisting of an input object *Xi* (typically, a vector) and a desired output value *Yi* (Supervisory signal or Label), an inferred function $g: X \rightarrow Y$, that is called Classifier, is produced in order to predict the correct output [12].

A wide range of supervised learning algorithms has been developed such as k Nearest Neighbour (k-NN), Support Vector Machines (SVM) and Bayesian Statistics [33]. However, four (4) critical issues should be strongly considered when using Supervised Learning algorithms: (i) the dimensionality of the input, (ii) the amount of training data, (iii) the Classifier complexity, and, (iv) the noise of output values.

As mentioned afore, very well known supervised learning algorithms are the k Nearest Neighbour (k-NN), Support Vector Machines (SVM) and Bayesian Statistics. The former concerns a supervised learning scheme which employs a set of already labelled observations in order to classify a smaller set of unknown data points; the classification is based on the majority vote of the nearest neighbours [19]. Support Vector Machines classify every observation into one of two given classes; such process renders SVM a non-probabilistic binary linear classifier [20]. After training the training procedure, an SVM training algorithm builds a model that predicts whether a new example falls into one category or the other. Finally, Bayesian Statistics use observations so as to calculate the probability that a hypothesis may be true, or else to update its previously-calculated probability [21].

4.2.3.2 Unsupervised Learning

The Unsupervised Learning schemes are based on unlabeled input objects *Xi* (vectors), attempting to determine the organization and explain the key features of data. This problem is closely related to the Density Estimation Problem in Statistics [16]. Data Clustering and Dimension Reduction are the most well known paradigms of unsupervised learning.

The core idea of Data Clustering is to partition a set of *N*, d-dimensional, observations into groups such that intra-group observations exhibit minimum distances (for example Euclidean distance) from each other, while inter-group distances are maximized. This idea can be implemented using three (3) different methods, (i) the Hierarchical Clustering, (ii) the Density-based Clustering, and, (iii) the Subspace clustering. In the first method it is attempted to conclude to successive clusters using the previously established ones. According to the Density-based Clustering, a cluster is considered as a region in which the density of data objects exceeds a threshold (DBSCAN [17] and OPTICS [22] are two typical algorithms of this family). Finally, the subspace clustering method searches for clusters that can only be represented in a particular projection/view (subspace, manifold) of the data [23].

The second well known Unsupervised Learning solution is the Dimension Reduction and could be split into two distinct phases; the first assumes a subset of the original variables (Feature selection) while the second transforms the data of the high-dimensional space to a space of fewer dimensions (Feature extraction). The key algorithm of this learning scheme is Principal Component Analysis (PCA) which performs an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of uncorrelated variables, called principal components [25].

4.2.3.3 Semi-Supervised Learning

Semi-Supervised Learning approach is actually a combination of both Supervised and Unsupervised techniques. In this hybrid method, a typically small amount of unlabeled data with a large amount of labelled data is used in order to produce a considerable improvement in learning accuracy.

Co-Training is the most famous method of this learning scheme [24]. Co-Training requires two views of the data, assuming that each example is described using two different feature sets that provide complementary information about the instance. Ideally, the two views are conditionally independent. The first step of this method learns a separate classifier for each view using any labelled examples while in the second step the most confident predictions of each classifier on the unlabeled data are used to iteratively construct additional labelled training data.

4.2.3.4 Reinforcement Learning

Reinforcement Learning problems are usually captured by agents interacting with their environment.

Contrary to the most forms of Machine Learning where the learner is explicitly told which actions to take, in Reinforcement Learning the learner has to discover which actions yield the most reward by experimenting. Moreover, in the most interesting and challenging cases, actions may affect not only the immediate reward but also the next situation and, through that, all subsequent rewards [18].

Apart from the agent and the corresponding environment, the four (4) following components of a reinforcement learning system need to be defined:

- A policy, which defines the learning agent’s way of behaving at a given time and suggests the mapping between a set of perceived states (s_t) of the environment to actions (a_t) to be followed,
- A reward function, which defines the goal in a reinforcement learning problem and maps each perceived state (or state–action pair) of the environment to a single number, a reward (r_t), indicating the intrinsic desirability of that state,
- A value function, which specifies what is good in the long run. The value of a state is the total amount of reward an agent can expect to accumulate over the future, starting from that state,
- Optionally, a model of the environment, which captures the environment perception.

The three (3) fundamental approaches that are dominant in the literature are the Monte Carlo, the Dynamic Programming and the Temporal Difference method.

The Monte Carlo Method is based on policy iteration imitation [27] which consists of two distinct phases:

Policy evaluation

- This phase holds under two basic assumptions. The first assumption implies that the Markov Decision Process is finite and, in fact, a table representing the action-values fits into the memory while the second one states that the problem is episodic and after each episode a new one starts from some random initial state,
- Given a stationary, deterministic policy π, the goal is to compute the function values $Q^{\pi}(s, a)$ (or a good approximation to them) for all state-action pairs (s, a),
- Then, the estimate of the value of a given state-action pair (s, a) can be computed by simply averaging the sampled returns which originated from (s, a) over time,
- Given enough time, this procedure can thus construct a precise estimate Q of the action-value function Q^{π}. This finishes the description of the policy evaluation step.

Policy improvement

- In the policy improvement step, as it is done in the standard policy iteration algorithm, the next policy is obtained by computing a *greedy* policy with respect to Q. Given a state s, this new policy returns an action that maximizes Q^{π}. In practice, one often avoids computing and storing the new policy, but uses lazy evaluation to defer the computation of the maximizing actions to when they are actually needed.

The Dynamic Programming Method can be either approached as a bottom-up or a top-down method. The former is based on the formulation of a complex calculation as a recursive series of simpler calculations while the latter is based on storing the results of certain calculations, which are later used again, since the completed calculation is a sub-problem of a larger calculation. Both methods have a basic requirement as they demand the Full Model of the environment. The most important algorithms using Dynamic Programming are the Value Iteration method for solving Markov Decision Process and the method of Undetermined Coefficients which can be applied to solve the Bellman equation [28].

The Temporal Difference (TD) method is a combination of the abovementioned Reinforcement Learning methods [29]. On the one hand, TD resembles a Monte Carlo method because it learns by sampling the environment, according to some policy, and, on the other hand, it is related to Dynamic Programming techniques because it approximates its current estimate based on previously learned estimates (a process known as bootstrapping). The most representative algorithm of Temporal Difference method is Q-Learning that works by estimating the values of state-action pairs. The value $Q(s, a)$ is defined to be the expected discounted sum of future payoffs obtained by taking action <*a*> from state <*s*> and following an optimal policy thereafter. Once these values have been learned, the optimal action from any state is the one with the highest Q-value. The main advantage of Q-learning is that it is able to compare the expected utility of the available actions without requiring a model of the environment.

4.2.4 Learning-Assisted Fuzzy Logic Reasoner

As presented earlier in Section 4.2, Cooperative Power Control based on Fuzzy Logic algorithm concludes to the identification of the optimum transmission power level for all nodes, in order to optimize network overall utility and, in parallel, mitigate interference.

The identification of the transmission power of the network elements derives from the extraction of the (global) maximum of the mathematical formula:

$$u_i\left(\gamma_i\left(p_i^{\ k}\right)\right) - a \cdot p_i^{\ k} \sum_{j \neq i} \pi_j^{\ k} \cdot h_{ji} \qquad (4.2\text{-}6)$$

The first part refers to the Shannon capacity (i.e. maximum bit rate), whereas the second part expresses the marginal loss in utility when other nodes increase their transmission power. However, the latter is multiplied by the coefficient α, intending to capture exactly the uncertainties that may occur in the network. Coefficient α is actually introduced in order to improve situation-aware decision making in the presence of uncertainties (e.g. large update time intervals) and potential problems in message exchange due to high mobility.

Coefficient α is extracted using Fuzzy Logic, which as stated suggests an attractive method for dealing with multi-objective and not well defined decision problems. However, the way past decisions affect network's performance is not taken into account according to the algorithm description in Section 4.2. This can be realized using learning techniques so as to set dynamically and more accurately the Fuzzy Logic membership functions based on the knowledge extraction from previous iterations.

The key idea is to add intelligence in the decision process by periodically monitoring the network's performance and stability, analyzing the monitored data and finally more accurately interpreting Fuzzy Logic inputs. From the learning schemes that presented before, the supervised learning appears to the most attractive mechanism. Such scheme shall evaluate the previous monitored instances and concurrently use data-mining techniques (i.e. clustering, k-Nearest Neighbour etc) for the grouping of the inputs and the corresponding outputs; the afore-described grouping shall be used to update the fuzzy reasoner so as to calibrate the way it interpret its environment (i.e. input membership functions). The impact of learning assisted Fuzzy Logic will be further investigated in the CONSERN WP3 scope.

