Formulation, implementation considerations, and first performance evaluation of algorithmic solutions – D4.1

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Abstract

This deliverable contains a first version of the algorithmic solutions for enabling opportunistic networks. The presented algorithms cover the full range of identified management tasks: suitability, creation, QoS control, reconfiguration and forced terminations. Preliminary evaluations complement the proposed algorithms. Implementation considerations towards the practicality of the considered algorithms are also included.

Keywords List

Opportunistic networks, algorithms, system requirements, technical challenges, opportunistic capacity extensions, opportunistic coverage extensions, infrastructure-less networks, traffic aggregation, mobile network operator, suitability determination, route selection, node selection, spectrum selection.

[1] Dissemination level codes: **PU** = Public
PP = Restricted to other programme participants (including the Commission Services)
RE = Restricted to a group specified by the consortium (including the Commission Services)
CO = Confidential, only for members of the consortium (including the Commission Services)

Executive Summary

The OneFIT project [1] is a collaborative research project that aims to design and to validate opportunistic networks (ON) management. The proposed solutions will provide enhanced wireless service provision and extended access capabilities for the Future Internet, through higher resource utilization, lower costs, and efficient management.

The project derived from the fifth call for proposals of the 7th framework programme (FP7) of the European Commission for research and technological development.

The purpose of this document is to define and to describe algorithms, which are necessary to realise a OneFIT opportunistic network.

These algorithms are defined in compliance with the OneFIT Functional and System Architecture (WP2). The first part (chapter 2) of this document summarises the high-level functional model that captures the different technical challenges associated to the management of ONs, identifying the corresponding functional modules.

Chapter 3 is the core of the document. It contains the description of each algorithm identified to manage an opportunistic network. For each of these algorithms, it is recalled which of technical challenges are addressed. There is also a State of the art dedicated to each proposed solution. For each algorithm a description is provided and first results obtained through simulations are presented and analysed when available.

Finally, chapter 3 summarises the most relevant conclusions of the deliverable, reflecting the six first months of work on WP4.

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Table of Acronyms

Acronym	Meaning
ANDSF	Access Network Discovery and Selection Function
AODV	Ad hoc On-Demand Distance Vector routing protocol
AP	Access Point
BS	Base Station
BSCW	Basic Support for Cooperative Work (Tool)
C4MS	Control Channels for the Cooperation of the Cognitive Management Systems
CC	Component Carrier
CCR	Cognitive Control Radio
CMON	Cognitive Management system for the Opportunistic Network
CPC	Cognitive Pilot Channel
CPE	Customer Premises Equipment
CR	Cognitive Radio
CSI	Channel State Information
CSCI	Cognitive management System for the Coordination of the Infrastructure
DOFDM	Discontiguous OFDM
DYMO	Dynamic Manet On-Demand Routing
GRP	Geographic Routing Protocol
HO	HandOver
DSA	Dynamic Spectrum Access
DSM	Dynamic Spectrum Manager
DSSS	Direct Sequence Spread Spectrum
E3	End-to-End Efficiency
EC	European Commission
ECN	Explicit Congestion Notification
FP7	7th Framework Programme
GA	General Assembly
HO	HandOver
ISM	Industrial, Scientific and Medical

JRRM	Joint Radio Resource Management
LCS	Least Channel Switching
LTE	Long Term Evolution
MANET	Mobile Ad-Hoc Network
MBF	Membership Function
MPR	Multipoint Relay
MSA	Maximum Satisfaction Algorithm
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OLSR	Optimized Link State Routing protocol
ON	Opportunistic Network
OneFIT	Opportunistic networks and Cognitive Management Systems for Efficient Application Provision in the Future Internet
PDF	Probability Density Function
POMDP	Partially Observable Markov Decision Process
QoS	Quality of Service
PC	Project Coordinator
PMT	Project Management Team
PU	Primary User
RAN	Radio Access Network
RAT	Radio Access Technology
REM	Radio Environment Map
RL	Reinforcement Learning
RRS	Reconfigurable Radio Systems
SAR	Segment Assignment Request
STREP	Specific Targeted Research Projects
SNR	Signal to Noise Ratio
SU	Secondary User
TM	Technical Manager
TVWS	TV White Space
UE	User Equipment

WP	Work Package
WMN	Wireless Mesh Network

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1. Introduction

OneFIT (Opportunistic networks and Cognitive Management Systems for Efficient Application Provision in the Future Internet) is a FP7 STREP Project aiming to design, develop and validate the concept of applying opportunistic networks and respective cognitive management systems for efficient application/service/content provisioning in the Future Internet.

