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Home and Alien Network Discovery, Awareness and Management Solutions

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Abstract:

Deliverable D10.2 focuses on the topics of neighbour and network discovery, analysing both intra-network and inter-network operations. The document presents the solutions proposed and currently under investigation within the Work Package 10 of the ACROPOLIS NoE.

The Deliverable first focuses on intra-network operations, starting from local level solutions for network organization and clustering in presence of mobility and sensing requirements, definition of a common control channel for local operations, and neighbour discovery.

The document moves next to network wide solutions, presenting a novel approach to routing in underlay cognitive radio networks combining beamforming and position information, as well as a solution for cognitive network association in a Wi-Fi like network.

Next, the Deliverable addresses solutions related to inter-network operations. First, an approach to automatic network recognition and classification is presented, and its performance evaluated in the case of multiple technologies coexisting in the 2.4 GHz ISM band. The document presents then two solutions for efficient cooperation and coexistence, the first aiming at efficient use of multiple RAT terminals, and the second, addressing scenarios where sensing is not feasible due to time constraints, proposing an alternative approach to sensing for determining transmission opportunities.

The document concludes by identifying open research issues and corresponding research lines for WP10 activities in the ACROPOLIS NoE.

Keywords: Neighbour discovery, network discovery, routing, Common control Channel

Document Revision History

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0.1	15.12.2011	Uniroma1	Initial structure of the document
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0.3	01.07.2012	Uniroma1, UPRC, KCL, EADS, EIT+	Updated plan of contributions, revised timeline
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1.00	27.09.2012	Uniroma1	Final proofreading

Executive Summary

This Document focuses on the topics of neighbour and network discovery, analysing both intra-network and inter-network operations. The document presents the solutions proposed and currently under investigation within the Work Package 10 of the ACROPOLIS NoE.

The document opens with the description and analysis of solutions proposed for intra-network operations, focusing on Home network and neighbour discovery, looking at both local level (neighbour discovery, definition of local common control channels) and global level (end-to-end protocols such as routing and admission control). The Deliverable moves next to inter-network operations, by analysing solutions for alien network discovery, recognition and classification, as well solutions for cognitive network selection and opportunistic access. The document closes with an analysis of open issues identified on the basis of the work presented in this Deliverable, in order to identify future research lines.

Section 2 focuses on home network discovery solutions. Building on the work carried out in ACROPOLIS and reported in Deliverable D10.1, the section presents solutions for both local and network wide protocols. The section first introduces a novel solution for network organization at the local level, which defines a novel clustering scheme taking into account the requirements of cooperative spectrum sensing as well as terminal mobility, introducing a sensing and mobility aware clustering metric. The proposed approach is compared with a flat, non-clusterized solution for sensing, and with a mobility-aware approach taken from the literature, showing the advantages of combining both sensing information and mobility in the performance of a cognitive wireless network. The proposal relies on the availability of a common control channel: how to define and design such a control channel is indeed the second main topic addressed in the section. A thorough analysis of in-band and out-of-band solutions, with the channel being defined using the same Radio Access Technology (RAT) or a different RAT, respectively, is carried out, moving from standardization efforts in IEEE, ITU and ETSI, where ACROPOLIS partners are directly involved.

The section moves on to present two additional examples related to neighbour discovery and definition of a common control channel: first, as a follow-up of the work started in D10.1, an evaluation of the impact of neighbour discovery performance on higher layer protocols, in particular network selection and association, is presented; second, a novel scheme for neighbour discovery taking into account lack of synchronization between network nodes as well as medium access control operation after neighbour discovery is presented and evaluated by simulation.

Section 2 moves then to end-to-end protocols, focusing on routing and network association as the basis for admission control. A solution for combined routing and beamforming in underlay cognitive radio networks is presented, building up on the work carried out during the first year of ACROPOLIS. The proposed solution takes advantage of beamforming to perform local-level path optimizations on the path selected according to a minimum distance, position-based routing protocol; the idea at the basis of the proposed approach is to take advantage of the hardware required to perform beamforming to introduce position information in the network operation. The section closes with the introduction of a novel solution for access point selection and network association in a Wi-Fi like cognitive network, based on the definition of a novel access point selection metric, taking into account both internal network performance and the presence of external transmissions; the metric may

form the basis for the definition of an admission control scheme taking into account the same aspects.

The next section in the deliverable, Section 3, addresses the problem of detecting, recognizing and classifying alien networks, and to use such information so to achieve an effective coexistence.

The Section starts by introducing a solution for automatic network recognition and classification, that takes advantage of MAC layer features in order to identify alien networks coexisting in the same area occupied by the cognitive network. Features taken into account in the analysis include delays typical to a specific MAC protocols, as well as maximum packet durations. The measurements taken on the set of such features are provided as an input to a classifier, that provides the best match within the set of known RATs. The idea behind the proposed approach is to take advantage of MAC (and possibly above) features so to abstract as much as possible from physical layer information, allowing for simple techniques for sensing, such as energy detection. The proposed approach is analysed in the context of a 2.4 GHz ISM scenario, using a combination of actual measurements and generated data, and then extended to the case of underlay Ultra Wide Band systems.

The availability of multiple RATs in the same device is a more and more common scenario. In this context, Section 3 moves on to address the issue of how to select the best RAT given Quality of Service (QoS) requirements and the characteristics and current conditions of each available RAT. Two approaches are presented, the first one relying on the intervention of a Central Management System gathering relevant information and taking the decision on the best RAT to be used by each terminal within its coverage, and the second one relying on a decentralized RAT selection carried out by the mobile terminals.

Obtaining the information required to take a decision in the cognitive network, may it be which RAT to use, or whether to transmit or not, may prove difficult or even impossible in some specific scenarios. The last part of Section 3 addresses such a case, focusing on a scenario where a secondary network attempts to access the channel in presence of a cellular primary network, characterized by fast dynamics. The proposed approach relies on the use of primary activity patterns to statistically determine which are the periods of time that guarantee a low probability of collision, without actual sensing taking place prior to the transmission attempt.

Finally, Section 4 takes the move from the problems analysed in the Deliverable and the proposed solutions to identify open issues and future research lines that will be addressed in the final year of the ACROPOLIS NoE.

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1. Introduction

The work carried out within WP10 in the first year of ACROPOLIS, and reported in Deliverable D10.1, focused on the identification and analysis of the major research topics relevant to WP10, in order to identify common research interests among ACROPOLIS partners, and to trigger fruitful collaborations on such topics.

Following the above analysis, several collaborations were started on all major identified topics. Results of this joint work are presented in this Deliverable, introducing the solutions proposed by ACROPOLIS partners to the issues identified during the first year.

The document addresses both internal network protocols, dealing with network organization and operation at local and global level, and solutions for guaranteeing an efficient coexistence with alien networks operating simultaneously with the cognitive network.

The Deliverable is organized as follows.

Section 2 presents solutions for internal network operations, starting with a novel proposal for local network organization taking into account sensing and mobility, and moving on to the analysis of issues related to the definition of Common Control Channels; the Section also addresses the problem of neighbour discovery, following up the work carried out in the first year of ACROPOLIS, and introduces a performance evaluation of neighbour discovery in a specific application scenario, as well as a new solution for neighbour discovery in asynchronous networks. The section moves next to end-to-end network solutions, presenting a solution for combined position-based routing and beamforming relying on Angle of Arrival (AOA) estimation to obtain position information and take advantage of it in the routing protocol, while independently performing a local optimization of the selected path thanks to beamforming. Next, a novel approach for access point selection in a Wi-Fi-like network, forming the basis for a possible admission control scheme, is proposed.

Section 3 moves to inter-network operations, and addresses the solutions for identifying alien networks and achieving coexistence. A solution for identification and classification of alien networks based on Medium Access Control (MAC) features, without relying on specific physical layer information, is proposed. The section also addresses the case of networks of devices characterized by multiple RATs, proposing solutions to take advantage of such features, and concludes with an alternative approach top coexistence, where sensing is replaced by a statistical analysis based on the patterns of primary activity in order to identify the best transmission opportunities.

Section 4 presents open research issues related to the proposed solutions, and identifies research lines that will be pursued in the framework of WP10 of ACROPOLIS.

Finally, Section 5 draws conclusions.

2. Home network discovery solutions

2.1 Local network discovery and management solutions

Following the identification of issues and report on state of the art for local network and neighbour discovery solutions carried out in Deliverable D10.1, this section deals with novel solutions developed within ACROPOLIS for neighbour discovery and local network organization, including the following aspects:

- Neighbour discovery;
- Network organization (e.g. clustered vs. flat network organization);
- Definition of common cognitive control channels.

2.1.1 Cooperative Spectrum Sensing and Network Organization in Mobile Cognitive Radio Networks

The Spectrum Sensing is one of the most challenging issues in Cognitive Radio (CR) systems because it is clear the importance for a CR device to be able to measure, sense, learn and be aware of the parameters related to the radio channel and about the spectrum usage by Primary Users (PUs).

For spectrum sensing to be effective and by all means useful to the operation of a CR system, several challenges need to be addressed:

- *Hardware Requirements* - Spectrum Sensing for CR may require high sampling rate, high resolution ADCs with large dynamic range, and high speed signal processors;
- *Hidden Primary User Problem* - The Hidden Primary User problem is the well known Hidden Terminal problem transposed in a CR scenario. It can be caused by many factors including severe multi-path fading or shadowing observed by Secondary Users (SUs) while scanning for PUs' transmissions;
- *Detecting Spread Spectrum Primary Users* - The two major Spread Spectrum technologies are Frequency Hopping (FHSS) and Direct Sequence (DSSS). Unlike fixed frequency devices, operating at a single frequency or channel (IEEE 802.11 a/g based WLAN), FHSS devices change their operational frequencies dynamically to multiple narrow-band channels. This hopping is performed according to a sequence that is known by both transmitter and receiver. DSSS devices are similar to FHSS devices, however, they use a single band to spread their energy. Spread Spectrum Primary Users are difficult to detect as the power is distributed over a wide frequency range even though the actual information bandwidth is much narrower. This problem can be partially avoided if the hopping pattern is known and perfect synchronization to the signal can be achieved. However, it is not straightforward to design algorithms that can do the estimation in code dimension;
- *Tradeoff between sensing duration and scheduling* - PUs can claim their frequency bands anytime while Cognitive Radio SU is operating on them. In order to prevent interference to and from PUs, SUs should be able to identify their presence as quickly as possible and should vacate the band immediately. This requirement brings a tradeoff between the speed (sensing time duration) and reliability of sensing. Sensing Scheduling (how often cognitive radio should perform sensing) is a design parameter that needs to be chosen carefully and the optimum value depends on the capabilities of CR itself and the temporal characteristics of PUs. If the PUs status is

known to change slowly, sensing scheduling can be relaxed. As an example, one can consider the approach followed in the IEEE 802.22 standard for the detection of TV channels; the presence of a TV station usually does not change frequently in a geographical area unless a new station starts broadcasting or an existing station goes offline. For this reason, in the IEEE 802.22 draft standard, the sensing period is selected as 30 seconds [1]. Another factor that affects the sensing frequency is the interference tolerance of PUs. For example, when a CR is exploiting opportunities in public safety bands, sensing should be done as frequently as possible in order to prevent any interference. Furthermore, CR should immediately vacate the band if it is needed by public safety units. The effect of sensing time on the performance of SUs is investigated in [2] and [3]. Optimum sensing durations to search for an available channel and to monitor a used channel are obtained. The goal is to maximize the average throughput of SUs while protecting PUs.

In order to improve Spectrum Sensing, several authors have proposed collaboration among SUs. The main goal is to exploit the space diversity of the nodes belonging to the same CR network to achieve better sensing performance. Since CR networks can be deployed both as an ad-hoc and an infrastructure network, two schemes for Cooperative Spectrum Sensing (CSS), distributed and centralized, can be defined.

In the distributed CSS scheme, each CR node takes and shares an independent decision on the PU presence in a channel. Consequently, each CR node locally receives the detection decision from the others and applies a fusion rule to obtain its final detection decision. The fusion rule can be the k out of N rule: if k or more nodes decide the hypotheses H1, then the node will decide for H1. When k = 1, the rule becomes the OR rule; when k = n the fusion rule works as the AND rule; when k = (n + 1)/2, the fusion rule becomes the majority rule, used when the cooperative nodes have approximately the same SNR level. It is important to note that if in the network there are CR nodes with significantly higher SNR levels than others, it is preferable to have cooperation only taking place between these nodes. For this reason, if a node has a significantly higher SNR than other nodes, it will be the only one that will take the sensing decision. Anyway, a decentralized network offers more scalability towards the number of nodes but requires, on the other hand, more signalling and computational charge to the single node.

Let n denote the number of collaborating SUs, experiencing independent and identically distributed fading/shadowing with same average SNR. It was shown that when sensors are conditionally independent (as in this case), optimal decision rule for individual sensors is Likelihood Ratio Test (LRT) [4]. However, optimum individual thresholds are not necessarily equal and it is generally hard to derive them. Let assume, to facilitate analysis, that all SUs employ energy-detection rather than LRT and use the same decision rule (with threshold λ). If a SU receives decisions from n − 1 other users and applies the OR rule (1 out of n), then the probabilities of detection and false-alarm for the collaborative scheme
(Q_d and Q_f, respectively) are [5]:

$$Q_d = 1 - \left(1 - P_d\right)^n \qquad (2\text{-}1)$$

$$Q_f = 1 - \left(1 - P_f\right)^n \qquad (2\text{-}2)$$

where P_d and P_f are the individual probabilities of detection and false alarm as defined before. The formulas show that, compared to local sensing, the collaborative scheme increases probability of detection as well as probability of false-alarm. However, the main effect is an improvement in detection performance as seen in simulations and in Figure 2-1.

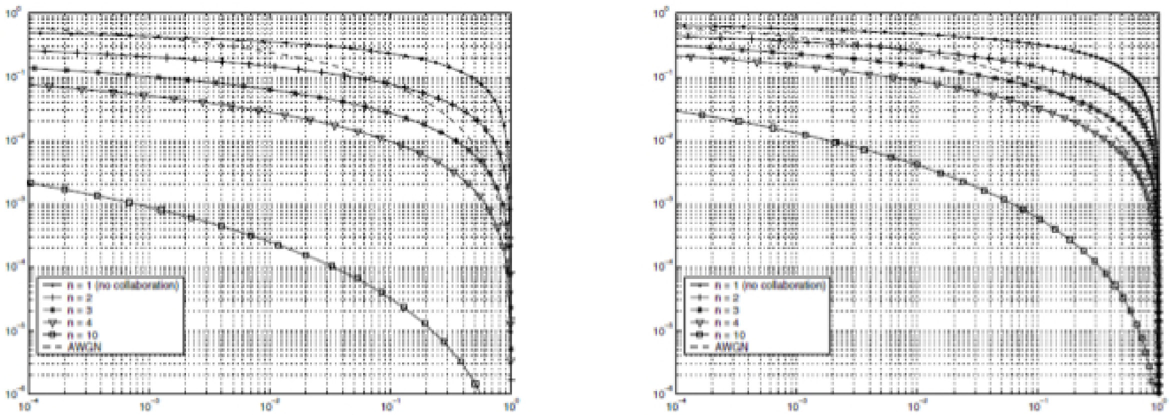


Figure 2-1: Q_{md} vs. Q_f under identically and independently distributed log-normal shadowing (σ_{dB} = 6) and Rayleigh fading scenarios, γ = 10 dB , m = 5. Different n and AWGN curves for comparison.

A detailed analysis of the potential benefits and drawbacks of cooperative spectrum sensing was already carried out within the activities of the ACROPOLIS NoE, and reported in [6]. In the present context, it is enough to remind that as shown in [5], shadowing correlation degrades performance of collaborative sensing when collaborating users are close. This is due to the fact that such users are likely to experience similar shadowing effects thereby countering the collaboration gain.

2.1.1.1 Clustering Algorithms for MANETs

When the network is infrastructure-based, it typically includes a Base Station (BS), or an Access Point (AP), to provide a connection to a backbone or to other networks. The BS will be the only device in the network that, using the local Spectrum Sensing decision by the SUs, will apply a fusion rule and then will broadcast the cooperative decision. Centralized networks are less scalable respect to the decentralized ones but they offer a better management of signalling and sensing information. After receiving the authorization from the BS, all the cognitive users initiate the spectrum sensing independently and then forward their observations to it. If the channels between cognitive users and the common receiver are perfect and decision fusion is employed at the BS, Q_f, Q_d and Q_{md} are defined as before.
In a distributed scenario, a Cognitive Radio network can be thought as an ad-hoc wireless network. This kind of network has gained worldwide attention in recent years. Particularly, mobile ad-hoc networks (MANETs) are networks consisting entirely of mobile nodes that communicate on-the-move without a central unit. Nodes in these networks generate user and application traffic and carry out network control and routing functions. Dynamic and random topologies lead to rapidly changing connectivity and network partitions and this, along with bandwidth and power constraints, poses new problems in network scalability, network control, especially in the design of higher level protocols such as routing, and in implementing applications with QoS requirements. Hierarchical routing provides a means to

tackle the above-mentioned problems in large scale networks. Clustering is the process of building hierarchies among nodes in the network. In this approach the mobile nodes in a MANET are divided into different virtual groups, and they are allocated geographically adjacent into the same cluster according to some rules, with different behaviours for nodes included in a cluster from those excluded from the cluster. It has been shown that cluster architecture guarantees basic performance achievement in a MANET with a large number of mobile terminals, providing at least three benefits:

- *Spatial Reuse of Resources to increase the system capacity*: with the non-overlapping multi-cluster structure, two clusters may deploy the same frequency or code set if they are not neighbouring clusters;
- *Increasing of routing performance*: The set of Cluster Heads (CHs) and gateways between clusters can normally form a virtual backbone for inter-cluster routing, and thus the generation and spreading of routing information can be restricted to this set of nodes;
- *Decreasing of virtual network dimensions*: A cluster structure makes an ad hoc network appear smaller and more stable in the view of each mobile terminal. Local changes need not be seen and updated by the entire network but only inside a cluster, and information processed and stored by each mobile node is greatly reduced.

Obviously, a cluster-based MANET has its side effects and drawbacks because building and maintaining a cluster structure usually requires additional cost compared to a flat-based MANET. The cost of clustering is a key issue to validate the effectiveness and scalability enhancement of a cluster structure. An analysis of different terms concurring in the definition of the clustering cost, as well as of possible clustering criteria, is carried out in [7]. Although a detailed description of clustering costs and criteria is out of the scope of this work, it is important to note that one of the main criteria used to distinguish different clustering algorithms is the mobility of nodes. Mobility is a prominent characteristic, and it is one of the main factors affecting topology change and route invalidation. For this reason, it is important to take the mobility metric into account in cluster construction, in order to form stable clusters. The idea is that by grouping mobile terminals with similar mobility behaviour into the same cluster, the intra-cluster links can become more tightly connected, leading to a decrease in the rate of re-affiliation and re-clustering [8]. Following this line of research, in 2001, Basu et al. proposed MOBIC [9]. It uses a mobility metric, referred to as the Aggregate Local Mobility (ALM), to elect CHs. First of all, a relative mobility metric is computed as the ratio of received power levels of successive transmissions by transmitting periodic Hello messages between a pair of nodes. The relative mobility metric at the node Y, with respect to node X, denoted as $M_Y^{rel}(X)$ be

$$M_Y^{rel}(X) = 10\log\frac{R_xP_{rX\to Y}^{new}}{R_xP_{rX\to Y}^{old}} \qquad (2\text{-}3)$$

where R_xP_r is the power detected at the node receiving the Hello message and it is indicative of the distance between the transmitting and receiving node pairs. If $R_xP_{rX\to Y}^{new} < R_xP_{rX\to Y}^{old}$, then $M_Y^{rel}(X) < 0$ and this will indicate that the two nodes are moving away with respect to each other. In the opposite situation $M_Y^{rel}(X) > 0$ and the two nodes are moving closer to each other. For a node with m neighbours, there will exist m such values of $M_Y^{rel}(.)$. Each node then calculates the ALM metric, denoted as M_Y for node Y, by calculating the variance (with respect to zero) of the entire set of relative mobility samples of all its neighbours, denoted as $M_Y^{rel}(X_i)$:

$$M_Y = \mathrm{var}_0\left\{M_Y^{rel}(X_i)\right\} = E\left[\left(M_Y^{rel}\right)^2\right] \quad (2\text{-}4)$$

with 1 ≤ i ≤ m. The node with lowest value of M becomes CH. In fact, a low variance value indicates that this mobile node is relatively less mobile to its neighbours. Only one re-clustering condition is defined: if two nodes with status of CH move into each other's range, re-clustering is deferred for a customizable time period (called Cluster Contention Interval, CCI) to allow for incidental contacts between passing nodes. If the nodes are in transmission range of each other even after the CCI time has expired, re-clustering is triggered and the node with the lower mobility metric assumes the status of cluster-head. A detailed description of the MOBIC algorithm is provided in [9].

It is easy to see that MOBIC is feasible and effective for MANETs with group mobility behaviour, in which a group of mobile nodes moves with similar speed and direction, as in highway traffic. Thus, a selected CH can normally guarantee low mobility with respect to its member nodes. However, if mobile nodes move randomly and change their speeds from time to time, the performance of MOBIC may be greatly degraded. Another drawback of this algorithm is that it uses signal strength as a measure of node mobility. However, because of noise, obstacles, variation in battery power, and other factors weight based on variation in signal strength may not be accurate, so stability of a node cannot be evaluated clearly. Also, the algorithm is looking at the stability of the CH alone, and not at the stability of the complete network. To ensure stability of the entire network, stability of gateway nodes should be taken into account as well.

MOBIC was the clustering algorithm chosen as the basis of the new framework presented in the next Section, taking in account the MOBIC metric and a sensing performance metric of CR nodes to form clusters and to choose CHs.

2.1.1.2 Cluster-based Cooperative Spectrum Sensing

In a Cognitive network, the clustering approach can be adopted not only for the same reasons for which it is adopted in MANETs but also to improve performance of CSS. The time and space varying nature of channel availability among cognitive radio nodes challenges connectivity and robustness of ad-hoc cognitive radio networks. It was shown that clustering of neighbouring cognitive radio nodes is a suitable approach to address this challenge. This is due to multiple issues. First of all, by forming clusters for sensing, the sensing reliability can be increased [10]. This prevents mainly interference originating from CR users to PUs, which is highly desirable. Secondly, sensing needs to be coordinated within a set of CR users to obtain reliable results. This typically requires all CR users within some cluster to stop data transmission on the operating channel and initiate the sensing process. Furthermore, by clustering, the potential for collisions (when vacating the channel due to PU appearance) among neighbouring clusters is reduced.

However, since the activity of primary users is generally not known to CR users in advance, the connectivity between CR nodes in a CRN is not guaranteed. Whenever a PU is detected to be using the working channel, CR nodes could, as example, switch to other idle channels. This can lead potentially to a connectivity cut off if there is no such alternative channel. As clustering leads to a dependency between the used working channel and the availability of the working channels for all CR nodes in a cluster, the clustering algorithm has a big impact on stability. Furthermore, the clustering algorithm also determines the connectivity between several clusters, which ultimately determines the robustness of the entire network with respect to connectivity. Hence, a desirable feature for a clustering algorithm is connectivity robustness, which means to build clusters such that multiple common channels are shared by cluster members and multiple common channels are maintained between neighbouring clusters. Many clustering algorithms have been proposed in the literature for ad-hoc ([11], [12], [13]) and sensors networks [14]. In ad-hoc networks, the major focus of clustering is to preserve connectivity (under static channel conditions) or to improve routing. In the context of sensor networks, the emphasis of clustering has been on longevity and coverage. Hence, none of this work takes into account the channel availability and the issue of robustness in CRNs. More recently, there has been interest in clustering for cognitive radio networks, as it is shown by several works and proposed algorithms.

In [10], the authors assume that the reporting channels (channels between cognitive users and the Base Station) experience Rayleigh fading and propose a cluster-based cooperative spectrum sensing method to improve the sensing performance. In this approach, it is assumed that clustering has been taken care of by higher layers using a generic distributed clustering algorithm for MANETs. Then, the user with the largest reporting channel gain is selected as CH, to collect the sensing results from all the other users in the same cluster and forward them to the BS. By employing such selection technique, they show that the reporting error due to the fading channel can be reduced, with an improvement in sensing performance. In [15], the authors rightly point out that the clustering approach proposed in [10] is a very interesting solution to the cooperative sensing problem, but the clustering criterion is not explicitly defined (rather, references to previous papers about clustering approach in wireless networks are given). Moreover, neither the definition of clusters nor the selection of the CHs is related to the sensing capabilities of the nodes. Moving from the above analysis, a novel scheme for cooperative spectrum sensing based on clustering is proposed in [15]. This scheme, referred to as Clustered Hybrid Energy-aware cooperative Spectrum Sensing (CHESS), takes into account sensing performance in cluster formation and cluster head selection. The scheme adopts a hybrid clustering approach that combines sensing reliability and energy efficiency. The goal of the CHESS scheme is to improve the accuracy of the sensing phase compared to standard, non-clustering-based solutions, while increasing energy efficiency and in turn extending network lifetime. The CHESS scheme is compared with the cooperation scheme without clustering proposed in [5]. The CHESS algorithm leads to the partition of the nodes in the secondary network in clusters, each cluster being managed by a cluster head. The CH is in charge of performing the sensing operation and of forwarding data traffic generated by nodes in the cluster to the BS. A secondary network operating in accordance to the CHESS algorithm can be in one of three possible states:

- *Training* - while in this state, secondary nodes evaluate their reliability in sensing the presence of the primary user, in order to determine the nodes that are most suitable to act as CHs;
- *Clustering* - while in this state actual cluster formation and CH selection take place;
- *Activity* - while in this state the secondary network operates normally, with nodes sending data to the BS through the CHs.

2.1.1.3 Impact of Mobility on the Performance of Cognitive Radio Networks

Mobility is one of the most important factors in wireless systems because it affects numerous network characteristics, such as network capacity, connectivity, coverage, routing, etc. It is also an inherent feature to support various types of wireless services in CRNs. For example, at the beginning, the IEEE 802.22 Working Group considered only stationary sensors (i.e. CPEs) in the standard draft. Recently, they adopted an amendment for the operation of portable devices. Despite its importance, however, mobility is still largely unexplored in the context of dynamic spectrum access. Allowing sensor mobility in CRNs introduces numerous challenges, making it necessary to revisit current system design and protocols, such as mechanisms for spectrum sensing, interference management and routing. If mobility is not considered, the design of a cognitive network can become very uncomfortable in terms of network performance, as it was shown in [16] with a simple example, focusing on routing performance. On the other hand, mobility is valuable resource for increasing the amount of information available on the external environment, as shown in [17], where the positive effect of mobility on cooperative sensing performance is discussed.

In conclusion, the review of the literature on this topic has introduced a number of interesting issues and possible scenarios for various research activities. First of all, solutions to engage the mobility on the cognitive environment are few. In addition, at the state of the art, the existing solutions seem to focus only on particular layers of the protocol stack (examples: solution addressed in [18] is basically referred to the network layer and solution in [19] is for transport layer only) and neglecting the idea (confirmed by the results obtained so far) that the mobility should be considered transversally with respect to layers.

2.1.1.4 Introduction to the new Framework: SENSIC

The basic idea, supported by the simulations results shown in the following, is that using MOBIC to cluster a cognitive network leads to a sub-optimal choice in terms of general management of the network (both for data throughput and sensing performance). This is mainly due to MOBIC procedures for the selection of the CH, the maintenance of the clusters and the possibility of re-clustering. By holding the main features of MOBIC that provide a good way to handle the mobility of nodes, the main innovation introduced by the proposed SENSIC (SENSing + mobIC) algorithm is in the evaluation of a sensing-related metric, calculated by each node in the network during a particular TRAINING phase handled by the BS. In the following, details are provided on the sensing metric definition and how this is used by the network, focusing in particular on the innovations introduced for the spectrum sensing technique and the clustering algorithm.

- Cognitive Network States: Three different states are defined for the network: TRAINING, SENSING or ACTIVITY. The state is related to the last result of the CSS on the Data channel, handled by the network and particularly by the Base Station node;
- Spectrum Sensing Technique: the sensing is cooperative and it exploits the hierarchical structure created for the nodes belonging to the network, Common Nodes and CHs. When the clustering procedure is complete, only CHs (chosen with SENSIC algorithm) in a particular cluster take a Local sensing decision about the PU presence on the Data channel. Then these decisions are transmitted to the BS. The use of a dedicate Control channel for the two-way control packets exchange is hypothesized. The BS is the central unit that will gather the CHs Spectrum Sensing results and, using a majority rule, will take a network cooperative decision about the

PU presence. If most of the CHs in the network locally sense the PU presence on the licensed Data channel (or, in a multi-channel scenario, on one or simultaneously on more that one channel), then that Data channel(s) is (are) declared BUSY by the BS. The BS will transmit this decision to the nodes through the control channel and the nodes inside the clusters associated with that (those) particular channel(s) will move into the SENSING state. In this state, the common nodes are not able to transmit data and the CHs will schedule a new local sensing phase later in time. On the other side, the nodes inside the clusters associated with the channel(s) declared FREE by the BS will move into the ACTIVITY state. In this case, the common nodes are able to transmit data packets and the CHs will schedule a new local sensing phase but also a data transmission phase using the associated Data channel(s).

- Clustering Algorithm: it is based on the one proposed in MOBIC [9] supported by the sensing metric and new functionalities. Network operation starts with a TRAINING phase, requested by the BS with a specific control packet. During this phase each node schedules a sensing phase and sends the local result to the BS. The BS will reply with the cooperative decision, obtained combining the local decisions according to a majority rule. The nodes will receive the BS decision and update a wrong decision counter if their previous decision is different from the BS one. The number of sensing phases inside the TRAINING state of the network is customizable, leading to a variable TRAINING DURATION. When the BS communicates the end of the TRAINING, each node will evaluate the sensing metric (SM):

$$SM = \frac{N_{Errors}}{N_{Sensing}} \quad (2\text{-}5)$$

where $N_{Sensing}$ is the number of total Sensing Phases during the TRAINING and N_{Errors} is the number of sensing errors during the TRAINING.

At this point, the nodes will also evaluate the MOBIC metric (MOBIC) as defined in [9]. The CHs will be chosen using both the sensing metric and the MOBIC one, in order to combine the reliability of the node in term of sensing performance with the physical behaviour of the same node in term of mobility degree, using the following global metric (SENSIC):

$$SENSIC = SM \bullet MOBIC \quad (2\text{-}6)$$

The SENSIC metric is defined so that the MOBIC metric will be improved (decreasing the absolute value) if the node had good sensing results during TRAINING phase. On the contrary, the MOBIC metric will be worsened (increasing the absolute value). The nodes with simultaneous good sensing performance and low mobility will have more possibilities to be chosen as CHs. The network, handled by the BS, leaves then the TRAINING state (resetting the error counter to zero) and starts the normal activity, switching between ACTIVITY and SENSING states depending on the CHs local sensing, the BS decisions and PU activity. The entire network will come back in the TRAINING state following a very simple rule: every time the CHs receive the BS global decision about the PU presence, they will compare the global decision with the own decision, in order to update an error-related metric defined as follows:

$$M_{Errors} = \begin{cases} M_{Errors} + RCC & if\ BS_{decision} \neq CH_{decision} \\ \max\left(0, M_{Errors} - RCC\right) & if\ BS_{decision} = CH_{decision} \end{cases} \quad (2\text{-}7)$$

where RCC is the so-defined Re-Clustering Coefficient, defined with a value minor or equal to one. When one of the CHs experiences a M_{Errors} equal to one, it will send a re-clustering request packet to the BS. At this point, the BS will force all the nodes in the network, with another control packet, to start a new TRAINING phase and a new calculation of the sensing metric. The Re-Clustering Coefficient is a customizable parameter, with possible values minor or equal to one: the value of this coefficient will determine the number of consecutive sensing errors allowed to any of the CH before the re-clustering request of one of them.

The clustering procedure (except for the sensing metric calculation) is not carried out in a particular network state but in a transversal way respect to the ACTIVITY and the SENSING states. This is due to the fact that the clustering algorithm is totally related to the instantaneous physical behaviour of the nodes, particularly to the mobility and, for this reason, the evaluation of the MOBIC metric has to be carried out during all the simulation time using an almost continuous exchange of Hello messages. The MOBIC re-clustering condition about two or more CHs in the same transmission range is implemented but this is not the only one addressing a re-clustering phase between node. A new re-clustering condition is defined: simply, when a common node in a cluster goes out the transmission range of its CH (practically, it does not receive Hello packets by the CH), it will able to choose a new CH (if in the meantime it has received a packet of another node with a better SENSIC metric) or to declare itself as a new (isolated, at the moment) CH (if in the meantime it has not received a packet of another node with a better SENSIC metric). Simulation results presented in the next subsection show a general improvement of the network performance due to these new functionalities introduced in the clustering algorithm.

2.1.1.5 Performance evaluation

Simulation settings

Performance evaluation was carried out in the framework of OMNeT++ version 4.1 simulator, in particular with the use of the MiXiM package, under both Windows and Linux operating systems. OMNeT++ (Objective Modular Network Testbed in C++) is a quite known tool for discrete event simulations [20].

Three different solutions were compared:

1. Non-clustered cooperative spectrum sensing;
2. MOBIC-clustered cooperative spectrum sensing;
3. SENSIC-clustered cooperative spectrum sensing.

Furthermore, in order to study also the impact of nodes Mobility, each solution was simulated both in a static (No Mobility) and mobile (Gauss-Markov Mobility Model) case.

Key features of the simulation environment are listed below:

- PU: the PU occupies for a random period of time its own licensed Data channel. Following an ON/OFF behaviour, the PU alternates Activity periods to Pause periods;
- Cognitive SUs: The Cognitive Network is formed by SUs able to use two different communication channels. One channel is dedicated for Control Packets (Sensing and

Clustering related) exchange. The other channel (the same of the PU transmissions) can be used for Data packets exchange;

- Mobility Model: The BS is a static node, fixed in the middle of the simulated playground. This helps to have a high probability (the exact value depending on the playground size, the used transmission power and, therefore, by the SUs transmission range) that all the BS-generated control packets reach all SUs. On the opposite, the SUs are evaluated both in a static case (No Mobility case) and in a Gauss-Markov mobility model case (Mobile case).
- Cognitive Network States:
    - Non-Clustered & MOBIC: The network can be in two different states, SENSING or ACTIVITY. The state is related to the last result of the Cooperative Spectrum Sensing on the Data channel, handled by the network and particularly by the Base Station node;
    - SENSIC: Three different states are defined for the network: TRAINING, SENSING or ACTIVITY. The state is related to the last result of the CSS on the Data channel, handled by the network and particularly by the Base Station node.
- Spectrum Sensing Technique:
    - Non-Clustered: The sensing is Cooperative. Each node in the network takes a Local sensing decision about the PU presence on the Data channel. Then these decisions are transmitted to the BS. The Base Station node is defined and used as central unit in order to gather the Local Spectrum Sensing results by the other nodes in the network and, using a majority rule, to take a network cooperative decision about the PU presence. If most of the nodes in the network locally sense the PU presence, then the Data channel is declared BUSY by the BS. The BS will transmit this decision to the nodes through the Control channel and they will move to the SENSING state. In this case, they only will schedule a new local sensing phase later in time. If most of the nodes in the network locally sense the PU absence, then the Data channel is declared FREE by the BS. The BS will transmit this decision to the nodes and they will choose as own state the ACTIVITY one. In this case, they will schedule a new local sensing phase but also a data transmission phase using the Data channel;
    - MOBIC & SENSIC: The sensing is cooperative as well, but it exploits the hierarchical structure created for the nodes belonging to the network (Common Nodes and CHs) in a different way respect the model presented in [10]: when the clustering procedure is complete, only CHs (chosen with MOBIC or SENSIC algorithm, respectively) in a particular cluster takes a Local sensing decision about the PU presence on the Data channel. Then these decisions are transmitted to the BS. The use of a dedicate Control channel for the two-way control packets exchange is hypothesized. The BS is the central unit that will gather the CHs Spectrum Sensing results and, using a majority rule, will take a network cooperative decision about the PU presence. The goals are to reduce the number of exchanged control packets (addressing a hopefully reduction of exploitation of resources by the nodes), to increase the possibilities to transmit data packets, and to evaluate the spectrum

sensing performance when this phase is addressed only by a subset of nodes in the network (in this case, the CHs chosen with particular algorithms).

- Data Transmission:
  - Non-Clustered: When the network is in the Activity state, the nodes are able to transmit data packets directly to the BS, using the Data channel. For this reason, a 1-hop transmission from nodes to BS is defined and analysed;
  - MOBIC & SENSIC: The clustered structure is also used in terms for Data Transmissions. When the network is in the ACTIVITY state, the common nodes inside a specific cluster are able to transmit data packets directly to the associated CH, using the Data channel. The forwarding of the data packets at the BS is then performed by the CH. It is important to note that also CHs can generate their own data packets.