4.3 Mechanisms for Cooperative Network Protocols

Global cross-layer, cross-network network optimizations will be realized using the components described in Section 3.3. The cooperation mechanisms focus on the following problems:

i) Gathering of network information and community priorities,

ii) Algorithms for deciding which network optimization techniques positively influence the network incentives,

iii) Activation and configuration of the network optimization techniques.

The following sections present the cooperative mechanisms which will be investigated.

4.3.1 Community Creation

Community creation algorithms are responsible for the autonomous creation of groups of independent devices. After deployment of the devices, the nodes first find out whether they can form a community with similar co-located devices. Joining a community has both benefits and disadvantages for a device. When a device joins a community, the community incentives might differ from the incentives of the individual device. In this situation, the community will optimize towards incentives that are suboptimal for the joining device. On the other hand, by joining a community, the device enters a stronger negotiation position, since a community can negotiate on behalf of a large group of nodes.

The partitioning of devices into separate communities can occur either at run-time or at design-time. To cope with dynamically changing network conditions, as well as to avoid complex and time-consuming manual network configuration, a non-manual approach is preferred. The methodology does not enforce a single community creation method: multiple approaches are possible to partition the devices into communities of directly connected devices.

4.3.2 Community Discovery

Community discovery algorithms focus on discovering co-located networks that use similar or different communication technologies. Community discovery consists of the following steps:

- Assignation of discovery nodes. Each community decides on the optimal number of devices that are needed to detect co-located communities. To bear minimal impact on the network performance, a subset of discovery nodes can suffice,
- Community discovery. Next, the discovery devices are used to detect the co-located communities. Community detection can be passive (i.e.: discovery devices passively scan for recognized packets on multiple frequencies in order to overhear existing communities) or active (i.e.: by broadcasting community advertisement messages over multiple frequencies containing information about the network settings that should be used to contact the advertising community).

Community discovery algorithms detect all the necessary network settings to (i) identify and characterize co-located communities and (ii) enable single hop communication between the discovery nodes of different communities.

4.3.3 Negotiation Algorithms

Negotiation algorithms investigate whether cooperation between different co-located communities (in the form of activating cross-network services such as interference avoidance) is beneficial.

To this end, each participating community should have a negotiation entity. This negotiation entity is either a single, central manager that is trusted by both communities or an entity that is distributed over several nodes of each community.

Negotiation algorithms typically include the following phases:

- Announcement of negotiation entity. The negotiation entity of each community regularly announces its presence to all nodes of the community by broadcasting 'negotiation advertise' messages,
- Collection of community profiles. All received community profiles are forwarded to the nearest negotiation entity where the negotiation process is initialized,
- Determine an influence rating for each service. For each available network service, the negotiation manager determines how the activation of the available service will influence the incentives of each community. For example, enabling a specific aggregation technique can increase the network lifetime incentive by 30%. To agree on estimated influence of network services, results can be used from (i) existing literature, from (ii) network simulators or from (iii) network monitoring agents,
- Negotiate on the optimal set of network services. Based upon these influence ratios, the negotiation entity calculates/negotiates about the optimal selection of services that should be activated. To calculate the optimal set of network services, several negotiation approaches are possible based on methods such as game theory, self-learning approaches or mathematical formulas.

4.3.4 Policy Enforcement

Finally, communities will want to check whether all other communities are 'playing by the rules', i.e.: are not cheating. Monitoring algorithms can be used to (i) investigate whether the selected services are actually activated and performing as expected and (ii) monitor the actual influence ratios of the activated services. If the set of services changes or the measured influence ratios differ greatly from the influence ratios used in the negotiation, a new negotiation process is started.

4.4 Cooperative Mechanisms in HetNet Environments

4.4.1 Power On/Off Cooperation Strategies

4.4.1.1 Game-Theoretic Concepts and Notation

In this section the energy-efficiency network decision making problem is described where a group of nodes coexist in a network and make simultaneous decisions. Game theory is used to analyze the problem [6][7]. Initially interest is to study power on/off cooperation strategies in sequential decision problems based on a game-theoretic model where the system is being controlled by multiple players. There are various ways in which such a cooperative strategy can be modelled; however, and for simplicity, corresponding investigations are initially focusing on n-player cooperative games, where cooperative implies common interest games.

More formally, a game Γ has three (3) components: (i) a set of N players, (ii) a set of possible actions (or strategies) for each player i, and (iii) a set of payoff functions (or utility functions or reward functions), one per player $\{r_i\}$ $i \in I$, mapping joint actions into real numbers. The set of N players is denoted as $I = \{ 1, 2, 3, \ldots, N\}$ and will usually take N to be finite. For each player $i \in I$, we denote by A_i the set of possible actions that a player can take, whilst the Cartesian product $A = A_1 \times A_2 \times \cdot \times A_N$ denote the action space of all action combinations. Players at each stage of the game independently select an individual action to perform. Both single stage (or strategic games or games in normal form) and repeated games (games in extensive form) will be studied. At any stage the N-tuple ($a_1, \ldots$, a_N) of individually chosen actions constitutes a joint action (or an action profile) and will be denoted by a or (a_i).

Finally, for each player $i \in$ I r_i: $A \rightarrow R$ denotes player i's payoff function (also called reward function or more commonly utility function). The payoff function measures the "usefulness" of action a for player i. Note that each player may assign different preferences to different actions. Each $a \in A$ is associated to a distribution of rewards characterized by an expected reward $R(a)$.

A game can be broadly defined as each player adjusts its strategy to optimise a utility (reward) function. A deterministic (or pure) strategy is a rational mapping that determines the action a player will select. Rationality implies that a player at any stage of the game will select the action that maximises the expected reward. In deterministic strategy games players select their actions simultaneously and independently and no player is informed about the decision of any other player prior to making his own decision. Although a player does not know in advance the action choices of the other players, predictions can be made by assuming rationality and given that the payoff functions of the players are all common knowledge.

As compared to a game of deterministic strategies, in a game with randomized strategies a player chooses actions according to some probability distribution. A randomized (or mixed) strategy σ_i for a player i is a probability distribution over his actions $a_i \in A_i$. For each player i $\Sigma a_i \in A_i$ $\sigma_i(a_i)$=1 where $\sigma_i(a_i)$ denotes the probability to use action a_i.

Clearly, a deterministic strategy a_i is a randomized strategy σ_i, where $\sigma_i(a_i) = 1$. The space of player i's randomized strategies is Σi. A randomized strategy profile $\sigma = (\sigma_1, \sigma_2, \ldots, \sigma_N)$ and the Cartesian product Σ_i forms the randomized strategy space Σ. The expected utility of player *i* under joint randomized strategy σ is given by

$$r_i(\sigma) = \sum_{a \in A} \left(\prod_{j=1}^{N} \sigma_j(a_j) \right) r_i(a) \qquad (4.4\text{-}1)$$

A reduced profile for player *i* is a strategy profile for all players but *i* (denoted a_{-i}). In the sequel, the notation a_{-i} will refer to a joint action of all players except player *i*, and (a_i, a_{-i}) will refer to a joint action where player *i* takes a particular action a_i.

Given a profile a_{-i}, a strategy a_i is a best response for player *i* if the expected value of the strategy profile (a_i, a_{-i}) is maximal for player *i*; i.e., player *i* could not do better using any other strategy $a_{i'}$.

Finally, the strategy profile a^* = (a_i, a_{-i}) is a Nash equilibrium if action a_i is a best response to a_{-i}, for every player *i*. An equilibrium (or joint action) is optimal if no other a_i gives a greater value of the payoff function.