Opportunistic Networks (ONs) are temporary, localised network segments that are created under certain circumstances. In the OneFIT vision, ONs are always governed by the radio access network (RAN) operator (which provides the resources, the policies and the knowledge – profiles, context, etc.), so they can be considered as coordinated extensions of the infrastructure network. ONs comprise both nodes of the infrastructure and infrastructureless devices. In previous deliverable D2.1 [2] five scenarios of applicability of ONs were identified, namely “Opportunistic Coverage Extension”, “Opportunistic Capacity Extension”, “Infrastructure supported opportunistic ad-hoc networking “, “Opportunistic Traffic Aggregation in the RAN” and “Opportunistic Traffic Aggregation in the Backhaul”. For each scenario different use cases were listed in which the ON concept can bring benefits to the different actors in the wireless networks arena.

Starting from the characteristics and needs related to the identified scenarios, a set of system requirements and technical challenges associated to the different stages in the management of an ON were also derived in D2.1 [2], from which the definition of the OneFIT functional and system architecture was developed in deliverable D2.2 [3]. Particular focus was given to the two most relevant building blocks of the architecture, which are the Cognitive management System for the Coordination of the infrastructure (CSCI) and the Cognitive Management system for the Opportunistic Network (CMON), since they include most of the functionalities to manage the ONs in their different stages.

The Control Channels for Coordination of Cognitive Management Systems (C4MS) constitute another key element for the operation of the ONs by enabling the delivery of guidance/assistance information from infrastructure towards the ONs and providing means for their management. C4MS concept was developed in deliverable D3.1 [4].

In the framework of the above precedents, this document is the first deliverable of the work package 4, whose main objectives are to conceptualize, formulate, develop and evaluate algorithmic solutions for the CMON and CSCI entities, in order to enable them to accomplish the different management tasks associated to the ONs. Proposed solutions need to be synchronized with the C4MS in order to pose requirements for the interface design, as well as fully exploit the information that C4MS carries. With these objectives in mind, the D4.1 deliverable will address mainly the following points:

- The identification of the main items on the specific requirements related to the creation, maintenance and termination of the opportunistic networks.
- The proposal of algorithmic solutions to solve these identified items.
- Preliminary evaluations of the performance achieved by the proposed solutions in the context of the considered scenarios
- First consistency evaluation in relation to the C4MS interface definition in deliverable D3.1 [4], through the identification of those information elements to be delivered through C4MS.

The rest of the document is organised as follows. Chapter 2 summarises the high-level functional model that captures the different technical challenges associated to the management of ONs. Based on this functional model, Chapter 3 contains the description of each identified algorithm to manage an opportunistic network. Each algorithm is associated to a number of technical challenges in the management of the ONs and the corresponding mapping to the use cases and scenarios identified in Deliverable D2.1 is provided. After the presentation of the state of the art associated to each algorithmic solution, the corresponding algorithms are described including the associated considerations on implementation. The performance evaluation plans are presented and, when available, initial results are given. Finally, the requirements for global consistency associated with C4MS are listed. Conclusions of the deliverable are summarised in Chapter 4.

2. High-level functional model

This chapter derives the functional model associated to an ON that will serve as a framework for the different algorithms presented in Chapter 3.