Simulations were carried out in a 2D-simulation playground of 700×700m. The communication channels between all the hosts in the network were simulated using a Simple Path Loss Model with a path loss coefficient α = 3 and a carrier frequency fc = 2.412GHz. The PU was kept in a fixed position (300 × 300m) and its behaviour (in terms of Activity and Pause duration) was characterized by a parameter called Activity Factor AF = 0.75 and by a Transmission Power TxPower = 110 mW. A fixed number of SUs (N_{Hosts} = 10) composed the cognitive network. The Base Station (the Host with index zero) was kept in fixed position in the middle of the environment (350 × 350m) while the initial positions of the other nodes were randomly chosen at the start of each simulation run. For each scenario, three different runs (with duration = 3 hours) with the same parameters were carried out.

Simulation results

Two main aspects were addressed in simulations: sensing performance, measured by the false alarm and miss detection rates, and communications performance, measured by the data throughput between common nodes and Base Station.

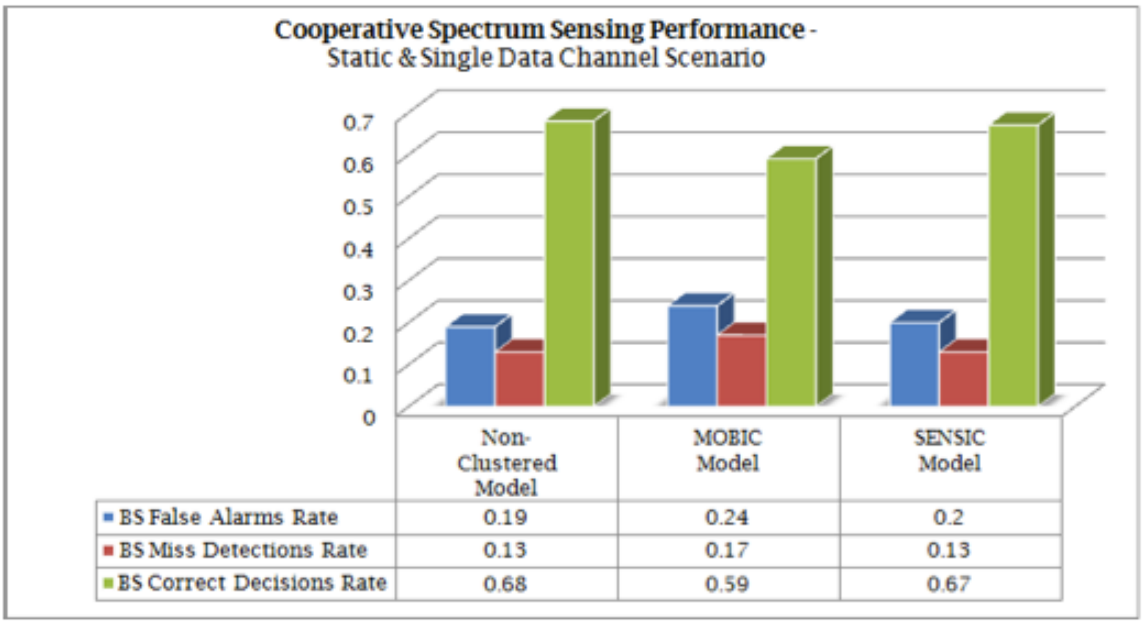


Figure 2-2: Cooperative Spectrum Sensing Performance - Static Scenario.

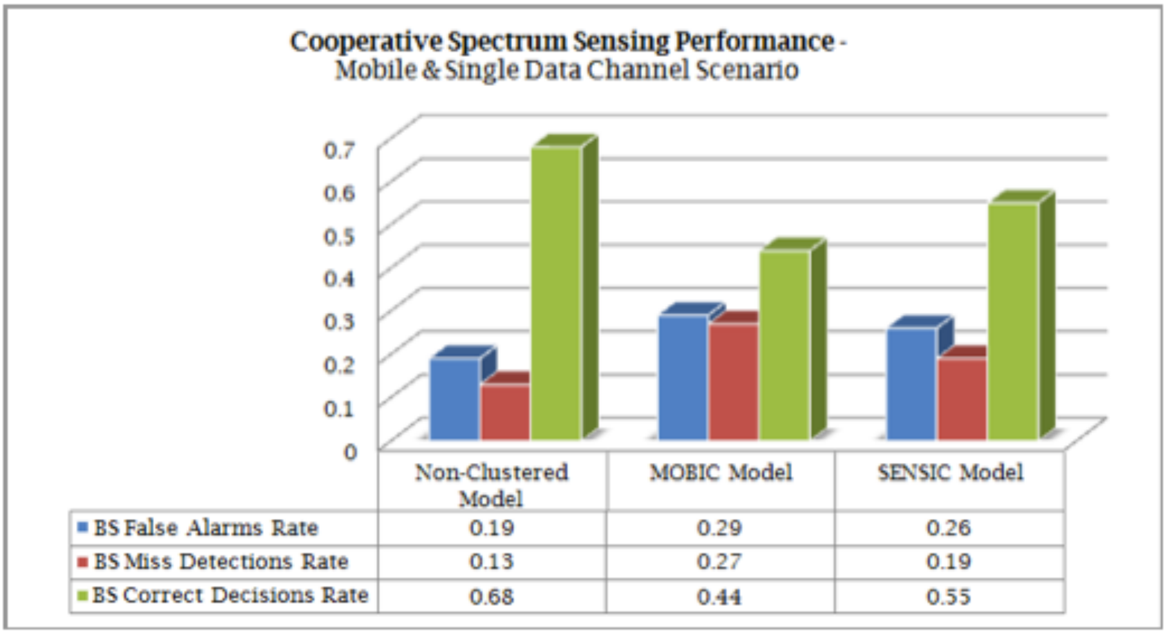


Figure 2-3: Cooperative Spectrum Sensing Performance - Mobile Scenario.

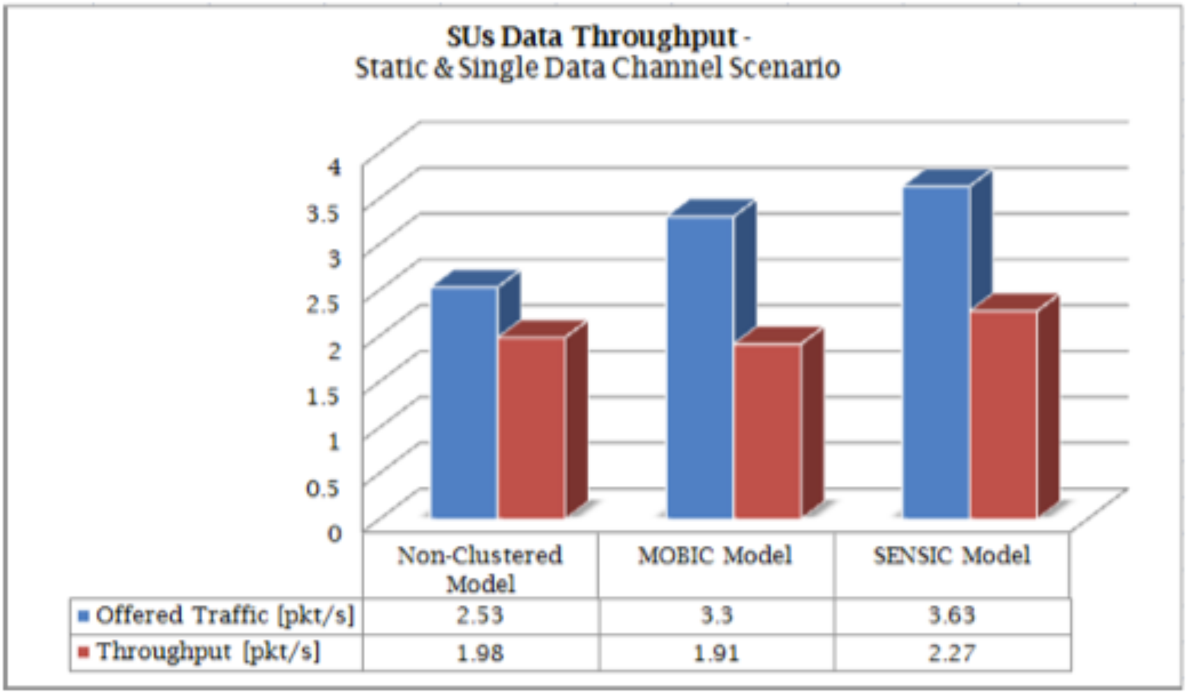
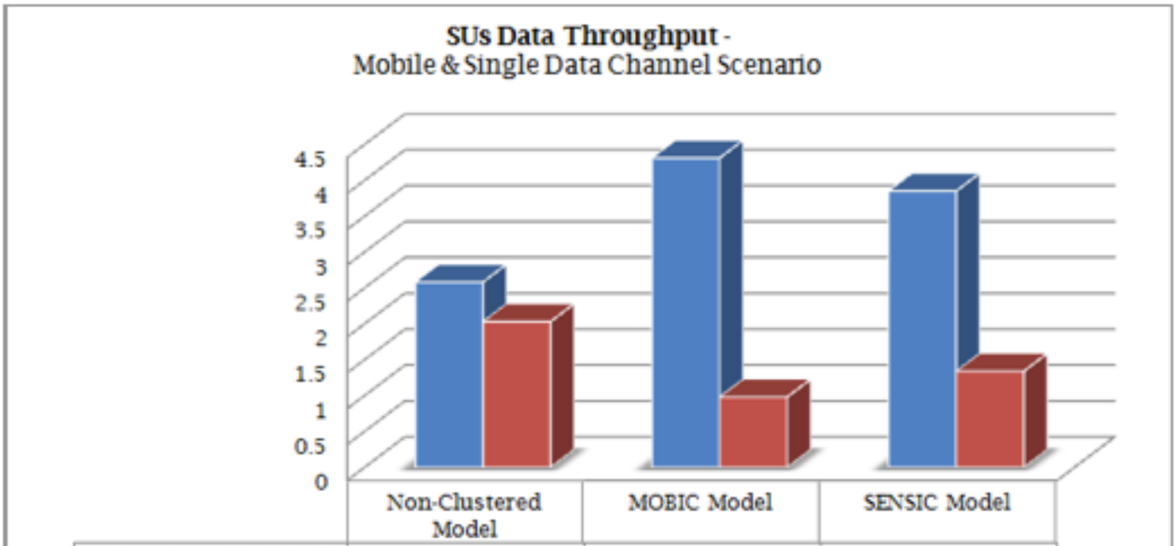


Figure 2-4: Communications performance: offered traffic and data throughput - Static Scenario.



	Non-Clustered Model	MOBIC Model	SENSIC Model
Offered Traffic [pkt/s]	2.58	4.31	3.85
Throughput [pkt/s]	2.03	0.98	1.34

Figure 2-5: Communications performance: offered traffic and data throughput - Static Scenario.

Figure 2-2 presents the results related to sensing performance in the case of a network of static SUs, while Figure 2-3 presents the results in the case of a network of mobile SUs.

Results show that SENSIC matches the sensing performance of the non-clustered solution (behaving significantly better than MOBIC) with a smaller number of devices on average. This seems to be very interesting in terms of energetic efficiency of the cognitive hosts: the use of a less number of hosts to sense the channel could lead to a better exploitation of resources and this can be interesting, as example, for an application of the cognitive network in a wireless sensors network with strong constraints of energy consumption.

The resources saved in the sensing phase by the clustered models allow an increase of data traffic offered, as shown in Figure 2-4 and Figure 2-5 for the static vs. mobile case. SENSIC, however, compared with MOBIC, seems to better manage this traffic growth, with a significant increase in throughput. Moving to the Mobile Case, the introduction of a mobility model (Gauss-Markov, in this work) generally degrades the sensing performance in the clustered models, but SENSIC reacts better than MOBIC to the effects of mobility.

2.1.2 Comparison of In-band and Out-of-band Common Control Channels for Cognitive Radio

Cognitive Radio capabilities such as opportunistic connection formation and networking require a means for networks and devices to discover each other, as it was widely discussed in D10.1. Such discovery may be achieved by scanning of spectrum and then computing the characteristics of the signals that are detected in that spectrum to ascertain the type of system producing those signals, hence the potential to connect to the networks or devices producing them. However, such a scanning only obtains current radio information, not necessarily other useful information such as the capabilities of devices producing the signals, which might be used for link formation and optimization purposes in CR. Moreover, given the extent of spectrum (and subsets thereof) that might be scanned and the wide range of possible signals using the spectrum, as well as the computational complexity in ascertainment of the types of signal in the spectrum, such scanning can be extremely time consuming and power-hungry. For these reasons, such scanning is rarely a practical solution for network and device discovery in CR, at least in a stand-alone sense.

Given this reality, it is widely accepted that a commonly recognized and understood means for communication is necessary among cognitive radios and networks, such that information assisting connectivity and other purposes can be exchanged. This information might comprise detail on locally available access mechanisms, the presence (e.g., IDs) and capabilities of other cognitive radios and networks in the area (achievable RATs, or at a lower level the capabilities of a possible underlying Software Defined Radio (SDR)), and information on spectrum usages or perhaps expected changes in usages as a part of an opportunistic reconfiguration or spectrum access change. One aspect of such a channel is a frequency selection; another aspect is a commonly known means (e.g., modulation and information structure) for sending this common information on such a channel.

There are other options, however, aside from such a channel being simply on a dedicated and widely harmonized frequency band. In terms of the implementation of such mechanisms/channels, two principle ways forward have been suggested:

- In-band Control Channels: The cognitive data is transported on top of an existing RAT; either using a separate control channel or an existing one by adding, e.g., specific IP-based packets;
- Out-of-band Control Channels: A dedicated physical channel is defined for the distribution of cognitive data (this is the example referred to above).

The second possibility (out-of-band channel) has been discussed at length at the ITU level, as it requires the reservation of a (globally harmonized) cognitive frequency band. However, wide support has not been gained at the ITU and further consideration of such a physical channel has been put on hold.

To serve the benefits of such a channel, the role of a Common Control Channel, in some circles known as the “Cognitive Pilot Channel (CPC)”, has been studied for the specific context of heterogeneous Cognitive Radio Systems (CRS). The CPC is defined as a channel (logical or physical) over which necessary information facilitating the operation of a CRS is communicated and can be used for providing information from the network to the terminals (user devices), e.g., frequency bands, available RATs, spectrum information and spectrum usage policies. Corresponding results have been contributed to the International Telecommunication Union Radiocommunication sector (ITU-R) in the scope of regulatory measures to facilitate the introduction of SDR and CRS. In 2009 the IEEE Dynamic Spectrum Access Networks Standards Committee (IEEE DySPAN-SC) published the IEEE 1900.4 standard [21] related to the efficient operation of heterogeneous CRS by introducing a "Radio Enabler". Corresponding studies were also performed within the ETSI Reconfigurable Radio Systems Technical Committee (ETSI RRS TC).

In line with such studies, this paper qualitatively and quantitatively compares the characteristics and performances of in-band and out-of-band options for common control channels serving cognitive radio purposes. In recent years, a number of papers have been published detailing usage examples and advantages of such Control Channels [22]- [26]. For example, [22] illustrates how Common Control Channels for Cognitive Radio may be exploited for orchestrating a heterogeneous indoor-environment. Reference [23] highlights that such channels might be utilized on a local level, comprising reciprocity mechanisms for details channel awareness. User-context dependent Virtual Connectivity Maps and details

how the behavioural statistics of a radio node can be modelled based on Markov-models whose parameters can then be distributed via a cognitive channel are presented in [24]. The exploitation of such a channel for the collection and distribution of radio measurements is addressed in [25].
The objective of a recent Technical Report in the ETSI RRS TC is a feasibility study on Control Channels for Cognitive Radio Systems (DTR/RRS-03008 (TR 102 684)) [26], where the focus is more on an In-band channel approach. The scope of this report is "to identify and study communication mechanisms: (1) for the coexistence and coordination of different cognitive radio networks and nodes, operating in unlicensed bands like the ISM band or as secondary users in TV White Spaces; (2) for the management of Opportunistic Networks (ONs), operating in the same bands as mentioned above." The report addresses various implementation options and presents several detailed solutions that are either system independent (such as an IP based provision of cognitive information) or system dependent (such as the introduction of new MAC/RRC messages). RAT independent as well as RAT dependent options are investigated including Diameter, Access Network Discovery and Selection Function (ANDSF), Internet Engineering Task Force (IETF) Protocol to Access White Space database (PAWS), Distributed Agents, 3GPP Radio Resource Control (RRC), IEEE 802.21 Media Independent Handover (MIH), IEEE 802.11, WiMedia UWB, Bluetooth and IEEE 802.19.1. RAT independent based approaches are quite generic; however an important drawback is that pre-established connectivity is required. On the other hand, RAT dependent based approaches (e.g. 3GPP RRC, IEEE 802.11, WiMedia and Bluetooth), are expected to represent low-latency solutions (i.e. no need to establish connectivity in advance). However they will need to be tailored to a specific system. The various options are compared in terms of the types of supported communication, the information delivery model, the requirement for basic connectivity, the level of extension of baseline standards required and the underlying protocols. The feasibility study concludes that "it seems that none of the proposed options is by itself suitable for enabling a full implementation" of information and knowledge-sharing mechanisms.

2.1.2.1 Information structuring, Requirements and transmission Ordering Options

This section describes the structure and requirements on the information that may be exchanged in the scope of cognitive wireless systems.

Information Types

First investigated are the different types of information that might assist cognitive radio and networking.

1. *Profiles, capabilities, requirements*
   Profiles are divided into terminal, base station, user and operator profiles. Terminal and Base Station (BS) profiles include:
   - General capabilities, e.g. Node ID, Node Type etc.;
   - Communication capabilities, e.g. Network interface capabilities, supported spectrum sensing techniques etc.;
   - Computing capabilities, e.g. CPU, memory size etc.;
   - Storage capabilities, e.g. caching size etc.;
   - Energy capabilities, e.g. battery capacity etc.;
   - ON capabilities, e.g. does the terminal/BS support ONs, incentives, how many times has the terminal participated in an ON etc.

Additionally, user profile provides information on the subscribed applications of a user, the user class of an application (i.e., the quality levels that the application can be provided to this user class. E.g. for streaming or browsing application type, a user that belongs to the 'High' user class the possible qualities of service shall be e.g., 2Mbps, 1Mbps or 512Kbps etc.). Also, the behaviour aspects of the user are taken into account. These aspects indicate the number of requests from a user in order to use an application and the usage characteristics. Usage characteristics include the estimated session duration and the estimated data volume transfer. Finally, operator profile shall include information on the elements (e.g. BSs) that the operator owns/ manages, its subscribers etc.

2. *Context information*
   Context information is divided into terminal and base station context. Terminal and BS context include:
   - General status, e.g. Node location, Context timestamp, Node mobility (in case of a terminal) etc.;
   - Communication status, e.g. interface status, RAT operated, demand and QoS offered per application, user class etc.;
   - Computing status, e.g. current CPU/memory usage;
   - Storage status, e.g. current cache usage;
   - Energy status, e.g. current battery level;
   - ON specific context, e.g. ON services offered, Supported ONs (ON paths from terminals to BSs –set of nodes and links), Potential ONs (neighbouring terminals that support ON) etc.
3. *Decisions information*
   Information on decisions is divided into decisions realted to infrastructure, terminals and ONs. Specifically, infrastructure and terminal decisions cover aspects on communication, storage and computing.
   - Communication Decisions, e.g. RAT to be operated (including assigned demand per application and user class, assigned terminals);
   - Storage Decisions, e.g. amount of cache to be used etc.
   - Computing Decisions, e.g. CPU or memory amount to be used etc.

   Additionally, ON decisions include:
   - Path selection (covering selected nodes and links);
   - Spectrum selection e.g. selected spectrum block such as central frequency, bandwidth, selected sensing technique (e.g. sensing detectors etc.) and transmission constraints (e.g. maximum allowed transmit power etc.).
4. *Knowledge information*
   Knowledge is related to acquired context and decisions made. For example, ON knowledge comprises information on the selected path between terminals and towards BSs, selected spectrum etc. (e.g., nodes and links used, spectrum used, QoS achieved etc.). Infrastructure-related knowledge includes: communication decisions (such as RAT operated, assigned demand per application and user class, assigned terminals etc.); storage decisions (such as amount of cache used etc.) and computing decisions (such as CPU/memory used etc.). Accordingly, terminal-related decisions include communication decisions (such as RAT operated, applications served, QoS offered etc.); storage decisions (such as amount of cache used by the terminal etc.) and computing decisions (such as CPU, memory used etc.).

5. *Policy information*
   Policies represent rules of the network operator that are imposed for certain reasons. In that respect network operator policies shall include:
   - Communication related policies (such as allowed interfaces, allowed relaying capacity etc.);
   - Computing related policies (such as allowed CPU usage, allowed memory usage etc.);
   - Storage related policies (such as allowed caching size etc.);
   - Energy related policies (such as allowed consumption etc.);
   - ON related policies (such as maximum number of nodes in an ON, maximum time to live, allowed applications and quality levels etc.);

Information Requirements

Table 2-1 summarizes the system requirements for common control channels [27].

Category	*Description*
General	*Communication with the infrastructure*: Common Control Channels should allow terminals to directly or indirectly communicate with the infrastructure.
	Communication between terminals: Common Control Channels should allow terminals to directly or indirectly communicate with each other.
	Versatile RAT use: Common Control Channels should be usable for different types of radio access technologies to enable operation of different types of homogeneous as well as heterogeneous networks. Common Control Channels should therefore provide radio technology independent mechanisms. However, radio technology intrinsic mechanism e.g. to broadcast certain information may also be supported.
Mobile Devices (Terminals)	*Mobility*: Common Control Channels need to be robust during user mobility. This means that the Common Control Channels should be robust against packet errors, node disappearance, etc. Common Control Channels should therefore allow reliable transfer of information.
	Relaying: Common Control Channels should allow forwarding of relevant signalling messages. The forwarding capabilities should be provided for homogeneous as well as heterogeneous networks.
Legacy RAN	*Preservation of legacy Radio Access Network (RAN) operation*: The impact of Common Control Channels on the legacy RAN operation should be minimized. Common Control Channels should minimize the impact on the "anchor" network, in terms of mobility (idle and connected), spectrum use, security/privacy, charging/billing.
	Compatibility with legacy RAN deployments: The impact of Common Control Channels on the RAN deployments should be minimized. Common Control Channels deployment should remain compatible with legacy and foreseeable RAN deployments/planning techniques, e.g. overlays of macro/femto/relay.
Protocol	*Information provision*: Common Control Channels should support the exchange of different type of information relevant operations within a CRS (including the management of opportunistic networks). This information includes context information, policies, decisions as well as pure signalling data and should be encoded compactly to minimize the signalling load.
	Unicast and Multicast addressing: Common Control Channels should support mechanisms to transmit information to a single node identified via an address, e.g. via unicast or dedicated mechanisms. Such a peer-to-peer connectivity should be supported also in cases without the existence of a direct link between the two communicating nodes (forwarding of signalling data shall be possible). Common Control Channels should also support mechanisms to transmit information to several nodes, e.g. via broadcast or multicast mechanisms.
	Secure and unsecure communication: Common Control Channels should allow for unsecured as well as secure data transmission, depending on the confidentiality of the data.
	Common Control Channels efficiency: The amount of signalling should be minimized.
Implementation	The reuse of existing protocols should be considered. Open, extensible protocols are preferred. Common Control Channels shall be capable of supporting several simultaneous signalling transactions per node.
Opportunistic Network Management	Common Control Channels should provide communication means to enable the realization of the management procedures related to: Opportunistic Network (ON) suitability determination, creation, maintenance and termination (this includes enabling on-the-fly negotiations and agreements). Common Control Channels should provide means for the exchange of ON relevant

	information within a network of a single operator. Providing means for the exchange of ON relevant information between the operators may optionally be supported.

Table 2-1: System requirements for Common Control Channels

Out-of-Band Approach

The out-of-band approach requires assumptions on the structure of the information that is transmitted. It is noted that there are two key approaches to the out-of-band approach: one is the on-demand variant, which is achievable in cases where a feedback link from the terminal to common channel controller is possible; the second is the variant that operates essentially as a data carousel, whereby information pertaining to areas (each known individually as a “location area”) in a grid within the transmission area of the channel is sent cyclically. This may also be combined with other information that is sent on a one-off basis (see Figure 2-6). The on-demand approach has already been investigated in various publications [24], [25], [27] and in the interests of space we do not do further work on that here. It is thought most appropriate to study the unidirectional case here, as less detailed work has been done on that.

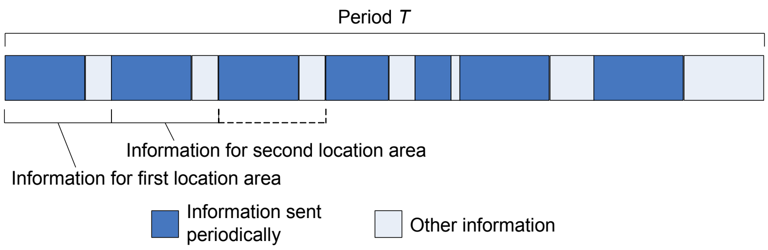


Figure 2-6: Transmissions on the out-of-band common control channel for different location areas.

As regards the structuring of information on a per-location area basis within the transmission scope of the control channel, one option is for the dimensions of each location area to be the same. In reality, however, there will be vast differences in the spatial density of changes as regards aspects such as connectivity options and spectrum availabilities which might be sent on such a channel. For instance, the coverage area of a transmitter of the out-of-band common control channel might encompass both relatively rural areas or parks with infrequent changes in spectrum availability and connectivity information, and dense urban areas with frequent changes, as well as anywhere in between these extremes. In this case, the size of each “location area” within the coverage area should be allowed to change.

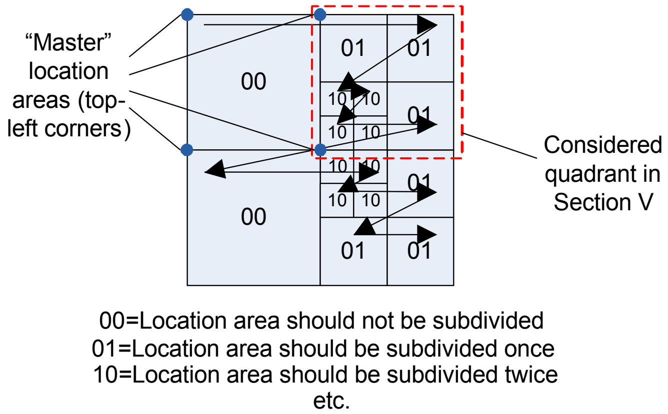


Figure 2-7: Order of information transmissions for the various location areas transmitted on the out-of-band common control channel.

Figure 2-7 presents one example of how such an area could be subdivided into "location areas" of different resolution. As regards the structuring of information here there are two possibilities. The first is that the location of the top-left of each location area is transmitted in the "header" of the information for the given location area, along with information on the dimension of the location area. A second option is that indicators be transmitted at the start of each location area to indicate how subdivided the area is.

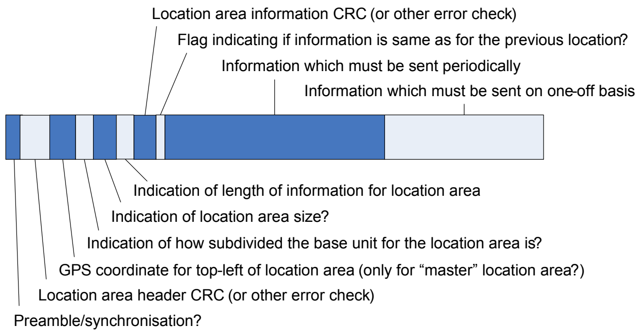


Figure 2-8: Example structuring of information (including headers) transmitted on the out-of-band common control channel.

This option reduces the amount of data that is necessary on the channel considerably. In the example of Figure 2-8, this it presented for the case where each "location area" might be divided into two, and a binary indicator is present in the header for each location area of the level of subdivision up to a factor of 1/8 of the original location area scale. Also indicated by arrows in this Figure is the order in which the information for location areas is transmitted on the out-of-band channel. In addition to this, information for each location area can be of a different length, therefore an indicator of the length of information for each location area is present in the header for the location area. The alternative of having the information set for each location area being the same length would lead to significant wastage of the channel capacity due to some location areas having a smaller amount of information. Such an indicator assists devices in knowing where the information for subsequent location area begins, such that they can listen to only the header of the subsequent location area and therefore avoid having to listen to and decode the content for the present location area. This detail along with other tentative detail is indicated in Figure 2-8.

Multi-RAT Case

When considering the adoption of out-of-band solutions involving multiple RATs, as some of those proposed in [26], it is worth noting that adopting a multi-RAT solution, where a RAT is used as the Common Control Channel for another RAT, poses several technical challenges, the major one being related to the different propagation conditions experienced by the signals emitted by the different RATs, due to different transmission parameters (transmit power, frequency, symbol rate), leading to different coverage areas for the different RATs. When considered in the general context of multihop networks, this issue leads to potentially different network topologies for the different RATs. Figure 2-9 provides an example of a set of devices using two different RATs, and shows how this can lead to different topologies, generating the well known hidden and exposed terminal problems, and correspondingly causing performance losses.

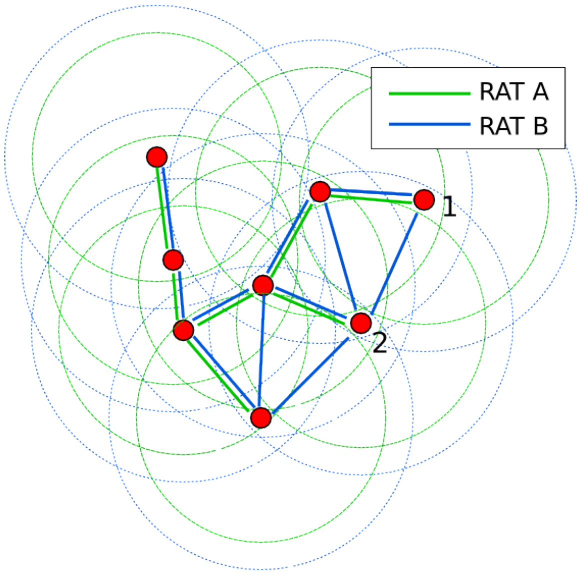


Figure 2-9: Impact of RATs with different propagation ranges on corresponding network topologies: Node 1 is hidden to Node 2 in the topology generated with RAT A, while it is visible in the topology generated by using RAT B.

2.1.2.2 Qualitative Assessment

This section first assesses the out-of-band and in-band approaches qualitatively.

Out-of-Band Approach

First, it should be observed that the out-of-band approach is generally intended to be a ubiquitous solution facilitating access in multiple locations, hence must generally be far more robust to coverage differences than can be achieved using an in-band solution on a operator's network. This is because such a solution may act as a fall-back or start-up mechanism to direct to appropriate connectivity options or other characteristics such as spectrum to use [21]. It is also observed, however, that plans to standardize an international band for a common channel out-of-band approach at the ITU-R have been unsuccessful, hence such a solution might have to rely on a plethora of locally-available channels or even opportunistic access, such as within the realm of TV white spaces.

The need for reliability of such an out-of-band control channel depends very much on the intended purpose of it. For example, under a purpose such as connectivity awareness the reliability of such a channel is not as much of a concern, at least within the context of the range of RATs that are already out there which provide pilots and other means for convergence to the range of locally available technologies and associated operators. Nevertheless, the use of a dedicated channel for such purposes is still preferable as it is far more efficient (both time- and energy-wise) than scanning for a range of separate pilots on a multitude of different frequency bands.

If such an out-of-band solution were to be used for means such as to indicate a change in local spectrum availabilities for opportunistic access or a network (e.g., spectrum usage) reconfiguration, then it would have to be far more reliable. It is noted that in order to avoid interference being caused, devices would likely already have a fail-safe transmission stop if they did not receive information on available spectrum, however, this would still cause significant disruption to the service of these devices so should therefore be avoided. Such a transmission stop could be similar to the enabling signal concept as specified for slave devices under current geolocation database specifications.

1. *Bootstrapping*
   Given the lack of a harmonized channel being available, one solution would be bootstrapping to common control channel. Such bootstrapping would likely only require an extremely low bandwidth, with a very simple repeat message indicating the parameters of the out-of-band common control channel in the given area. Such characteristics facilitate deployment of the channel in multiple locations. Moreover, a small number such bootstrap channels on well know frequencies might exist internationally in different regions, given that it will likely not be possible for each such a bootstrap channel to be harmonized. One logical solution would be for one such bootstrap frequency band to be provided for each ITU region.

In-Band Approach

Given that the in-band approach utilizes the channels that are already available in the mobile network, the characteristics of these channels are well understood. Hence, for the in-band approach, it is simply a matter of matching the requirements of such information (data rate, delay) to logical channel capabilities within the range of RATs that the information might be deployed upon.

An important observation here is that the common channel information will share capacity with other information on such in-band channel, even through such channels do routinely specify different prioritizations in the form of traffic classes. Modeling of the competing traffic load must therefore also be undertaken, in order to understand its effect on the common control channel traffic. Such modeling can usually be done using probabilistic methods, yielding a given probability of available capacity being more than a given amount for the control channel. This modeling must dependent on the mix of traffic types existing on the channel. The other key ingredient here is understanding of the traffic load for the in-band approach. This is many cases might be similar to that for the out-of-band approach, although can clearly vary based on the range of common channel applications that are practical for these two approaches. Aspects of such traffic load can be ascertained in reference to Section 2.1.2.1.

2.1.2.3 Quantitative Assessment

This section assesses the out- band and in-band approaches quantitatively.

Out-of-band Approach

If is assumed that information is transmitted cyclically on the radio enabler with a fixed period, and only a tiny contiguous proportion of this information is required by the terminal E.g. that information relating to the terminal's location, that relating to the terminal's class, and so on.

Given b being defined as the bit error rate, and n as the number of bits over which each error check is performed, the probability of the data acquisition failing one time (i.e. in the first pass) or more is

$$1-(1-b)^n . \qquad (2\text{-}8)$$

The probability of it failing for N or more passes (i.e. the CCD) is:

$$(1-(1-b)^n)^N . \qquad (2\text{-}9)$$

The expected number of passes required to acquire the information is therefore (given that expectation is the summation of CCD over all space):

$$\sum_{N=0}^{\infty}(1-(1-b)^n)^N . \qquad (2\text{-}10)$$

Assuming that the period of the channel is T, the expected additional duration which a terminal will have to wait due to failed passes of the required (e.g. "start-up", periodic ongoing) information is:

$$T\cdot\sum_{N=1}^{\infty}(1-(1-b)^n)^N . \qquad (2\text{-}11)$$

A uniform distribution in the range (0,T) can be assumed for the duration a terminal will have to wait for the initial pass of the information it requires from the enabler. Hence the overall expected wait from power-up (e.g. for "start-up" information) is

$$T\left(\frac{1}{2}+\sum_{N=1}^{\infty}(1-(1-b)^n)^N\right) . \qquad (2\text{-}12)$$

T in this equation can be represented in terms of the data rate *d* (in bits per second) of the enabler, and the total amount of information *I* required to be sent per period on the enabler (measured in bits). Therefore $T=I/d$. Moreover, the total amount of information required to be sent on the enabler is the information per location or information per class I_C, multiplied by the number of locations or the number of classes etc., N_C, hence, $I=I_C\cdot N_C$.

Analyzing *I*, we attempt to assess how much information would be required to be sent in each period of the channel. If we assume that the CRC for the header is a form of CRC-16, then that takes 16 bits. The size of the preamble is a difficult question depending on a number of factors (such as the underlying radio access mechanism), but here we assume that it is possible for it to be only as much as 16 bits. As regards the geolocation information, using IEEE 1900.6 as an example a "Reference Geolocation" (used to define sensor absolute and relative positions) is defined as three elements consisting of one 1900.6 "Angle" data type to represent each of latitude and longitude, and a signer integer to represent elevation. It is noted that the "Angle" data type is specified as fixed point with a minimum value of -180 degrees and maximum of 180 degrees, and a resolution of 1 micro-degree. Given this, each "Angle" can be sufficiently represented by either a signed or unsigned 32-bit integer, meaning that 64 bits is required to represent latitude and longitude. If we assume that the location area size is indicated in the header (i.e., for the case where "location areas" are not sub-divided), it is sufficient to represent this by a 16-bit integer in metres, giving a location area dimension of up to ~65km. Assuming this is represented in two dimensions, this requires 32 bits. As regards the length of information transmitted for a separate location area, quite likely it will be a small amount of some few kilo-bytes at most, hence here we assume that a 16-bit integer is again enough to represent such detail. Given all of this and again assuming that the GPS corner location and location area dimension is sent in each location area (i.e., no subdivision), the total length of the header is 16+16+64+32+16=128 bits.