The following game-theoretic distinctions [6] are of interest for further consideration:

- **Strategic Games vs. Extensive Games** - A strategic game is a model of a situation in which each player chooses his actions once and for all, and all players' decisions are made simultaneously (that is, when choosing an action each player is not informed about the action chosen by any other player). By contrast, the model of an extensive game specifies the possible orders of events; each player can consider his plan of action whenever he has to make a decision.
- **Non-cooperative vs. Cooperative Games** – A distinction can be made between two types of games: those in which the sets of possible actions of individual self-interested players are primitive strategies and those in which the sets of possible joint actions of groups of players are primitive strategies. Sometimes, models of the first type are referred to as "non-cooperative", while those of the second type are referred to as "cooperative". Sometimes, “cooperative” refers to the result of self-interested players when they share the same common objective (utility) function or to the long term behaviour of extensive games. The decision problem is cooperative since each agent’s reward is drawn from the same distribution, reflecting the utility assessment of all agents. The agents wish to choose actions that maximize the (expected) reward.
- **Games with Perfect vs. Imperfect Information** - The third distinction is between games where the players are fully informed about each others' moves, and games where the players may be imperfectly informed and often have to make decisions under conditions of uncertainty. The players may be (i) imperfectly informed about events that happen in the game, e.g., due to partial observability of the environment, (ii) uncertain about non-deterministic actions of the other players, (iii) uncertain about the reasoning of the other players, e.g., other players’ payoff functions, and (iv) uncertain about the (objective) parameters of the environment.
- **Static vs. Stochastic Games** – In static repeated games transitions to new states are deterministic and solely determined by the chosen actions of the players. A stochastic game is a dynamic game played by one or more players in a sequence of stages with probabilistic transitions. In each stage the players select actions and each player receives a payoff that depends on the current state and the chosen actions. The game moves to a new random state whose distribution depends on the previous state and the players’ actions. The game is repeated a finite or infinite number of times if the game is a finite-horizon game or an infinite-horizon game respectively. A player’s total payoff is defined as the typically discounted sum of the stage payoffs, e.g., $\sum_{i=1:N} \gamma^i r_i$, where rewards received after i time

steps are discounted exponentially by a factor of γ^i. A 1-player stochastic game is equivalent to a Markov Decision Process (MDP).

4.4.1.2 Cooperative Games

This section describes the basic game theory concepts that will potentially be used for the modelling and the analysis of the power on/off scenario and further the development of algorithms that would reach stable energy-efficient solutions.

4.4.1.2.1 Models of Cooperative Games

As stated earlier cooperative games can be divided in (i) games consisting of self-interested players where cooperation is sought as a result of a player's rationality according which players choose actions that maximize their individual payoff and (ii) games consisting of players having a common interest. In the former category solution approaches can be found such as auctions, bargaining, market equilibrium, contract-net based negotiation etc. This category typically entails negotiations among players that try to maximize their own payoff and will therefore be referred to as cooperation based on automated negotiations or as cooperation among self-interested players based on negotiation. In the latter, cooperative solutions comprise coalition games and coordinated games. In the sequel a short description of the above concepts is provided.

4.4.1.2.1.1 Cooperation Among Self-Interested Players Based on Negotiation

Mechanism design is an area of game theory that concerns itself with how to engineer incentive mechanisms that will lead independent, self-interested players toward outcomes that are desirable from a system-wide point of view. An outcome of a game can be practically anything, for instance the assignment of a network resource to a player. The challenge therefore is to design incentives and non-manipulable mechanisms in which no player can benefit from not participating in the game and not abiding by the rules of the mechanism. A standard way to deal with the above two problems is to provide payments to the players in exchange for their services. Such payments can be implemented by means of pricing payoff functions. Solution approaches include:

- **Auctions** – Auction theory [6] analyses protocols and player's strategies in auctions. An auction consists of an auctioneer who possesses an item and potential bidders who would like to acquire the item. In an auction the payment function of an auctioneer is defined by the maximum price he can sell the item and depends on the valuation of the bidders, i.e., the highest price bidders are willing to pay for the item. Various auction protocols exist including, English (first-price open-cry), first-price sealed-bid, Dutch (descending) and Vickrey (first-price sealed-bid).
- **Bargaining** – In a sequential bargaining setting [10], players alternate in making offers to each other in order to reach a mutually beneficial agreement. Bargaining protocols typically include discounting at each bargaining round in order to guarantee that the bargaining process will reach a solution agreement at a finite number of rounds.
- **Equilibrium Market Mechanisms** – General equilibrium theory provides a distributed method for efficiently allocating goods and resources among players based on market prices. A market has two types of players, consumers and producers. A general equilibrium of market mechanism corresponds to an efficient solution which takes into account trade offs between market players and the fact that the values of different goods to a single player may be interdependent. The most common algorithm to search a general equilibrium is the price atonement process [8] which is a steepest descent search method.
- **Contract Net** – General equilibrium mechanisms assume global prices mediated by a single mediator. The Contract Net protocol [9] is a distributed negotiation in the task allocation domain that deals with situations where neither a mediator nor a global price is known. In

the protocol, players may suggest contracts to each other, and make their decisions whether to accept or reject a contract based on some well-defined marginal cost calculations. Based on these marginal costs the contractor pays the contractee some amount resulting in a situation where no player is worse off with a contract than without it. A player can be both a contractee and a contractor at the same time and he may also subcontract out tasks it committed to earlier via another contract.

4.4.1.2.1.2 Cooperation Based on Coordination and Coalition Formation

One approach of cooperation game is to have the cooperation analysed by modelling the game using coalitional game theory [6][7]. A coalitional game is distinguished from a non-cooperative game primarily by its focus on what groups of players can achieve rather than on what individual players can do and by the fact that it does not consider the details of how groups of players act internally. For coalitional games, users cooperate by forming coalitions. A class of coalitional games is considered for which every coalition can be described by a single number, interpreted as the payoff available to the coalition. The share of the payoff received by players in a coalition is called a **payoff vector**, which can be arbitrarily shared among the members of a coalition (transferable payoff) or might be strictly determined by the nature of the game (non-transferable payoff).

In a coalitional game with transferable payoff each coalition C is characterized by a single number $c(C)$, called the worth of C, with the interpretation that $c(C)$ is a coalition action's payoff distributed in any way among the members of C. A coalitional game (with non-transferable) payoff comprises a more general concept, in which each coalition cannot necessarily achieve all distributions of some fixed payoff.

A coalitional game (with non-transferable payoff) consists of (i) a (finite) set of players I, (ii) for each coalition C, a set of actions A_C, and (iii) for each player $i \in I$, preferences over the set of all actions of all coalitions of which he is a member. An action of the grand[1] coalition I is defined as "stable" if no coalition can break away and choose an action that all its members prefer. The set of all stable actions of the grand coalition is called the "core". The idea behind the core is analogous to that behind Nash equilibrium of a non-cooperative game: an outcome is stable if no deviation is profitable. In the case of the core, an outcome is stable if no coalition can deviate and obtain an outcome better for all its members. For a coalitional game with transferable payoff the stability condition is that no coalition can obtain a payoff that exceeds the sum of its members' current payoffs.

Another approach is having cooperation analysed by means of a coordination game [6] which is a kind of a potential game [11]. A game is considered to be a potential game if the incentive of all players to change their strategies can be expressed in one global function, the potential function P. More specifically, a game $\Gamma = (I, A, \{u^i\})$ is an exact potential game if there exists a function $P: A \rightarrow R$ such that for all $i \in I$, all $a \in A$, and all $a'_i \in A_i$, $P(a_i, a_{-i}) - P(a'_i, a_{-i}) = r_i(a_i, a_{-i}) - r_i(a'_i, a_{-i})$. The function P is called an exact potential function for the game Γ.

Based on the above definition of an exact potential game, a coordination game is defined as follows:

- A coordination game is a game in which all users have the same payoff function, i.e., $r_i(a) = G(a)$ for all $i \in I$. Note that a coordination game is an exact potential game with potential function $P = G$.
- A dummy game is a game in which each player's payoff is a function of only the actions of other players, i.e., his own action does not affect his payoff. That is, $r_i(a) = D_i(a_{-i})$ for each $i \in I$.

[1] The grand coalition (the set of all the players) is denoted by I and an arbitrary coalition by C.

Dummy games are also exact potential games where $P(a) = 0$ (or any other constant function). Any exact potential game Γ can be written as the sum of a coordination game and a dummy game, i.e., if there exist functions $G : A \rightarrow R$ and $D_i : A_{-i} \rightarrow R$ such that $r_i(a) = G(a) + D_i(a_{-i}), \forall\ i \in I, \forall\ a \in A$. The exact potential function of this game is $P(a) = G(a)$. A straightforward way of identifying exact potential games is given in [11].

4.4.1.2.2 Coordination Mechanisms

Action selection becomes difficult if there are many optimal joint actions. Without coordination there is a risk choosing suboptimal uncoordinated joint action. The general problem of equilibrium (optimal joint action) selection can be addressed in three different ways [58]: (i) conventions or rules are adopted by all players and which if followed ensure coordination [12], (ii) communication between players is admitted so as an agreement on an joint action can be achieved, based on negotiation and/or dynamic coalition formation, and (iii) learning of coordinated actions through repeated play of the game with the same players [13][14].