Due to the feature of being operator-governed, the life cycle of an ON comprises the following phases: (1) Suitability determination, where the operator assesses the convenience of setting up a new ON according to the triggering situation, previous knowledge, policies, profiles, etc., (2) Creation, which includes the selection of the optimal, feasible configuration (i.e. selection of the participant nodes, the spectrum and the routing pattern) for the new ON, (3) Maintenance, which involves monitoring and controlling the QoS of the data flows involved in the ON, as well as performing the appropriate corrective actions when needed and (4) Termination, when the motivations for the creation of the ON disappear or the ON can no longer provide the required QoS and, therefore, the operator will provide the mechanisms to handle the handovers and to keep applications alive if it is possible. The sequential view of the ON management and decision making process is summarized in Figure 1. A more detailed description of the main management stages in the ON life cycle is provided in the following:

1) Suitability determination: Based on the observed radio environment and some established criteria, this stage will decide the time and place where it is suitable to set-up an ON. The suitability assessment is the result of a rough feasibility analysis in order to keep complexity moderate. The suitability determination analysis will be initiated by a suitability determination trigger. Typically, this will be a pre-established criterion. This functionality will require acquiring the pertinent inputs from context awareness and dynamically detecting when the criterion is met. Once the trigger is activated, the following functionalities are identified:
    a) Identification of potential nodes. In order to devise which nodes may form the ON, there is the need to include discovery procedures leading to the identification of candidate nodes with certain associated characteristics (capabilities, location, etc.).
    b) Identification of potential radio paths. Based on identified potential nodes, it is important to derive the proper routes across the nodes forming the ON. There is the need to introduce mechanisms leading to the identification of spectrum opportunities that also ensure that the resulting interference conditions are acceptable.
    c) Assessment of potential gains. Based on the potential nodes and radio paths specific metrics to quantify the gain that can be achieved by the ON will be computed.
2) Creation: The suitability stage will provide one or several possible configurations for an ON, whose feasibility and potential gains have been roughly estimated. With these positive expectations, the creation stage will perform a detailed analysis (thus probably requiring additional context awareness and/or more accurate estimations related to diverse aspects of the radio environment). Therefore, the same functionalities as for the suitability determination stage are identified, although the specific algorithmic solutions are envisaged to be different. The creation stage will eventually take the decision on whether to set-up an ON or not. In positive case, all the necessary procedures and associated signaling will be triggered.
3) Maintenance & Termination: The ON will be dynamic in nature during all its operational life-time. Capabilities for the ON reconfiguration will provide the necessary adaptability to changing conditions. Correspondingly, this stage comprises the following elements:
    a) Monitoring. This will dynamically acquire all the relevant information that may influence decision making processes around the ON (i.e. Monitoring module will feed Reconfiguration decisions module). Relevant changes include changes in nodes,

spectrum, finalisation of an application, changes in the gains achieved with the ON, etc. The observation of the finalisation of end-users' applications will lead to a termination decision and the corresponding signaling will be triggered in order to release the resources used by the ON.