Regarding the connectivity information, we assume that this is sent periodically, i.e., there is no "one-off" information included. Given this, the information that is sent is assumed to be structured as follows [27]:

- Operator 1 ID
    - RAT 1 ID
        - Frequency 1
        - Frequency 2
    - RAT 2 ID
        - Frequency 1
    - …
- Operator 2 ID
    - RAT 1 ID
        - Frequency 1
- …

We assume that the information amounts per IDs and frequencies are similar to as stated in [27]. Moreover, we take the simple case of the UK where there are 5 operators, 4 of which are transmitting GSM on both 900MHz and 1800MHz (this is not the case in reality, whereby some of them are not using 900MHz), as well as UMTS at 2GHz. The 5th operator only transmits UMTS at 2GHz. At 20 bits per operator, 4 bits per RAT, and 16 bits per frequency, this gives, 344 bits to represent the UK situation. Perhaps we can also represent a couple of Wi-Fi access points for one of the operators, giving an additional 56 bits. The total for this rather simplified scenario is therefore 400 bits per "location area". The total of the header plus the payload for each "location area" is therefore 528 bits.

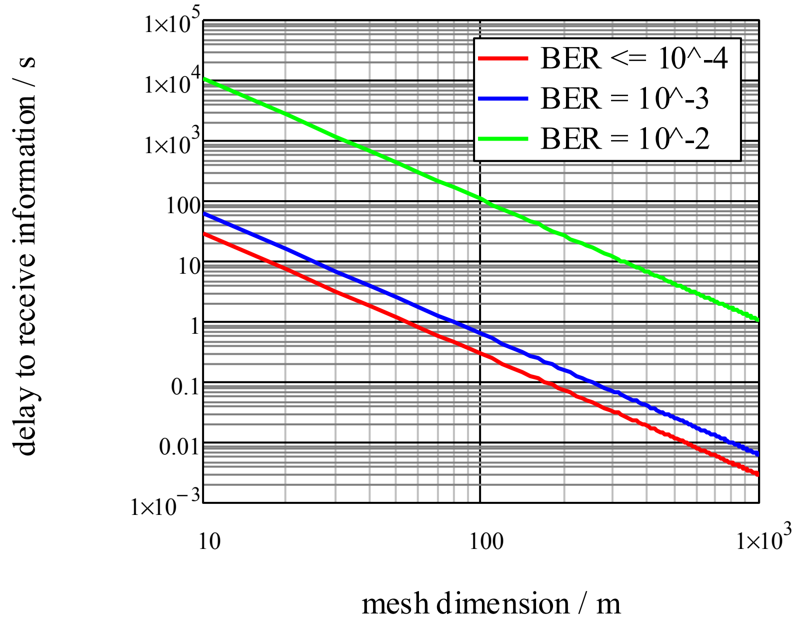


Figure 2-10: Average time taken for a terminal to receive out-of-band common control channel information for non-subdivided location areas vs. bit error rate; transmission range fixed at 1km.

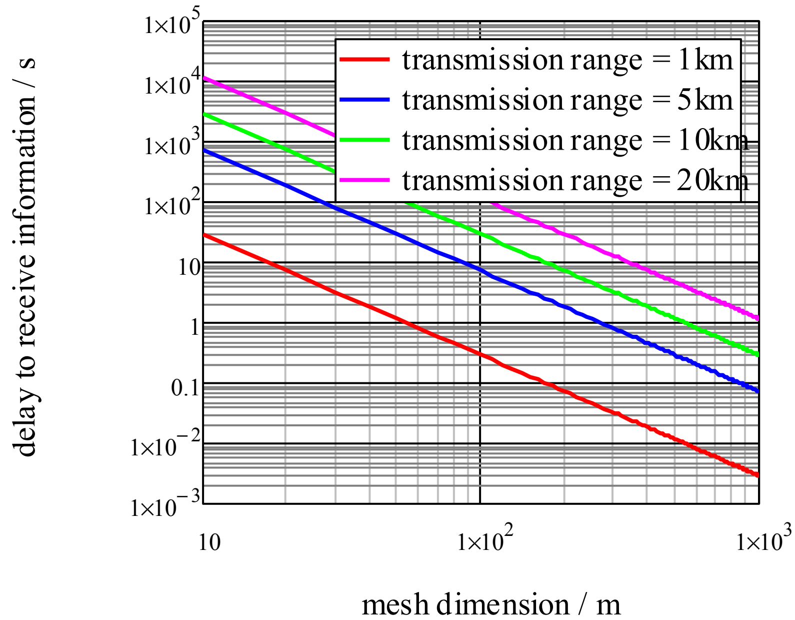


Figure 2-11: Average time taken for a terminal to receive out-of-band common control channel information for non-subdivided location areas vs. transmission range of the out-of-band channel; bit error rate fixed at 10^{-4}.

Figure 2-10 and Figure 2-11 show performance against BER the transmission range of the enabler and the location area size in terms of the dimension of the sides (*x* and *y* dimensions matching). It is noted that results might also be easily plotted/adapted to be in terms of frame error rate with a given coding rate hence an ability to access a given error probability, but this is very specific to the framing of the information and other aspects such as its coding.

Here we attempt to assess performance where an alternative structuring of transmitted information is assumed as represented in Figure 2-7. We consider both cases: (i) where all location areas include all information indicated above (but still the sub-division applies, in order to minimize the number of necessary location areas), and the alternative where the sub-division bits (indicated in Figure 2-7) are used such that only the "master location area" need include the information on the GPS coordinate and the size of the location area. In this latter case, the GPS information and location area size information can be removed from the headers of all subdivided location areas, however, devices located within the sub-divided location areas must receive all headers up from prior location areas until and including the most recent "master location area" in order to be able to locate themselves within the appropriate location area of the out-of-band channel. Also in this latter case, 2 bits must be added to all headers in order to indicate the level of sub-division.

For the following analyses, we define the scenario such that it is directly comparable with the prior results by assuming that the smallest subdivided location area is equivalent to the size of each of the location areas in the prior results for which sub-division does not apply. This is equivalent to assuming that exactly the same information is represented for some of the smallest-level sub-divided location areas, therefore allowing the location areas to be combined into location areas of double or four-times the size (in *x* and *y* dimensions) of the smallest sub-division. We assume exactly the same sub-division scenario as indicated in the top-right quadrant of Figure 2-7. Moreover, we assume that there is exactly the same probability of a device being in each of the subdivisions indicated in Figure 2-7, by virtue of the assumption that "busyness" of the area in terms and rate of RAT changes is proportional to the "busyness" in terms of population density of the area which is proportional to the "busyness" in terms of the density of devices in the area.

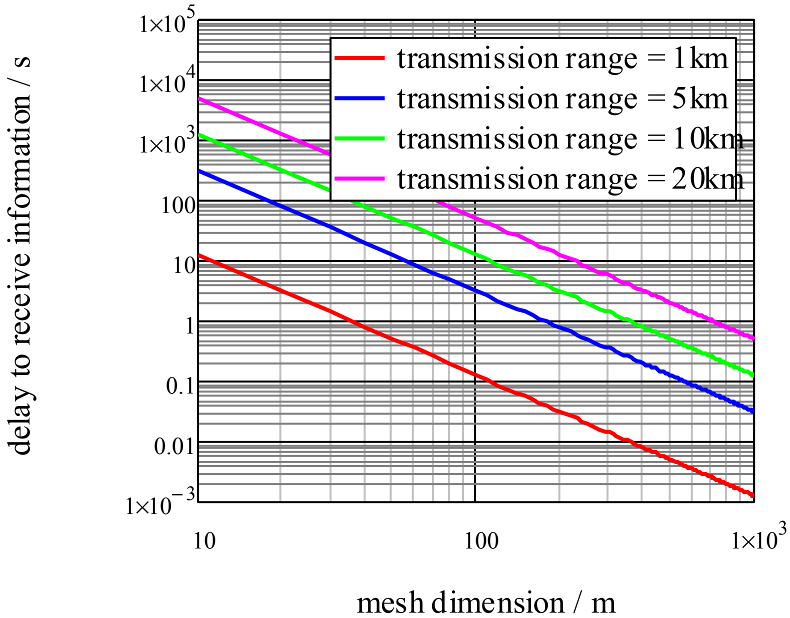


Figure 2-12: Average time taken for a terminal to receive out-of-band common control channel information for subdivided location areas using the scheme and scenario of the top-right quadrant of Figure 2-7, versus transmission range and location area dimension

size and with bit error rate fixed at 1km. Here it is assumed that full headers are transmitted/received.

Given this assumption, Figure 2-12 plots performance in terms of average time taken to receive information for the relevant location area against the size of the location area in terms of its *x* and *y* dimensions (*x*=*y*) and transmission range. Here the full headers are transmitted for each of the location areas, with no subdivision. Despite the transmission of full headers, this subdivision scheme shows considerable savings; for the location area dimension of 10m (similarly to as would be require to represent availabilities of access points at a very high density, such as WLANs), and a out-of-band channel transmission range of 1km, the time to receive is reduced from 29.26s to 12.80s. For the 100m location area dimension with a 5km transmission range (a configuration that might be appropriate for simple indication of availabilities of network operator/RATs on the out-of-band channel), the time to receive is reduced from 7.32s to 3.20s.

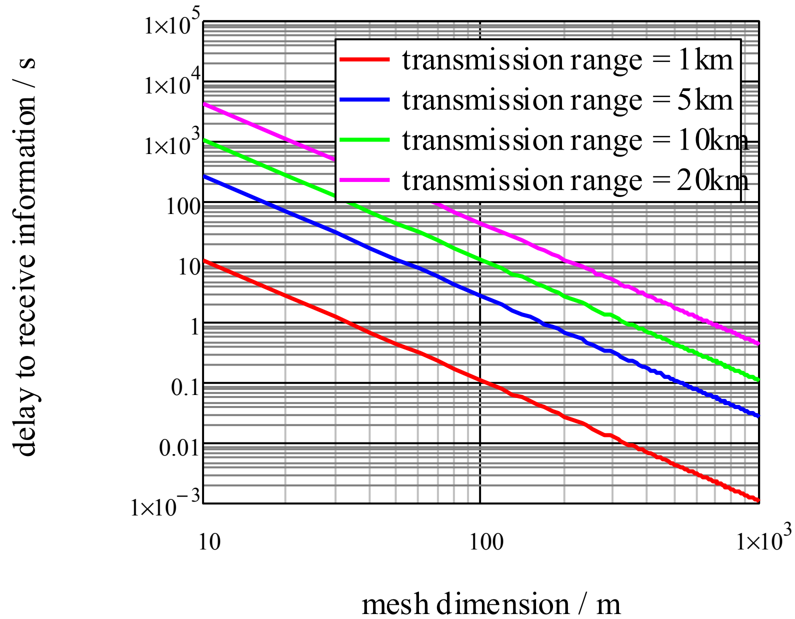


Figure 2-13: Average time taken for a terminal to receive out-of-band common control channel information for an equivalent scenario to Figure 2-12. Here it is assumed that the reduced headers are transmitted/received (as per utilization of the subdivision bits indicated in Figure 2-7).

For the alternative case, where the reduced headers are used, results are plotted in Figure 2-13. As compared with the location area sub-division scheme where the full headers are used, for the location area dimension of 10m and a out-of-band channel transmission range of 1km, the time to receive is reduced from 12.80s to 11.07s. For the 100m location area dimension with a 5km transmission range, the time to receive is reduced from 3.20s to 2.77s. The use of this header reduction scheme therefore results in an additional saving of some 10% for this given precise scenario. It is noted, however, that this saving varies dependent on the scenario (e.g., maximum location area subdivision ratio and the number of subdivided location areas per "master location area"); moreover, should the BER be higher this time saving through the scheme would quickly revert to a loss in time due to the extra amount of information for combined headers that must be received in order to locate the transmitted information for the appropriate location area. For instance, if the BER is increased to 10^{-3} for the 10m location area dimension and 1km transmission range case, the two cases give an average download time of 27.63s and 27.15, i.e., a saving of only half a second. If the BER is increased to $5 \cdot 10^{-3}$ the times are 314.3s and 483.1s, i.e., an increase in time to receive the information of approximately 50% through this header reduction solution.

In-band Approach

Some experimentation work has been carried out (e.g. [28], [29]) focusing on in-band solutions. Specifically, considering that Common Control Channels may be logical channels transporting information on top of a physical network architecture, some simulations have been performed building on top of the JADE/JADEX Platform [30], [31]. Various network infrastructure element or user devices, coupled with a high level interface (based on XML) to other components, are connected through this platform. The JADE/JADEX agents that have been used for the implementation exploit Agent Communication Language (ACL) messages, which are serialized and transmitted over TCP. The source code of JADE/JADEX has been modified, so as to enable recording the timestamp (according to the operating system time), the total number of received or sent bytes, as well as the signalling data bytes of every message that is sent or received by an agent. This recording is realized for each agent (network element/user device). Such recordings have been realized for three types of situations, namely normal operation, failure of a Base Station transceiver and hot spot (congestion) [28]. During normal operation a Base Station registers with the platform sending a Base Station Profile and receives a corresponding Infrastructure Decision. The failure of a transceiver in the simulation is achieved by switching off a specific transceiver. In case of a transceiver failure event, the Base Station informs of its altered configuration by sending its modified profile. In case of a hot spot situation, the Base Station sends its context information and receives configuration directions (infrastructure decisions) and policies.

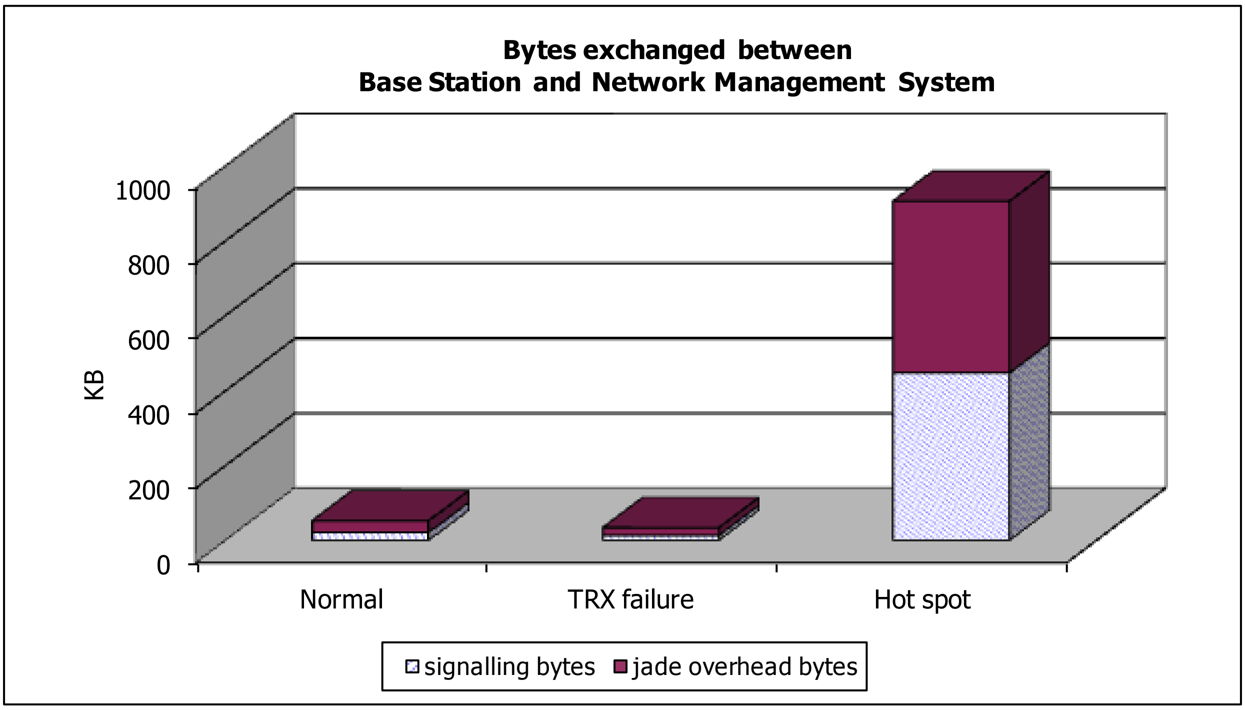


Figure 2-14: Number of bytes for signalling versus overhead [28].

Figure 2-14 presents the number of bytes exchanged between the Base Station and a Cognitive Network Management System (CNMS) for signalling versus the number of bytes added as overhead by the JADE platform for the three types of situations. As can be observed, for the normal operation and the transceiver failure the number of bytes exchanged is quite low as the exchanged messages do not comprise a large set of information.

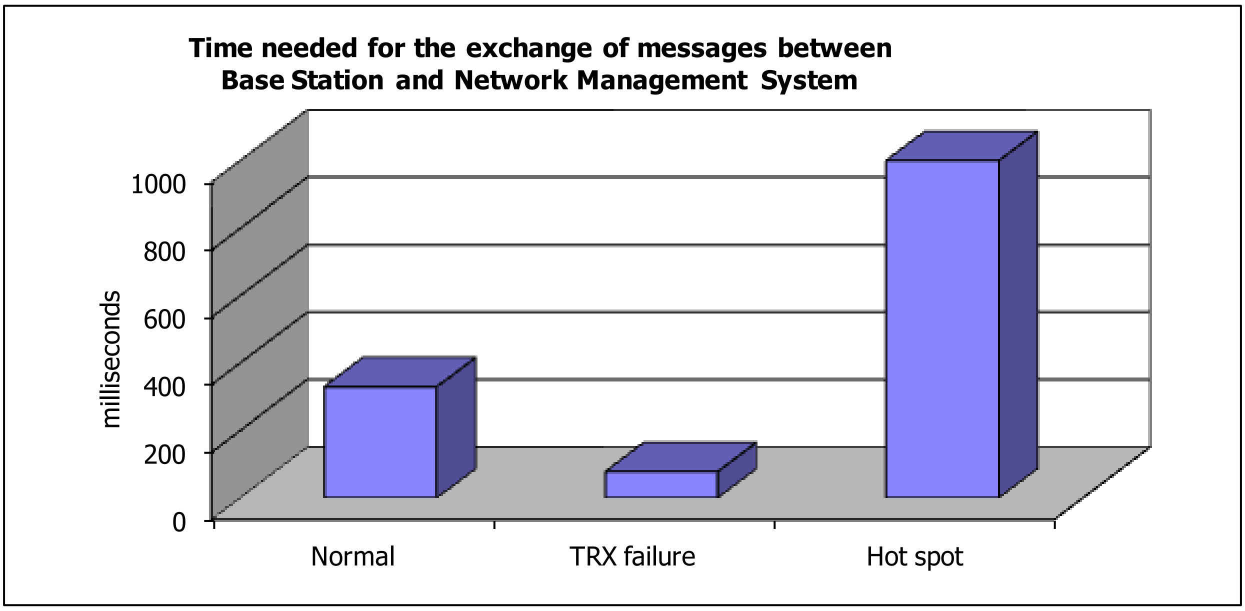


Figure 2-15: Time required for the exchange of information [28].

For the hot spot case the amount of data exchanged is much larger. However, even in this case, the volume of exchanged bytes is not extremely high. Similar conclusions can be drawn from Figure 2-15, which presents the time required for the exchange of information between the Base Station and the CNMS for the three types of situations. Finally, Figure 2-16 shows how the number of bytes in the exchanged information for the normal operation increases as the number of transceivers comprised in a certain Base Station increases. This provides an indication of how the operation of the platform is affected by increasing the network size. As can be observed there is a linear increase in the number of bytes, which is a natural consequence of the increased data that has to be transmitted.

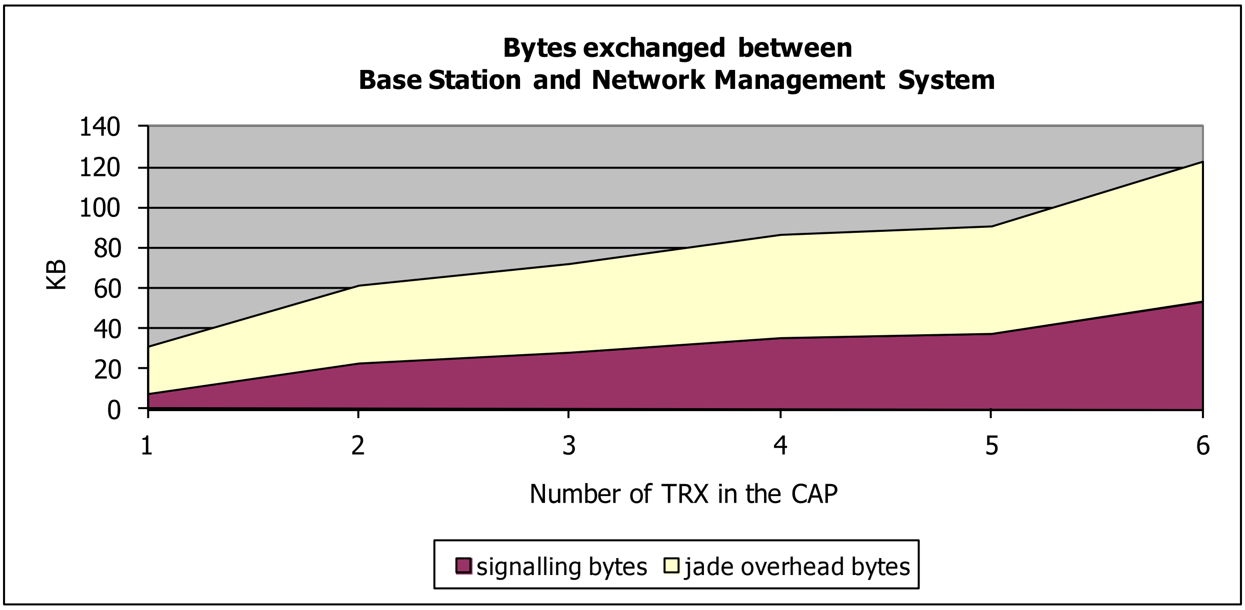


Figure 2-16: Number bytes for signalling bytes versus overhead when increasing the number of transceivers for a Base Station [28].

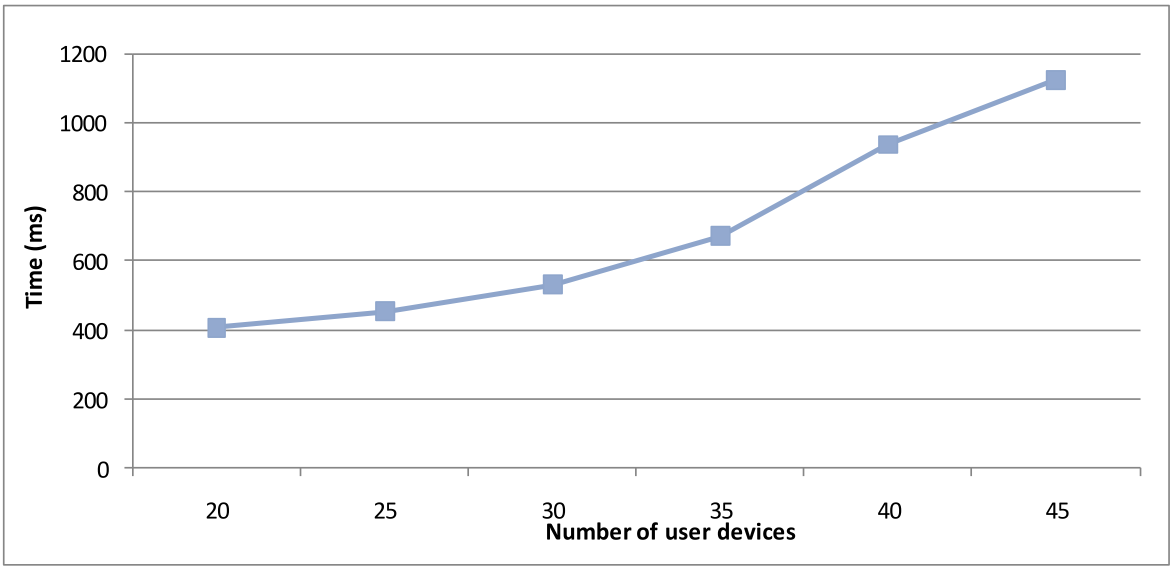


Figure 2-17: Time required for terminals to obtain policies after a reconfiguration occurs on the network side vs. number of terminals considered.

In summary, although there is some overhead (due to the agent platform) the overall amount of information exchanged (even in situations where there is large amount of data that needs to be transmitted) is realistic.

Finally, Figure 2-17 depicts the time required for terminals to obtain policies after a reconfiguration occurs on the network side as the number of terminals increases. More specifically, it is considered that a network management entity sends updates on policy information (via a common control channel) to user devices

Additional results, presented in [29], have been derived through the analysis of the data structures that would be transported over (logical, in-band) control channels. The results have been derived without focusing on a particular implementation option. More specifically, a cognitive network management architecture, is considered, aiming at the optimized management of future wireless networks operating in versatile radio environments. A performance evaluation methodology, which was set up for measuring the signalling loads that the operation of the architecture will bring to the managed network, is presented. The methodology is described, and useful results with respect to the signalling load produced for management purposes in an indicative scenario are presented and analysed. These results can be exploited to provide guidelines for the appropriate design of common control channels for Cognitive Radio, in terms of corresponding interfaces and messages that will ensure that the overall network operation will not be compromised from such deployment.

Further experiments are required for further performance assessment of information and knowledge sharing over Common Control Channels for Cognitive Radio.

2.1.3 Role of neighbour discovery in distributed learning and knowledge sharing algorithms for cognitive wireless networks

As introduced in Deliverable D10.1, neighbour discovery can be defined as the process of acquiring information about the local environment, aiming at determining the presence of other devices, the capabilities of such devices, and the information available at them. Neighbour discovery is instrumental in the setup and operation of a wireless network since it forms the basis of key functions like network association, network organization (e.g. clustering) and support for both local (e.g. Medium Access Control) and end-to-end algorithms and protocols (e.g. routing in multi-hop networks).

In the general case of networks where multiple channels are available, neighbour discovery can be defined as a two steps process:

1. Allow devices to converge on the same channel;
2. Exchange the information required to achieve discovery before one of the devices moves to a different channel. The problem of neighbour discovery is particularly challenging in the case of cognitive wireless networks, as the set of channels may differ among devices due to different decisions on the presence of other systems on some of the potentially available channels. For this reason, neighbour discovery in the context of cognitive radio networks has been investigated by several groups of researchers, see for example [32]-[35].

Algorithms that rely on an accurate and fast neighbour discovery include in particular distributed learning and knowledge sharing.

This work focused in particular on distributed learning mechanisms applied to the problem of optimal selection by a device in a set of candidate networks/configurations, in terms of the QoS levels that can be achieved. In particular, for the implementation of the learning mechanism, concepts from Bayesian statistics will be considered to build knowledge on the context of the device [36], [37], leading to the estimation (based on the collection of measurements) of the conditional probabilities for a certain network to achieve a certain QoS level for a particular application. In this context, it is essential to complement learning mechanisms with a reliable solution for the exchange and distribution of information.

To this respect, Cognitive Control Channels (CCC) can provide an effective solution in supporting such exchange, as discussed in Section 2.1.2. In general, however, the set-up of a common channel will foresee a neighbour discovery phase. An accurate performance evaluation of distributed learning algorithms requires thus to take into account the efficiency in the establishment of a common communication channel, and thus of the underlying neighbour discovery scheme, in order to determine the impact of missed neighbour detections and the corresponding incomplete local information.

In this framework, the goal of this work was to analyze the impact of neighbour discovery, and in particular of discovery failures, on algorithms for distributed learning, focusing on the issue of reduced efficiency in setting up a common communication channel.

2.1.3.1 Distributed learning for optimal network selection

Considering an arbitrary user that carries a terminal and has a subscription with a Network Operator (NO), distributed learning mechanisms can provide the status of a device and of its environment; this includes for example the available networks belonging to or collaborating with the NO, their Quality of Service (QoS) capabilities. Focusing on the QoS level capabilities that can be obtained, and assuming the application of Bayesian statistics concepts, the learning mechanism collects measurements and updates the conditional probabilities that a certain network can achieve a certain QoS level for a particular application. The user can use a certain set of applications, based on his/her subscription. The corresponding context information for this user includes:

- A set of candidate networks. The set of candidate networks is a subset of the available networks. It comprises networks that are compliant also with the policies of the Network Operator, i.e. the selection of these networks for the particular user and terminal is allowed.
- The set of QoS levels, for each network and application, at which an application can be offered by a certain network. This set of QoS levels comprises those that are achievable in the particular context of operation (e.g., radio channel conditions) and compliant with the policies of the operator for each application. A QoS level corresponds to a set of QoS parameters, such as bit rate, delay, jitter, etc. It should be noted that the scheme presented here is generic with respect to selected QoS parameters. Each parameter can be associated with a set of reference values for a specific network. For example, for the bit rate parameter a set of reference values could include the values 6, 12, 24, 36, 48, 54 Mbps. A QoS parameter can take a value among this set of reference values when a particular network is considered. In this respect, the set of QoS levels that can be achieved in a particular context can derive as the Cartesian product of the various reference value sets for the QoS parameters.

- The conditional probabilities, which provide an estimation of how probable it is that a specific QoS parameter, will reach a certain value, for an application, given a certain configuration.
- A probability density function value, which quantifies the knowledge regarding context. The probability density function offers a more aggregate estimation regarding the probability to achieve a certain combination of QoS parameters, which corresponds to a QoS level, for an application, given a certain network. This expresses the probability that a certain network will support a specific application and QoS level combination. In other words, the values of the density function express the knowledge on how probable a particular network-application-QoS level triplet is, compared to all other possible triplets.

The update of the conditional probabilities and probability density function values constitutes the learning process. The update of these relies on approaches suggested in [38]-[41]. It should be noted that the update of context information and knowledge is continuous, while the device is on the move. As a device moves there is usually some degree of overlap between its previous context and its current context. Thus, when the device moves into a new area, the context learning process does not have to start from the beginning. Previously obtained applicable information and knowledge, in the form of conditional probabilities and the probability density function, may still be exploited.

2.1.3.2 Impact of neighbour discovery on distributed learning

The establishment of the common control channel at the basis of the information exchange required by the distributed learning process introduced in Section 2.1.3.1 will in most cases be the result of a neighbour discovery phase. In particular, the common control channel is used by mobile devices and networks to exchange the information required by a device to evaluate the conditional probabilities introduced in the same Section, so to determine the best candidate network to achieve a given QoS for a given application.

Under ideal conditions, the neighbour discovery phase is assumed to be always successful, so that all devices and networks within radio coverage are able to communicate and exchange the context information needed for optimal network selection. In this case, it is shown in [42], for a scenario characterized by a device selecting between two candidate networks, that optimal selection based on context information leads to better performance than legacy selection schemes, in particular when one of the candidate networks shows a variation in the offered QoS.

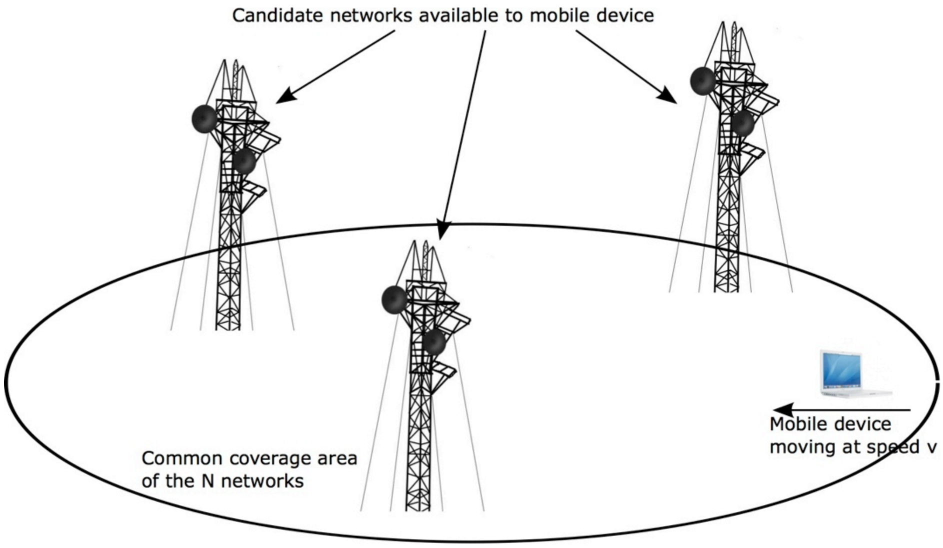


Figure 2-18: Reference scenario considered in the evaluation of neighbour discovery on distributed learning.

The reference scenario is the one envisioned in Figure 2-18, where a mobile device enters an area where N candidate networks are available, and has a limited time T_{ND} to complete neighbour discovery and start communicating over the selected network. The overall time T for which the given set of networks will be available is determined by the ratio between the coverage range R of the networks and the speed of the mobile device v; it can be safely assumed that in order for the scenario to make sense, the network discovery time must be significantly lower than the total available time, that is $T_{ND} /T \ll 1$.
In order to assess the impact of imperfect neighbour discovery, one can model the optimal network selection scenario as a neighbour discovery problem where N+1 entities, given by the mobile device and the set of N candidate networks, try to complete discovery in order to establish a common channel and exchange the context knowledge. In the worst case, such a scenario is characterized by the need of all N+1 entities to reach reciprocal awareness and exchange information, each entity potentially adopting a different set of available channel as a result of different propagation conditions and different sensing decisions. Such a worst case would fall in the *Free-for-all* category introduced in [33] and would thus constitute a difficult neighbour discovery problem. Even in the more favourable case, when the device is only required to connect to any of the N networks, neighbour discovery could still prove challenging, in particular in the case of medium-to-high mobility and in presence of detection errors.

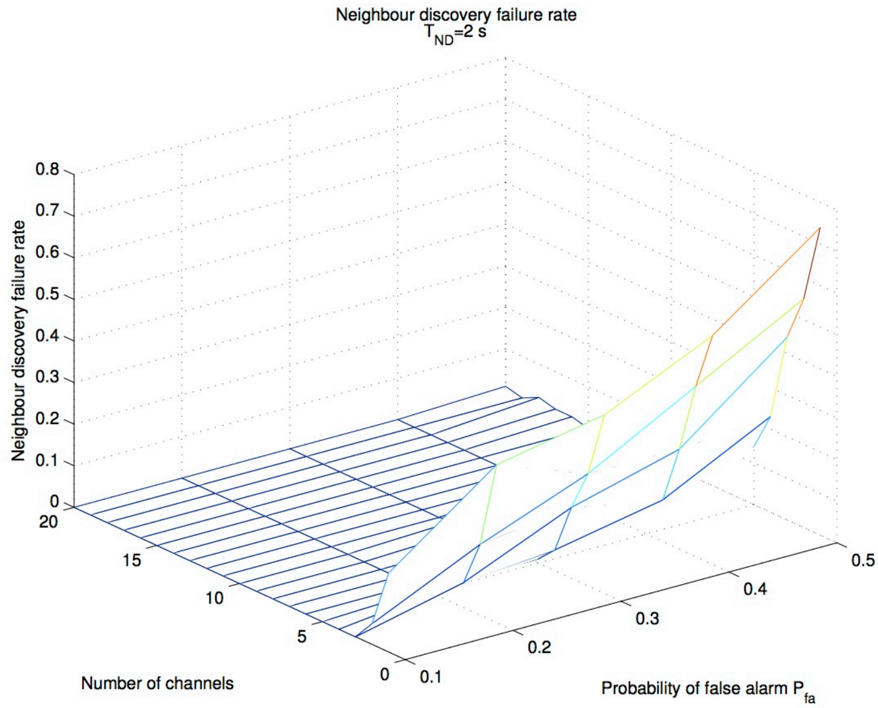


Figure 2-19: Neighbour discoveryt failure rate as a function of the probability of false alarm and number of channels in the case T_{ND} = 2s.

As an example Figure 2-19, shows the failure rate in neighbour discovery for the random algorithm introduced in Deliverable D10.1 as a function of the probability of false alarm and of the total number of channels, assuming a device speed v = 5m/s, a coverage range R = 1000m, and imposing that $T_{ND} / T = 0.01$, leading to T_{ND} = 2s. Figure 2-19 highlights that when the number of channels is low, even low values of probability of false alarm can lead to significant failure rates. In the network selection problem this would translate in a device failing to receive context information regarding a network, potentially reducing the achievable performance.