4.4.1.2.3 Learning in Cooperative Games

One especially simple, yet often effective, learning model for achieving coordination is fictitious play [13][15]. Each player i keeps a count $M^j_{a_j}$, for each $j \in I$ and $a_j \in A_j$, of the number of times the player j has used action a_j in the past. When the game is encountered, player i treats the relative frequencies of each of player j's moves as indicative of his current (randomized) strategy. That is, for each player j, player i assumes that player j plays action $a_j \in A_j$ with probability $Pr^j_{a_j} = M^j_{a_j} / \left(\sum_{a'_j \in A_j} M^j_{a'_j} \right)$. This set of strategies forms a reduced profile a_{-i}, for which player i adopts a best response. After the move, player i updates his counts appropriately, given the actions used by the other players.

In this stage it is assumed that the state is fully observable to all players. That is, the set of players, the set of each player's actions and the payoff of each player is common knowledge among the players. This assumption is often unrealistic. Action selection is more difficult if players are unaware of the rewards associated with various joint actions. In such a case, Reinforcement Learning (RL) can be used by the players to estimate, based on past experience, the expected reward associated with individual or joint actions.

One particular implementation of RL is Q-learning. In Q-learning, the Q-value, $Q(s,a)$, is a function that provides a numerical estimate of the value of performing an individual action a at a given state $s \in \Omega$ of the environment. The state s of the environment is a parameter-value vector which elements consists of observed parameters and Key Performance Indicators (KPI) that can be monitored and collected by the player. The player updates its estimate $Q_n(s,a)$, based on its current estimate $Q_{n-1}(s,a)$ and the sample (a, r) as follows:

$$Qn(s,a) \leftarrow Qn\text{-}1(s,a) + \lambda(r(s,a) + \max Qn\text{-}1(s',a')) \qquad (4.4\text{-}2)$$

where the sample (a, r) is the experience obtained by the player: action a is performed resulting in payoff/reward r and to the new state s' with a new joint action a' to be taken. λ is the learning rate $(0 \leq \lambda \leq 1)$, governing to what extent the new sample replaces the current estimate. Assuming an infinite number of iterations the algorithm converges to a value $Q_n(a)$, $n \rightarrow \infty$.

The model will not be further investigated, but mention it here since it subsumes the two special cases in which Q-learning could be applied in the study. Firstly, players learn independently Q-values for their individual actions based on the above equation. In other words, they perform their actions, obtain a reward and update their Q-values without regard to the actions performed by other players. Secondly, players learn Q-values for joint actions as opposed to individual actions. This implies that each player can observe the actions of other players. To determine the relative values of their individual actions, each player maintains beliefs about the strategies of other players.

Here, empirical distributions can be used, possibly with initial weights as in fictitious play. Agent *A*, for instance, assumes that each other agent *B* will choose actions in accordance with *A*'s empirical distribution over *B*'s action choices.

4.4.1.3 Power On-Off Modelling

In this section the energy-efficiency network decision making problem among a group of sites is further modelled based on the concepts of game theory and cooperative games.

4.4.1.3.1 Basic Assumptions

In this section reward functions will be expressed in terms of energy savings and key performance indicators. In a negotiation-based game setting the network consists of self-interested sites each one striving to maximise its individual energy saving while maintaining the coverage and capacity required. In a coordination game all sites strive in common to maximise the energy saving and increase network performance indicators.

More specifically, the power on-off system model will consists of a set of *N* wireless sites forming a heterogeneous network of BSs. The network is heterogeneous in the sense that different types of BSs are deployed, e.g., macro and indoor pico, each type having different energy and usage characteristics. BSs can be of two types: macro 3-sectored sites comprising three different cells per BS and pico omni-sites comprising one single cell. In the sequel, we will use the term cell instead of BS as the distinction is of no interest from a modelling point of view.

With respect to the energy characteristics the two types of cells, macro and pico differ in 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 Ratio (SIR) 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 lacks many of the advanced features used in macro cell equipment. The antennas of pico cells are omni-directional and 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 be the basic assumption for a series of studies that will target power setting solutions in a heterogeneous network of cells with no, partial and/or total coverage overlap.

4.4.1.3.2 Power On-Off Game Theory Model

For the game-theoretic analysis an heterogeneous network can be described as a game Γ consisting of *N* macro and pico cells which correspond to the set of *N* players indexed by $i \in I = \{1, 2, 3, \dots, N\}$. In its simplest form the set of possible actions that a cell can take is to set power on or off. Let the binary variable $A_i \in [0, 1]$ denote the action of i^{th} cell to setting power on ($A_i = 1$) or off ($A_i = 0$) then the power or energy consumption profile of the network is given by

$$\overline{\mathrm{P}} = \overline{\mathrm{A}}\overline{\mathrm{P}}_{\mathrm{total}} \qquad (4.4\text{-}3)$$

where $\overline{\mathrm{A}} = (\mathrm{A}_1, \mathrm{A}_2, \cdots, \mathrm{A}_\mathrm{N})$ represents a joint action (or a network action profile) based on individually chosen actions A,i i.e., power on, power off, and $\overline{\mathrm{P}_{\mathrm{total}}} = (\mathrm{P}_{\mathrm{ACin1}}, \mathrm{P}_{\mathrm{ACin2}}, \cdots, \mathrm{P}_{\mathrm{ACinN}})$ is the vector representing the maximum transmitted power of the cells in the network. For each cell there is a payoff utility function U_i defined by means of one or more of the key performance indicators as described in section 0 and the energy consumption in the network.

As described in section 0, the energy consumption of a cell is defined by means of power supply as a function of user load. Let $\overline{\mathrm{O}} = (\mathrm{O}_1, \mathrm{O}_2, \cdots, \mathrm{O}_\mathrm{N})$ be a fixed load distribution of users among the cells

$\overline{\mathrm{P_{load}}}(\overline{\mathrm{O}}) = \left(\mathrm{P_{ACin1}}(\mathrm{O_1}), \mathrm{P_{ACin2}}(\mathrm{O_2}), \cdots, \mathrm{P_{ACinN}}(\mathrm{O_N})\right)$ be the power consumption vector for the given load distribution. For the macro cells PACi(Oi) is computed based on $\mathrm{P_{AC}} = \mathrm{P_{ACRF}} + \frac{\mathrm{P_{BBU}}}{\mathrm{P_{PBB}}}$ and for pico cells it is assumed that power consumption is independent of load i.e., $P_{ACi}(O_i) = P_{maxi}$. 4.4-3 can be now rewritten as follows

$$\overline{\mathrm{P}} = \overline{\mathrm{A}}\overline{\mathrm{P}}_{\mathrm{load}}(\overline{\mathrm{O}}) \tag{4.4-4}$$

It has to be noted that $\overline{\mathrm{A}}$ is defined in terms of $\overline{\mathrm{O}}$ as $\overline{\mathrm{A}} = (\overline{\mathrm{O}}) > 0$ i.e., only the cells that have users to serve as given by $\overline{\mathrm{O}}$ are powered on.

For any $\overline{\mathrm{P}}$ and $\overline{\mathrm{O}}$, the total network energy consumption is given by

$$\epsilon(\overline{\mathrm{P}}, \overline{\mathrm{O}}) = \sum_{\mathrm{i}=1}^{\mathrm{N}} \left(\mathrm{P_i}(\mathrm{O_i})\right) \tag{4.4-5}$$

Finally, if $\overline{\mathrm{U}}(\overline{\mathrm{O}}) = \left(\mathrm{U_1}(\mathrm{O_1}), \mathrm{U_2}(\mathrm{O_2}), \cdots, \mathrm{U_N}(\mathrm{O_N})\right)$ denote the utility vector of the individual cell utilities then the network utility function is given by

$$\mathrm{u}(\overline{\mathrm{O}}) = \sum_{\mathrm{i}=1}^{\mathrm{N}} \left(\mathrm{U_i}(\mathrm{O_i})\right) \tag{4.4-6}$$

For a game in strategic form the objective is to find a joint action $\overline{\mathrm{A}}$ or a user distribution $\overline{\mathrm{O}}$ for which the corresponding $\overline{\mathrm{P}}$ optimise the following expression.

$$\min_{\mathrm{u}} \max_{\epsilon} \mathrm{f}\left(\mathrm{u}(\overline{\mathrm{O}}), \epsilon(\overline{\mathrm{P}}, \overline{\mathrm{O}})\right) \tag{4.4-7}$$

where f corresponds to an aggregating or multi-objective function.

Based on an analysis of the above game possible equilibrium solutions will be derived. These will be then used to study strategies as in a repeated games setup where at any stage the *N* nodes will decide on a set of individual actions that will optimise the above objective. Cooperation and coordination of actions in combination with suitable forms of reinforcement learning will be further evaluated.

4.4.2 Cooperative DAS Mechanisms

The pre-coding process is optimized to decide whether to switch on or off the distributed antenna for the intention of energy saving.