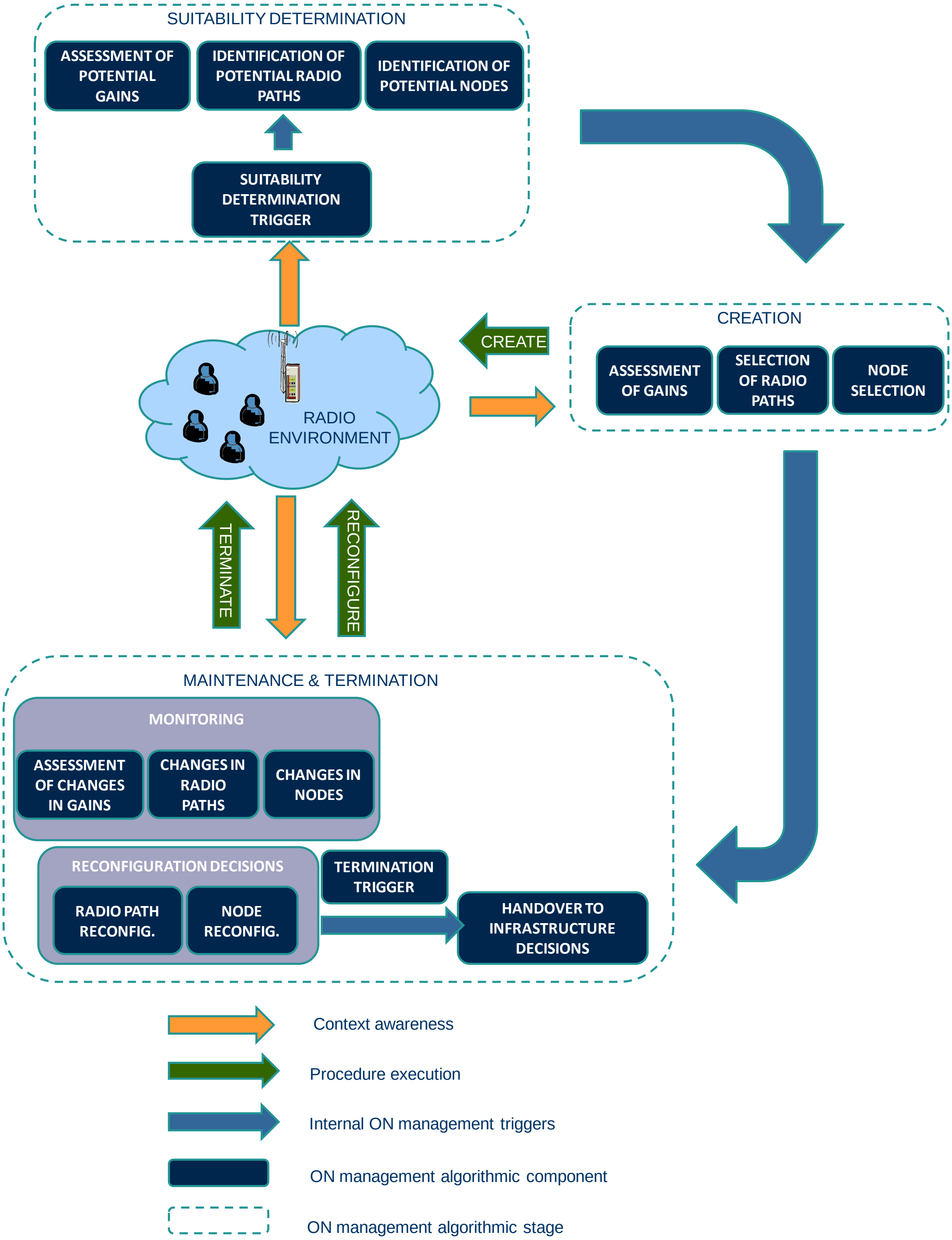


Figure 1: Sequential view of the ON management and decision making process

b) Reconfiguration decisions. This will decide on all the appropriate changes at the ON configuration in order to achieve the most efficient operation of the ON. Reconfiguration decisions will be supported by other functionalities like discovery procedures for the identification of new nodes, identification of spectrum opportunities, etc. Reconfiguration decisions will be executed using the procedures and associated signaling specified in the system.

c) Handover to infrastructure decisions. If a termination decision has already been made (e.g. assessment that the gains achieved with the ON are inadequate, forced termination due to inability to maintain the ON with the desired QoS, etc.) but there are on-going services that are expected to survive ON termination, handover decisions are needed to properly transfer on-going services via the network infrastructure (e.g., selection of infrastructure nodes, selection of the services to be handled, modification of QoS settings, etc.).

It is worth noting that the core functionalities to be undertaken along the ON life cycle are related to (1) Nodes (i.e. who is around the ON), (2) Radio paths (i.e. what communications means can be considered and how to establish communications around the ON) and (3) Assessment of gains (i.e. where and when the observed conditions advise to be supported by means of an ON). Clearly, while keeping some degree of commonalities, the specific algorithmic component to be considered for each of these core functionalities at the different ON management stages is expected to be different. This is illustrated in Figure 2.