2.1.4 Solutions for neighbour discovery: Asynchronous Rendezvous Protocol for Cognitive Radio Ad Hoc Networks

There is a number of papers focusing on quorum based asynchronous rendezvous [43],[44]. However, these papers as well as other works dealing with the asynchronism, do not handle the channel heterogeneity in the generation of channel hopping sequences and do not handle the details of asynchronous operation and rendezvous between the devices. Oppositely, the **RAC2E-gQS** [45] takes into consideration the *heterogeneity* in terms of the channel priority among the CR nodes. Furthermore, the protocol covers the details of the operation of the nodes *prior the rendezvous* ([45], Sections 4.2 and 4.3) and *after the rendezvous*, i.e. the control channel operation [46].

The **RAC2E-gQS** rendezvous protocol for CRANs utilizes the asynchronous and randomness properties of the RAC2E protocol [46], and it investigates the suitability of two different channel search orders that are based on: (1) random selection utilizing weights and utility functions (*UP* approach), and (2) utilizing a grid Quorum System-based channel mapping (*gQ-RDV*) protocol [47], [48] taking into account channel heterogeneity (in terms of channel quality).

The **RAC²E** [46] is a MAC protocol for distributed CRN environments. The protocol relies on an *asynchronous* operation of the nodes, eliminating the need of synchronization establishment, which is a difficult task in the distributed environments. It fosters even an additional randomization among the nodes to ensure rapid rendezvous on a particular temporary unused channel from the primary system. The operation of the rendezvous phase is illustrated on Figure 2-20. Each CR aiming to establish a control channel independently selects a random rendezvous cycle duration of the Tc_{i_j}.. This time duration is selected uniformly in the range [T_{min}, T_{max}]. The chosen Tc_{i_j} interval is further segmented into M time slots, with each slot (having a duration of $\tau_{i\_j}= Tc_{i\_j}/N$) assigned to a particular channel unoccupied by the primary users.

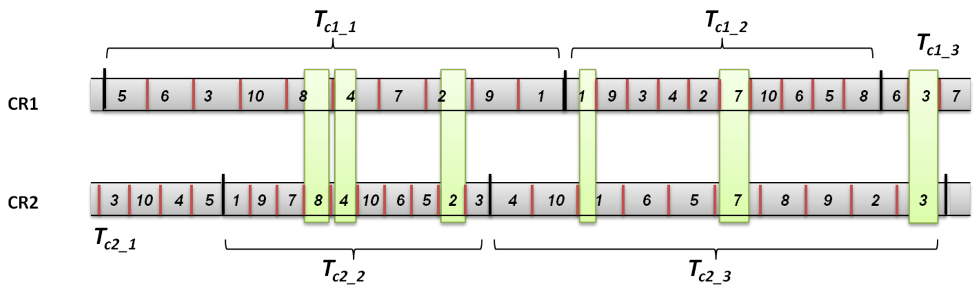


Figure 2-20: operation of the rendezvous phase in RAC2E

The random cycle duration and asynchronous operation provides overlapping between the both cognitive radios in the free channels (ch_i, i=1,...,10)
In each slot interval τ_{i_j}, the CR sends a short beacon message at the beginning and end of the slot to signalize its presence in the channel. As Figure 2-21 illustrates, the randomization (i.e. asynchronous operation of the both nodes) guarantees that at least one of the beacon messages will be delivered to the other nodes tuned to the same channel at the moment.

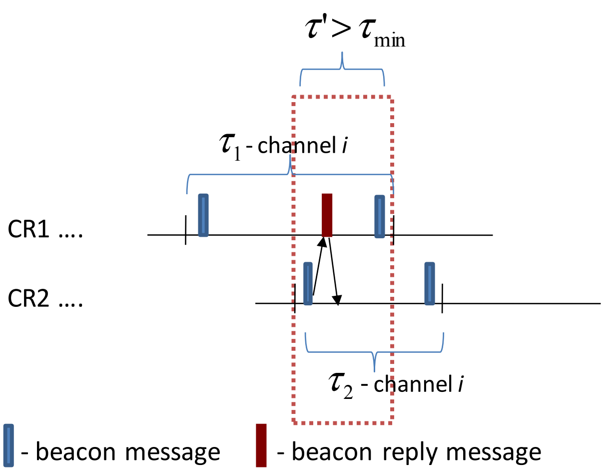


Figure 2-21: Rendezvous at channel *i* event

The **gQ-RDV** [47], [48], a fully distributed rendezvous protocol focuses on both the symmetric and asymmetric channel view (the same and different number, respectively, of available channels in individual sets). The outcome of the algorithm provides an input to the channel hopping sequences called channel hopping orders. Each CR maps its channels according to the channel quality without any exchange of information, where the best channels get *priority*. The best channel is mapped according to the chosen *quorum* (Figure 2-22 illustrates the grid quorum system idea).

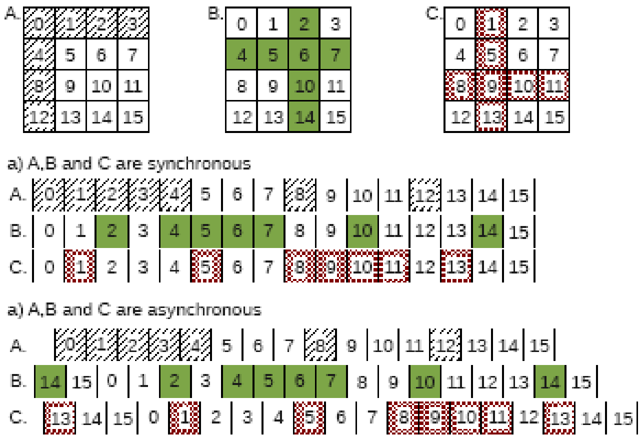


Figure 2-22: Grid based quorum with 16 slots in cycle

Hence, CRs that allocate a common best channel, while having the *same* number of available channels, will *always* meet thanks to the *quorum intersection property* (if satisfying the RCP they also always meet regardless cycle misalignment).

The combination of the *asynchronous* RAC^{2}E protocol with the *grid-quorum based channel mapping* (gQS) can yield a powerful **RAC^{2}E-gQS rendezvous protocol** [45] for asynchronous operation in a distributed environment assuring rapid rendezvous between the cognitive nodes.

RAC^{2}E improves noticeable the rendezvous performances of the gQS for the *same channel ranking lists* (exact the same channel priority order, e.g., 1, 2, 3, 4, 5 of both CRs) and *different channel ranking lists* (opposite channel priority order, i.e., 1, 2, 3, 4, 5 of CR1, and 5, 4, 3, 2, 1 of CR2)*;* the cases with 5, 10 and 20 channels have been investigated):

- An average number of potential RDVs per cycle of *gQS* in slot synchronized CRANs is
  - 6.5 (same list), 3.6 (different list) with *5* channels,
  - 13.3 (same list), and 6.7 (different list) with *10* channels and
  - 26.6 (same list) and 13.4 (different list) with *20* channels.

- Whereas **RAC^{2}E-gQS** average number of potential RDVs per cycle increases to:
  - 13.0 (same list), and 7.1 (different list) with 5 channels,
  - 26.6 (same list), and 13.4 (different list) with 10 channels and
  - 53.3 (same list), and 26.5 (different list).

Comparing **RAC^{2}E** with a random UP selection and the **gQS** approach, in the case of *different* channel rankings the UP performances differ from the grid-based methods: lower number of free channels results in worse average number of RDVs per cycle compared to the gQS methods; higher number of available channels results in better performances than the gQS schemes.

Although the methods experience the same or similar average number of potential RDVs per cycle, they differ in the inter-rendezvous time variance as depicted in Figure 4. For the same number of average potential RDVs per cycle, a higher variance means that channel RDVs occur in bursts, leaving longer gaps between bursts, while the lower variance represents the case when channel RDVs are more regularly distributed in time; the *lower variance* case is better since it assures that two CRs going online do not be stuck into the long no-RDV gaps before a successful RDV.

RAC^{2}E-gQS definitely outperforms **RAC^{2}E** using UP selection in the case with a small number of channels (e.g., 5 in [45]) and *different* channel ranking list, and in the case with a large number of channels (e.g., 20 in [45]) and the *same* channel ranking list.

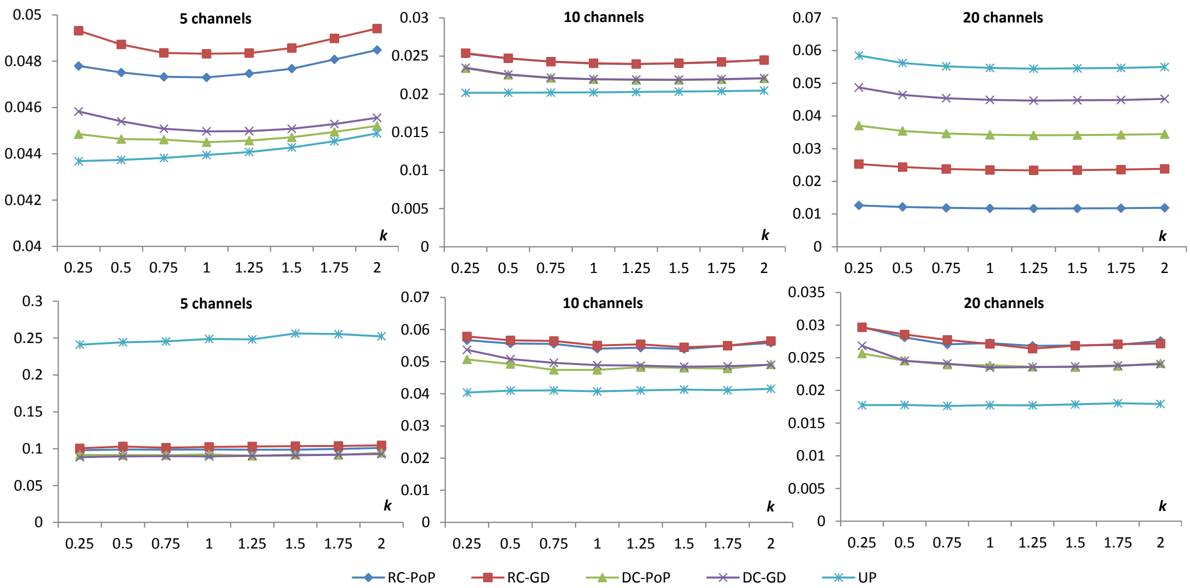


Figure 2-23: Inter rendezvous time variance [sec^2] versus randomization coefficient k, first row: same channel ranking case, second row: different channel ranking case [45].

2.2 End-to-end protocols

Key issues in end-to-end protocols for cognitive networks were identified in D10.1. This section presents the solutions defined within ACROPOLIS based on joint work by WP10 partners.

2.2.1 Solutions for routing in cognitive networks

Recently, the huge successes of wireless applications have lead to an exponential increase in the demand to regulatory authorities for spectrum allocation. Resultantly, the spectrum has become an expensive entity, leading to a struggle between the private, public and military sectors for the right to access the spectrum resource. Amongst the various solutions that have been proposed to tackle this problem, cognitive radio networks (CRN) have achieved the highest popularity. The more general concept of the cognitive radios (CR) enables the primary and the secondary users to co-exist within the same spectrum band, provided that the quality of service (QoS) requirements of the primary users are not affected. The primary spectrum users allow spectrum access to the secondary users as long as the interference generated within the secondary network is less than a tolerable interference level for the primary users [49].

So far, most of the research on cognitive radios has been focused on single-hop scenarios, tackling physical (PHY) layer and/or MAC layer issues [50]. However, recent research finding have highlighted the potentials of multi-hop cognitive radio networks [51]. The cognitive paradigm can be applied to different scenarios of multi-hop wireless networks, one such scenario being the cognitive radio ad hoc network which consists of CR nodes which communicate with each other in a peer to peer fashion through ad hoc connections [52]. To fully realize the potential of such networks, cross-layer design issues must be addressed, for example, the routing decisions at the network layer should be made in conjunction with the PHY layer characteristics.

In the above framework, the present work focuses on the specific case of an underlay secondary network, adopting transmit beamforming in order to guarantee coexistence with the primary nodes. Although beamforming has been proposed in the past as a way to improve the capability of secondary network nodes to meet QoS requirements set by a primary network [53], [54], this work goes beyond previous attempts by taking into account beamforming in the selection of relays in multi-hop connections. The proposed approach defines a metric that, relying on position information available at local level, modifies the path originally selected by the routing algorithm so to improve network performance while guaranteeing coexistence requirements; potential solutions for retrieving the required position information that take advantage of the same hardware used to implement the beamforming scheme are also discussed. The proposed strategy is compared with previous work that adopted beamforming in the secondary network without changing the path; the simulation setup used for such comparison is described in detail.

2.2.1.1 The Network Architecture and System Model

We consider a multi-hop cognitive radio network where the primary and the secondary nodes are randomly distributed within a specified region. Our goal is to route data between the secondary source and destination nodes in an energy efficient manner while minimising the co-channel interference amongst the secondary nodes. Furthermore, we aim to keep the interference imposed on the primary users by the secondary transmissions within the allowed interference shaping margins (ISM) required by each primary user.

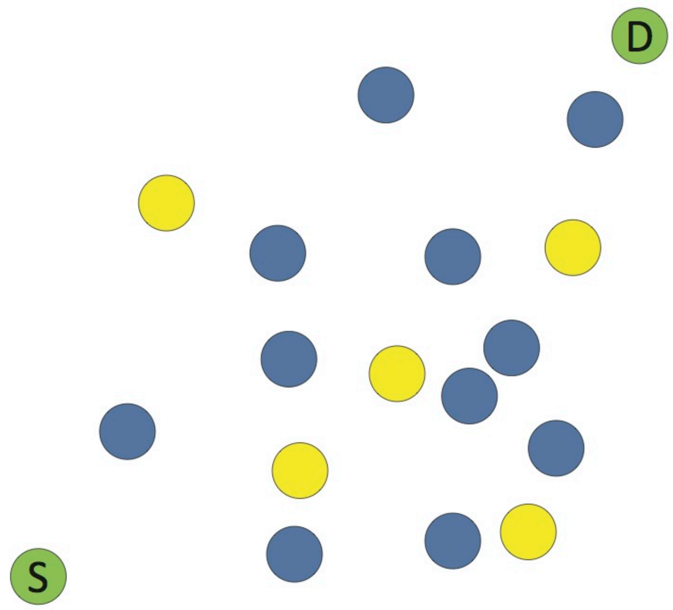


Figure 2-24: An ad hoc network consisting of randomly distributed primary and secondary nodes.

Figure 2-24 shows an example scenario where the yellow circles represent the primary nodes while the blue circle represent the secondary nodes. The secondary source and the destination nodes are also labelled in the figure.

It is assumed that each secondary node consists of a uniform linear array (ULA) with N transmit antennas with an element spacing of half a wavelength. For reception, both the primary and the secondary nodes utilize a single receive antenna. Thus, the considered scenario forms a multiple-input single-output (MISO) communication link. Such scenario makes sense in a multi-hop network, as the adoption of receive beamforming would make the implementation of broadcast and flooding procedures overly complicated.

Denoting the beamforming weight vectors by $\mathbf{w}_{ir} \in C^{N\times 1}$, where x_i represents the secondary transmitter while yr rep- resents the secondary receiver, the transmitted signal is given as:

$$\Psi_i = \mathbf{w}_{ir} s_r \tag{2-13}$$

where s_r is the data symbol intended for the receiver y_r. The signal received at y_r can be expressed as:

$$\mathrm{Y}_r = \mathbf{h}_{ir}\mathbf{w}_{ir} + n_r \tag{2-14}$$

where n_r is the receiver noise with power P_n while $\mathbf{h}_{ir} \in C^{1\times 1N}$ is the spatial channel response vector between transmitter xi and receiver yr. $\mathbf{h}_{ir}$ can be written as:

$$\mathbf{h}_{ir} = [h_{i,r,1}\ h_{i,r,2} \ldots h_{i,r,N}], \tag{2-15}$$

where $h_{i,r,k}$, $k \in [1 \ldots N]$, models the channel between the k-th element of the transmitter x_i and the receiver y_r and can be written as:

$$h_{i,r,k} = e^{j\frac{2\pi\Delta}{\zeta}(k-1)\sin(\theta_{ir}+\phi)} A\sqrt{1/L_{ir}}, \quad (2\text{-}16)$$

where Δ is the antenna element spacing, ζ is the wavelength while θ is the angle-of-departure (AoD) relative to the array antenna broadside; ϕ represents a small deviation from θ_{ir} with normal distribution, i.e., $\phi \sim N(0,\sigma^2)$, where σ represents the angular spread of local scatters surrounding node y_r. Finally, A represents the fading coefficient between the transmitter and the receiver while L_{ir} is the distance dependant path loss.

2.2.1.2 Transmit Beamforming Strategy

In our transmit beamforming strategy, we aim to minimize the total transmitted power subject to certain constraints. These constraints are the interference margins of the primary nodes and minimum signal-to-noise-ratio (SNR) requirements of the secondary nodes. Instead of using instantaneous channel state information (CSI), we use the second order statistics of the channel state information at the transmitting nodes, i.e., $\mathbf{R}_{ir} = \mathbf{E}[\mathbf{h}_{ir}^{\mathbf{H}}\mathbf{h}_{ir}]$ and $\mathbf{R}_{pm} = \mathbf{E}[\mathbf{h}_{pm}^{\mathbf{H}}\mathbf{h}_{pm}], 1 \le m \le M$, where $\mathbf{R}_{ir}$ and $\mathbf{R}_{pm}$ are the channel autocorrelation matrices for the secondary receiver r and m-th primary node, respectively. It is assumed that the secondary transmitters have knowledge about the locations of all the primary nodes within their transmission range. Instead of using a large number of samples to obtain the second-order statistics, we use the expression derived in [55] to obtain these statistics directly. Thus, the *(k,l)*-th entry in the matrix **R** can be written as:

$$\mathbf{R}(k,l) = \frac{A^2}{L} e^{j\frac{2\pi\Delta}{\zeta}(l-k)sin(\theta)} e^{-2\left[\frac{\pi\Delta\sigma}{\zeta}(l-k)cos(\theta)\right]^2}. \quad (2\text{-}17)$$

Minimum Transmit Power Beamforming Strategy

In this strategy, the transmit power at secondary node i is minimized as follows:

$$\begin{gathered} \text{minimize } p_i^t \\ \text{subject to } SNR_r \ge \gamma_r, I_m \le \varphi_m, 1 \le m \le M \end{gathered} \quad (2\text{-}18)$$

Where p_i^t is the power transmitted from node i, SNR_r is the received SNR at node r, γ_r is the minimum required SNR for node r, I_m is the interference imposed on primary node m while ϕ_m is the upper bound on maximum allowed interference towards the primary node m due to secondary transmissions.

SNR_r is given by:

$$SNR_r = \frac{p_r}{P_n}, \quad (2\text{-}19)$$

where p_r is the power received at node r and is given by:

$$p_r = \mathbf{w}_{ir}^{\mathbf{H}} \mathbf{R}_{ir} \mathbf{w}_{ir}. \quad (2\text{-}20)$$

Similarly, the interference exerted upon the m-th primary user can be written as:

$$I_m = \mathbf{w}_{ir}^{\mathbf{H}} \mathbf{R}_{pm} \mathbf{w}_{ir}. \quad (2\text{-}21)$$

Finally, the total transmission power p_i^t can be written as

$$p_i^t = \mathbf{w}_{ir}^{\mathbf{H}} \mathbf{w}_{ir}. \quad (2\text{-}22)$$

Thus, the problem in Eq. (2-18) can be rewritten as

$$\begin{aligned} &\text{minimize } \mathbf{w}_{ir}^{\mathbf{H}} \mathbf{w}_{ir} \\ &\text{subject to: } \begin{array}{c} \mathbf{w}_{ir}^{\mathbf{H}} \mathbf{R}_{ir} \mathbf{w}_{ir} \geq \gamma_r P_n, \\ \mathbf{w}_{ir}^{\mathbf{H}} \mathbf{R}_{pm} \mathbf{w}_{ir} \leq \varphi_m, 1 \leq m \leq M \end{array} \end{aligned} \quad (2\text{-}23)$$

Since the problem defined in eq. (2-23) is non-convex, it has to be converted into convex SDP form, which can solved by an SDP solver like SeDuMi. To do this, we define a new matrix $\mathbf{F}_{ir} = \mathbf{w}_{ir} \mathbf{w}_{ir}^{\mathbf{H}}$. With this matrix, eq. (2-23) can be written as:

$$\begin{aligned} &\text{minimize } \mathrm{tr}[\mathbf{F}_{ir}] \\ &\text{subject to: } \begin{array}{c} \mathrm{tr}[\mathbf{R}_{ir} \mathbf{F}_{ir}] \geq \gamma_r P_n, \\ \mathrm{tr}[\mathbf{R}_{pm} \mathbf{F}_{ir}] \leq \varphi_m, 1 \leq m \leq M, \\ \mathbf{F}_{ir} = \mathbf{F}_{ir}^{\mathbf{H}} \geq 0. \end{array} \end{aligned} \quad (2\text{-}24)$$

Notice that we have used the rotation property of the trace operator, i.e., $tr[AB] = tr[BA]$, to arrive at $\mathbf{w}_{ir}^{\mathbf{H}} \mathbf{R}_{ir} \mathbf{w}_{ir} = \mathrm{tr}[\mathbf{R}_{ir} \mathbf{w}_{ir} \mathbf{w}_{ir}^{\mathbf{H}}] = \mathrm{tr}[\mathbf{R}_{ir} \mathbf{F}_{ir}]$.
Further details about the above derived formulation can be found in [1]. As a final note on the above beamforming strategy, in order for it to be applied, an estimation of the direction towards the intended receiver and victim primary and secondary receivers must be available. Depending on the scenario, it can be assumed that such information is made available by dedicated positioning hardware (e.g. GPS) in each device, and subsequent position information exchanges, but a more general approach can be envisioned, where the same ULAs used for beamforming allow to obtain the desired position information. A potential solution to achieve this result is discussed in detail in the following subsections.

Estimation of Direction to Intended Receiver

The uniform linear arrays required to implement the beam-forming strategy introduced in Section III have the additional advantage of enabling each network device to obtain information about the relative directions of arrival of signals emitted by other devices. The general problem faced by a network device in determining the Directions Of Arrivals (DOAs) of signals emitted by m other devices by means of a uniform linear array of antenna elements is depicted in Figure 2-25, where it is assumed that each signal can be represented as a plane wave impinging on the array.

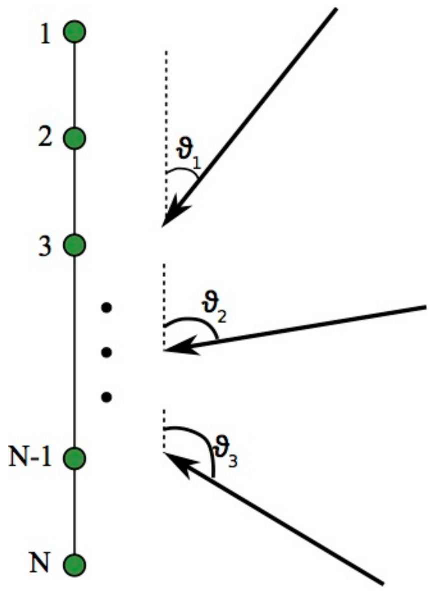


Figure 2-25: Example of a Direction Of Arrival estimation for *m=3* signals at an antenna array composed of *N* elements.

One of the major issues in obtaining accurate information on the DOA of signals is the fact that multiple signals may arrive simultaneously on the antenna array and the number m of such signals is in general unknown. The problem is typically easier to solve if the number of antenna elements is larger than the number of signals to be dealt with. Note that in the specific scenario considered in this work, this condition translates in imposing that the total number of neighbours to be processed simultaneously by a node during the DOA estimation is lower than the number of array elements: this can be achieved by proper scheduling during such phase, as further discussed in the following. It should furthermore be noted that solutions exist for the case m>N as well.

A well known class of algorithms for the DOA estimation problem using a ULA takes advantage of techniques first applied to the spectrum estimation problem. Among these, a particularly well known solution is the MUSIC algorithm, relying on the subspace decomposition of the covariance matrix estimated from the signal received on each antenna array element from the targets [56], briefly described in the following.

Let us consider an ULA of N elements receiving m signals. The signal received by the *k*-th element of the array can be written as:

$$g_k(t) = \sum_{i=1}^{m} s_i(t) a(k, \theta_i) + n_k(t) \tag{2-25}$$

where $s_i(t)$ is the *i*–th signal, $a(k,\theta_i)$ is a steering function that describes the effect of the propagation from the position of the device emitting the *i*-th signal to the *k*-th array element and $n_k(t)$ represents thermal noise present at the same element. Moving to the frequency domain one has the following matrix representation (where the dependence from frequency is omitted):

$$\mathbf{G} = \mathbf{A} \cdot \mathbf{S} + \mathbf{N} \tag{2-26}$$

where $\mathbf{G}$ is a N x 1 vector representing the spectrum of the received signal at each array element obtained from the N x m matrix $\mathbf{A}$, representing the values of the Fourier transform of the steering functions, the m x 1 vector $\mathbf{S}$ containing the transforms of the incident signals and finally the N x 1 vector N representing the noise introduced at each array element. The MUSIC algorithm uses the information present in the matrix G to obtain and estimate of the covariance matrix $\mathbf{C}$ defined as:

$$\mathbf{C} = \mathbf{E}\left[\mathbf{G} \cdot \mathbf{G}^*\right] = \mathbf{AE}\left[\mathbf{S} \cdot \mathbf{S}^*\right]\mathbf{A}^* + \mathbf{E}\left[\mathbf{N} \cdot \mathbf{N}^*\right] = \mathbf{AE}\left[\mathbf{S} \cdot \mathbf{S}^*\right]\mathbf{A}^* + \lambda \mathbf{C_0}, \tag{2-27}$$

where it is assumed that signals and noise are uncorrelated. As long as the condition N > m is verified, $\mathbf{C}$ is not a full rank matrix, and as a consequence it has determinant equal to:

$$det(\mathbf{C}) = det\left(\mathbf{AE}\left[\mathbf{S} \cdot \mathbf{S}^*\right]\mathbf{A}^* + \lambda \mathbf{C_0}\right) = 0. \tag{2-28}$$

Note that in the special case where noise is characterized by zero mean and variance σ^2 one has $\lambda = \sigma^2$. As shown in [56], due to the properties of the $\mathbf{S}$ and $\mathbf{A}$ matrices, eq. (2-28) is only solved by choosing λ as the smallest eigenvalue of the $\mathbf{S}$ matrix λ_{min}; furthermore such smallest eigenvalue will have a multiplicity equal to n = N − m. In turn, this leads to the conclusion that there will be n eigenvectors $\{e_{m+1}, \cdots, e_N\}$ of $\mathbf{C}$ associated to λ_{min} that will verify the condition:

$$\mathbf{AE}\left[\mathbf{S} \cdot \mathbf{S}^*\right]\mathbf{A}^* \cdot \mathbf{e_i} = \mathbf{A}^* \cdot \mathbf{e_i} = \mathbf{0}, i = m+1, \cdots, N. \tag{2-29}$$

Such eigenvectors define thus a subspace (referred to as the *noise* subspace) orthogonal to the subspace defined by the columns of the $\mathbf{A}$ matrix. The values $\theta_1, \cdots, \theta_m$ of the *m* angles of arrival can be then identified by introducing the *MUSIC pseudospectrum,* defined as:

$$P_{MU} = \frac{1}{\mathbf{a}^*(\theta)\mathbf{E_n} \cdot \mathbf{E_n^*}\mathbf{a}(\theta)} \tag{2-30}$$

where $\mathbf{E_n} = [\mathbf{e_{m+1}}, \cdots, \mathbf{e_N}]$. The peaks of the pseudospectrum as it varies as a function of θ identify the direction of arrival of the *m* signals.

From DOA estimation to positioning

The DOA technique described in the previous section provides an estimation of the direction of arrival of a signal. Under ideal conditions the DOA output would be the exact angle of arrival of the signal, thus defining the *locus* of the possible positions of the source emitting the signal as a line, commonly referred to as Line Of Bearing (LOB) [57]. In a 2D scenario two such measurements taken by two different devices in known positions are enough to determine the position of the source of a signal as the intersection of the corresponding LOBs. In a real-world scenario, DOA measurements will be affected by error, the accuracy of the measurements being determined by the SNR of the signal and the number of antenna elements [58].

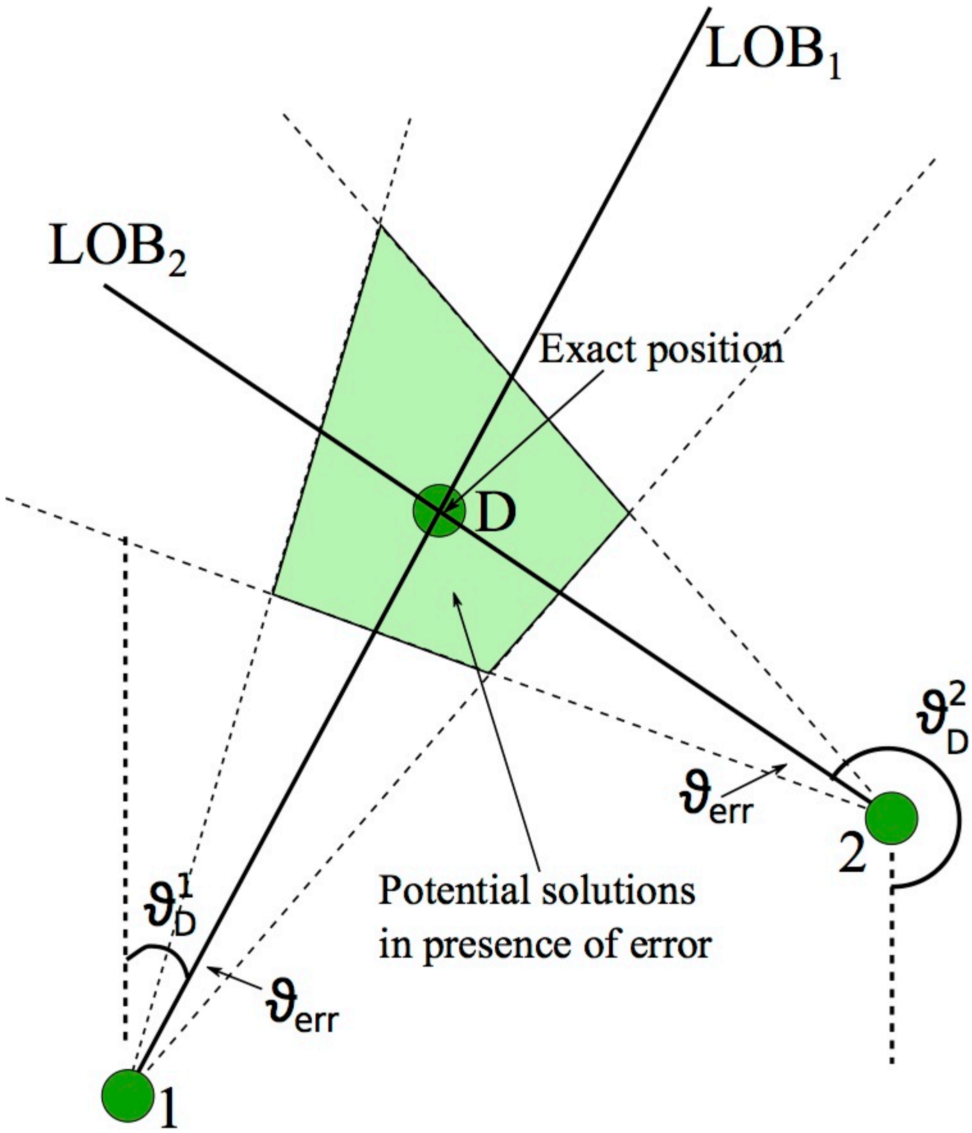


Figure 2-26: Example of DOA-based positioning in a 2D scenario: exact solution (intersection of Lines Of Bearing LOB_1 and LOB_2) vs. possible solutions in presence of a maximum DOA error θ_{err}.

Figure 2-26 shows an example of DOA-based positioning outcome in the perfect vs. imperfect measurement case, assuming that DOA measurements are affected by a

maximum error equal to ϑ_{err}. The solution of the positioning problem in presence of angle measurement error will in general require the adoption of either iterative [57] or not iterative [59] approaches.
A similar approach has been proposed in the past as a potential solution for the positioning of mobile phones, having Base Stations taking DOA measurements and reporting them to a central processing unit [60]. In the scenario considered in this work, it should be noted that the computation of the position of a device emitting a signal based on the DOA measurements taken by two devices D_1 and D_2 requires the following two conditions to be met:

1. D_1 and D_2 must be within communication range, in order to exchange the angle measurements;
2. D_1 and D_2 must share the same coordinate system, so that angle measurements can be properly combined.

The latter condition, in particular, can pose a significant hurdle to the deployment of a DOA-based positioning algorithm. A similar issue has been however addressed in the past for the case of a Time Of Arrival (TOA) based approach, proving that the problem can be solved provided that network density is high enough and that variations in network topology are rare enough to allow for the distributed positioning algorithm to converge after each variation [61], [62].

DOA estimation and positioning support at the MAC layer

It was mentioned previously that proper scheduling should be adopted during the procedure of DOA estimation so that the number of simultaneous transmissions can be kept under control, ensuring an easier solution of the DOA estimation problem. This can be achieved by defining dedicated MAC functions that enable devices to reserve a portion of channel time to the transmission of signals for DOA estimation. A similar approach was adopted in the IEEE 802.15.4a standard [63] in order to enable a range measurement procedure, leading to a definition of a MAC superframe divided in a Contention Free Period (CFP) and a Contention Access Period (CAP), with ranging measurements taking place in the CFP part of the superframe, so to avoid excessive interference during the execution of the ranging algorithm.
The overhead introduced by adopting the above approach for MAC layer support to DOA and positioning can be reduced by adapting the periodicity of DOA estimation periods to the estimated rate of topology variations: for static or quasi-static networks this would lead to a negligible overhead after the initial set-up phase is completed. A detailed definition of the MAC protocol and of the DOA estimation and positioning algorithms will be addressed in future work along this research line.

2.2.1.3 Multi-hop Cognitive Radio Routing Schemes with Hop-by-Hop Beamforming

Multi-hop Position-Based Underlay Cognitive Radio Rout- ing Concept

The availability at network nodes of position information on both neighbouring nodes in the secondary network and primary receivers allows for the introduction of position- based optimizations in the routing protocol, with the goal of guaranteeing the best possible performance to the secondary network, while meeting the constraints imposed by coexistence with primary receivers. In general, position information can be introduced in two different ways in the operation of a routing protocol: either in the routing algorithm (e.g. determining which nodes participate in the routing discovery process based on their position, as in [64]), or in the routing metric, as proposed in [65], [66]. A detailed discussion of how position information can be used in the routing algorithm for underlay cognitive radio networks is presented in [67], where a preliminary analysis of the potential advantages of introducing a beamforming technique in a multi-hop cognitive radio network is carried out. Note that in the analysis presented in [67] beamforming was not taken into account at all in the selection of the end-to-end path, but rather introduced when forwarding data packets along the selected path. In the present work the idea of introducing beamforming in a multi-hop cognitive network is taken a step farther by allowing limited modifications to the path selected at the routing layer based on the expected impact on neighbouring secondary nodes and primary receivers. Details on the proposed solution are provided in the following subsection.

The Proposed Algorithm

In this section, we utilize transmit beamforming to design a routing algorithm for a multi-hop cognitive radio network. The objective of the algorithm is three-fold:

1. To minimize the end to end power consumption.
2. To minimize the co-channel interference imposed within the secondary network.
3. To minimize the number of primary interference constraint violations.

To achieve the goals set above, we adopt a centralized approach whereby the optimal power saving route is initially calculated through Dijkstra’s algorithm by using the point to point link costs without beamforming, which can be written as:

$$LC(i,r) = \frac{\gamma_r P_n}{|h_{ir}|^2}, \qquad (2\text{-}31)$$

where $LC(i,r)$ represents the link link cost between transmitter x_i and receiver y_r while all the other parameters have already been defined in Section 2.2.1.1. After this initial step, the algorithm modifies the selected route by using a new cost metric which we introduce later in this section. To ensure that the modified route does not deviate too much from the optimal power saving route, the cost metric is used only on alternate hops, for example, for every odd numbered hop of the optimal route, the hop destination is selected based on the proposed cost metric, while the destinations of the even numbered hops remain unchanged. We now propose a cost metric which is used to select the node which is most suitable to act as a relay. The proposed metric takes into account the potential impact of the selection of a relay on the primary receivers and other secondary nodes, within the transmission range of the source and the candidate relay node. In the following, we refer to the source, relay and destination nodes as S, R and D, respectively. A terminal R will only be eligible as a relay if it meets all the following conditions:

1. S does not violate the interference constraint of any of the primary users when it transmits data to R using beamforming;
2. R does not violate the interference constraint of any of the primary users when it transmits data to D using beamforming;
3. The position of R is such that the distance between R and D, indicated as distRD, is not larger than the distance from S to D, distSD. This condition ensures physical connectivity between the selected relay and D and it ensures that the algorithm remains loop free.