4.4.2.1 Joint Pre-Coding in Multi Cell Environment

There are totally *N* sectors in the system. It is assumed that there are M_{BS} transmit antennas at a base station in a sector. Each mobile is equipped with M_{UE} receive antennas. When there is only one UE scheduled in sector *i*, the received signal vector can be formulated as:

$$\mathbf{r}_i = \mathbf{H}_{ii}^H \mathbf{x}_i + \underbrace{\overbrace{\sum_{\substack{j=1 \\ j \neq i}}^{N} \mathbf{H}_{ij}^H \mathbf{x}_j}^{\text{inter-cell interference}} + \mathbf{n}_i}_{\mathbf{u}_i} \tag{4.4-8}$$

$M_{UE}\times 1$ column vector $\mathbf{r}_i$ is the received signal vector of UE in sector *i* and each element of the vector denotes the received symbol in each receive antenna. $M_{BS}\times 1$ column vector $\mathbf{x}_i, (i = 1, \cdots, N)$ is the signal vector transmitted by M_{BS} antennas in sector *i*. The first term in (4.4-8) denotes the useful signal received by the UE in sector *i* and the second term is the interference from all other sectors.

Let the Hermitan transpose of the M_{BS}×M_{UE} matrix $\mathbf{H}_{ij}$ be the channel matrix between the BS of sector *j* and the UE in sector *i*. If the UE has only one receive antenna, $\mathbf{y}_i, (i=1,\cdots,N)$ and $\mathbf{H}_{ij}$ degrade into scalar variable y_i and the M_{BS}×1 column vector $\mathbf{h}_{ij}$ respectively. $\mathbf{n}_i$ is the thermal noise of UE in sector *i*.

In case of closed loop joint transmission, the transmit vector of the BS is estimated according to the downlink CSI $\mathbf{H}_{ii}$, fed back by UE. It is assumed that the estimate and feedback is ideal and that the channel does not vary during the transmission. Given the covariance matrices of the BS in all sectors, the transmission rate of the UE in sector *i* is upper bounded by the mutual information between transmit and receive signal vectors.

$$\begin{aligned} r_i &\le E_H\left\{I\left(\mathbf{x}_i;\mathbf{y}_i\left|\mathbf{Q}_{i,opt},\mathbf{Q}_{j,opt}\right.\right)\right\} \\ &= E_H\left\{\log\det\left|\mathbf{I}+\mathbf{H}_{ii}^H\mathbf{Q}_{i,opt}\mathbf{H}_{ii}\left(\sum_{\substack{j=1\\ j\neq i}}^{N}\mathbf{H}_{ij}^H\mathbf{Q}_{j,opt}\mathbf{H}_{ij}+N_0\mathbf{I}\right)^{-1}\right|\right\} \end{aligned} \tag{4.4-9}$$

If cell interference is not considered, the input covariance matrix of the BS in sector *i* is the solution to the following maximization problem:

$$\mathbf{Q}_{i,opt} = \arg\max_{\mathbf{Q}_i\in\mathbf{X}} \log\det\left|\mathbf{I}+\mathbf{H}_{ii}^H\mathbf{Q}_i\mathbf{H}_{ii}/N_0\right| \tag{4.4-10}$$

If the total power constraint is considered, e.g. $\mathrm{X}=\left\{\mathbf{Q}_i\left|\mathrm{Tr}\left(\mathbf{Q}_i\right)\le P_i\right.\right\}$, the problem can be solved by the water-filling algorithm. Considering that the transmit power cannot be moved from one DAS node to another, the capacity optimization should be carried out with the constraint $\mathrm{X}=\left\{\mathbf{Q}_i\left|\mathbf{Q}_i\left(t,t\right)\le P_i/M_{BS}\right.\right\}$. In case that the UE has only one antenna, it is proved that Equal Gain Transmission (EGT) [52] achieves the solution to (4.4-10). The pre-coding vector can be expressed as

$$\mathbf{w}_i = \exp\left(j\angle\mathbf{h}_{ii}\right) \tag{4.4-11}$$

Where $\angle$ denotes the angle of each complex element in the vector. If we substitute the covariance matrix in (4.4-9) with $\mathbf{Q}_{j,opt}=P_j\mathbf{w}_j\mathbf{w}_j^H$ the transmit rate obtained by EGT can be simplified as:

$$r_{\mathrm{EGT}} = E_{\mathbf{h}}\left\{\log\left(1+\frac{P_i\left\|\mathbf{h}_{ii}\right\|_1^2}{\sum_{j=1,j\neq i}^{N}P_j\left|\left\langle\mathbf{h}_{ij},\exp\left(j\angle\mathbf{h}_{jj}\right)\right\rangle\right|^2+M_{BS}N_0}\right)\right\} \tag{4.4-12}$$

4.4.2.2 Energy Aware Pre-Coding

In the sense of single cell, it is better to allocate equal power among all antennas in order to achieve maximum transmit diversity. However, the DAS nodes that are far away from the UE contribute little to the received signal power but may cause severe interference to the adjacent cell. Taking both the energy efficiency and the inter-cell interference into account, it is better to power off antennas that are far away from the UE. Thus, a power on/off indication matrix can be introduced in the pre-coding matrix as:

$$\mathbf{w}_i = \mathrm{diag}\left(d_1,d_2,\cdots,d_{N_T}\right)\exp\left(j\angle\mathbf{h}_{ii}\right) \tag{4.4-13}$$

The binary diagonal element is determined according to portions of the total received power of each transmit antenna. If some of the transmit antenna contribute most part of the total received power, they have significant effect on the users' performance. And these antennas should be power on. On the contrary, those contribute trivial to users' performance should be power off. The energy aware on/off indicator can be defined as following:

$$d_i = \begin{cases} 1 & \dfrac{N_T P_i}{\sum_{k=1}^{N_T} P_k} > \text{thrd\_off} \\ 0 & else \end{cases} \qquad (4.4\text{-}14)$$

4.4.2.3 Energy-Aware Scheduling

In a proportional fairness 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:

$$U = \sum_k \log \bar{R}_k \qquad (4.4\text{-}15)$$

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:

$$D_k(f) = \frac{R_k(f)}{\bar{R}_k(f-1)} \qquad (4.4\text{-}16)$$

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:

$$U = \frac{\sum_k \log \bar{R}_k}{\sum_k \bar{P}_k} \qquad (4.4\text{-}17)$$

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 decision function:

$$D_{k'}(f) = \frac{\sum_k \log\left[\left(1-\frac{1}{T}\right)\bar{R}_k(f-1)\right] + \frac{1}{T-1}\frac{R_{k'}(f)}{\bar{R}_{k'}(f-1)}}{\left(1-\frac{1}{T}\right)\sum_k \bar{P}_k(f-1) + \frac{1}{T}P_{k'}(f)} \qquad (4.4\text{-}18)$$

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:

$$\bar{R}_k(f) = \begin{cases} \left(1-\frac{1}{T}\right)\bar{R}_k(f-1) + \frac{1}{T}R_k(f) & \text{user } k \text{ is scheduled} \\ \left(1-\frac{1}{T}\right)\bar{R}_k(f-1) & \text{user } k \text{ is not scheduled} \end{cases} \qquad (4.4\text{-}19)$$

$$\overline{P}_k(f)=\begin{cases}\left(1-\frac{1}{T}\right)\overline{P}_k(f-1)+\frac{1}{T}P_k(f) & \text{user } k \text{ is scheduled}\\ \left(1-\frac{1}{T}\right)\overline{P}_k(f-1) & \text{user } k \text{ is not scheduled}\end{cases} \quad (4.4\text{-}20)$$

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 get a higher scheduling priority. A suboptimal simplification of equation (4.4-18) is as follows

$$U(k)=\frac{R_k(f)}{R\bullet T_k(f-1)} \quad (4.4\text{-}21)$$

4.4.3 Cooperative Relay Scheduling

4.4.3.1 Basic Cooperative Relay Mode Decision Scheme

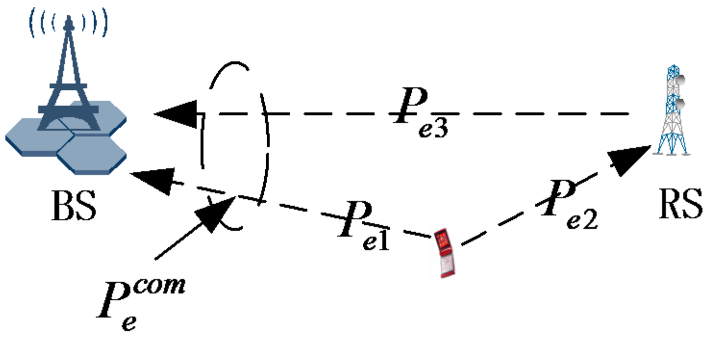


Figure 4-2: Transmitting signal paths in cooperative relay.