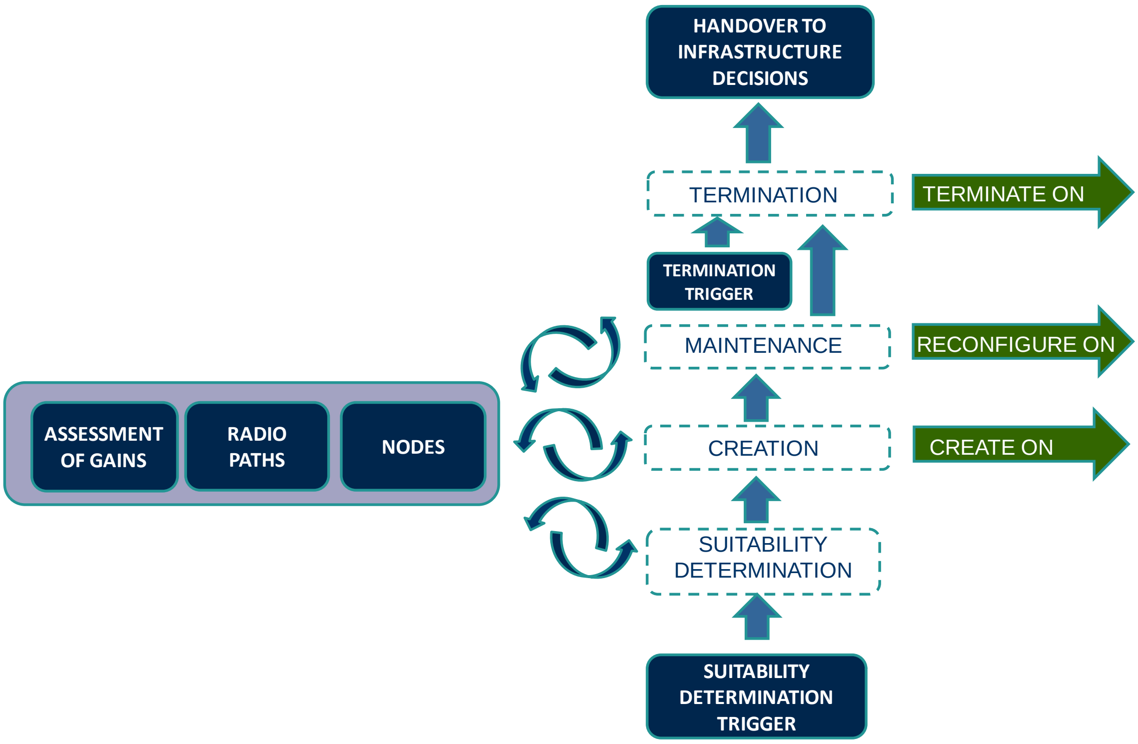


Figure 2: Functionalities along the ON life cycle

3. Algorithms description

3.1 Overview

This chapter describes the algorithms to be developed and implemented. The purpose of these algorithms is to answer to the different technical challenges of the different stages of the ON lifecycle identified in chapter 2. To be consistent, while some of these algorithms are related to several system functions identified in the functional model, the organisation of the algorithms in this section considers the main addressed function. The list of algorithms is given below:

Suitability determination

1. Discovery of terminals supporting opportunistic networks
2. Spectrum opportunity identification and selection
3. Machine learning based knowldege acquisition on spectrum usage
4. Techniques for aggregation of available spectrum bands/fragments
5. Knowledge based suitability determination
6. UE to UE Trusted direct path

Creation

7. Selection of nodes and routes
8. Route pattern selection in ad hoc network
9. QoS and Spectrum aware routing techniques
10. Application cognitive multipath routing in wireless network

Maintenance

11. Multi-flow routes co-determination
12. Techniques for network reconfiguration - topology design
13. Content conditioning and distributed storage virtualization/aggregation for context driven media delivery

It has to be noticed that there is no specific algorithm related to the “ON Termination” function, but the associated procedures are implicitly included in the other algorithms. Other algorithms related to the “ON Termination” function would be defined later, if it is identified that this function requires specific behaviours, which are separated from the “ON maintenance” function.

3.2 Algorithm on discovery of terminals supporting opportunistic networking

3.2.1 Technical challenge addressed

This algorithm focuses on the technical challenge to efficiently discover candidate terminals in a given geographical area, which are supporting opportunistic networking.

3.2.2 Rationale

Opportunistic networks can comprise network elements of the infrastructure as well as terminals.

The focus of this algorithm is to improve the candidate node discovery procedure of terminals. Investigations on improving discovery procedures of infrastructure elements are not evaluated because the network elements of the infrastructure have already established a relationship with each other during the node start-up procedure.

An efficient discovery of candidate nodes is required in order to have an efficient creation and maintenance of the opportunistic networks.

3.2.3 Use cases mapping

Traditional discovery procedures need to be extended with information if a node is supporting opportunistic networking for the scenario 1 “Opportunistic coverage extension”.