The above description translates into the cost *Cost(S, D, R)* associated to the generic terminal R as a potential relay between S and D defined as:

$$Cost(S,D,R)=\begin{cases} \sum_{i=1,i\neq R}^{N_S^S} I(S,R,i)+\sum_{k=1,k\neq D}^{N_R^S} I(R,D,k) & if \begin{cases} \sum_{l=1}^{N_S^P}\left\lfloor \frac{I(S,R,l)}{I_{MAX}(l)} \right\rfloor + \sum_{l=1}^{N_R^P}\left\lfloor \frac{I(R,D,m)}{I_{MAX}(m)} \right\rfloor = 0 \\ dist_{RD} \leq dist_{RD} \end{cases} \\ +\infty & otherwise \end{cases} \quad (2\text{-}32)$$

where:

1. N_k^S is the number of secondary terminals within the transmission range of terminal *k*;
2. N_k^P is the number of primary receivers within the transmission range of terminal k;
3. *I(x, y, z)* is the interference generated by *x* towards the generic receiver *y* (either primary or secondary) when transmitting to *z*.

The candidate relay node which gives the minimum value for the above cost function is selected as the next hop destination. Figure 2-27 shows an example scenario where the green nodes are the secondary source and destination nodes, the yellow nodes are the primary nodes while the nodes labelled as R1,..., R6 are the candidate relay nodes.

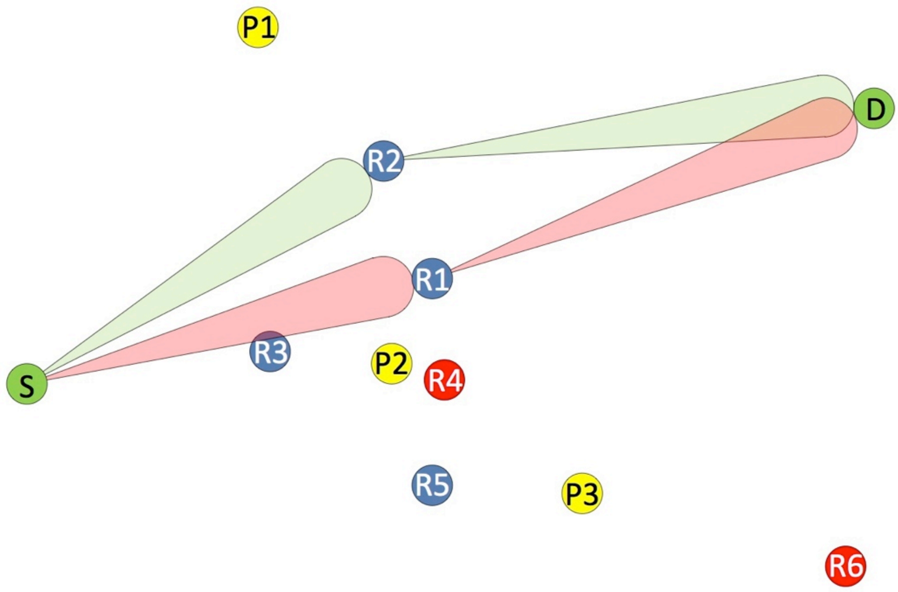


Figure 2-27: Demonstration of the proposed cost metric.

Amongst the candidate relay nodes, the nodes in blue are the eligible candidates while the nodes in red, i.e., R4 and R6 are not eligible to act as relays. R4 is rejected because S cannot transmit to R4 without violating the interference constraint of P2 while the distance between S and R6 is larger than the distance between S and D. The Dijkstra's algorithm selects R1 as the best option to act as a relay. However, it can be seen that if the data is transmitted to R1, a lot of interference is exerted upon R3. On the other hand, if R3 is selected as the relay, then interference will be exerted up R1 when R3 forwards the data to D. Using the proposed cost metric, the best option in this case is to select R2 as the relay. As a final comment, it is worth noting that the relay selection metric is defined so to operate at local level, without any interaction with the routing algorithm; this allows, in theory, to combine the proposed path optimization approach with any routing algorithm. An explicit introduction of beamforming-related information in the metric of the routing algorithm will be addressed in future work.

2.2.1.4 Performance evaluation

The performance of the proposed solution was evaluated by means of computer simulations executed by combining a signal processing tool (MATLAB) and a network simulator (OMNeT++) as follows:

1. MATLAB was used to implement the transmit beam- forming strategy introduced in Section III and to analyse the performance of the route optimization approach defined in Section 2.2.1.3 by measuring the interference generated towards each secondary node as well as the average number of constraints set by primary receivers that are met.
2. OMNeT++ was used to test the proposed strategy in presence of actual packet transmissions, moving from results generated in MATLAB.

Details on the implementation, the scenario considered during simulations, as well as simulation results are presented in the following subsections.

Simulation scenario and setup

The MATLAB code was used to simulate a network of secondary nodes equipped with a ULA with $N = 8$ antenna elements and a spacing between adjacent elements $d = 0.125$ m, corresponding to half a wavelength for a carrier frequency $f_c = 2.4$ GHz, and capable thus to perform DOA estimation and beamforming. An angular spread $\Delta\theta = 2^o$ was introduced around the exact angle for each measurement in order to account for DOA measurement errors, and taken into account in the optimization procedure. A noise power $P_n = -101$ dBm was assumed at each receiver, while the path loss exponent for propagation was set equal to $\alpha = 2$. MATLAB was used to solve the optimization problem of eq. (2-24) by taking advantage of the SeDuMi solver provided by the cvx package [68], imposing an upper bound ϕ_m on the allowed interference towards the primary nodes and a minimum SNR level of γ_r = 10 dB for all the secondary nodes. The following steps were executed in MATLAB for each run:

1. Generation of a topology composed of N_S secondary nodes and N_P primary nodes randomly deployed in an area of X_{max} = 50 m by Y_{max} = 50 m square meters;
2. Generation of N_{conn} connection requests in the secondary network with random source and destination nodes, random duration uniformly distributed between *minDuration* and *maxDuration* and random delay from the previous connection

request from same source node uniformly distributed between *minDelay* and *maxDelay*; then, for each connection request:

   a. Selection of the best path according to the minimum power routing strategy defined in Section 2.2.1.3;
   b. Optimization of the path according to the proposed metric, defined again in Section 2.2.1.3;
   c. Measurement of interference generated towards secondary nodes not involved in the connection with and without optimization;
   d. Measurement of number of primaries for which the constraint on the maximum interference value is met with and without optimization;

3. Export to file of the data required by OMNeT++, consisting in:
   a. primary and secondary network topology;
   b. the list of the N_{conn} generated connection requests, including source, destination and duration;
   c. original and optimized paths for each connection;
   d. the reduction in the interference *I(x,y,z)* perceived in *y* guaranteed by the introduction of beamforming in the link from *x* to *z*, for all *x*-*z* pairs involved in any connection, for both original and optimized paths.

The inputs generated in MATLAB were used in a simulated secondary network built in OMNeT++, with each secondary node characterized by the architecture shown in Figure 2-28.

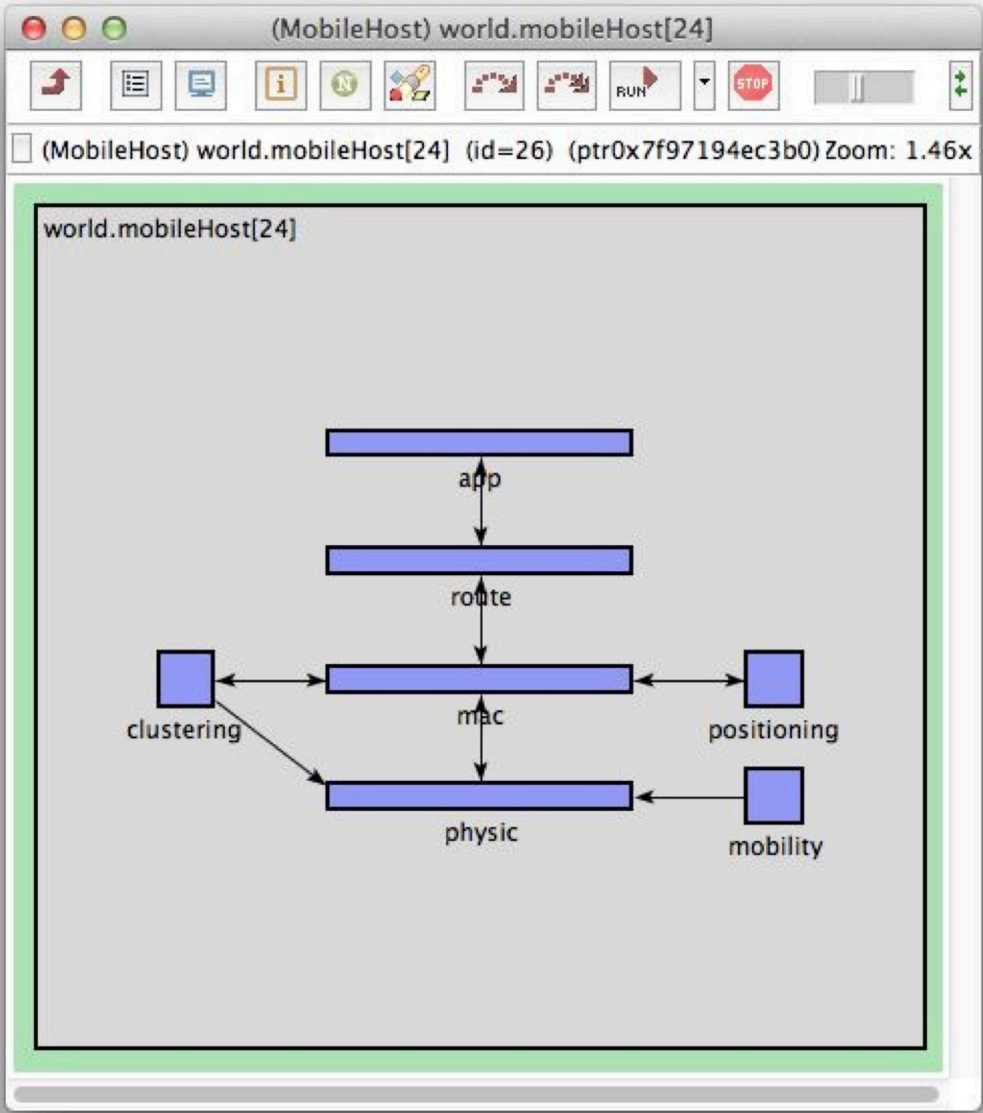


Figure 2-28: Secondary node architecture implemented in OMNeT++.

With reference to such architecture, it should be noted that:

- the mobility and clustering modules were not activated, as a static network with flat organization was assumed in this work.
- the positioning module was configured so to provide perfect position information about all network nodes.
- the application module for a generic node *x* was in charge of reading from file connection requests having *x* as source, and generate for each connection packets of size *appPacketSize* bits spaced in time by a constant delay set to

applicationRate/appPacketSize (modeling thus a Constant Bit Rate (CBR) packet stream) for a time equal to the connection duration read from file;

- the routing module for a source node *x*, upon receiving from the application module the first packet of a connection, was in charge of a) loading from file the corresponding end-to-end path determined in MATLAB, b) record such path in each packet; the routing module of intermediate nodes took care of forwarding the packet towards the destination by reading the next hop from the packet itself, while the routing module of a destination node simply forwarded the packet to the application module.
- the MAC module implemented a simple Aloha protocol without retransmission, taking care of immediately forwarding packets received from the routing module to the physical layer module and viceversa.
- the physical layer module had the responsibility of trans- mitting and receiving packets taking into account path loss, propagation delays and interference generated by packet collisions.
- The impact of interference, in particular, was modeled with an accuracy significantly higher than what currently found in existing OMNeT++ frameworks, such as INET [69] and MixiM [70], in order to ensure a correct analysis of the impact of the proposed optimization on network performance. The simulator is in fact able to keep track of all transmitted packets and, for each packet reception, determines the interference level on a symbol by symbol basis (note that, as binary modulation was considered in all simulations, in the following bits will be considered in place of symbols). Consecutive bits subject to the same interference are grouped into so called bit regions: Figure 2-29 shows an example of packet reception where four different regions are identified due to varying interference conditions.

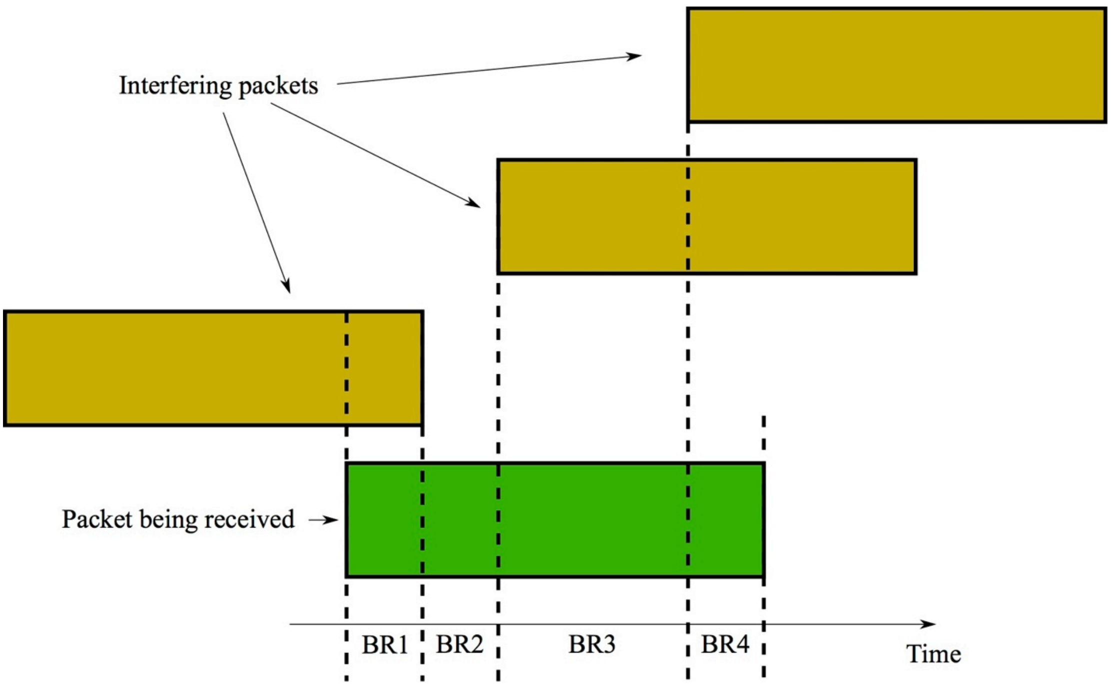


Figure 2-29: Example of bit region identification during a packet reception in OMNeT++; 4 Bit Regions (BR1 to BR4) are identified based on the variations in the set of interfering packets.

Next, for each bit region the average Bit Error Probability (BEP) is evaluated by adopting the Standard Gaussian Approximation for the interference power, and the number of bit errors is randomly determined according to the BEP. Finally, the total number of bit errors generated is evaluated by summing up errors introduced in each bit region, and compared with the maximum number of errors admitted for the packet as determined by the adoption of a Reed-Solomon code with a coding rate RS_{rate} = 0.835 (corresponding to a correction capability roughly equal to 10% of the packet bits) in order to decide if the packet is correctly received or discarded. The following steps were executed in OMNeT++ for each run:

1. Loading of primary and secondary network topologies from file;
2. Loading of connection requests from file and for each request:
    a. Generation of packets
    b. Forwarding of packets along the end-to-end path read from file;
    c. Measurement of end-to-end throughput and other relevant metrics.
3. Averaging of measured metrics.

Table 2-2 presents values assumed by the simulation parameters defined above.

Parameter	**Value(s)**
Number of secondary nodes N_S	50
Number of secondary nodes N_P	From 10 to 50
Number of connection requests per run N_{conn}	1000
Minimum connection duration minDuration	25 s
Maximum connection duration maxDuration	75 s
Min delay between connection requests *minDelay*	50 s (High Traffic) / 500 s (Low Traffic)
Max delay between connection requests *maxDelay*	100 s (High Traffic) / 750 s (Low Traffic)
Transmission rate at physical layer	1 Mb/s
Maximum transmission power for secondary nodes	1 µW
Application packet length *appPacketSize*	512 bits
Application source rate *applicationRate*	320 kbit/s

Table 2-2: Simulation settings

Simulation Results

1. *Matlab results:* Figure 2-30 shows the average interference imposed on the secondary nodes when the data is routed between the secondary source and destination nodes. To en- sure continuity of the simulations, the constraint on primary interference is relaxed if the cost of eq. (2-32) is $+\infty$ for all the secondary nodes within the transmission range of the transmitter for a specific hop. As can be seen from the figure, the optimized routing with beamforming, i.e., routing with the

proposed cost metric, gives the best performance in terms of interference imposed within the secondary network. As expected, routing without beamforming gives the worst performance. Furthermore, it must be mentioned here that to compare the performance of routing with beamforming and optimized routing with beamforming, one must also consider the number of primary constraint violations, since we relax the primary interference constraint when none of the secondaries is able to satisfy this constraint. To make this comparison, Figure 2-31 shows the number of primary constraint violations for different number of primary nodes.

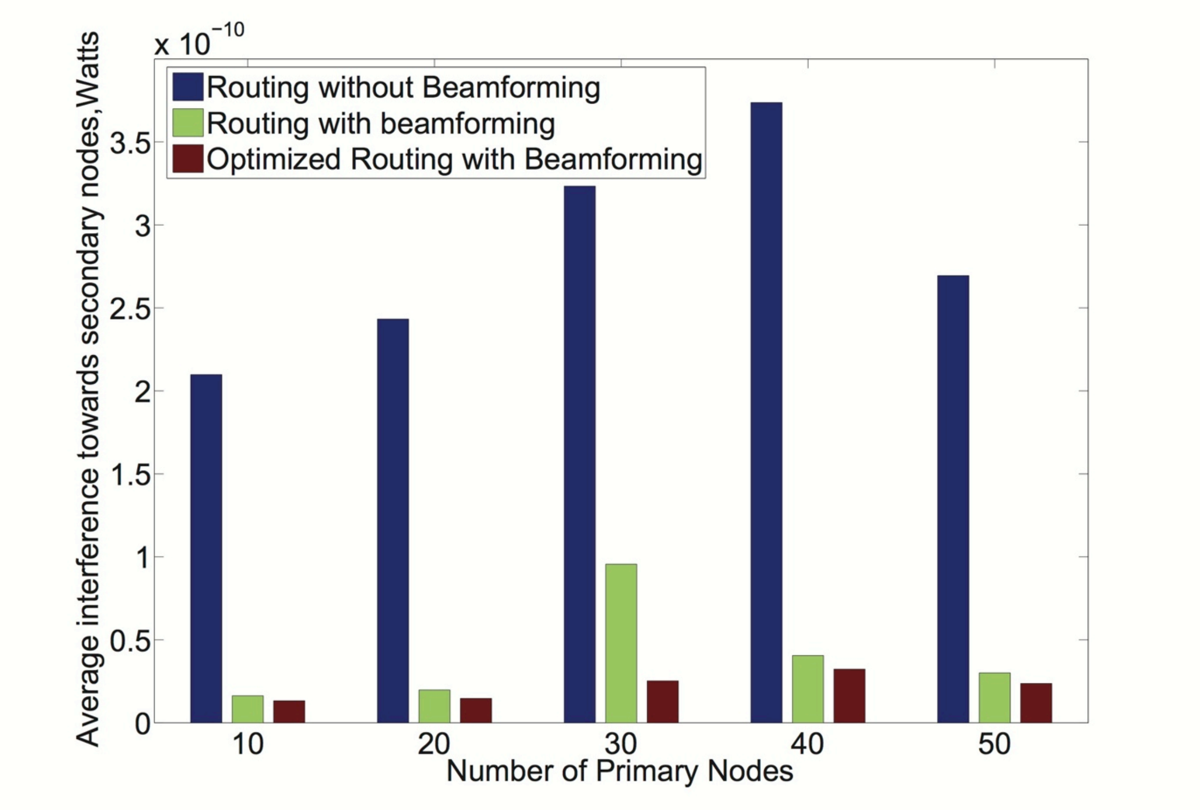


Figure 2-30: Average total interference exerted upon the secondary nodes between source and destination.

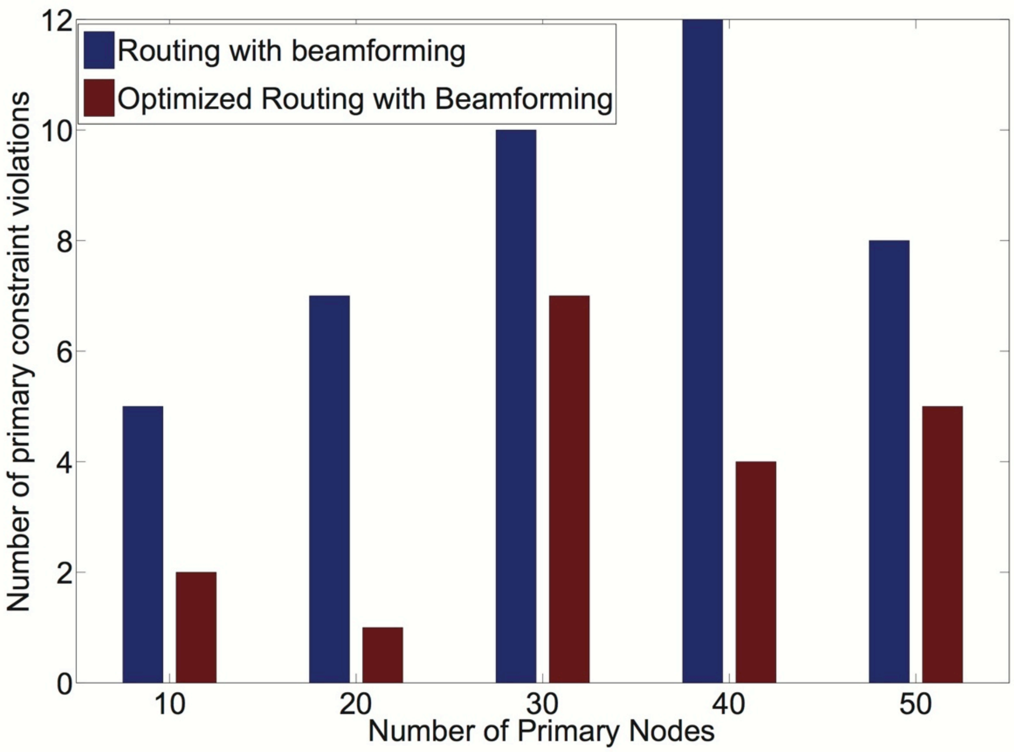


Figure 2-31: Number of primary constraint violations

.

From Figure 2-30 and Figure 2-31, it can be seen that the difference in performance between the optimized and non-optimized routing with beamforming in Figure 2-30 is large when the corresponding difference in primary violations in Figure 2-31 is relatively small, e.g., the performance when the number of primary nodes is 30. Otherwise, when the difference in performance in Figure 2-30 is small, the difference in the number of primary constraint violations is relatively large. In order to have a fair comparison between the two, the number of primary constraint violations for routing with beamforming and optimized routing with beamforming should forced to be the same.

2. *OMNET++ results:* OMNeT++ simulations considered the following four different scenarios, obtained by varying the traffic load in the secondary network and the number of primary nodes:
   - *Low traffic, free network* - Low traffic (obtained by setting the *minDelay* and *maxDelay* variables to the corresponding values in Table I) and no primary nodes;
   - *Low traffic, constrained network* - Low traffic and N_P = 10 primary nodes;
   - *High traffic, free network* - High traffic (obtained by setting the *minDelay* and *maxDelay* variables to the corresponding values in Table I) and no primary nodes;
   - *High traffic, constrained network* - High traffic and N_P = 10 primary nodes.

The throughput, defined as the ratio between end-to-end received packets and generated packets was measured in the four scenarios above for the three strategies previously introduced in the paper:

- Routing without beamforming, where omnidirectional antennas are considered;
- Routing with Beamforming, where beamforming is adopted for each hop, but the path is not modified;
- Optimized Routing with Beamforming, where beamforming is adopted for each hop, on a path optimized as proposed in Section 2.2.1.3.

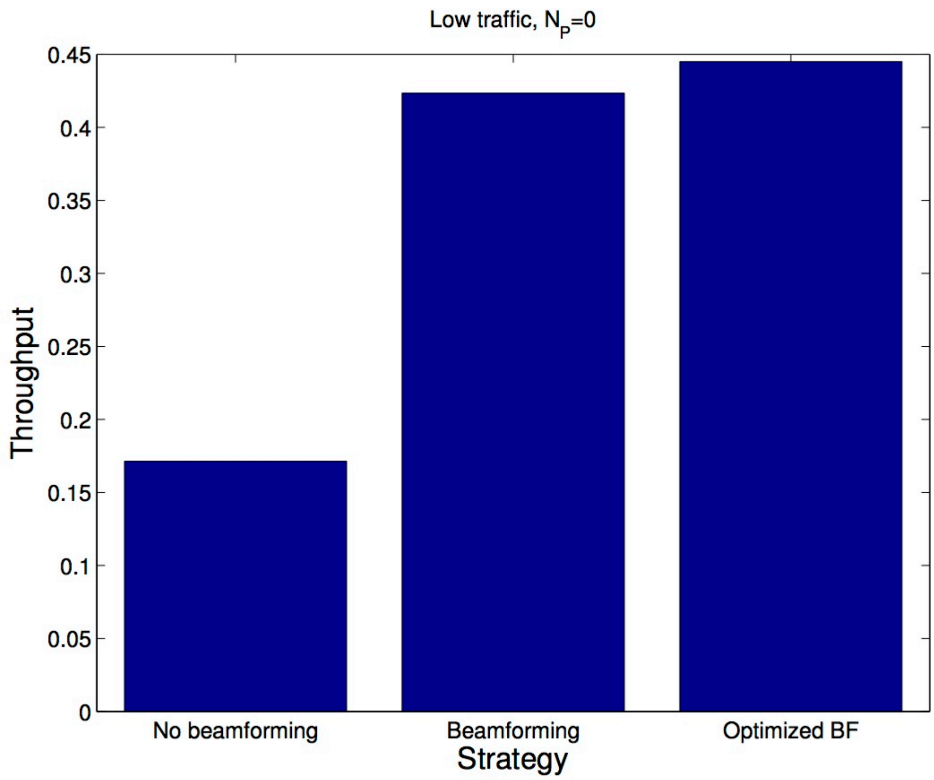


Figure 2-32: Throughput in the *Low traffic, free network* scenario for the three considered routing strategies.

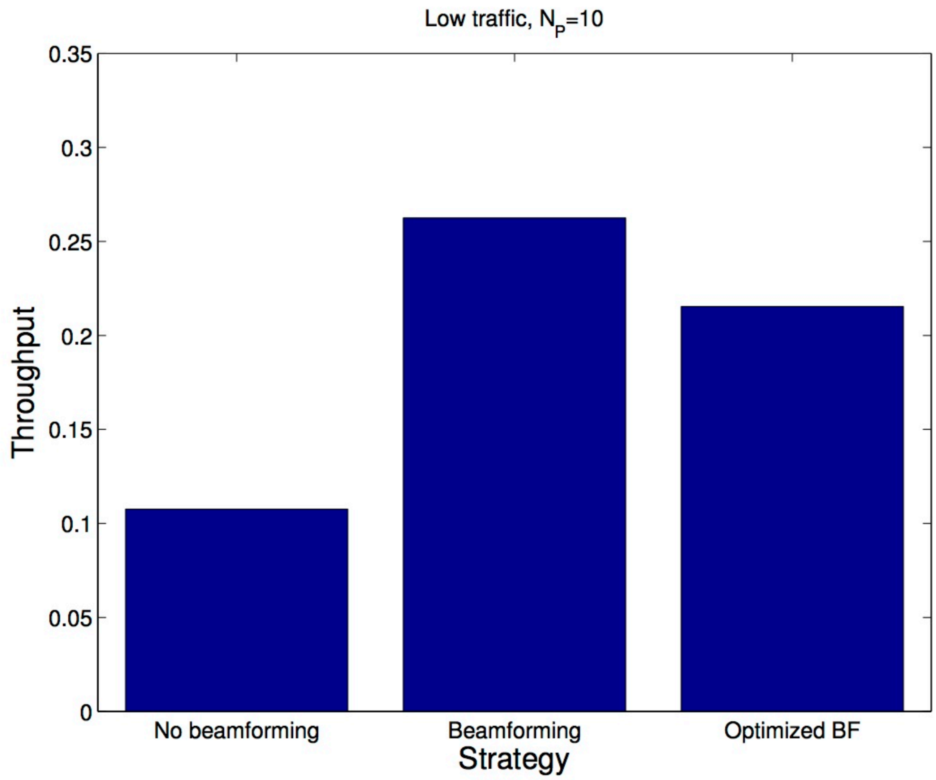


Figure 2-33: Throughput in the *Low traffic, constrained network* scenario for the three considered routing strategies.

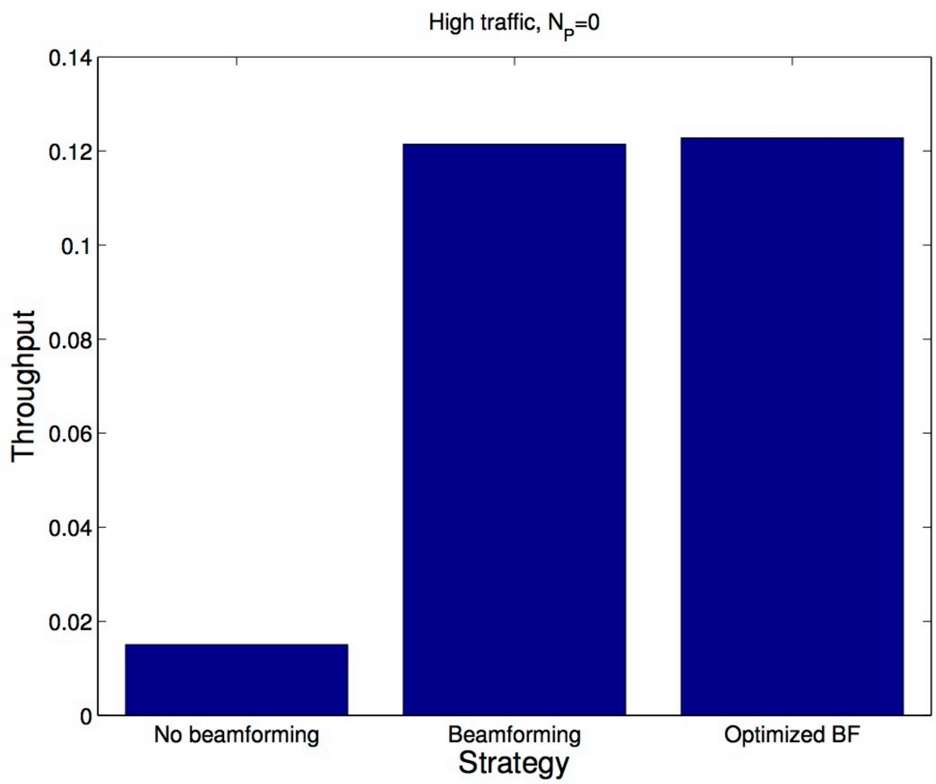


Figure 2-34: Throughput in the *High traffic, free network* scenario for the three considered routing strategies.

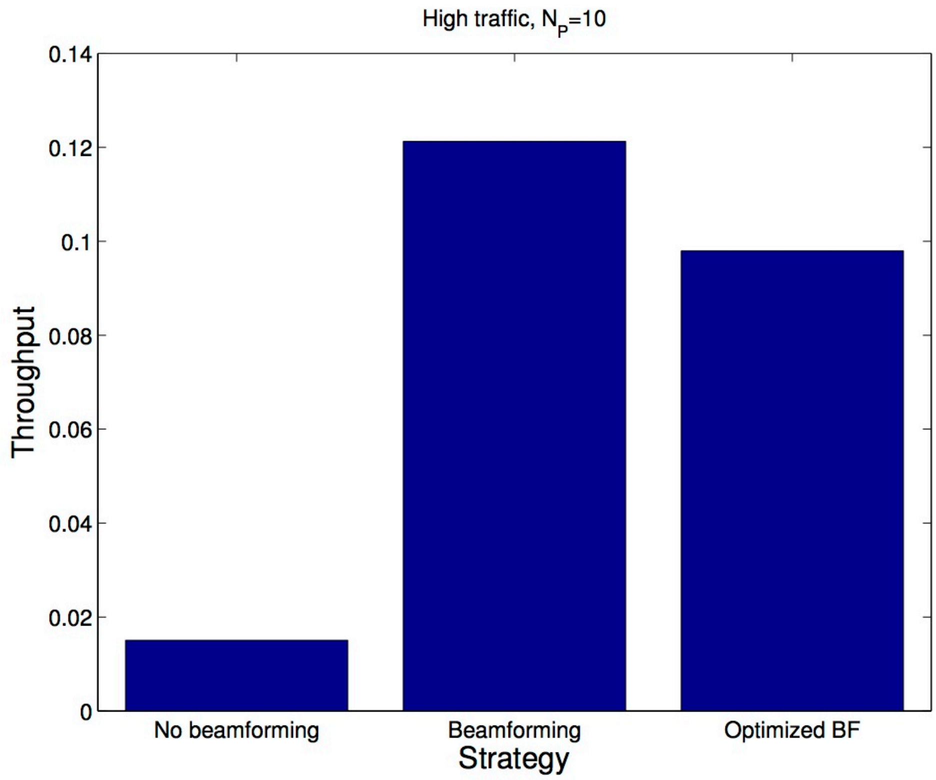


Figure 2-35: Throughput in the *High traffic, constrained network* scenario for the three considered routing strategies.

Figure 2-32 present the throughput in the case of the *Low traffic, free network* scenario. The Figure shows that in this scenario the optimization in the routing path leads to an increase in throughput, as on each other hop the strategy is able to select the node that provides the lowest amount of interference to neighbouring nodes, thus increasing the probability of correct packet reception throughout the network. Moving to the *Low traffic, constrained network* scenario, Figure 2-33 shows that the introduction of constraints determined by the presence of a significant number of primaries has the impact of reducing the gap between the two BF-based strategies, due to the fact that in several cases potential relays that would lead to lower interference in the secondary network are discarded as they do not satisfy the hard constraint on the level of interference towards one or more primary receivers. Figure 2-34 shows how the throughput is affected in the *High traffic, free network;* results show how for all strategies performance is significantly reduced due to the higher number of collisions, and the corresponding higher average value of the interference power during packet reception. Finally, Figure 2-35 shows results in the *High traffic, con- strained network,* that introduces again the presence of the primary nodes; interestingly, results highlight that in this case the Optimized Routing with Beamforming leads to slightly worse results compared to simple Routing with Beamforming. It should be note however that, as shown by Figure 2-31, this comes together with a better coexistence capability with primary receivers, highlighting the presence of a trade- off between coexistence and secondary network performance.

A fair comparison of the different routing strategies would require to force all of them to meet to the same extent the requirements set by the primary nodes.

We focused on transmit beamforming and routing in a multi-hop, ad hoc cognitive radio network. After a detailed introduction to the transmit beamforming strategy, we outlined the techniques that can be used to estimate the position of network devices by using direction of arrival information. Then, we proposed a new cost metric which was used to design an optimized, beamforming based routing algorithm with three-fold objective: to minimize the end to end path power consumption; to minimize the co-channel interference imposed within the secondary network and to minimize the number of primary interference constraint violations. To evaluate the performance of the proposed algorithms, we combined two different simulation platforms, i.e., MATLAB and OMNeT++. While MATLAB was used to implement the transmit beamforming strategy and to analyze the performance of the route optimization approach, OMNeT++ was utilized to test the proposed strategy in presence of actual packet transmissions, moving from results generated in MATLAB. Simulation results from MATLAB confirmed that the optimized routing algorithm outperformed the original routing algorithm in terms of both, the interference generated within the secondary network and the number of primary interference constraint violations. The simulations carried out in OMNeT++ confirmed the improved throughput of the secondary network when no constraints from primary nodes are imposed, while they highlight a trade-of between coexistence capability and secondary network performance when the presence of primary nodes has to be taken into account.

2.2.2 Network association and admission control in cognitive networks

2.2.2.1 WLAN architecture

The IEEE Standard 802.11 establishes that the architecture of a Wireless Local Area Network (WLAN) is based on different components or stations (STAs) that interact with each other in order to exchange data in a wireless scenario. All these components must be equipped with wireless Network Interface Controllers (wNICs).

In turn, stations can be categorized into APs or clients. The formers represent the base stations; they transmit and receive electromagnetic waves over a radiofrequency channel to and from devices that are allowed to communicate with. The latter category is composed by wireless devices that could be in movement and must be equipped with wNICs.