A UE located in the middle cell may have different options to access the central BS as discussed in Section 2.4.4, the optimal path is the path by which the maximum cell capacity is met. Under the assumption that the maximum cell capacity is met and in order to avoid the additional energy consumption introduced by relay node, it can be switched off if it is not selected by any UE. The cooperative relay scheme (decoding and forwarding) provide the basis for choosing among different transmission paths. The determination of the optimal path is discussed below.

The bit error rate for UE directly transmitting signal to BS is

$$r=h_1 s+I_1+n_1 \quad (4.4\text{-}22)$$

where r denotes the received signal, h1 is the channel impulse, s is the sent signal after demodulation, I1 is the interference from other neighbour cell and n1 is the thermal noise.

Here, the equivalent noise can be expressed as:

$$\sigma^2=\frac{\| I_1\|^2+\| n_1\|^2}{\| h_1\|^2} \quad (4.4\text{-}23)$$

$$P_e = erfc(\frac{1}{\sqrt{2}\sigma}))*0.5 \quad (4.4\text{-}24)$$

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:

$$P_c = (1 - P_{e3})(1 - P_{e2}) + P_{e2}P_{e3} \quad (4.4\text{-}25)$$

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

$$P_e = 1 - P_c = P_{e2} + P_{e3} - 2P_{e2}P_{e3} \quad (4.4\text{-}26)$$

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

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

$$\begin{aligned} r_1 &= h_1 s + I_1 + n_1 \\ r_3 &= h_3 s + I_3 + n_3 \end{aligned} \quad (4.4\text{-}27)$$

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:

$$\begin{gathered} \widehat{r} = (\|h_1\|^2 + \|h_3\|^2)s + (h_1^* I_1 + h_3^* I_3) + (h_1^* n_1 + h_3^* n_3) \\ \Downarrow \\ \widehat{r} = s + \frac{(h_1^* I_1 + h_3^* I_3) + (h_1^* n_1 + h_3^* n_3)}{(\|h_1\|^2 + \|h_3\|^2)} \end{gathered} \quad (4.4\text{-}28)$$

Then, the equivalent noise can be expressed as:

$$\sigma^2 = \frac{\|h_1\|^2\|I_1\|^2 + \|h_3\|^2\|I_3\|^2 + \|h_1\|^2\|n_1\|^2 + \|h_3\|^2\|n_3\|^2}{(\|h_1\|^2 + \|h_3\|^2)^2} \quad (4.4\text{-}29)$$

$$P_{com}^{[1]} = erfc(\frac{1}{\sqrt{2}\sigma})*0.5 \quad (4.4\text{-}30)$$

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:

$$P_{c2} = (1 - P_{e2})(1 - P_{com}^{[1]}) \quad (4.4\text{-}31)$$

Case 2. The signal received by relay is incorrect:

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

$$\begin{aligned} r_1 &= h_1(+s) + I_1 + n_1 \\ r_3 &= h_3(-s) + I_3 + n_3 \end{aligned} \tag{4.4-32}$$

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

$$\begin{gathered} \widehat{r} = (\|h_1\|^2 - \|h_3\|^2)s + (h_1^* I_1 + h_3^* I_3) + (h_1^* n_1 + h_3^* n_3) \\ \Downarrow \\ \widehat{r} = \frac{(\|h_1\|^2 - \|h_3\|^2)}{\|h_1\|^2 + \|h_3\|^2)} s + \frac{(h_1^* I_1 + h_3^* I_3) + (h_1^* n_1 + h_3^* n_3)}{(\|h_1\|^2 + \|h_3\|^2)} \end{gathered} \tag{4.4-33}$$

The equivalent noise is:

$$\sigma^2 = \frac{\|h_1\|^2\|I_1\|^2 + \|h_3\|^2\|I_3\|^2 + \|h_1\|^2\|n_1\|^2 + \|h_3\|^2\|n_3\|^2}{(\|h_1\|^2 - \|h_3\|^2)^2} \tag{4.4-34}$$

and the related error probability is

$$P_{com}^{[2]} = erfc(\frac{1}{\sqrt{2}\sigma})*0.5 \tag{4.4-35}$$

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

$$P_{c1} = P_{e2}(1 - P_{com}^{[2]}) \tag{4.4-36}$$

According to formulas (4.4-26) and (4.4-31), the probability of correct BS decoding can be provided by combining the signals from the UE and the relay as:

$$P_c = P_{c1} + P_{c2} = (1 - P_{e2})(1 - P_{com}^{[1]}) + P_{e2}(1 - P_{com}^{[2]}) \tag{4.4-37}$$

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 the best one for maximum the frequency efficiency can be chosen.

$$P_e = \begin{cases} P_e^d, & P_e^d \le P_e^f, P_e^d \le P_e^c \\ P_e^f, & P_e^f \le P_e^d, P_e^f < P_e^c \\ P_e^c, & P_e^c < P_e^d, P_e^c < P_e^f \end{cases} \tag{4.4-38}$$

P_e^d : $Direct\ transmitting\ error\ rate$

P_e^f : $\mathrm{Re}lay\ forward\ error\ rate$

P_e^c : $\mathrm{Re}lay\ cooperation\ error\ rate$

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

In order to achieve the system frequency efficiency improvement, we use the optimal principles such as minimize maximum method (fminimax function in Matlab), where we minimize the maximum Pe of the UE) to find the suitable power allocated to each UE and its serving relay.

For the first phase, the objective function (4.4-37) is mainly based on the maximum system cell capacity and unused relay nodes will be switched off to reduce the energy consumption under the assumption that the maximum system cell capacity is met. Another possible solution is to define an objective function based on the minimum network energy consumption including the power consumption of the UE, the BS and the relay nodes, or based on a proper trade-off between the cell capacity and system energy consumption. Additionally Network coding may be also taken into account in next step.

4.4.3.2 Energy-Aware Cooperative Relay

In this section the evaluation of the average energy consumption per bit of the cell is discussed.

Let $\mathrm{E_r}$ define the average energy consumption for a relay to transmit one bit and let the average energy consumption of UE transmission be defined as:

$$E_u = \begin{cases} E_u^d, & if\, P_e^d\, isselected \\ E_u^f, & if\, P_e^f\, isselected \\ E_u^c, & if\, P_e^c\, isselected \end{cases} \tag{4.4-39}$$

Suppose that the re-transmission threshold of the bit error rate is $\mathrm{P_e^t}$, then the average energy consumption per bit $\overline{\mathrm{E^d}}$, in case that $\mathrm{P_e^d}$ is selected, can be formulated as:

$$\begin{aligned} \overline{E^d} &= E_u^d + E_u^d P_e^d + E_u^d (P_e^d)^2 + \ldots + E_u^d (P_e^d)^{N^d} \\ &= E_u^d \sum_{i=0}^{N^d} (P_e^d)^{N^d}, \quad i \in N \\ where\;\; N^d &= \max\{N_i \mid (P_e^d)^{N_i} \le P_e^t, N_i \in N, i \in N\} \end{aligned} \tag{4.4-40}$$

Similarly, the average energy consumption per bit $\overline{\mathrm{E^f}}$, in case that $\mathrm{P_e^f}$ is selected, can be formulated by:

$$\begin{aligned} \overline{E^f} &= (E_u^f + E_r) \sum_{i=0}^{N^f} (P_e^f)^{N^f}, \quad i \in N \\ where\;\; N^f &= \max\{N_i \mid (P_e^f)^{N_i} \le P_e^t, N_i \in N, i \in N\} \end{aligned} \tag{4.4-41}$$

The average energy consumption per bit $\overline{\mathrm{E^c}}$, in case that $\mathrm{P_e^c}$ is selected, can be formulated by:

$$\begin{aligned} \overline{E^c} &= (E_u^c + E_r) \sum_{i=0}^{N^c} (P_e^c)^{N^c}, \quad i \in N \\ where\;\; N^c &= \max\{N_i \mid (P_e^c)^{N_i} \le P_e^t, N_i \in N, i \in N\} \end{aligned} \tag{4.4-42}$$

Thus the average energy consumption per bit of the whole cell $\overline{\mathrm{E}}$ can be formulated as:

$$\begin{aligned} \overline{E} &= p^d\, \overline{E^d} + p^f\, \overline{E^f} + p^c\, \overline{E^c} \\ &= p^d E_u^d \sum_{i=0}^{N^d} (P_e^d)^{N^d} + p^f (E_u^f + E_r) \sum_{j=0}^{N^f} (P_e^f)^{N^f} + p^c (E_u^c + E_r) \sum_{k=0}^{N^c} (P_e^f)^{N^c}, i, j, k \in N \\ where\;\; N^d &= \max\{N_i \mid (P_e^d)^{N_i} \le P_e^t, N_i \in N, i \in N\} \\ N^f &= \max\{N_i \mid (P_e^f)^{N_i} \le P_e^t, N_i \in N, i \in N\} \\ N^c &= \max\{N_i \mid (P_e^c)^{N_i} \le P_e^t, N_i \in N, i \in N\} \end{aligned} \tag{4.4-43}$$

and $\mathrm{p^d}$, $\mathrm{p^f}$, $\mathrm{p^c}$ are the probability for the case that $\mathrm{P_e^d}$, $\mathrm{P_e^f}$, $\mathrm{P_e^c}$ are selected in (4.4-38), correspondingly.

5. Key Issues and Trade-Offs

5.1 Trade-Offs in Cooperative Network Coding

As described in Sections 2.1, 3.1 and 4.1, a cooperative relay node using a compress-and-forward network coding strategy can improve energy efficiency in a scenario of interfering femtocells by helping resolve the interference at the decoders. The price to pay for this reduction in transmit power is the additional complexity of the operations carried out by the relay node and the two receivers and the additional bandwidth required to reliably convey the relay message to the receivers. Hence, we can identify two relevant trade-offs in the design of such cooperative mechanism: 1) energy efficiency versus relay bandwidth and 2) energy efficiency versus relay and receivers complexity.

The relay bandwidth is easily identified as the bandwidth of the orthogonal (i.e. interference free) channel where the relay message is sent to the end users. Since the relay node performs a quantisation operation on the sensed signal and the relay message consists of the quantisation index, the relay message size increases with the size of the quantisation codebook. On the other hand, a finer quantisation increases the interference resolution at the two decoders; hence the energy efficiency of the primary message transmission is also increased. This trade-off can be evaluated by simulating the system performance in terms of transmit power for different granularities of the quantisation codebook, at a fixed average throughput.

The other important trade-off in the design of a relay-base network coding scheme is between transmit power saving and added complexity of both relay and end users. On one hand, the relay has to perform a quantisation operation, i.e., a closest lattice point search, on the sampled received signal. On the other hand, the two receivers have to modify the LLR calculation to include the additional information provided by the relay message. Both types of operations increase in complexity as the codebook size increases. Therefore, this energy efficiency versus complexity trade-off can be evaluated by simulating the system performance in terms of transmit power for different granularities of the relay quantisation codebook, at a fixed average throughput, and then by mapping the codebook granularity to the number of additional floating point operations required by the relay and the receivers.

5.2 Key Issues and Trade- Offs in the Cooperative Power Control Algorithm

The cooperative power control mechanism aims at identifying the optimum transmission power of the network elements. Such procedure suggests a complex task, where several inputs need to be correlated; the aforementioned correlation concerns optimization in a holistic manner, taking into account that several network components take place in the optimization procedure. Fuzzy logic is an ideal tool for dealing with multi-variable problems (i.e. optimization of the network elements' transmission power) with contradictive objectives, i.e., energy optimization in network level.

A fuzzy inference system (Figure 5-1a) consists of three parts, namely the fuzzifier, the inference engine and the de-fuzzifier. The fuzzifier undertakes the transformation (fuzzification), of the input values (crisp values) to the degree that these values belong to a specific state, e.g., low/high, using the membership functions μ(x) (Figure 5-1b). Then, the inference system correlates the inputs and the outputs using simple "IF…THEN…" rules; each rule results to a certain degree for every output. The aforementioned rules are simple rules that capture experts' knowledge related to the decision making procedure. Thereinafter, the output degrees for all the rules of the inference phase are being aggregated. The actual decision comes from the defuzzification procedure, where the aggregated values are interpreted to a certain degree of a state.

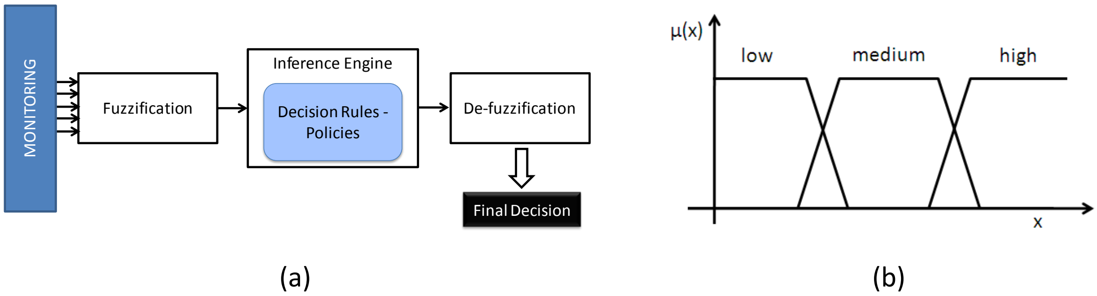


Figure 5-1: (a) Schematic representation of a Fuzzy Logic Reasoner, (b) Membership function.

The main benefits of the use of fuzzy logic mainly are related to the three distinct parts of a fuzzy inference system and its nature. More specifically, the fuzzy reasoners deal with uncertain or imprecise data based on the way the environment is modelled (i.e. fuzzification and defuzzification procedures). Furthermore, the rules used to correlate the inputs and the outputs are simple, which consequently simplifies the building of the inference building and updating. As far as the hardware requirements of the fuzzy inference systems are concerned, the reasoners have limited computational and memory requirements and so they can be executed on limited hardware. On the other hand, the environment's representation (through the membership functions) need to be carried out very carefully in order to be realistic and meaningful.

Furthermore, key trade-off of the cooperative power control algorithm is the maintenance of balance between the number of cooperative nodes and the messages' exchange among them. As it was described analytically in Section 4.2, the main target of this algorithm is to increase network overall utility and mitigate interference. However, this is achieved through exchange of messages (which actually carry the "interference prices" value), which results in a signalling overhead in the network. This overhead in turn, leads to interference in the network, although it is considered of low level. Therefore, it is evident that a trade-off is emerged during the nodes cooperation in terms of interference mitigation. Additionally, a crucial trade-off has to be considered in terms of fairness among the nodes. This trade-off appears when some of the cooperative nodes are obliged to transmit at low energy (which consequently results to lower QoS) for a long time period in order to conform to the algorithm rules and policies. Therefore, it should be ensured that a balance between fairness and the optimal algorithm's operation is striked.

5.3 Key Issues and Trade-Offs in Cooperative Network Protocols

Sections 2.3, 3.3 and 4.3 describe how co-located networks can discover each other, negotiate shared incentives and make joint decisions on cooperation. This framework can be employed to optimize for the incentive of 'energy efficiency', utilizing a number of different network services that have the effect of improving energy efficiency. For example, joint routing improves energy efficiency in fixed transmit-power scenarios, as it decreases the number of hops from source to destination. Similarly, packet aggregation improves energy efficiency, as it reduces the number of packet transmissions.

However, employing this framework also bears its cost in energy spending. In principle there are three sources of added energy cost that are involved to varying degree in the different steps of the cooperation model:

1. Extended periods of radio operation: Discovery nodes operate their radio for longer periods than other nodes, to scan the spectrum and discover co-located networks.
2. Control packet transmissions: Discovery nodes send their findings to Negotiating entities in the form of additional packets. Negotiating entities announce their presence throughout

their network. Negotiating entities exchange negotiation messages with negotiating entities of co-located networks.

3. Processing: All the entities that constitute this framework perform dedicated calculations and execute the relevant algorithms.

There is a natural trade-off between the energy savings achieved by cooperation, and the increased consumption of energy by the involved mechanisms. This trade-off can be evaluated through a combination of techniques. The increased consumption of power due to radio operation for discovery can be calculated quite accurately. The power consumption by control packets can be evaluated through calculation of the number of additional packets, and rather accurate estimates of the power necessary for transmission and reception of a packet. Energy consumption due to added processing can be evaluated through measurements of the time these calculations take. In addition, actual measurements of power consumption can be made in a proof-of-concept implementation, which will run over a test bed that supports such measurements.