The IEEE Standard 802.11 defines the Basic Service Set (BSS) such as the group of all stations that communicate with each other. There exist two kinds of BSS; the independent and the infrastructure. The first one is an ad-hoc network without access points and the second one permits the communication between clients belonging to different networks through the access points. Finally, the MAC address of an access point is said to determine the identification of the BSS; that is, to establish the BSSID (BSS Identification).

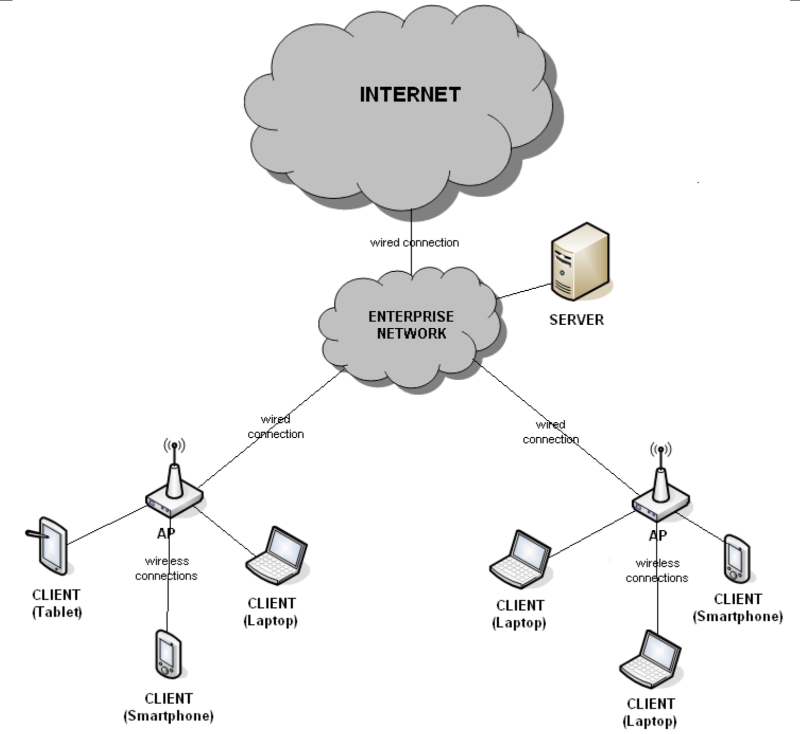


Figure 2-36: WLAN architecture example

2.2.2.2 The Access Point selection issue in a Wi-Fi WLAN

Clients or STAs can play many different roles within a WLAN, needed to choose the access point to connect to, in order to establish a connection with it and hence to set down the desired data transmission. Some of these roles or activities could be classified into the beaconing, scanning, decision, association and information exchange processes, by following the IEEE 802.11 family of standards' regulations. The work described in this section focuses on the association step.

Periodically, over a given channel an AP sends in a broadcast manner a management frame established by the standard as a beacon frame, in order to let all the STAs, which are tuned in the same channel, know about its existence by proportioning the needed information for its recognition, identification and synchronization. In effect, beacon detection over different channels in a progressive way is the process known as channel scanning and deployed by the STAs in such a manner to create a list with all neighbour APs and hence characterize every single channel with parameters as AP's MAC address, AP's service set identifier (SSID), the beaconing interval, the data rate supported by the AP and the power received from the AP known as received signal strength indication (RSSI).

Nevertheless, the algorithm that leads the STAs to choose the AP with who connect to is not explicitly described by the standard; in fact, the AP selection is left as a vendor-specific issue.

Nowadays, this matter is commonly faced by manually tuning the own wireless device into the channel over which is received the highest AP's power (RSSI) from a connection preference list based on the possible APs and networks to connect to. Mainly, STAs are configured to select the AP with the highest measured RSSI. Afterwards, if the RSSI goes down below a threshold the STA can begin a "roam" with another particular AP that allows a stronger reception in power terms.

However, this association mode based on the strongest signal strength does not take into account many other parameters that could deteriorate the communication between STA and AP. For instance, the highest RSSI value could correspond to an AP that is plenty full of already associated STAs and hence has an increased channel occupancy that perhaps does not permit the new STA to transmit at a desired data rate, leading to a decreased STA's throughput. Moreover, an enhanced communication scenario should be that in which devices continually need to find the best wireless connection at new locations without any user input; that is, in an automatic manner that permits mobile devices to easily find the best available wireless connection.

Therefore, although the AP selection based on the greatest RSSI value represents the easiest and straightest procedure so far, in the last decade many different studies have been done in order to improve the connections' quality of service under the Wi-Fi fashion. For instance in [71] the efficacy of this association mode is examined; the authors showed that the algorithm normally choose an AP with bad connections conditions when an AP with better connections conditions is in the same area. Even worst, was shown that in fact this selection mode's performance is not better than a random AP selection.

Thence, the AP selection method based on the strongest signal or RSSI value is at present a non optimal solution for an enhanced wireless communication; it is mainly a non automatic process, it is an insufficient input to conclude about the link quality and hence, normally it does not satisfy the requirements for a better quality of service. Lately, the cognitive concept has become a keyword for researchers against the AP selection issue. Different approaches based on a cognitive scheme have been proposed so far in order to take into account other link metrics for the AP selection in an automatic manner.

Beheemarjuna et al. presented in [72] a novel application of the cognitive networking concept that pushes for a more autonomous access point called CogAP, where all the cognitive capabilities are only taken into account for building a prototype access point device; that is, the cognition is only performed by the network-side (the access point) and not by the user-side of the wireless network. Here, the role of the CogAP device is to predict the network traffic due to historical traffic traces so as to learn about the traffic conditions of the network and hence predict the future load over the channel and promote a dynamic channel selection.

On the other hand, in [73] is proposed a cognitive access point selection scheme performed by the user-side of the wireless network in which a station has to gather information about the past link conditions and throughput so as to predict the performance of the network in the hypothetic case that channel with that access point had been chosen and hence to select the best available access point, since the link conditions point of view. The prediction is based on Multi-layer Feed-forward Neural Network approach (MFNN), in which is taken into account the correlation between the link conditions and throughput in both, the past time and the present time.

In [74] Nguyen et al. propose a user-centric approach for the access point selection that tries to minimize the number of unnecessary reconfigurations (unnecessary handover) of a station as well as to achieve load balancing for the overall networks. Here, handover is modelled by a cost function based on the dwell-time (staying time of a station in an area covered by access points) estimated from user's mobility and covered area under four different algorithms. In this case, the AP selection scheme is built by both, the network-side and the user-side entities.

2.2.2.3 The proposed Wi-Fi association metric

The main objective of this dissertation is to propose a novel scheme for the AP selection process within a Wireless Local Area Network by enhancing the most common selection method so far, that one based only on the RSSI value for each AP during the scanning period, with the introduction of environment's information due to the spectrum sensing technique.

Unlike [72] and [74], this method does not force the overall network to complicate the technology because the complexity of the sensing process is done by terminals who want to enhance its own performance; that is, for the APs is irrelevant if nodes develop cognitive functions or not because the method is based only on a user-side approach.

On the other hand, this AP selection method does not require the employment of complex elaboration schemes as Neural Networking or MFNN in [72] or [73] respectively. The AP selection method proposed here is simple; substantially based not only on the RSSI value as mainly has been done so far, but on sampling the same channels analysed during the normal scanning process in order to add more information about them as the general channel occupation as well as channel occupation due to another Wi-Fi entities and channel occupation due to non Wi-Fi entities who potentially could operate over the same channel.

The parameters

The sake of this cognitive AP selection is to take into account a set of parameters that allows terminals to evaluate a new metric for a better wireless connection. These metric's parameters are defined as follows:

- Received signal strength indicator (RSSI)
  The Institute of Electrical and Electronics Engineers through the IEEE Standard 802.11 describes the RSSI as the strength of the received signal in a wireless fashion in arbitrary units. Normally, this parameter is used by the networking card within the wireless hosts in order to determine whether the power level that is being received by the antenna is above a threshold at which point the station is able to receive an information packet instead considerate it as noise. Thereby, the RSSI is the most diffused parameter so far for the AP selection in a WLAN. The strength of the signal received from the APs are stored in a list by an interested station during its previous scanning process and consecutively the decision of which AP represents the best option to associate to is made on the basis of the highest RSSI value. This parameter is defined as follows:

$$\mathrm{RSSI_{mW}} = \frac{\mathrm{Ptx}\ \lambda^2}{(4\pi)^2\ d^{\alpha}} \qquad (2\text{-}33)$$

  where:
    - Ptx is the transmitted power;
    - λ is the used wavelength;
    - d is the distance between transmitter and receiver;
    - α is the pathloss coefficient.

- Occupation time factor
  The occupation time factor is a sensing-related parameter since it is obtained by the spectrum sensing process and it is defined as the amount of time the channel is sensed busy relative to the scanning period. The channel is considered busy every time the power level of a sensing sample is above the sensitivity threshold and for an amount of time equal to the time between this sample and the next one. Therefore, the overall amount of time the channel is sensed busy is equal to the sum of the duration of every sample that is above of the pre-established threshold:

$$\text{Occupation}_{\text{time}_{\text{factor}}} = \frac{\text{Occupation}_{\text{time}}}{\text{Scanning}_{\text{time}}} = \text{N}\frac{\text{Sample}_{\text{duration}}}{\text{Scanning}_{\text{time}}} \qquad (2\text{-}34)$$

  Where:
  - N is the number of samples above the threshold during the scanning process;
  - $\text{Scanning}_{\text{time}}$ is the amount of time the station spends in scanning the channel.
- Wi-Fi occupation time
  Similarly to the Occupation time factor, the Wi-Fi occupation time is a parameter obtained during the gathering process of the environment information through the spectrum sensing technique. This is here defined by taking into account two possible scenarios: with a not Wi-Fi entity and with another Wi-Fi network respectively, who operate over the same radiofrequency channel and hence interfere the communication between AP and station previous to the association process.
  In general, the channel is considered interfered when the overall amount of time of the expected packets that are received by the station does not correspond to the total amount of time the channel is sensed busy. The Wi-Fi occupation time is split into two factors:
  - Wi-Fi occupation time factor, calculated as the sum of the duration of every single packet that is received by the radio and is recognized as a Wi-Fi packet by the MAC sub layer during the time channel is sensed busy:

$$\text{WiFi occupation}_{time_{\text{factor}}} = \frac{\sum_{\text{i=1}}^{I} \text{WiFiPacket}_{\text{duration}}(i)}{\text{Occupation}_{\text{time}}} \qquad (2\text{-}35)$$

    where:
    - I is the overall number of Wi-Fi packets received by the radio;
    - $\text{WiFiPacket}_{\text{duration}}(\text{i})$ is the duration of the i^{th} received Wi-Fi packet, with i between 1 and I;
    - $\text{Occupation}_{\text{time}}$ is the amount of time the channel is considered busy, as calculated for the Occupation time factor previously introduced.
  - Internal Wi-Fi occupation time factor, introduced to measure the interference caused by other Wi-Fi networks, and defined as the sum of the duration of every single packet received by the radio and recognized by the MAC sub layer as a Wi-Fi packet that comes or is to the AP of interest with respect of the overall time of Wi-Fi packets; that is, the duration of every packet that contains in the MAC header any address, in the transmitter or

receiver sections, that corresponds to the AP MAC address during the time channel is sensed busy due to the transmission of Wi-Fi packets:

$$\text{Internal WiFi occupation}_{\text{time}_{\text{factor}}} = \frac{\sum_{j=1}^{J} \text{FromToAP}_{\text{WiFiPacket}_{\text{duration}}}(j)}{\sum_{i=1}^{I} \text{WiFiPacket}_{\text{duration}}(i)} \quad (2\text{-}36)$$

where:

- J is the overall number of Wi-Fi packets received by the radio that come to or are at the AP of interest;
- $\text{FromToAP}_{\text{WiFiPacket}_{\text{duration}}}(j)$ is the duration of the j^{th} received Wi-Fi packet that comes to or is at the AP of interest, with j between 1 and J;
- $\sum_{i=1}^{I} \text{WiFiPacket}_{\text{duration}}(i)$ is the amount of time the channel is considered busy by a Wi-Fi transmission, as calculated in the Occupation time factor due to a non-Wi-Fi entity case.

The metric

Once the parameters described above are obtained, a unique metric merges them in order to get only one description for every single radiofrequency channel that is required to be analysed during the scanning process. Moreover, the decision of which AP represents the best option to associate to is based on the highest value of the metric among the set of scanned channels.

Finally, the performance metric is described as follows:

$$METRIC(k) = \frac{1}{N_{AU}+1}\Big[\overline{RSSI}_{mw}(k) + \Big(1 - Occupation_{time_{factor}}(k)\Big) + \text{WiFi occupation}_{time_{factor}}(k) + \text{Internal WiFi occupation}_{time_{factor}}(k)\Big] \quad (2\text{-}37)$$

where:

- k is the index of the kth radiofrequency channel that is required to be analysed during the scanning process;
- N_{AU} is the overall number of active users associated to the access point of interest (information contained in the Beacon and Probe Response frames defined in the IEEE 802.11 standard);
- $\overline{RSSI_{mW}(k)} = \frac{RSSI_{mW}(k)}{\max\_RSSI_{mW}}$ is the normalized value of the $RSSI_{mW}(k)$ with respect to the maximum received $RSSI_{mW}$ during the scanning/sensing process.

2.2.2.4 Cognitive Network Simulator

The proposed metric was evaluated by means of computer simulations, relying on a novel simulation framework for wireless cognitive networks, based on the combination of the OMNeT++ discrete event simulator with Matlab, developed jointly by Uniroma1, KCL and EADS to assess the performance of wireless cognitive networks in realistic scenarios. The framework was used for several joint studies within the framework of both WP10 and WP9 (e.g. in the analysis of the impact of mobility on cooperative spectrum sensing).

The popular INET framework shipped as part of the OMNeT++ was extended with the introduction of cognitive functionalities and integrated with a more accurate wireless channel model developed in Matlab, which can be employed to simulate propagation effects of any radio activity and serves at the same time as input for spectrum sensing algorithms.

The implementation of network nodes with spectrum sensing capabilities has been accomplished in accordance with the structure in the IEEE 1900.6 standard. This is the most appropriate solution to guarantee the development of legacy-compliant devices and facilitate interoperability among terminals from different manufacturers.

The standard identifies three main entities involved in the spectrum sensing activity:

- **Cognitive Engine (CE)**: the entity responsible for the cognitive control mechanisms, the collection of sensing measurements and the assessment of spectrum availability
- **Sensor**: the entity that takes sensing measurements according to the configurations and commands requested by the CE
- **Data Archive (DA)**: a storage unit for sensing-related information

The interactions among these entities are intended to take place using the interfaces provided by three Service Access Points (SAPs): the Measurement-SAP (M-SAP), exploited to access the sensing-related information; the Application-SAP (A-SAP), used by the control application to benefit from the sensing services; and the Communication-SAP (C-SAP), which is at users' and clients' disposal to provide communication between the aforementioned entities.

The simplifying assumption has been made in this work that a node with spectrum sensing capabilities, later on referred as "sensing node", is always embodying a CE (which is optionally provided with a DA) and at least one Sensor entity, as illustrated in Figure 2-37.

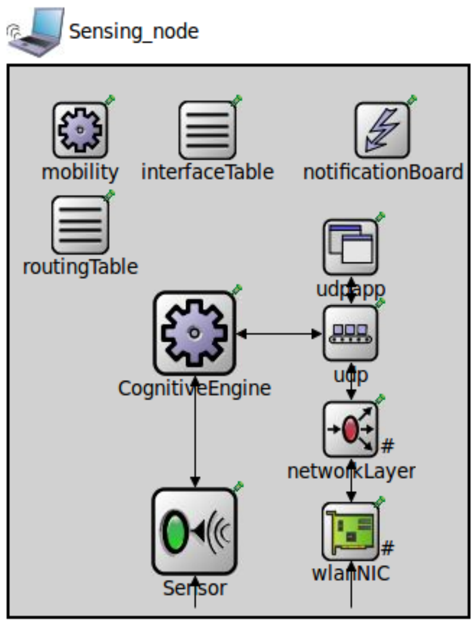


Figure 2-37: Information management architecture with a centralised data archive and cognitive engine.

As a consequence, some of the requirements on the definitions of primitives to be used for the communication among the entities involved in spectrum sensing may be relaxed. Specifically, the C-SAP in this case is solely interconnecting the CE entities of peer sensing nodes; hence, sensor entities belonging to different sensing nodes communicate by means of their integrated CEs.

Since the standard does not constrain the specific protocol to be used, two different methods were developed for the interactions among entities in the same sensing node and the communication between peer CEs. In the first case the most efficient solution is to exploit the utility called Notification Board: this module, already included in the standard INET framework, collects any notification of parameters, variables and module state changes occurring inside the network node throughout the simulation period. A module interested on a particular event can subscribe to it, so that it will receive all the corresponding notifications as soon as a change has been indicated.

The utilization of this module is the most straightforward method to communicate within a compound module and allows distributing notifications to a set of subscribers avoiding the definition of specific communication protocols or the transmission of duplicated messages over multiple ports.

On the other hand, peer sensing nodes are logically connected through their combined CEs at the application level of a standard ISO/OSI protocol stack, and their interaction is regulated by a dedicated messaging protocol.

A subset of the primitives defined in the standard has been implemented to accomplish the tasks of configuring the measurements and retrieving the sensing output:

- **Get_Spectrum_Measurement_Description**: this primitive is used by the CE to require to the serving sensors a description of their capabilities
- **Set_Sensor_Measurement_Objectives**: with this primitive the CE transmits to the serving sensor the configuration of the measurement campaigns (in term of campaign duration and band of frequency to be sensed)
- **Set_Sensor_Measurement_Profile**: describe what a sensing report should contain (number and order of channels to be scanned, report rate and mode, noise floor threshold etc.)
- **Channel_Measurement_Value_Resp**: used by sensors to provide the CE with sensing measurements
- **Sensing_Related_Information_Send**: send sensing information to peer CE in another sensing node
- **Sensing_Related_Information_Receive_Req**: request sensing information for a peer CE in another sensing node

The subset of functions employs the following parameters (a detailed description of the complete set of parameters is provided in the standard):

- Status
- MeasuRange
- SensingMode
- FrequencyResolution
- LocationTimeCapability
- StartTime
- EndTime
- Bandwidth

- ChOrder
- ChList
- ReportRate
- Scan.LowerThreshold
- ReportingMode
- NoisePower
- SignalLevel
- InfoSource
- InfoDestination

The current implementation allows any CE to acquire a description of the sensor capabilities (frequency band to be scanned, sensing techniques to be used etc.) and configure the sensor measurements by means of instructions on the temporal duration of the sensing campaign, the channel to be scanned and their ordering, the report rate and the report mode (that is if the CE expects to receive hard, soft or quantized reports).
Finally, a pair of additional primitives is used to send and receive the sensing-related information among peer CEs.
The architecture just described was used to perform a performance analysis of the proposed association metric, with early results reported in the next subsection.

2.2.2.5 Preliminary simulation results

A *symmetric* scenario was considered in the performance evaluation, foreseeing a network composed by two access points symmetrically distributed within a grid of wireless nodes as depicted in Figure 2-38.

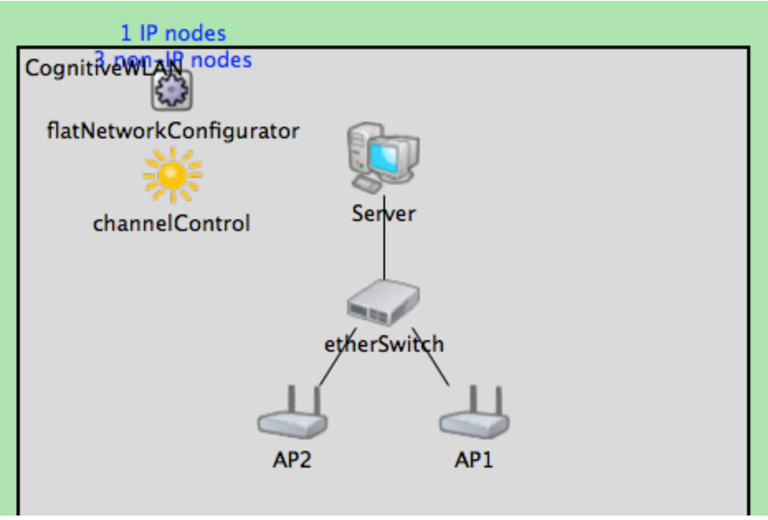


Figure 2-38: Scenario considered in performance evaluation:

Three different configurations were considered in such scenario:

- *normal configuration*, in which the network only contains nodes that potentially belong to any of the two access points;

- *Wi-Fi entity configuration*, where an ad-hoc Wi-Fi network is introduced in physical proximity to the first access point (AP1), operating over the same channel of the second access point (AP2);
- *Non-Wi-Fi entity configuration*, in which a wireless non-WiFi entity is introduced in physical proximity to AP1, again operating over the same channel of the AP2.

Simulation results in the case of a grid of 16 Wi-Fi devices are presented in the following, exemplified in Figure 2-39 for the normal configuration case. The analysis of a wider set of topologies and larger sets of nodes is currently ongoing.

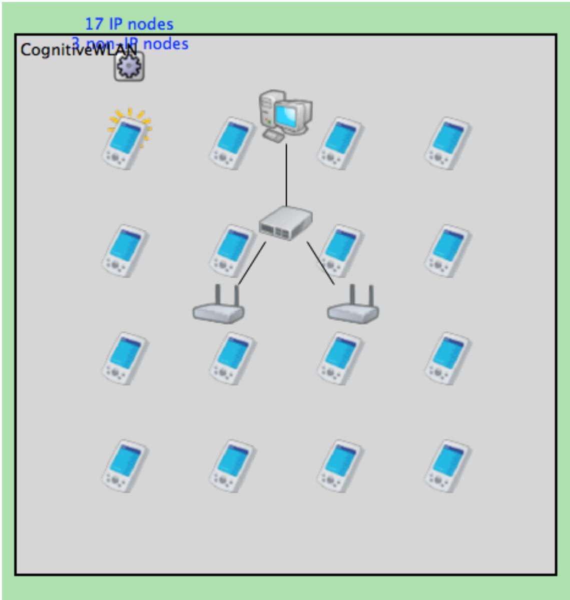
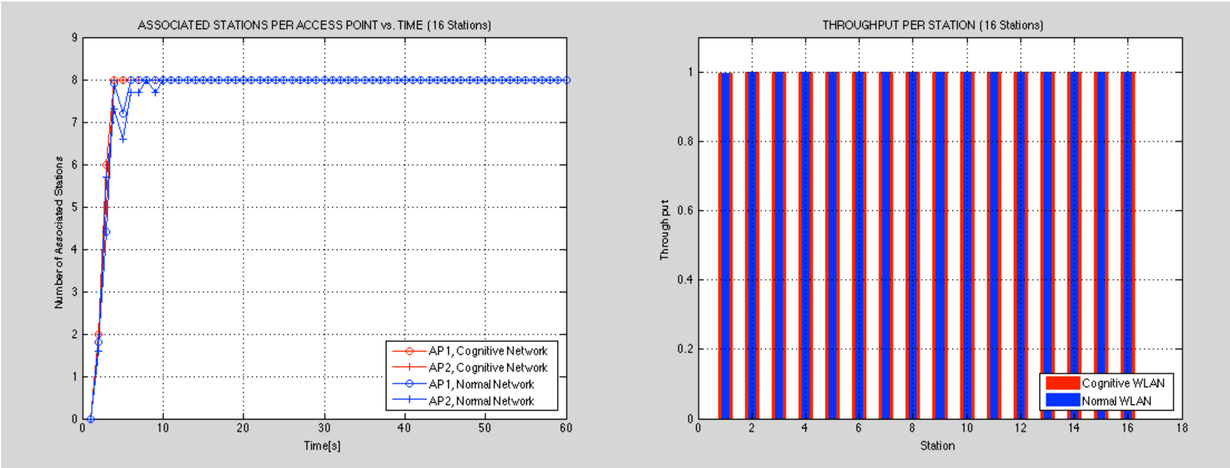


Figure 2-39: Normal configuration for a set of 16 stations.

Performance evaluation focused on the comparison of the proposed metric with the most common solution, relying on RSSI for the selection of the access point. Three performance indicators were considered:

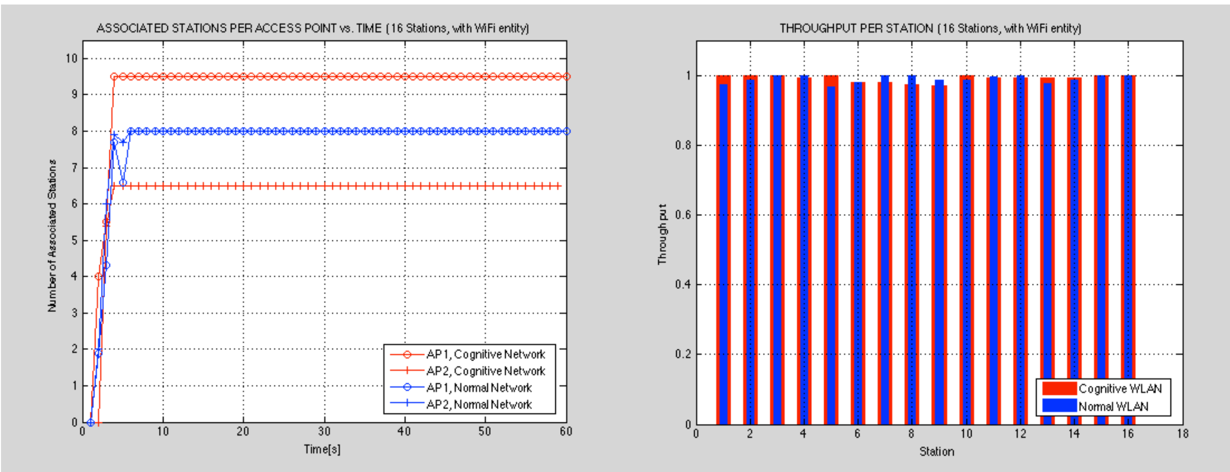
1. *Number of associated stations*, measuring the number of nodes associated to each of the two APs;
2. *Throughput per node,* showing the throughput for each node in the network;
3. *Average throughput,* showing the value of the throughput averaged on all nodes, irrespectively of the selected AP, whenever the throughput per node does not show a clear advantage of a metric over the other.

Figure 2-40 shows the simulation results for the first two indicators in the normal configuration, while Figure 2-41 presents the same indicators in the Wi-Fi entity configuration. Due to the symmetry of the scenario the cognitive network tries to balance the load into both access points in both Normal and Wi-Fi entity configurations. In the Wi-Fi entity configuration, however, the balancing takes into account the alien Wi-Fi entity, leading to an asymmetrical association to the APs, with a larger number of nodes associating to AP1. Throughput is however above 95% in all cases, leading to the conclusion that the alien Wi-Fi entity does not impact significantly network performance, mainly due to the act that the alien network still obeys to the CSMA/CA rules when transmitting packets.



a) b)

Figure 2-40: Simulation results for normal configuration, 16 stations (a) Associated Stations as a function of time, b) Throughput per node).

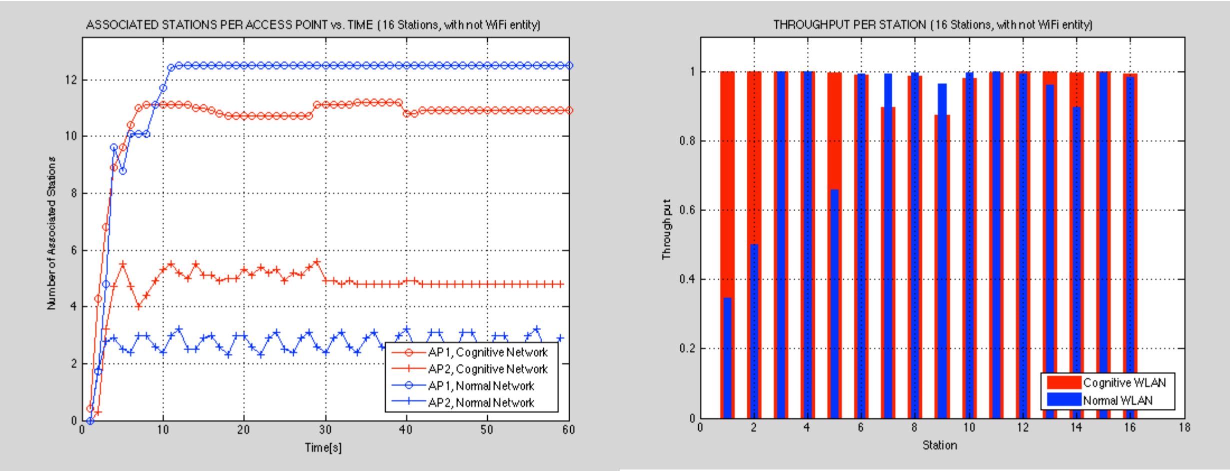


a) b)

Figure 2-41: Simulation results for Wi-Fi entity configuration, 16 stations (a) Associated Stations as a function of time, b) Throughput per node).

Figure 2-42 presents the results in the Non-Wi-Fi entity configuration, showing that while 3 cognitive nodes choose the disturbed access point and hence obtain a throughput less than 90%, the large majority of the cognitive nodes are associated with the undisturbed access point, achieving a throughput equal to 1. The RSSI-based metric also leads to a large majority of the nodes choosing the unaffected access point, mainly due to failures in association procedure to AP2 due to the jamming signal by the non-Wi-Fi device, but in each run it was observed that, overall, a lower total number of nodes were able to associate, leading to a worse result in terms of fairness in the access to the network for the different devices, depending on their physical position.

Overall, the cognitive association metric also leads to better network performance, as shown in Figure 2-43, comparing the average throughput for the two metrics and highlighting roughly a 10% difference in favour of the cognitive association metric.



a) b)

Figure 2-42: Simulation results for Non-Wi-Fi entity configuration, 16 stations (a) Associated Stations as a function of time, b) Throughput per node).

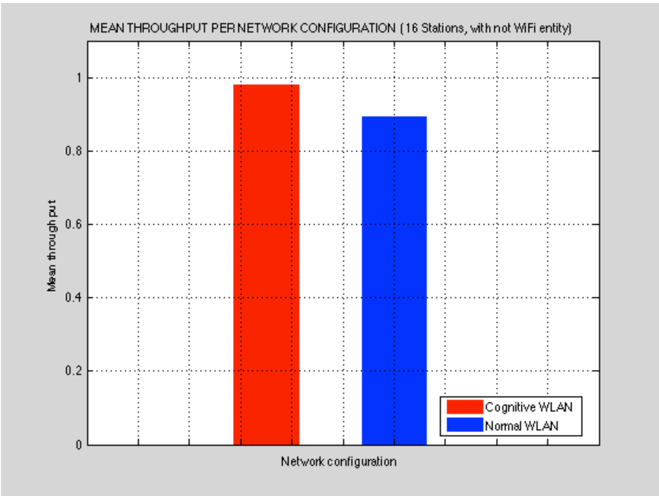


Figure 2-43: Average throughput for Non-Wi-Fi entity configuration, 16 stations.

2.2.2.6 From network association to admission control

The proposed association strategy is the first step towards the creation of a cognitive admission control strategy that takes into account load balancing as well as external environment conditions in determining the number of stations that can be admitted to the network. This could be achieved by imposing thresholds on the expected traffic load and minimum throughput per AP, thus assigning new stations so to meet such thresholds until no AP can accommodate a new association request, leading to an access refusal. The definition of such admission control strategy, and of the mechanisms to determine the thresholds as a function of Quality of Service (QoS) requirements is currently ongoing.

3. Alien network discovery and management solutions

This Section deals with solutions for detection, identification and management of alien networks by a cognitive network. The section is divided in two main subsections. The first one, Section 3.1, focuses thus on how to understand if (and which) other systems are operating in the same area as the cognitive network, and presents a way to determine the presence of other wireless systems based on a classification solution relying on higher layers features, and Inter-network discovery algorithms and protocols.

The second subsection, Section 3.2, moves instead on how to either take advantage of the presence of multiple systems (Section 3.2.1), or at least efficiently coexist with such systems (Section 3.2.2), taking advantage of the information available on them in order to adapt the behaviour of the cognitive network.

3.1 Automatic network recognition and classification

In this section a possible solution, based on MAC layer features, for alien network discovery, automatic recognition and classification is presented. In particular, the 2.4 GHz ISM band is taken into account. The reason of this choice resides in the fact that many different and widespread networks operate in this band, that is open for use without any particular license. Well-known examples of technologies operating in this band are:

- Bluetooth (IEEE 802.15.1, [75]);
- Wi-Fi (IEEE 802.11, [76]).

The idea that resides under the approach of using MAC layer features is that every network has its own particular and peculiar MAC behaviour, as expressed in the Standard that defines each technology. Based on the study of these Standards, a MAC peculiar behaviour can be identified for each type of network. Furthermore, some features that reflect these MAC behaviours can be found, and through these features, a recognition and classification process can be carried out.

The Standards define the networks MAC layer behaviour, as for example maximum or minimum durations for certain types of packets, or even fixed durations. The same rules can be determined for the silence gaps that fall between the packets. Other rules that the Standard may specify can be a regular and predetermined transmission of a packet, or the transmission of acknowledgment packets after the reception of data packets.

In particular, a time-domain packet diagram must be obtained. This diagram shows the presence vs. absence of a packet in every instant. With the term “packet” here it is intended a MAC layer information unit, that in some technologies is effectively called “packet”, in some other ones “frame” or “datagram” or in other ways. Note that the content of these packets, i.e. which bits they are carrying, is not relevant for the scope of this recognition. What is important is only the packet pattern, that is whether a packet is present or not.

This approach has the big advantage of being extremely simple, and thus keeping a high computational efficiency. In fact, only a simple Energy Detector is needed. Through this, the short-term energy that is present on the air interface can be computed. After defining a threshold value, all the consecutive short-term energy values that are higher than the threshold can be considered as a packet. In this way, the packet diagram can be formed using energy detection. As for determining the threshold value, it is dependent from the device that is used and from the noise floor measured in “silence condition”, i.e. when no other wireless device is transmitting.

3.1.1.1 Bluetooth

The first technology considered in the study was Bluetooth [75]. Only considering the MAC layer behaviour (skipping all the details about physical layer), very important for the scope of this section is the division of the time axis into time slots. Every device has a clock with a period of 312.5 µs. A time slot duration of 625 µs is defined, that is two clock cycles, and the time axis is divided into time slots, all of this duration. Every packet transmission can start only at the beginning of a time slot. A packet can last an odd number of time slots; in particular, there can be 1-time slot packets, 3-time slots packets and 5-time slots packets. A communication between the master device and a slave device is usually composed by alternate packets (one from master and one from slave), since each device waits for a "return packet" (at least an acknowledgment) after sending a packet.

Following these rules, imposed by the Standard, it is clear that a Bluetooth MAC packet exchange pattern is characterized by packets that start every time slot duration, or at multiples of this value, if considering the multi-slot packets. Furthermore, many acknowledgment packets are expected; the so called "NULL" packet is the one used for acknowledgment, and it has a fixed length of 126 bits, that corresponds to a fixed duration of 126 µs considering the bitrate of 1 Mb/s. The other packets have also minimum and maximum durations, imposed by the Standard.

This rules set turns out into a Bluetooth peculiar pattern, that can be exploited through the use of features for the automatic recognition and classification.

It is important to note that a Bluetooth communication system is dimensioned considering a bandwidth of 1 MHz in a single instant. By using an Energy Detector, the hopping sequence is unknown, and therefore it is impossible to know to which channel to be tuned to in every instant. In this condition, a simple way to catch the energy of all the packets that the devices send and receive is to sense the entire ISM 2.4 GHz band, i.e. all the 79 channels; by doing this, however, the noise power will be much higher, and this must be taken into account in the phase of determination of the threshold for the high vs. low energy value.

A possible alternative is to sense a lower bandwidth, in order to decrease the sensed noise power. In this way, however, all the packets sent in channels outside the sensed band are not caught. Considering that the "choice" to use a single channel has a uniform probability density, i.e. in mean there are no channels that are chosen more than others, sensing a lower bandwidth can still be a good trade-off between considered bandwidth and "packet loss" (in sensing term).

3.1.1.2 Wi-Fi

The Wi-Fi technology is defined in [76]. Even here considering only MAC layer, important for our scope, the Distributed Coordination Function (DCF) is used, that employs a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) access scheme. Furthermore, Request To Send – Clear To Send (RTS/CTS) mechanism is optionally adopted. Other enhances and improvements to these simple schemes in the medium access are also introduced, such as Enhanced Distributed Channel Access (EDCA) and Hybrid Coordination Function (HCF) Controlled Channel Access (HCCA).