5.4 Trade-Offs and Problem Scope in Heterogeneous Networks

As already mentioned within CONSERN cooperation is enabled in three different dimensions: (i) coordination of actions, (ii) collaboration by means of information exchange and (iii) cooperation technologies at any communication layer (Figure 5-2). A similar version of the picture can be found in [3]. This Cooperation, Collaboration and Coordination (C3) framework captures three different aspects enabling different radio nodes to working together. These three key aspects can be broadly defined as:

- Collaboration refers to the information processing and exchange between nodes. The level of collaboration between any two nodes may range from node independent information processing and retrieving, e.g., sensing and monitoring, without any information exchange (i.e., no information exchange between nodes) to full knowledge sharing including information retrieving, pre-processing, aggregation, learning and exchange (i.e., full information collaboration between nodes);
- Coordination refers to the decision and configuration control the level of which is ranging from independent action decisions (i.e., no coordination of actions among the nodes) up to joint action decisions among the nodes about reconfigurations ;(i.e., fully coordination among the nodes);
- Cooperation refers to cooperative transmission technologies ranging from full cooperative transmission to independent transmission. Cooperative transmission can be found at all layer mechanisms ranging from network coding and CoMP (L1/PHY), cooperative ARQ (L2/MAC) and multi-radio transmission diversity (L3/RRM).

It is expected that by increasing the level of any of the cooperation, collaboration and/or coordination dimensions, it will increase performance gains. Any increase on performance is achieved at a cost of higher energy induced by the additional signalling overhead. Similarly, by reducing the signalling overhead, it would reduce the energy cost associated to it but it would restrain possible performance gains that can be achieved by C3.

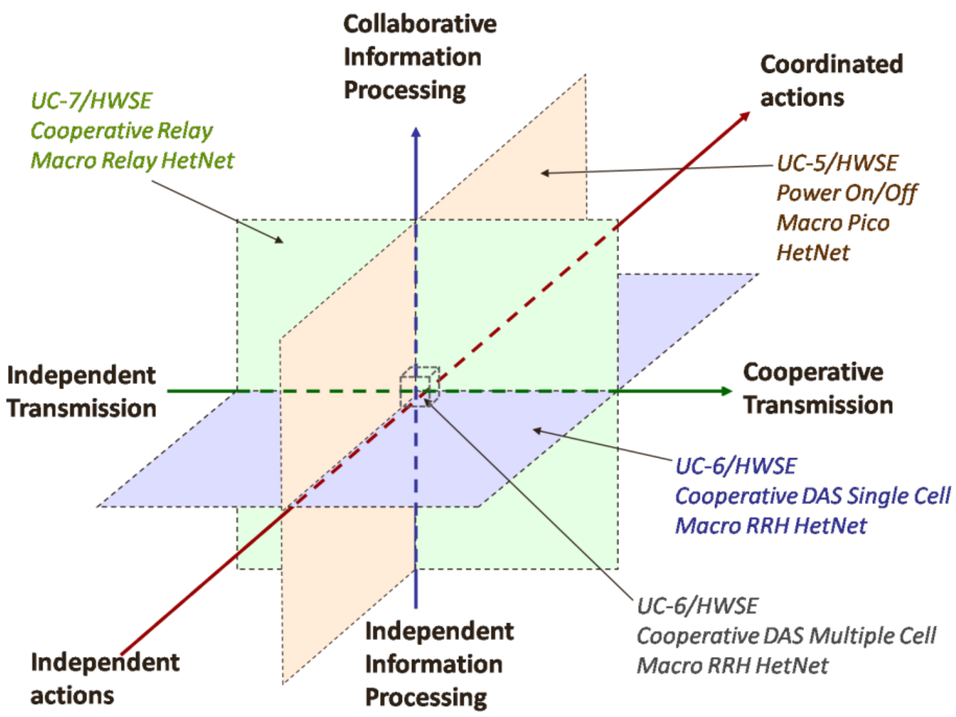


Figure 5-2: Cooperation, Coordination and Collaboration axes.

The studies to be performed within the heterogeneous scenario are different utterances of the performance maximization versus energy minimization trade off. More specifically, the power on/off scenario illustrates performance gains vs. energy costs along the action coordination and information collaboration axes. The power on/off scenario is independent of the cooperation transmission technology used and in the problem scope of this scenario independent transmission is assumed.

The cooperative relay case study touches upon the performance gains along the cooperative transmission L1/L2 and information collaboration dimensions. In this scenario coordination of actions is given since coordination and/or synchronization is inherent to any cooperative transmission technology including network coding, CoMP and cooperative ARQ.

Finally, the cooperative DAS case study focuses on two different combinations of dimensions. The cooperative single cell DAS exploits gains by combining cooperative transmission and coordinated actions (e.g. in terms of synchronization, as in CoMP). In fact it can be assumed that collaboration is inherent in the single-cell optimization since information from different RRHs is processed by the cell itself. On the other hand the multiple cell manifestation of the cooperative DAS case study involves all three dimensions of cooperative transmission, coordination of configuration and information exchange collaboration.

Furthermore, the power on/off case study is an RRM/L3 mechanism addressing energy-efficient cooperative decision control, while cooperative Relay and cooperative DAS which are L1/L2 mechanisms addressing the energy-aware cooperative transmission. (The division of energy-efficient cooperative decision and energy-aware cooperative transmission has been described in the introduction.)

C3 objectives will be represented by means of appropriate utility functions that will possibly also allow for analyzing the trade-offs in terms of game-theoretic equilibrium solutions, as explained later in Section 4.4.

6. Summary and Future Work

This document has provided system models on which optimisation algorithms using cooperation between (network) nodes can be developed. When searching for energy-efficient solutions to transfer information between network nodes and/or networks, cooperation between the constituting elements is seen as a feasible way to go. This deliverable has from a set of selected use case scenarios studied in [2] identified some problems related to network energy-efficiency, reliability and performance. The use cases are selected based on that they provide different challenges and consequently also their solutions are different. In this way a wide area of problems will be dealt with. To solve these problems, energy-aware system models have been developed which from the enablers studied in [3], enable cooperation techniques between network nodes and networks to be used, e.g., network coding, distributed power control, interference management, energy savings and SON.

Saving energy in a network often comes with the cost of a decreased network performance (coverage and capacity) or reliability. Current network technologies do not take the energy consumption in network nodes into account since the primary goal in past developments has mostly focussed on network performance and reliability. One of CONSERN ideas is to also consider how cooperation can be used to decrease the energy consumption without sacrificing performance or reliability.

The material presented in this deliverable will be further elaborated on and studied in future WP3 deliverables. To guide this work, cooperative algorithms will be developed and will, for the system and energy models provided, be analysed both by theoretical analysis and by means of simulations. The different use cases outlined will be elaborated on as follows:

- In the context of indoor femto base stations, the potential benefit of cooperative network coding will be analysed and suitable parameters will be defined. To analyse the use case, metrics suitable for evaluation will be developed.
- In the context of cognitive radio for licensed bands, cooperative power control algorithms based on fuzzy logic will be studied. Learning schemes for evolution of the power control algorithms will be studied in order to adapt the network elements' operation taking into account previous decisions. The focus of the learning scheme will be the identification of methods for evolving the way a network element interprets the monitored data.
- In the context of communication in unlicensed bands cooperative community creation, community discovery and negotiation algorithms will be studied. Appropriate techniques for describing community profiles will be developed. A negotiation protocol and decision making engine will be implemented and validated experimentally.
- In the context of homogeneous networks, algorithms for adapting network elements to the most energy efficient pattern utilizing knowledge from its own and its neighbours will be developed. In this scope, selected functions targeting cooperative adaptation to time-variant topologies will be considered and mechanisms for cooperative convergence of network elements to their optimal operating points will be realized, e.g., through game theoretic approaches. To maximise the energy gains the balance between autonomic and cooperative decision and control will be studied. Finally, error resiliency issues under energy constraints will be investigated for enhanced element and system-level dependability.
- In the context of information fusion, a specific model related to fault identification shall be developed. The goals of such model will be the information fusion in the neighboring network elements so as to provide a high level validation of the monitored information, taking into account correlations between tha monitored data. The information fusion high level methodology has been presented in Section 3.5.1, and focuses in the introduction of

the «Integration» block in the «Information Cycle» [41]; such block is responsible for the incorporation of the valid data in the information base. Moreover, working in information model will include the refinement of the initial model so as to incorporate respective advances in the cooperation mechanisms, e.g. the network discovery, cooperative power control, network coding etc and better capture the smart element's abstraction. specific requirements for information and knowledge sharing are expected to further challenge the information model towards expansion to a knowledge model for better identify and infer on correlations among the managed system entities. Such knowledge model will have to reflect the different capabilities of the system entities as local and global (shared) knowledge.

In the future deliverable D4.2 (WP4) a layered reference architecture for CONSERN will be defined; a self-growing, a cooperative and an autonomous layer. The focus in WP4 is on the self-growing layer while the focus in WP3 is on the cooperation layer. In the cooperation layer the nodes/networks cooperate with its environment by collecting, processing and communicating information. Thus the work done in WP3 fits nicely into the overall CONSERN architecture. In order to justify the theoretical work done in WP3 it is expected that some of the algorithms can be implemented and demonstrated in the WP5 set-up.

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