Different InterFrame Spaces (IFSs) are also defined. In particular, relevant for recognition is the Short InterFrame Space (SIFS), the shortest of the IFSs. It is important for us because it is used before the transmission of an acknowledgment (ACK) packet or a CTS packet. It is defined as the time duration between the end of the last symbol of the previous packet and the beginning of the first symbol of the following packet, as seen at the air interface.

Since the data-ACK packet exchange appears to be effectively really used, based on real traffic analysis in a scenario with medium to high traffic, the SIFS, among the different IFSs, is the most likely to occur. This is very important because it has a nominal value of 10 μs.
This value of 10 μs is important in this context because it is a silence gap value that occurs very often in a Wi-Fi transmission and, most important, is peculiar of this technology, i.e. it characterizes this type of network

3.1.1.3 Recognition and automatic classification

Now some MAC layer features are proposed, based on the analysis done on their MAC layer behaviour.
As for Bluetooth, the presented features are the following two [77]:

- packet duration;
- packet inter-arrival interval.

The reason for the choice of these features resides in the fact that they reflect some behaviours peculiar of Bluetooth. In fact, acknowledgment packets are very common in the packet exchange pattern, and the NULL packet, used for the acknowledgment, has a fixed duration of 126 μs. Furthermore, it can be expected that, if large amount of data must be sent, packets are filled efficiently as much as they can; in this way, they often reach their maximum length, i.e. their maximum duration. As defined in the Standard, maximum duration are: 366 μs for 1-time slot packets, 1622 μs for 3-time slot packets, and 2870 μs for 5-time slots packets. Some fixed, minimum and maximum duration values defined in the Standard are reported in Table 3-1.

	Fixed duration [μs]	Min duration [μs]	Max duration [μs]
Time slot	625		
NULL packet (ACK)	126		
1-TS packet		126	366
3-TSs packet		1250	1622
5-TSs packet		2500	2870

Table 3-1: Bluetooth packet durations, as defined by the Standard

For these reasons, these maximum and fixed values of packet durations, specific of this technology, may occur very often in a Bluetooth communication. Moreover, if during a "blind" packet sensing operation (i.e. without knowing which network is active and transmitting), these values of packet durations are met frequently, they can be the sign of the presence of a Bluetooth network.
The packet inter-arrival interval feature is chosen given that Bluetooth provides a slotted communication, with a time slot duration of 625 μs that is peculiar of this technology. When the "blind" sensed packet exchange pattern presents a value of 625 μs (or its multiples, considering multi-slots packets and "packet loss" if sensing a bandwidth lower than the whole ISM band) for the packet inter-arrival interval, the probability that these sensed packets are Bluetooth packets is reasonably high.

These two features were tested capturing Bluetooth packets with a Universal Software Radio Peripheral (USRP2) device used as Energy Detector, and the short-term energy over time window with length N (E_N) was obtained:

$$E_N(\mathbf{r}) = \sum_{i=1}^{N} |r_i|^2 \cdot T_S \qquad (3\text{-}1)$$

where **r** is the received sequence, r_i is the i^{th} sample of the sequence, and T_S is the sampling period.

From the short-term energy a packet exchange sequence was derived, and then the features were applied. Figure 3-1 shows the distribution of the packet duration (first feature), while Figure 3-2 shows the distribution of the packet inter-arrival interval (second feature).

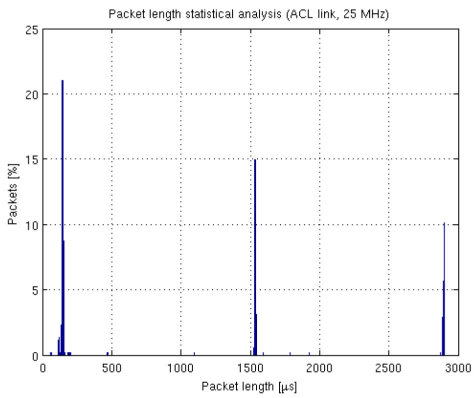


Figure 3-1: Bluetooth packet duration distribution

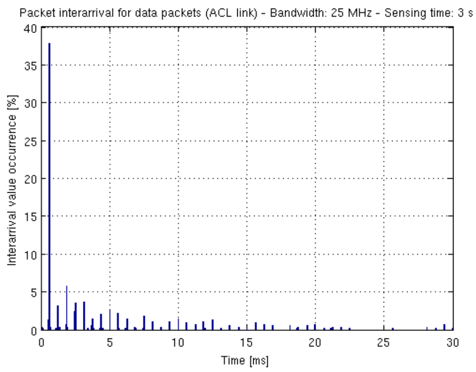


Figure 3-2: Bluetooth packet inter-arrival interval distribution

From the histogram in Figure 3-1 it can be observed that most values are well concentrated around three values centred at: 144 µs, 1540 µs and 2890 µs. These values are related to the duration of the NULL packets and to the maximum durations of the 3 and 5-time slot packets (see Table 3-1). This is reasonable since the Bluetooth transport layer does its best to encapsulate data into packets as efficiently as possible, and ACKs are needed. The presence of these three peaks indicates that the proposed feature is Bluetooth-specific.

Even in Figure 3-2 a peak value stands out. This inter-arrival peak value is at 628 µs, closely resembling slot duration of 625 µs, (there is only a difference of about 0.48% between these two values). The other peaks are extremely lower than the one at 628 µs. It is important to note that they are spaced of about one slot duration.

For these reasons, the proposed features seem to be valid for the purpose of this approach, since they show a MAC layer behaviour that is Bluetooth-specific, and that may permit its recognition in an heterogeneous networks scenario.

In the Wi-Fi case the following two features are considered [78]:

- duration of silence gaps identified as SIFS;
- duration of the longest packet, considering all the packets between two consecutive silence gaps previously identified as SIFS.

The first feature was proposed based on the fact that the exchange of a data packet followed by an acknowledgment packet is very common. These two packets are therefore separated by a silence gap defined as SIFS, whose duration is fixed by the Wi-Fi Standard at 10 µs. This value is characteristic for Wi-Fi, and therefore if such a value is found in the analysis of this feature, it probably means that the packet exchange pattern is one of a Wi-Fi communication.

The second feature was chosen because the longest packet in a block delimited by two SIFS should present a value range quite restricted, in which the contained values may be quite different from the ones encountered in a Bluetooth communication. Even this feature can, therefore, be useful for Wi-Fi automatic recognition.

The selected features are therefore used for classification. In particular, after choosing the desired classifier, they take part in the classifier's training phase, in order to fit the classifier's parameters [79]. This training phase must obviously be done by applying the features to a packet exchange pattern coming from a known network, in order to indicate that the obtained features values are peculiar of that specific technology. This training must be done with all the decided features, and for all the technologies that are considered.

After the training step, the trained classifier is ready to perform its automatic network recognition and classification.

Wi-Fi vs. Bluetooth automatic classification

An example is presented here in order to show how this approach can be carried out in practice: Wi-Fi vs. Bluetooth automatic classification [78], in which only the two proposed features specific for Wi-Fi are exploited.

In order to extract the SIFSs, differentiating them from the non-SIFS silence gaps, the following rule was adopted: a silence gap was considered as SIFS if the duration of the 60% of the i^{th} packet, $Pduration_i$, was higher than the duration of the whole $i^{th}+1$ packet, $Pduration_{i+1}$:

$$0.6 * Pduration_i > Pduration_{i+1} \qquad (3\text{-}2)$$

This is based on the consideration that a SIFS separates a data packet (preceding) from an acknowledgement packet (following), and that a data packet is considerably longer than an acknowledgement one.

The Wi-Fi traffic, i.e. the Wi-Fi packet exchange diagram, is real traffic obtained through a "Sniffer Station", a packet capturing device. This device is a personal computer with a real-time kernel Operating System, running a packet capturing application, specifically developed, and with a Network Wireless Adapter turned into “monitor mode”. The “monitor mode” allows to intercept every packet within the receiver’s range (and not only those directed to the device, as happens with the Network Wireless Adapter in “normal mode”). The packet capturing application and the real-time kernel permit to obtain the whole packets with accurate time-stamps, i.e. arrival times.

The packet traffic was generated by three other personal computers tuned to an Access Point, in different conditions of traffic load (low, medium and high packet exchange number).

As for the Bluetooth traffic, the packet exchange pattern was obtained using simulated packets, generated using MATLAB®. Two Bluetooth devices are considered, a master and a slave, who send their packets alternately, performing a data-ack exchange: every packet sent receives an acknowledgement. The simulated data packets are of all the three types: 1, 3 and 5 time-slot packets, depending on their length. For the acknowledgment the NULL packet is used, whose duration is 126 µs. Based on the Standard specifications, a jitter of ± 10 µs on the arrival time is considered; the jitter was modeled by a Gaussian distribution, with zero mean standard deviation σ=10/3 µs.

After the feature extraction, a block of packets results in a point in the 2-dimensions features space (two features were considered).

Four linear classifiers were used in this study-case [79], [80]:

- Perceptron;
- Pocket;
- Least Mean Squares method (LMS);
- Sum Of Errors squares estimation (SOE).

The choice to use linear classifiers, and not more complex ones, capable of granting better performance, is always in order to keep the system as simple as possible. More complex classifiers can be added later to perform a more accurate classification, if necessary and desired.

The extracted features were used for the classifiers training. The trained linear classifiers results, therefore, as straight lines in the features space. Figure 3-3 and Figure 3-4 show the features space with the trained linear classifiers: in Figure 3-3 only single-slot Bluetooth packets are used, while in Figure 3-4 multi-slot Bluetooth packets are used.

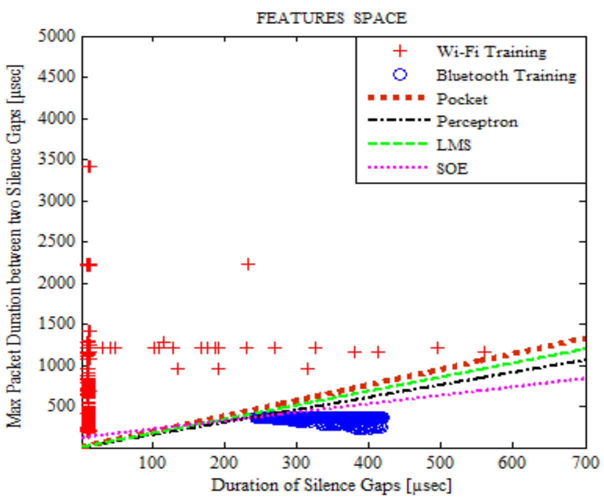


Figure 3-3: Features space with single-slot Bluetooth packets and trained classifiers.

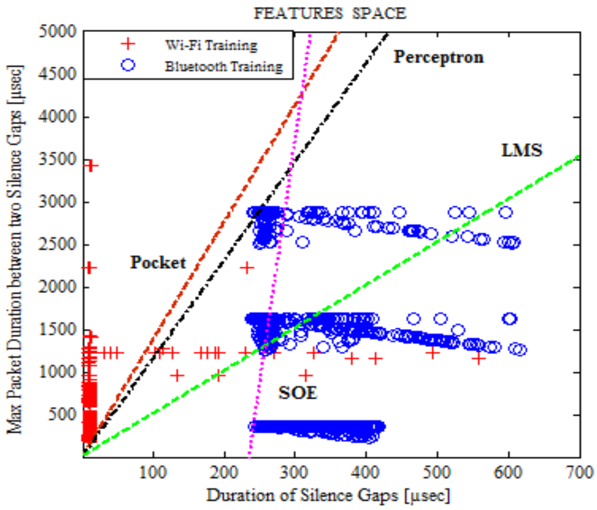


Figure 3-4: Features space with multi-slot Bluetooth packets and trained classifiers.

As it can be seen, since the two classes (Wi-Fi and Bluetooth) are not separable in the case of multi-slot Bluetooth packets (Figure 3-4), the classifiers will commit some errors in the classification phase. Perceptron and Pocket graphically seem to separate better the two classes, and it can be expected that these two classifiers will obtain better classification results than LMS and SOE.

The classifiers were used for classification tests, using other packet exchange patterns, i.e. not belonging to the training set. Results of these tests are reported in Table 3-2 (Bluetooth single-slot packets case) and Table 3-3 (Bluetooth multi-slot packets case).

Classifier	Input network	Classification into Wi-Fi	Classification into single-slot Bluetooth
Perceptron	Wi-Fi	100% [352/352]	0% [0/352]
Perceptron	Bluetooth	0% [0/456]	100% [456/456]
Pocket	Wi-Fi	100% [352/352]	0% [0/352]
Pocket	Bluetooth	0% [0/456]	100% [456/456]
LMS	Wi-Fi	100% [352/352]	0% [0/352]
LMS	Bluetooth	0% [0/456]	100% [456/456]
SOE	Wi-Fi	100% [352/352]	0% [0/352]
SOE	Bluetooth	0% [0/456]	100% [456/456]

Table 3-2: Classification test results, Bluetooth single-slot packets.

Classifier	Input network	Classification into Wi-Fi	Classification into multi-slot Bluetooth
Perceptron	Wi-Fi	98.86% [348/352]	1.14% [4/352]
Perceptron	Bluetooth	0.43% [2/462]	99.57% [460/462]
Pocket	Wi-Fi	98.86% [348/352]	1.14% [4/352]
Pocket	Bluetooth	0% [0/462]	100% [462/462]
LMS	Wi-Fi	99.43% [350/352]	0.57% [2/352]
LMS	Bluetooth	34.85% [161/462]	65.15% [301/462]
SOE	Wi-Fi	99.72% [351/352]	0.28% [1/352]
SOE	Bluetooth	29.87% [138/462]	70.13% [324/462]

Table 3-3: Classification test results, Bluetooth multi-slot packets.

These results clearly show that the correct classification rate is perfect for all the four considered classifiers in the Bluetooth single-slot packets case, where the two classes (Wi-Fi and Bluetooth) are separable. Correct classification rate cannot be perfect in the second case (Bluetooth multi-slot packets), since the packets are not separable, but it is still really high, very close to 100%, for all the classifiers.

In order to recreate a possible real multi-network scenario, multi-network packet traffic was generated, by mixing the two mentioned test sets. Furthermore, three different scenarios were considered:

- Wi-Fi as predominant network, i.e. the number of Wi-Fi packets is higher than the Bluetooth one (1000 Wi-Fi packets vs. 200 Bluetooth packets);
- Bluetooth as predominant network, i.e. the number of Bluetooth packets is higher than the Wi-Fi one (2000 Bluetooth packets vs. 1000 Wi-Fi packets); here only multi-slot Bluetooth packets are used, since this case is more general;
- balanced scenario, i.e. the number of Wi-Fi packets is the same of the Bluetooth one (1000 Wi-Fi packets vs. 1000 Bluetooth packets).

Classifier	Input network	Classification into Wi-Fi	Classification into multi-slot Bluetooth
Perceptron	Wi-Fi predominant	86.07% [315/366]	13.93% [51/366]
Perceptron	Bluetooth predominant	17.22% [134/778]	82.78% [644/778]
Perceptron	Balanced	41.53% [211/508]	58.47% [297/508]
Pocket	Wi-Fi predominant	86.07% [315/366]	13.93% [51/366]
Pocket	Bluetooth predominant	17.1% [133/778]	82.9% [645/778]
Pocket	Balanced	41.34% [210/508]	58.66% [298/508]
LMS	Wi-Fi predominant	90.16% [330/366]	9.84% [36/366]
LMS	Bluetooth predominant	37.79% [294/778]	62.21% [484/778]
LMS	Balanced	56.89% [289/508]	43.11% [219/508]
SOE	Wi-Fi predominant	90.71% [332/366]	9.29% [34/366]
SOE	Bluetooth predominant	36.89% [287/778]	63.11% [491/778]
SOE	Balanced	56.1% [285/508]	43.9% [223/508]

Table 3-4: Classification test results, multi-network environment.

Table 3-4 reports the obtained results for this case. Pocket and Perceptron classifiers, despite their simplicity, seem to obtain the best results, by always reaching a correct classification rate higher than 80% in case one network is predominant respect the other one. LMS and SOE reach a correct classification rate higher than 90% when Wi-Fi is predominant, but this rate is lower (about 60%) when the predominant network is Bluetooth.

In the balanced scenario the correct classification rate is lower, but it must be noticed that by obtaining rates close to 50%, it reflects the situation of the environment, where two different types of wireless networks are present “with the same percentage”, i.e. their presence is balanced. In this case there could be the necessity to perform more investigation, for example with more features or using a cross-layer cognitive engine, i.e. with additional information coming from other architectural layers. This seem not necessary in the two scenarios where a technology is predominant to the other one; in these cases the MAC sub-layer features exploitation seem to lead to an automatic network correct classification with a high percentage.

3.1.1.4 Extension to underlay networks: Ultra Wide Band networks

The same concept can also be extended to other types of networks. Interesting is the case of underlay networks, that occupy a much higher bandwidth and a wider range of frequencies; these types of networks can be seen as a sort of “substrate” for the other wireless networks, and can also affect the recognition and classification process of the cognitive radio.

An example is Ultra Wide Band (UWB) networks [81]. This communication system is defined in IEEE Standard 802.15.4a, and uses impulse radio. In fact the duration of the pulses used in this technology is 700 ps to 1 ns; due to this really short duration, the occupied bandwidth is extremely high (some Gigahertz).

The extension of the approach explained before [82], in order to reach automatic network recognition and classification, must not be intended in the sense of MAC layer features. In fact the different bandwidth usage does not permit a direct comparison of this layer's behaviour. Anyway the extension of the approach to this kind of networks is in the simplicity of the feature analysis that can be done.

In this context, a physical layer feature can be used. The impulsive nature of this kind of signal can be exploited and compared to the continuous waveform signals used in traditional communication systems. This different nature can be shown through appropriate features, and therefore used for recognition. In particular, an analysis on the short-term energy can be a key operation, capable of highlight the difference between impulsive signals and continuous signals. In fact, continuous signals should present a constant energy profile (if the window used to measure the short-term energy is not exaggeratedly short, i.e. it contains at least a period of the transmitted signal), while the energy profile of a UWB signal should present many discontinuities, that depends on the fact that sometimes the window used to measure the short-term energy includes one (or more) pulse, and sometimes not. Obviously the short-term energy windowing must be sufficiently short, otherwise, a mean value of many pulses is obtained, not reflecting the impulsive nature of the signal.

Preliminary studies on constant vs. impulsive energy profiles were carried out until now, in which Bluetooth was used as example of continuous signal network. Short-term energy was computed for both signals, the impulsive one and the continuous one, using different values of window duration. Considering the Bluetooth continuous-wave signal, it can be seen that the wider the window width, the smaller the fluctuation of the short-term energy gets: as the window width increases, the short-term energy becomes flatter. An example is shown in Figure 3-5.

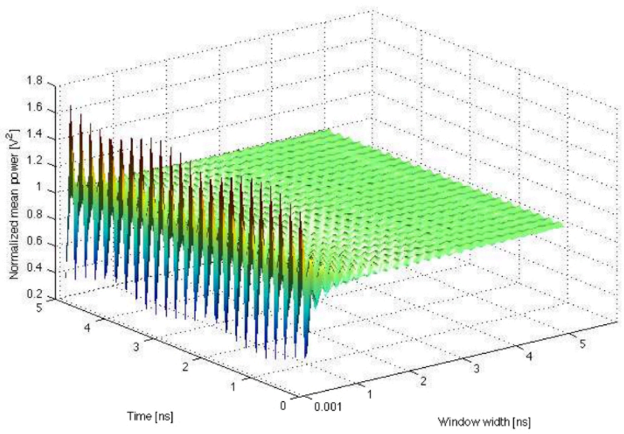


Figure 3-5: Short-term energy of a Bluetooth signal, function of time and window width.

Upon analysis, the short-term energy profile of the UWB signal clearly appears very different: with a short window width it has impulsive nature, shown by the presence of peaks; as the width of the window increases, it does not assume a smoother behaviour, as in the previous case, but it presents even higher peaks, as it can be seen in Figure 3-6 and Figure 3-7. Furthermore, short-term energy appears extremely concentrated in very few discrete values.

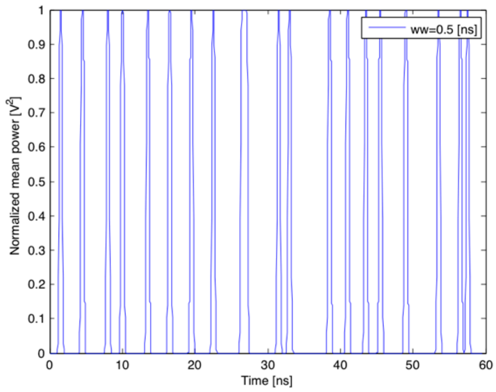


Figure 3-6: Short-term energy of a UWB signal, with a window width equal to 1 pulse duration.

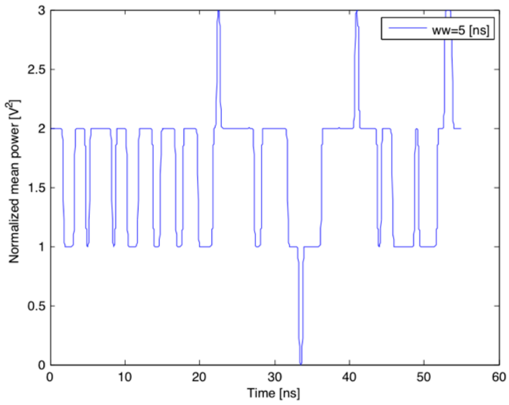


Figure 3-7: Short-term energy of a UWB signal, with a window width equal to 10 pulse duration.

Even if these first results are still preliminary, and deeper studies need to be done under this aspect, it can be seen that, with a proper window width, the short-term energy of a continuous waveform (Bluetooth, in this case) is approximately flat, while the one of an impulsive signal (UWB) is multi-static and very discontinuous. Most important, they are clearly very different. This difference could be exploited for the UWB network detection.

3.2 Solutions for coexistence and cooperation between different networks

This section will focus on the issue of how taking advantage of the presence of multiple networks, including the following aspects:

- Presence of multiple Radio Access technologies and selection of best RAT given the information on coexisting networks;
- Cooperation between different networks based on joint selection of MAC and network parameters.

3.2.1 Presence of multiple Radio Access technologies and selection of best RAT given the information on coexisting networks

The exploitation of the multiple RATs via the selection of the best RAT for the connection of cognitive mobile terminals (MTs), can be performed either by the cognitive mobile terminals themselves or in collaboration with a Central Management System.

3.2.1.1 Selection with guidance by a Central Management System

A Central Management System (CMS) would guide the cognitive MTs to the best RAT selection via suitable directives, which would have the form of policies and will guide the cognitive terminals to the most suitable decisions for their needs. The CMS is aware of the technical characteristics/capabilities of the operating Radio Access Networks-RANs (e.g. operating radio access technology, operating frequency bands, offered QoS level, etc) either by direct communication with the networks or Common Control Channels, such as the Cognitive Control Channel. Each CMS is responsible for a specific geographical area. In order to accomplish its operation, the CMS would collect information from the cognitive terminals and the operating Access Points/Base Stations in its area. We use the term Access Point for the network element at the lowest level of the operational network level, independently from its operating RAT, with which the MT has active link for accommodation of its traffic (e.g. Base Station for GPRS, Node-B for UMTS, evolved Node-B for LTE, Access Point for IEEE 802.11).

The information, which is collected from the MTs, has to be sufficient to support CMS operation but not excessively large, because the prerequisite operation of the cognitive devices for procurement and processing of the demanded information, would burden MT's computational and power resources. Furthermore, significant augmentation of this information, such as detailed information about MT's hardware and software characteristics (e.g. device model and version, power consumption and power saving schemes, total size of memory, supported coding schemes) and criteria that constitute the deciding factors of user's strategy fro the final RAT selection, may lead to optimization of CMS operation, but simultaneously, it will considerably complicate the computational approach of the respective optimization problem that CMS have to solve. The comprehensive information for MT's status will be used for the determination of MT's behaviour in the framework of its own strategy, in its internal function for the final RAT selection in compliance with CMS's directives. This information for a MT m should comprise [83][84]:

- Its current Configuration $c_m = (r, f)$, in RAT $r \in R$ and operating frequency f, where *R*, is the set of all the different existent RATs. In case of MTs with multihoming capabilities (i.e. MTs that can maintain simultaneous different links via different RATs and/or frequencies), the configuration of each active interface *if*, $c_{m,if} = (r, f)$, is sent to CMS.

- Its Geographic Coordinates (longitude, latitude) at time point t $GC_m(t) = (lo, la)$.

- Its Mobility Profile $MP_m = (v, d, mvp)$, where *v* is the velocity, *d* is the direction and *mvp* is the moving pattern of the MT. The moving pattern *mvp* defines a specific behaviour of the MT, in terms of moving behaviour for specific recorded routes, in conjunction with information for user preferences. For example, a specific record of moving pattern in mobility profile can be the fact that the user travels by train going to her office every morning (definite track with known average speed and speed variance), and during the ride she reads her emails through the cheapest RAN, independently of the service data rate, and she downloads music files being connected to the RAN with the higher data rate and cost less in value than a specific price.

- The RAN ran_j with which, each interface *if* of MT has active link. In case of ad-hoc connection, the MT sends information for the neighbouring MT (e.g. an identification number for the MT or most probably its IP address), with which has active link and employs it as relaying node.

- The measured level of Signal Strength for every active interface of MT $SINR_{m,if}$, as this reflects of SINR (Signal-to-Interference-plus-Noise Ratio).

- The requested service $s \in S_m$, where S_m is the set of services that can be requested by MT *m.* It holds that $S_m = S_{m_{sub}} \cup S_{m_{nsub}}$, where $S_{m_{sub}}$ is the set of services that the user has been subscribed to, $S_{m_{nsub}}$ is the set of services, of her network operator or co-operated network operators that the user can use without being a subscriber to them, and $S_m \subseteq S$ (where S is the set of all the possible services).

- The demanded QoS level for each requested service s, which is comprised of a set of specific QoS Indicators $QoSI_s$.

- The measured QoS level of each operative service s, which is comprised of a set of specific QoS Metrics $QoSM_s$. QoS Metrics illustrate the conditions in several communication layers, for example in physical layer by means of the physical rate or Bit Error Rate, in MAC sublayer by means of the access delay, in network layer by means of throughput or blocking probability, etc.

The CMS collects from each Access Point ap_l in its area:

- The Radio Access Network ran_j to which it belongs.

- Its operating frequency f_{ap_l}.

- The bandwidth allocated to uplink and downlink $\left(BW_{UL_{ap_l}}, BW_{DL_{ap_l}}\right)$.

- Its geographical position given in x-y coordinates $\left(x_{ap_l}, y_{ap_l}\right)$.

- Its coverage area CA_{ap_l}, which is defined as the area in which the Signal-to-Interference–plus-Noise Ratio (SINR) is above a specific threshold, common for all the Access Points of the managed RANs of the same RAT.

- The current load $CL_{ap_l}(t_1)$ e.g. at time t_1, which is defined as the percentage of the aggregate current active users in relation with the possible maximum number of connected users, with specific minimum QoS level.

- The predicted load for the time period $Dt=(t_1,t_2]$, $PL_{ap_l}(Dt)$. The Predicted Load is defined as the percentage of the aggregate predicted connected users in relation with the possible maximum number of active users, with specific minimum QoS level.

- Its Mean level of Signal Strength $mSINR_{ap_l}$, which is the Mean level of Signal Strength for all the connected terminals to it.

- Its Aggregate Throughput AT_{ap_l}, which is defined as the sum of the throughputs of all the connected terminals.

- Its Spectral Efficiency SE_{ap_l}. The Spectral Efficiency is the Aggregate Throughput of the connected terminals divided by the sum of the allocated bandwidth to uplink and downlink.

Furthermore the CMS may communicate with network management systems and obtain the spectrum holes $Sh_{ran_j,f}$ in terms of frequency ranges for its managed geographical area. For each frequency range, a minimum time frame *T* at which frequencies of this range are disposed for secondary usage and maybe the maximum power level $P_{SU,max}$, at which secondary MTs are permitted to transmit, may also be declared.

The CMS divides its managed area to managed sections, the determination of which is based on the number of MTs and APs and the processing method. The managed section is approximated by a "known" mathematical function from MTs, different for each managed section, which represents the geographical coordinates of the spots that constitute the managed section.

The CMS uses the Geographic Coordinates $GC_m(t)$and the Mobility Profile MP_m of MTs, in order to estimate the most probable geographical section ms in which each MT will be in time frame $\Delta t=[t_a,t_b]$. Approaches for relative estimations have already been developed [85] [86]. From the estimated position of MTs, the CMS computes the probable population of each ms_k for the specific time frame Δt, $POP_{msk,\Delta t}$. For the probable population $POP_{msk,\Delta t}$ of ms_k for the specific time frame Δt, CMS estimates:

- The distribution of MTs to RANs $dn_{msk,\Delta t}(RAN)$, from the RANs with which MTs have active links.
- The distribution of all active links of MTs to RATs and corresponding operating frequencies $dc_{msk,\Delta t}(r,f)$, from configuration of MTs c_m.
- For each service *s* the distribution of applicant MTs to demanded QoS Levels $dqd_{s,msk,\Delta t}(QoSI_s)$, and the distribution of active MTs to measured QoS Levels

$dqm_{s,ms_k,\Delta t}(QoSM_s)$, from QoS Indicators $QoSI_s$ and QoS Metrics $QoSM_s$, respectively.

Furthermore, for each ran_j, for the specific time frame Δt, the distribution of MTs to measured QoS Levels $dqml_{s_n,RAN,\Delta t}(QoSM_{s_n})$ for each service s_n .

The time frame Δt is variable and its determination depends on the environment of the CMS. For example, if the CMS operates in a radio environment that is characterized by periods of relatively high variability, the CMS will demand high frequency of provided measurements from RANs and MTs in these periods, and will shorten the time frame Δt for which the aforementioned information is calculated, in order the relevant estimations to coincide with the real networks' conditions.

The above information/distributions are sufficient in order the CMS to assess the networks' status. This information is used as input to optimizations processes, which are based on different techno-economical criteria. The optimization algorithms and the significance factor for each criterion would be negotiated between the operators of the managed networks by the CMS. The results are transformed to policies, which are directives that guide the cognitive MT's behaviour. Examples of policies are presented in Table 3-5:

General Policy	**Policy for Spectrum Secondary Usage**
pid x **IF** { ms_k **AND** [*TimePeriod*==(t_{i-1}, t_i)] **AND** [*service* ==*s*] } **THEN** {*1*=ran_j,*2*=ran_m, *3*=ran_n...}	**pid y** **IF** { ms_k **AND** [*TimePeriod*==(t_{i-1}, t_i)] **AND** [*service* ==*s*] } **THEN** SU_f with $P_{SU_f,max}$ }

Table 3-5: Polices structure for guidance to RAN selection

In the general policy with identification number (pid) equal to x, it is suggested to MTs in managed section ms_k in time period (t_{i-1}, t_i), $i \in N$, to select ran_j as first choice for operating RAN, ran_m as second choice, etc. In the policy example for secondary spectrum usage with identification number equal to x, it is suggested to MTs in ms_k in time period (t_{i-1}, t_i), $i \in N$ which are interested for *service s,* to use frequency SU_f, which is available in this area for secondary usage, with Power Transmission $P_t \leq P_{SU_f,max} \cdot ms_k$.

3.2.1.2 Selection of best RAT by cognitive mobile terminals

Cognitive MTs utilizing the awareness of the presence of networks that operate different RATs in its neighbourhood (which can be obtained through appropriate control channels (CPC), communication with adjacent MTs and sensing the electromagnetic environment), can select the best RAT based on the terminal capabilities, user preferences, context and policies. Concisely:

- MT's capabilities comprise, at least, the set of potential configurations, such as the Radio Access Technologies that the MT is capable of operating with the associated transmission power levels, the set of applications/services that can be used and the sets of QoS levels associated with the use of each application/service.
- User preferences comprise the user satisfaction (named utility volume) regarding the use of an application/service at a particular quality level and the maximum price that the user is willing to pay in order to use certain services at specific QoS levels (corresponding to a set of defined QoS parameters, such as bit rate, delay, jitter, etc.).
- Context reflects the current status of the device and the conditions in its present environment. So, context information should include data about available access networks in its neighbourhood and their corresponding status (operating frequencies, available sources, coverage, etc.), and data relevant to the device status (coverage at the current location, power available, etc). Moreover, context information may comprise the status of other devices in the area regarding their activity and ability/intention to cooperate.
- Policies, as presented in the previous section, are a set of rules that guide the cognitive MT's behaviour. Specifically, policies from network management entities are used as input during the decision process for selecting the most appropriate operating RAT.

The selection of the optimal RAT, except the initial network selection, may be triggered as a reaction to a situation currently encountered, such as a degradation of the perceived QoS level, the availability of a RAT connection that offers better QoS, or the need for specific QoS level from a demanded application/service. It may also be triggered in a proactive manner, by making use of experience obtained over time.

The MT, in order to take the final decision, estimates the most likely capabilities of candidate networks/configurations in terms of the QoS levels that can achieved. This can be accomplished via suitable learning mechanisms. For the implementation of the learning mechanism, concepts from Bayesian statistics can be utilised to build knowledge on the context of the device [87][88]. Specifically, as already mentioned, the MT may initially obtain information on available networks in the area where it is currently located through awareness networking via a CPC or through communication with devices in the vicinity. This information, refined by relevant policies and potentially user restrictions/preferences, provides the set of candidate networks. The candidate examined networks consist of a subset of the home network and the networks that belonging to collaborating network operators. MT collects measurements from these networks and based on those measurements may estimate:

- The conditional probabilities, which provide an estimation of how probable it is that a specific QoS parameter, will reach a certain value, for an application, given a certain configuration that specific networks can achieve.
- The probability density function value, which provides a more aggregate estimation regarding the probability to achieve a certain combination of QoS parameters, which corresponds to a QoS level, for an application, given a certain network. Namely, the probability density function expresses the probability that a certain network will support a specific application and QoS level combination.

The update of the conditional probabilities and probability density function values constitutes the learning process, and may rely on approaches suggested in [89][90][91][92].

The decision process for selecting the optimal device configuration (RAT) is an optimisation problem that takes into account current context, profile information, policies and knowledge, as this reflects to the aforementioned probabilities/function. For the decision process, a knowledge-based scheme named Cognitive MADM [87], which is based on multiple attribute decision making (MADM), such as in [93] [94], can be utilized. In Cognitive MADM scheme, user preferences are implicitly expressed as a vector of weights, where each value indicates the importance of a certain QoS level parameter such as bit rate, delay, jitter, etc. The appropriateness value, which is used to rate configurations (networks and QoS level combinations) with respect to network capabilities and thereof corresponding user satisfaction that can be achieved, is calculated. The appropriateness values for all candidate networks are updated every time the conditional probabilities and probability density function values are updated. This happens when a new measurement is obtained from the environment. The configuration with the highest appropriateness value is selected. In case the same appropriateness value is derived for several configurations, the configuration that imposes the smallest reconfiguration cost (in terms of time and resources) is selected. For example, in case the currently used network scores an equally high appropriateness value as other networks it is preferable as it does not entail a handover of the device to a different network. An overview of the Cognitive MADM is depicted in Figure 3-8.

Specifically, the scheme the appropriateness value $av(u,i)$ for user u, for a candidate network i, is calculated using the formula [95]: $av(u,i) = f(i,a,q) \cdot \left(\sum_{j=1}^{M}(wgt_{uj})(nf_{ij})\right)$ where

- $f(i,a,q)$ is the probability density function value for network i, application a, and QoS level q;
- (wgt_{uj}) indicates the importance of the j-th QoS parameter (j =1,…,M) for user u;
- (nf_{ij}) is the normalisation factor for the j-th QoS parameter for network i, which is required for facilitating the comparison of the QoS capabilities of the various candidate networks.

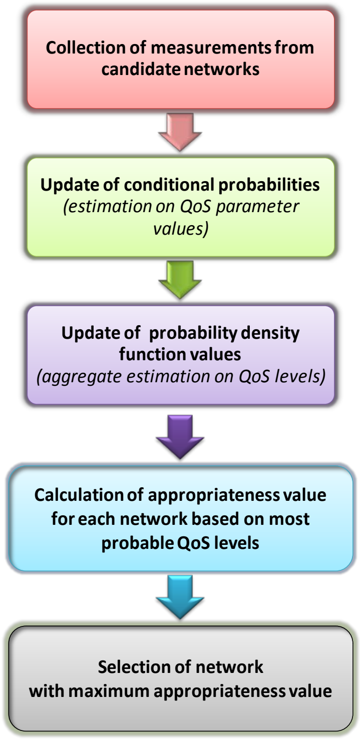


Figure 3-8: Overview of the Cognitive MADM

3.2.2 Opportunistic Access Technique using Stochastic Models

The main problems when considering a cellular primary network is the fast dynamics of the cellular network and the presence of several primary transmitters. In this case the traditional sensing-based techniques are not any more efficient since (1) these techniques have not been studied with the presence of multiple transmitters and power control and (2) they can be very slow compared to the fast dynamics of the traffic of most cellular networks. To solve the problem of multiple transmitters, some location-based approaches [96]-[98] were proposed, especially after the adoption of regional database driven techniques by the FCC [99]. Again, these methods will fail to provide good performance in operational networks, especially with primary networks characterized by power control, fast scheduling and short duty cycles, which is unfortunately the case for most cellular networks.

3.2.2.1 Problem Formulation

Due to the limitations of sensing- and location-based techniques, we explore in this section another approach that does not require any sensing. This will allow secondary networks to overcome the problem of primary fast dynamics and multiple transmitters. Our approach is to exploit the information about primary activity patterns and perform statistical transmission with enough low probability to guarantee primary constraints. Therefore, we use alternating renewal theory [100]-[103] to determine the periods of time where the secondary users can transmit while satisfying statistical primary constraints. Recently, several papers proposed mechanisms based on alternating renewal theory [104][105] to estimate the best channel to transmit or the available time to transmit after detecting a free channel. These methods are based on the sensing-before-transmit concept, which again yields poor performance in case of highly dynamic primary networks. In this section, we develop a general framework based on stochastic opportunistic access with different types of primary constraints without the need for sensing. Then, we study in detail the case where the primary ON/OFF period durations are modelled with exponentially distributed parameters, which is one of the cases encountered in mobile networks [97].

We consider a secondary network that can opportunistically access the licensed spectrum of a primary network under strict constraints guaranteeing the required Quality of Service (QoS) for primary users. Our objective is to find the best secondary activity patterns (i.e., time periods where the secondary node can transmit) over different primary channels leading to the highest possible capacities or lowest transmission delays, while satisfying primary constraints.

The considered primary network comprises *M* base stations using *N* channels. The coverage area of its cells is determined by the region where the required QoS is guaranteed with a specific probability and is usually estimated using planning tools. Each base station has an activity pattern on a given channel that can be different from the activity patterns of other base stations or on other channels. The activity patterns are represented by an alternating renewal process of ON (active) and OFF (idle) periods. The durations of the ON and OFF periods of base station *j* on channel *k* are assumed to be independent from each other and represented by independent identically distributed random variables $T_{ON}^{j,k}$ and $T_{OFF}^{j,k}$, respectively. These variables follow general distributions with cumulative distribution functions (CDFs) $F_{j,k}$ and $G_{j,k}$, respectively. This model has been found to be realistic for several legacy systems such as GSM and DECT [97].

In the secondary network side, we consider a network with infrastructure including *L* stationary nodes (i.e. base stations) and a variable number of mobile terminals associated to the different stationary nodes. We assume that the positions of the secondary base stations with respect to the primary base stations are known, for instance, through regional database as suggested by the FCC [99]. However, this is not a requirement for the proposed approach that can be also implemented without knowing primary base station locations.

Cellular networks will allow opportunistic access only when they can still control and guarantee the desired QoS for their users. Hence, several performance metrics can be defined based on the type of network and application. In this study we consider the following metrics without limiting the developed framework that can be extended to take into account other metrics as well:

- θ: Average fraction of time during which a primary transmission is interfered by secondary activity:

$$\theta = \frac{E(T_{\rm ON}^{j,k} | \text{A secondary is active})}{E(T_{\rm ON}^{j,k})} \qquad (3\text{-}3)$$

  where $E(T_{ON}^{j,k})$ and $E(T_{ON}^{j,k}$|A secondary is active) are the expectation values of the primary ON periods over time for a given cell j and its conditional expectation given that a secondary node is active, respectively. The primary network can be interested that the users in a given cell will only lose data in $\theta \times 100\%$ of their transmission time. This is the case for applications that are sensitive to bit error rate such as background download. In this case, the primary network requires that $\theta < \theta_{th}$ in all cells.

- ρ: The ratio between the average number of primary ON periods lost and the average number of the total ON periods. In this case we assume that if an ON period is partially interfered (i.e., only a part of the transmission is interfered) it will be lost, for instance due to the loss of the preamble. Thus, it can be used especially in the case where the ON periods represent whole packets of a user, such as in the case of the uplink of a Wi-Fi network. For this metric the primary network requires that $\rho<\rho_{th}$.

We define *S* as the set of metrics that the primary operator defines to enable access to its spectrum in an opportunistic way. To estimate these metrics, we consider that a primary receiver *j* is interfered by a secondary node *l* if the latter transmits and the probability that the received interference by *j* due to this transmission is higher than given threshold ι_{max} exceeds ε. Formally, we can write this condition as

$$Pr\{I_{lj} > i_{max}\} > \varepsilon \qquad (3\text{-}4)$$

where I_{lj} is the interference experienced by primary receiver *j* due to the transmission of secondary node *l*. The channels that can be shared by secondary nodes as well as the values of ι_{max} and ε are determined by the primary planning tools [100]. To encourage primary operators to share their spectrum, we assume that any approximation in the computation of the metrics is conservative with respect to primary protection. Therefore, we assume that when a primary is interfered, all data transmitted during the interference time are discarded and considered to be erroneous. Moreover, the coverage area of any base station is considered to be the disc enclosing the real coverage area. By using proper propagation models and shadowing models, this disc can be determined. The same conservative approach is used to determine the coverage area of secondary base stations. In general cellular activity patterns are not stable over time. However, for limited periods of time (i.e. in the order of few hours) the activity pattern can be relatively stable. Thus, the primary network can characterize these periods by the most conservative pattern (i.e. the pattern that is the most sensitive to secondary activity).

3.2.2.2 Secondary Transmission Framework

Since no sensing is required in our approach, the secondary node will have a period of transmission ($\bar{T}_{ON}$) followed by a period where it is inactive ($\bar{T}_{OFF}$). The sum of these two durations forms the frame of secondary node with duration $\bar{T}$. In general, the frame duration can be either fixed or variable depending on the adopted model. The capacity of the secondary can be maximized by maximizing the ratio $\bar{T}_{ON}/\bar{T}$, whereas the delay can be minimized by decreasing the value of $\bar{T}$.

Different types of activity patterns can be designed for the secondary network. In general we can divide these patterns into two groups: stochastic and periodic. In stochastic patterns, secondary node *l* will have a policy to be active during a period $\bar{T}_{ON}$ and inactive during a period $\bar{T}_{OFF}$ using channel *k*, which follow specific distributions represented by their CDFs $F_{l,k}$ and $G_{l,k}$. The type of the distributions and their parameters should be computed using $F_{j,k}$ and $G_{j,k}$ for each possible interfered primary cell *j*. The periodic transmission is a special case of the stochastic transmission, where $\bar{T}_{ON}$ and $\bar{T}_{OFF}$ are constant values. In this study we consider the periodic transmission since (1) it contains less variables and it is easier to find the optimal solutions, and (2) it provides more predictable behavior of the secondary activity. However, it is possible to extend the model presented here to the general case by using the approach developed in [103] for the case of several simultaneous alternating renewal processes.

Secondary transmitters are assumed to be cooperative in terms of scheduling the use of primary channels to guarantee that the primary constraints are preserved; the secondary nodes are only allowed to transmit during the scheduled ON periods. Since the secondary ON and OFF periods on each channel are scheduled on a relatively long time scale (e.g. several minutes or hours), synchronization between the different secondary transmitters is possible. This constraint can be relaxed for distant secondary node clusters, where the interference from one cluster to a given primary receiver is negligible whenever the interference from the other cluster is higher than $\iota_{\max}$.

The estimation of θ and ρ can be performed using alternating renewal theory and Laplace-Stieltjes transforms as it is shown in [106]. The ON-OFF periods in wireless communication can follow different types of distributions such as exponential, lognormal, Pareto and Erlang distributions. With the exception of the exponential distribution, it is difficult to derive closed form expressions for θ and ρ. However, numerical evaluation can be done by appropriate extensions of the Cléroux-McConalogue algorithm [107] to evaluate the convolutions. In particular, numerical evaluation of these two metrics have been presented in [102] for Weibull and log-normal distributions.

If *F* and *G* follow exponential distributions with parameters λ and μ, we can easily obtain

$$\theta = \frac{\bar{T}_{ON}}{\bar{T}} \qquad (3\text{-}5)$$

$$\rho = \frac{\lambda\bar{T}_{ON} + 1}{\lambda\bar{T} + 1} \qquad (3\text{-}6)$$

It is interesting to see that θ is independent of the primary activity and ρ depends only on the distribution of primary ON periods.

The above equations define the relation between the secondary activity pattern and primary performance metrics. For a specific threshold θ_{th} of θ, all values of $\bar{T}_{ON}$ and $\bar{T}_{OFF}$ are allowed if they can meet the condition defined in Eq. (3-5). This case is suitable especially for real time applications where short delays in transmission are needed since the secondary node can define its transmission periods without any constraints. The maximum achievable $\bar{T}_{ON}/\bar{T}$ is constant and equal to θ_{th}. However, this is not the case for ρ since the values of the durations should be always positive. Therefore, when considering a threshold ρ_{th} the secondary transmission period should satisfy the following condition:

$$\bar{T} > \left(\frac{1 - \rho_{Th}}{\rho_{Th}}\right)\frac{1}{\lambda} \qquad (3\text{-}7)$$

This means that the OFF duration of the secondary node may be much higher than the average duration of the ON periods of the primary. This can be very limiting for the case where the secondary wants to have real time communications such as voice. Moreover, from Eq. (3-6), we can write

$$\frac{\bar{T}_{ON}}{\bar{T}} = \rho_{Th} - \left(\frac{1-\rho_{Th}}{\lambda\bar{T}}\right) \quad (3\text{-}8)$$

which is always lower than the value obtained if the same threshold is used for metric θ. Furthermore, it is an increasing function on $\bar{T}$. Therefore the secondary node should make a tradeoff between increasing its data rate and decreasing delay transmission.

For brevity we only consider that the secondary objective is to maximize $\bar{T}_{ON}/\bar{T}$ in the following. Without the need to do any sensing, the proposed DSA approach based on stochastic models can find the values of $\bar{T}_{ON}$ and $\bar{T}$ that can be used by a secondary node to transmit on channel k based on the knowledge of $F_{j,k}$ and $G_{j,k}$ for all potentially interfered primary cells. The approach is divided into two main steps for each channel:

- Find the potentially interfered primary cells,
- Determine the values of $\bar{T}_{ON}$ and $\bar{T}$.

A primary transmission is interfered by secondary activity if the condition expressed by Eq.(3-4) is met. Let us consider that the secondary node transmits with fixed power *P* and assume a log-normal distributed shadowing factor with standard deviation σ. Then, Eq.(3-4) can be rewritten as a condition on the distance d_{sj} separating the secondary transmitter s and the primary receiver j: $d_{sj} < d_{\text{th}}$ [96] where

$$d_{Th} = \mathcal{P}_{sj}^{-1}\left[P - i_{max} + \sigma\sqrt{2}\, erf^{-1}(1-2\varepsilon)\right] \quad (3\text{-}9)$$

In the above equation erf^{-1} is the inverse of the error function and $\mathcal{P}_{sj}^{-1}$ is the inverse of the distance dependent path loss function.

In order to estimate d_{sj} we need to determine the position of the primary receiver and secondary transmitter. For each transceiver we have two distinct cases. The transceiver can be either a MT or a BS. If it is a BS, then its position is known. Otherwise, the worst case position is considered, which is the closest position to the secondary transmitter (resp. primary receiver) on the circle enclosing the coverage area of the primary (resp. secondary) base station. Hence, we can write

$$d_{sj} = \begin{cases} D_{sj} & if\ two\ BSs \\ max\{0, D_{sj} - R_s\} & if\ primary\ BS\ and\ secondary\ MT \\ max\{0, D_{sj} - R_j\} & if\ primary\ MT\ and\ secondary\ BS \\ max\{0, D_{sj} - R_j - R_s\} & if\ two\ MTs \end{cases} \quad (3\text{-}10)$$

where R_s and R_j are the radii of the circles enclosing the coverage areas of the secondary and primary base stations respectively and D_j is the distance separating the two base stations. Once the distances towards the neighbouring cells are computed, the condition in Eq. (3-9) is verified for all of them. The set of potentially interfered primary cells ξ is then determined as follows:

$$\xi = \{j = \{1,2,\cdots,M\} | d_{sj} < d_{Th}\} \quad (3\text{-}11)$$

Let us assume that the primary operator wants to have a constraint on s metrics from set $\bar{S} = \{k_i | k_i \in S, i = \{1,2,\cdots,s\}\}$ that can include any of the metrics defined by the primary network. In our approach, the procedure to compute the activity pattern satisfying primary constraints and maximizing $\bar{T}_{ON}/\bar{T}$ is divided into three phases.

The first phase aims at finding the secondary activity pattern corresponding to each potentially interfered cell; for each base station j in set ξ, $\bar{T}_{ON}^{(j)}$ and $\bar{T}^{(j)}$ for a given channel k are computed using the alternating renewal theory and the functions $F_{j,k}$ and $G_{j,k}$. The second phase uses the computed values of $\bar{T}_{ON}^{(j)}$ and $\bar{T}^{(j)}$ to reevaluate all metrics for each base station except base station j which was evaluated in the previous phase. The obtained values are denoted $k_i^{(j)}$. In the third phase, the procedure chooses the activity pattern corresponding to cell j determined as follows

$$j = \arg\max_{j \in \xi} \left\{ \frac{\bar{T}_{ON}^{(j)}}{\bar{T}} \middle| \, k_i^{(j)} < k_{i,Th}^{(j)} \; \forall k_i \in \bar{S} \right\} \tag{3-12}$$

3.2.2.3 Simulations and Results

We evaluate the proposed approach in a simple system of seven hexagonal primary cells, where only the downlink case is considered. Each primary base station is located at the centre of the cell and transmitting with a power of 30 dBm in each channel. The primary users of each cell are uniformly distributed inside a disc of radius of 1 km. We consider only one channel in our study and assume that only one primary user can be served on this channel at a given time in each cell. The secondary nodes are considered to be some kind of access points that can be at any place in the network and can transmit with a maximum allowed transmit power of 30 dBm.

The simulations are repeated for 100 different positions of the secondary nodes distributed in a uniform manner in the zone covering the whole primary system. We assume that the secondary users served by a node are uniformly distributed inside a circle of radius 100m. We also assume that the activities of the primary base stations follow an exponential distribution with the same parameters of ON/OFF periods (i.e., λ and μ). Thus, we can define the duty cycle (DC) of a base station as the proportion of time where the base station is active and is equal to $\mu/(\lambda + \mu)$. In the simulations, we use the Xia-Bertoni propagation model [109]. Given a frequency f in GHz and distance d_{XY} between transmitter X and receiver Y, path gain G_{XY} is given by $G_{XY}(d_{XY}) = \mathcal{P}_{sj}(d_{XY}) = K_{XY} + \beta_{XY}\log_{10}(f) + \alpha_{XY}\log10(d_{XY})$, where K_{XY}, β_{XY} and α_{XY} are constants computed using the Xia-Bertoni model. The obtained propagation constants are collected in 1. We also consider a log-normal shadow fading with zero mean and a standard deviation of 7 dB.

	α	*B*	*K*

Primary BS ↔ Secondary node	37.6	21	113.2
Secondary node ↔ Primary terminal	37.6	21	122.1

Table 3-6: Constants of the propagation model.

The primary metrics are evaluated for each case and compared to the thresholds. For this we assume that a primary cell is interfered when the received interference due to secondary activity is higher than $\iota_{\max}$ = -100 dBm. We also assume that ε, ρ_{th} and θ_{th} are all equal to 0.05. The secondary performance is evaluated in terms of average capacity and allowed transmit power. The capacity is computed as the normalized Shannon capacity in bits/s/Hz, $C = \log_2(1 + \text{SINR})$. The SINR is computed considering only the interference from primary network and noise power. All techniques were evaluated for different values of λ and the duty cycle. In our technique, the value of $\bar{T}_{ON}$ is computed from Eq.(3-5) and Eq.(3-6) , and the value of $\bar{T}$ has been computed as the minimum value satisfying Eq. (3-7).

Sensing techniques in the presence of multiple transmitters have not been studied heavily. There are some preliminary works in this topic that were proposed in [96][98]. However, these solutions will give lower results in systems with fast power control, fast scheduling, and fast changes in the ON/OFF periods such as the case of mobile networks. Therefore, we consider instead a perfect mechanism but assuming one transmitter in the multi-transmitter case, which gives an upper bound for sensing-based techniques.

Using this assumption, the sensing technique can detect any OFF period where there is no active base station. Therefore, the OFF periods in this case are the intersection of the OFF periods of the seven cells. We assume that the sensing mechanism can detect an aggregate OFF period with a probability P_d = 0.95, which corresponds to the considered ε in our algorithm. Moreover, we assume that the probability of false alarm is equal to 0.1 as it is normally considered in the existing works.

The location-based technique is a simplified version of the method proposed in [96]. The main idea is to allow the secondary to transmit with a power that will interfere with the closest base station with a probability ε. The technique assumes that the positions of the base stations and the secondary nodes are known. In this case, a secondary node l inside the coverage area of an active primary network will not be able to transmit, which is not the case in the proposed approach. To determine the closest active base station, the secondary node compares the received power S_l (i.e., the sum of all received powers from active primary base stations) to a location-specific threshold $S_{th}(l)$ for each base station l. This threshold depends on the known distance D_{ls} between s and l and is defined by

$$S_{Th} = erf^{-1}(2\varepsilon - 1)\sigma\sqrt{2} + P - \mathcal{P}_{ls}(D_{ls}) \quad (3\text{-}13)$$

Using this threshold, the closest active BS is determined by

$$j = arg \min_{l}\{D_{ls}|S_l < S_{Th}(l)\} \quad (3\text{-}14)$$

First, We note that all the values of ρ and θ obtained using the proposed approach were always satisfying the primary conditions. Specifically, in the case of the location- and sensing-based techniques, these values were very low due to the conservative approaches considered.
In the stochastic-based approach, the secondary node transmits with its maximum allowed power during time $\bar{T}_{ON}$, and it stops any transmission during $\bar{T}_{OFF}$. Since the transmission schedule only depends on λ as can be seen from Eq.(3-6), the average transmit power over time is always the same for the same value of λ. Figure 3-9 shows that it is also an increasing function of this parameter. This is normal because $\bar{T}_{ON}/\bar{T}$ is an increasing function of λ as can be seen from eq. (3-8).

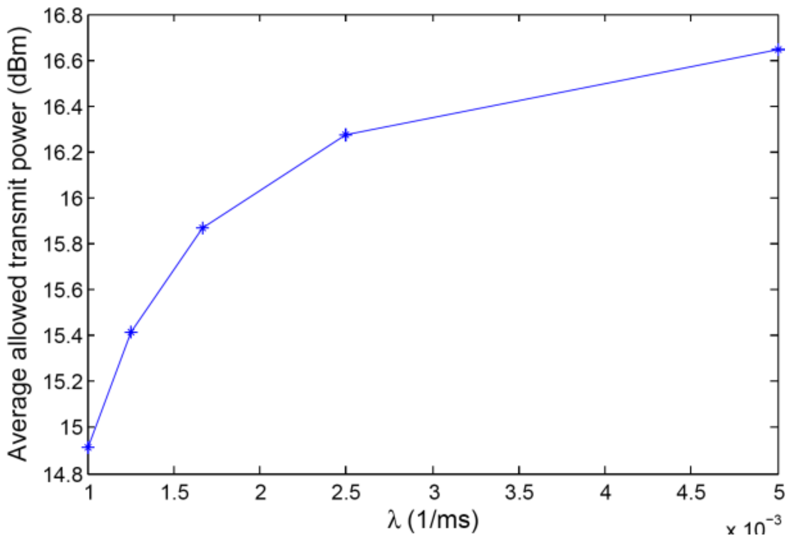


Figure 3-9: The average allowed power as a function of λ when the secondary uses the stochastic-based method [106].

In Figure 3-10 and Figure 3-11, we show the distributions of the transmit powers as function of the primary duty cycle, when the location- and sensing-based techniques are used, respectively. The figures show that compared to the stochastic technique the transmit powers are very low especially for high duty cycles. It should be noted that when the location-based technique is used, 12% of the secondary nodes are not allowed to transmit at all. This is the case when the secondary is at the boundary of coverage zones of two or more cells and thus the common OFF periods of the covering base stations are rare for high values of the duty cycle. Moreover, this percentage becomes 97% when the sensing-based technique is used, since the appearance of common OFF periods between the seven cells is very rare for high duty cycle. In fact, according to [101], the probability of having an OFF period in one base station after long time is $\lambda/(\lambda + \mu)$ which is 1 − DC, where DC is the duty cycle. Therefore, for 7 cells and a duty cycle of 0.9 the probability of having OFF period in the 7 cells simultaneously is 10^{-7}.

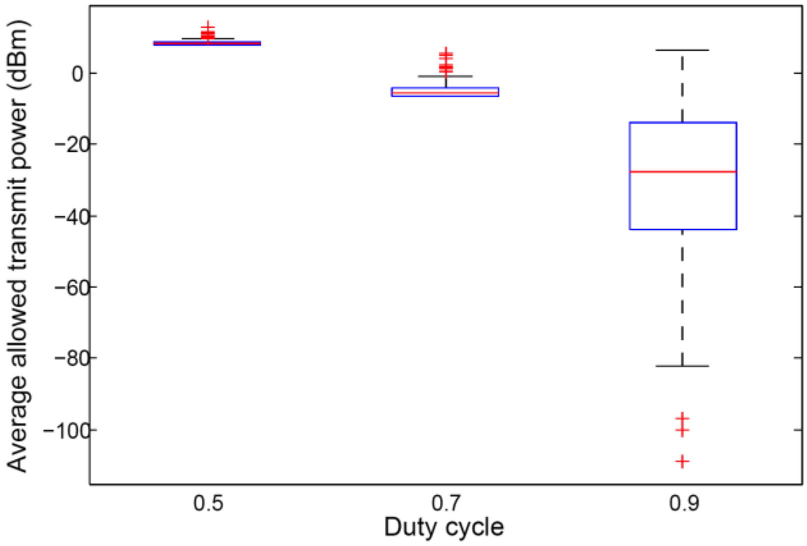


Figure 3-10: The average allowed power as a function of the duty cycle when the secondary uses the location-based method for λ = 0.005 ms^{-1} [106].

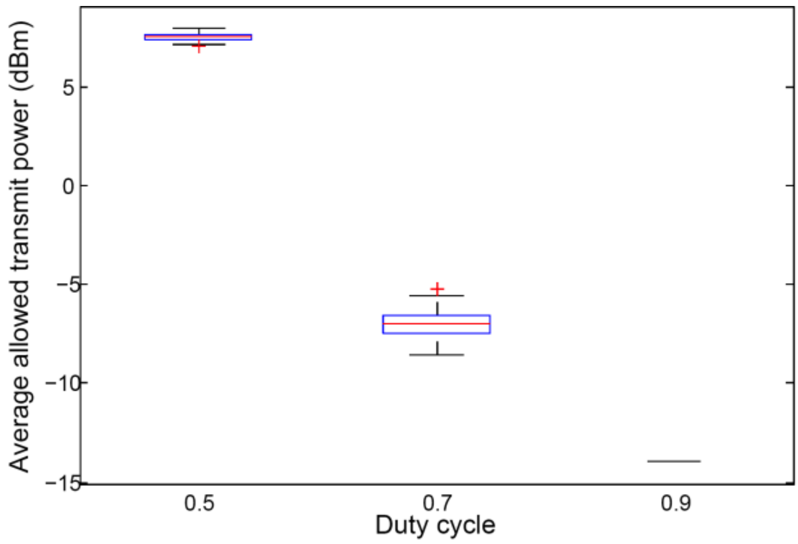


Figure 3-11: The average allowed power as a function of the duty cycle when the secondary uses the sensing-based method for λ = 0.005 ms^{-1} [106].

We shall now study the impact of primary activity on the performance of the secondary users. Figure 3-12 shows the distribution of the capacity as a function of the primary duty cycle and for two values of λ. Although the average transmit power of the stochastic-based technique is very high compared to the other two, the average capacity is relatively low in comparison, especially for low duty cycles. This is due to the fact that in the proposed method, the transmission time is always fixed to the same small value, and the instantaneous capacity is logarithmic function with respect to the transmit power. The figure shows that both sensing-based and location-based techniques lead to relatively high capacities ranging from 2 to 30 bits/s/Hz when the duty cycle is lower than 0.5. These capacities decrease drastically with the increase in the duty cycle and especially for the sensing-based technique that does not allow any transmission when the duty cycle is higher than 0.5. On the contrary, the stochastic-based approach has a rather stable performance for a given value of λ since it does not depend on μ. Even for a duty cycle of 0.9, this technique allows transmission with median capacity around 0.5 bits/s/Hz. The decrease in capacity with respect to the duty cycle is due to the interference generated by the primary network. This leads to a decrease in the instantaneous capacity.

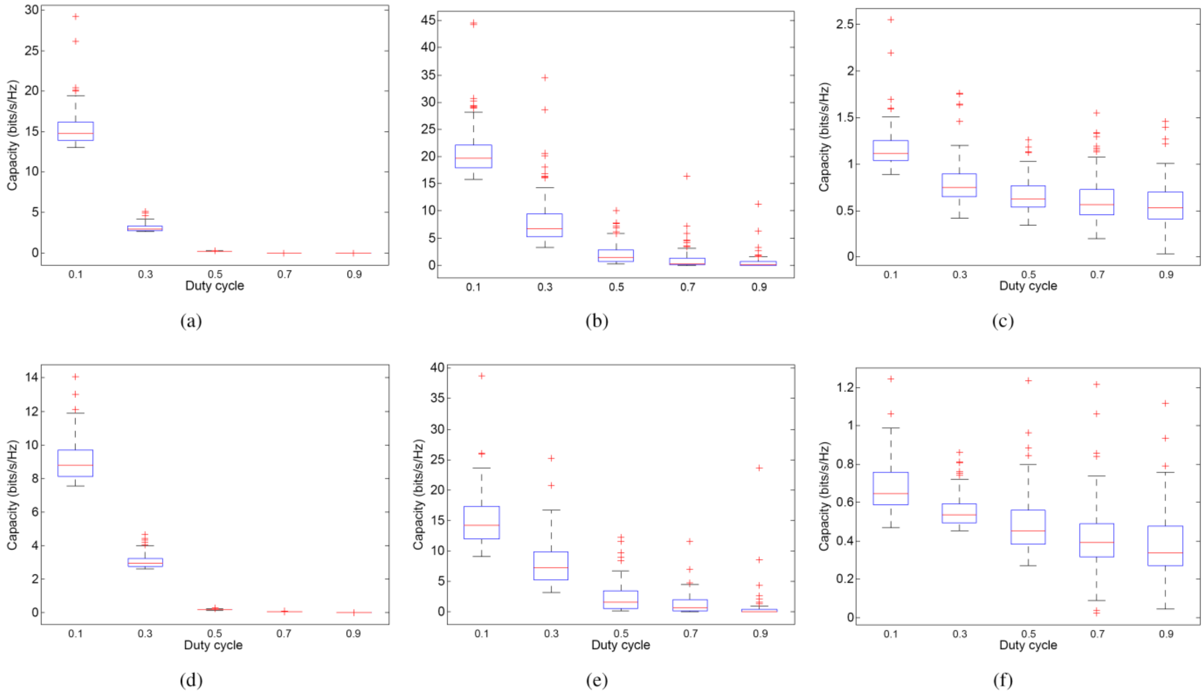


Figure 3-12: The capacity distribution as a function of the duty cycle for different values of λ when using (a,d) sensing-based, (b,e) location-based and (c,f) stochastic-based techniques. The first row gives the distributions for λ = 0.005 while the second raw for λ = 0.001 [106].

4. Open issues and future research directions

This document proposes solutions addressing several fundamental aspects in the design of a cognitive wireless network, at both local and network wide level. During the work required to design and analyse such solutions several open research issues were identified: addressing such issues by further enhancing and extending the proposed solutions will be the goal of WP10 activities. A summary of the issues identified so far, and of the corresponding future lines of research, is provided as follows.

- Local network protocols for neighbour discovery and network organization:
    - Impact of mobility on network topology – the solution proposed in this document for network organization for mobile cognitive networks, as well as the solutions previously proposed in the literature, deal with the impact of mobility on cooperative sensing accuracy under the assumption of a reasonably stable topology in the secondary network, allowing reliable control information exchange among secondary nodes. As discussed in previous work carried out in ACROPOLIS (see e.g. D9.1), having a reliable control channel is fundamental in cooperative sensing performance: the impact of mobility on the secondary network should thus be taken into account in order to determine actual performance of sensing-aware network organization schemes.
    - Common control channel definition – the work carried out so far focused on the analysis of the two possible options for common control channel definition (in-band vs. out-of-band): further steps are required to provide a quantitative comparison of the two alternatives. Activities along this line have already started among interested ACROPOLIS partners, and will be further increased.
- Network wide protocols for internal operations:
    - Cross-layer routing cost function combining beamforming and position-information – the work presented in the second part of Section 2, allowing for local optimization of an end-to-end path selected by the routing protocol, constitutes an intermediate step between the solution presented in D10.1, where beamforming was applied to a fixed path, and the final goal of this activity, that is a full fledged routing solution composed of a cost function taking into account position information, beamforming capabilities and network status, and of a routing algorithm allowing the efficient exchange of the information required to evaluate such cost function towards the determination of the best end-to-end path. Definition of such a cost-function as well as of the routing algorithm were already started, and will be the focus of the future activities on this specific topic.
    - Admission control solutions – the work presented in this document, presenting an access point selection strategy by means of a novel cost function, is the first step towards the definition of a complete solution for admission control and network associations. Several ACROPOLIS partners are now cooperating in the definition of such solution, combining theoretical modelling and verification by simulations.
- Alien network coexistence and cooperation:

- Extension of sets of technologies and features in automatic network recognition - other technologies operating in the ISM 2.4 GHz band should be included in the recognition (as, for example, ZigBee – IEEE 802.15.4), and additional features should be added in order to better separate the different technologies in the features space and therefore obtain better performance, in particular in the case of multiple simultaneous networks.
- Specification of suitable protocols in the scope of cooperation mechanisms, allowing devices to exchange context information and knowledge in a concrete structured way, thus increasing the reliability of the context acquisition and learning functionalities.

A research issue that proved to be horizontal to most of the activities reported in this document, and presently being investigated within WP10, is the impact of network organization and architecture on the performance of the proposed solutions: the overhead of setting up a centralized network organization vs. the potential performance gain when compared to a distributed, flat organization is a topic relevant to local, network-wide and even inter-network solutions, and will be definitely one of the main issues under investigation during the next year (coherently with the activity 10.4 descripted in the ACROPOLIS Description of Work), with results expected to be reported in the upcoming D10.3 deliverable.

5. Summary and Conclusions

This Deliverable addressed the issue of neighbour and network discovery in cognitive wireless networks, presenting the solutions developed within the Work Package 10 of the ACROPOLIS NoE. The activities addressed both internal network operations and solutions for inter-network coexistence.

Section 2 presented solutions for home network discovery, covering both local and network wide protocols. Section 2.1.1 introduced a novel solution for network organization and clustering, where the clustering metric explicitly takes into account mobility and sensing performance, aiming at the selection of cluster heads that guarantee the best sensing performance, while taking into account relative mobility between nodes. Next, Section 2.1.2 focused on the definition of a Common Control Channel, discussing the possible solutions (in-band vs. out-of-band) and the actual status of standardization activities on this topic. Section 2.1.3 addressed the issue of how the need of a neighbour discovery phase in order to build a common control channel, by analysing the performance of a random neighbour discovery scheme in an application scenario characterized by mobile devices imposing a strict time schedule in order to complete neighbour discovery. Section 2.1.4 still focused on the problem of neighbour discovery, presenting a solution for Medium Access Control in asynchronous networks that also takes into account the neighbour discovery performance.

The second part of Section 2 moved to network wide protocols: section 2.2.1 presented a solution for combined position-based routing and beamforming that takes advantage of the hardware required to do beamforming in order to retrieve and build position information to be provided to the routing function. Section 2.2.2 moved then to the problem of network association, proposing an access point selection strategy that constitutes the first step towards an admission control procedure currently under investigation.

Next, Section 3 moved to inter-network solutions for alien network detection and coexistence. Section 3.1 introduced an automatic network recognition and classification algorithm relying on the analysis of MAC layer features for recognition and classification of alien networks even in presence of simple detection hardware (e.g. energy detector). Section 3.2.1 analysed a possible solution for taking advantage of multiple Radio Access Technologies, by means of a smart selection of the best RAT for each device, either centralized or distributed. Finally, Section 3.2.2 presented a solution for opportunistic access by a secondary network when real-time or short term sensing is not an option due to the dynamicity of primary activity, relying on statistical analysis of primary activity patterns to determine the best transmission opportunities for the secondary devices.

Based on the work carried out in WP10 and presented in the previous sections, Section 4 highlighted the research issues that are still open, and will drive the research activities for WP10 in the months to come.

The work presented in this Deliverable is the result of strict cooperation between the partners in WP10, and led to several publication in international journals and conferences; extensions and improvements to the proposed solutions are in most cases already being addressed, aiming at additional achievements in terms of scientific publications in the last year of the NoE, thanks to the increasing mutual knowledge and cooperation between WP10 participants.

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Glossary and Definitions

Acronym	Meaning
A-SAP	Application-SAP
ACK	Acknowledgement
ACL	Agent Communication Language
ALM	Aggregated Local Mobility
ANDSF	Access Network Discovery and Selection Function
AP	Access Point
BEP	Bit Error Probability
BER	Bit Error Rate
BF	Beamforming
BS	Base Station
BSS	Basic Service Set
BSSID	Basic Service Set IDentification
C-SAP	Communication-SAP
CAP	Contention Access Period
CBR	Constant Bit Rate
CCC	Cognitive Control Channels
CCI	Cluster Contention Interval
CDF	Cumulative Density Function
CE	Cognitive Engine
CFP	Contention Free Period
CH	Cluster Head
CHESS	Clustered Hybrid Energy-aware cooperative Spectrum Sensing
CMS	Central Management System
CNMS	Cognitive Network Management System
CPC	Cognitive Pilot Channel
CPE	Clint Premises Equipment
CPU	Central Processing Unit
CR	Cognitive Radio
CRC	Cyclic Redundacy Code
CRN	Cognitive Radio Network
CRS	Cognitive Radio System
CSMA/CA	Carries Sense Multiple Access with Collision Avoidance
CSS	Cooperative Spectrum Sensing
CTS	Clear To Send
DA	Data Archive

DC	Duty Cycle
DCF	Distributed Coordination Function
DECT	Digital Enhanced Cordless Telecommunication
DOA	Directions Of Arrival
DSA	Dynamic Spectrum Access
DSSS	Direct Sequence Spread Spectrum
EDCA	Enhanced Distributed Channel Access
ETSI	European Telecommunications Standards Institute
ETSI RRS TC	ETSI Reconfigurable Radio Systems Technical Committee
FCC	Federal Communications Commission
FHSS	Frequency Hopping Spread Spectrum
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile communications
HCCA	Hybrid Controlled Channel Access
HCF	Hybrid Coordination Function
IEEE	Institute of Electrical and Electronic Engineers
IEEE DySPAN-SC	IEEE Dynamic Spectrum Access Networks Standards Committee
IETF	Internet Engineering Task Force
IFS	Interframe Space
ISM	Industrial, Scientific and Medical
ISM	interference shaping margins
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union Radiocommunication sector
LMS	Least Mean Squares
LOB	Line Of Bearing
LRT	Likelihood Ratio Test
LTE	Long Term Evolution
M-SAP	Measurement-SAP
MAC	Medium Access Control
MADM	Multiple Attribute Decision Making
MANET	Mobile Ad-hoc NETwork
MFNN	Multi-layer Feed-forward Neural Network
MIH	Media Independent Handover
MISO	Multiple-Input Single-Output
MT	Mobile Terminal

NO	Network Operator
PAWS	Protocol to Access White Space database
PU	Primary User
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RRC	Radio Resource Control
RSSI	received signal strength indication
RTS	Request To Send
SAP	Service Access Point
SDP	Semi-Definite Programming
SDR	Software Defined Radio
SIFS	Short Interframe Space
SM	Sensing Metric
SNR	Signal-to-Noise Ratio
SOE	Sum Of Errors
SU	Secondary User
TOA	Time Of Arrival
ULA	Uniform Linear Array
UMTS	Universal Mobile Telecommunications System
USRP	Universal Software Radio Peripheral
UWB	Ultra Wide Band
WLAN	Wireless Local Area Network
XML	eXtensible Markup Language