Further improvements to the discovery procedure can be made by providing guidance from the infrastructure, e.g. about other terminals in the vicinity, their location and supported/active frequencies. Such an improved procedure is relevant for scenario 2 “Opportunistic capacity extension”, scenario 3 “Infrastructure supported ad-hoc networking” as well as scenario 4 “opportunistic traffic aggregation in the radio access network”.

3.2.4 State Of The Art

Two types of procedures are typically used for the discovery:

a) Discovery procedure using broadcasting

The most common discovery procedure is that one node (e.g. a base station, a WLAN Access Point or a terminal in an ad-hoc network) sends out broadcast information while other nodes are listening on such information.

Dependent on the radio access technology, different methods are used to broadcast information:

- Beacons are used e.g. in 802.11 WiFi networks [5] to periodically send out information like Service Set Identifier (SSID), timestamp, supported data rates and capability information. Beacons are sent out by access points as well as typically by at least one node in an ad-hoc network.
- Broadcast messages are used by base stations (e.g. GSM, UMTS, LTE) to provide cell-related information to all users in a cell.

b) Discovery procedure using probing

A node (e.g. a terminal) sends out a discovery-request (e.g. probe-request in 802.11) and waits for a discovery-answer (e.g. probe-response in 802.11). Such a discovery response typically contains information like capability information and supported data rates.

3.2.5 Algorithm description

To improve the terminal discovery procedure, additional information shall be provided by extending existing discovery messages (broadcast/beacons/probes) and/or to provide it via an existing link from the infrastructure.

The following cases can be distinguished:

a) Reuse of existing discovery procedures (reference case)
b) Extend existing beacons/probes with information if opportunistic networking is supported
c) Extend existing beacons/probes with information if opportunistic networking is supported as well as further information or restrictions, e.g. with which operator opportunistic networking is supported
d) In addition to the previous procedures, further information is provided by the infrastructure, e.g. on which RAT and frequencies to scan first.

Figure 3 shows a discovery procedure using probes in the example for scenario 1 “opportunistic coverage extension” where UE1 is out of coverage of the infrastructure. In such a scenario, no guidance can be provided by the infrastructure but the probe message can be extended with information on what kind of opportunistic network is intended to be created.

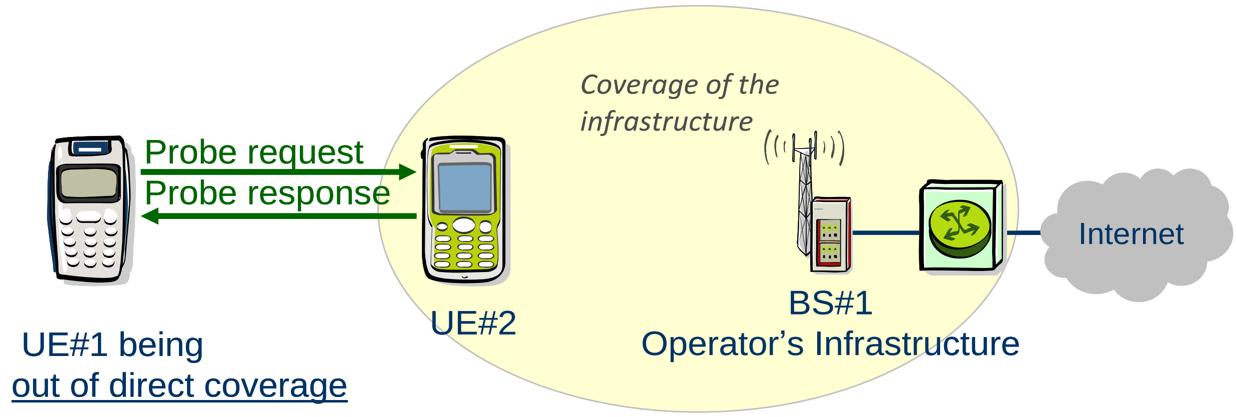


Figure 3: Traditional discovery procedure using probes

Figure 4 shows a discovery procedure which is guided by the infrastructure. In this example, UE#1 is instructed via C4MS to send out probes on a given RAT and frequency while UE#2 is instructed to listen on probes on the same RAT and frequency. Both UEs report the results back to the infrastructure so that the infrastructure can make further decisions for the creation of an opportunistic network.

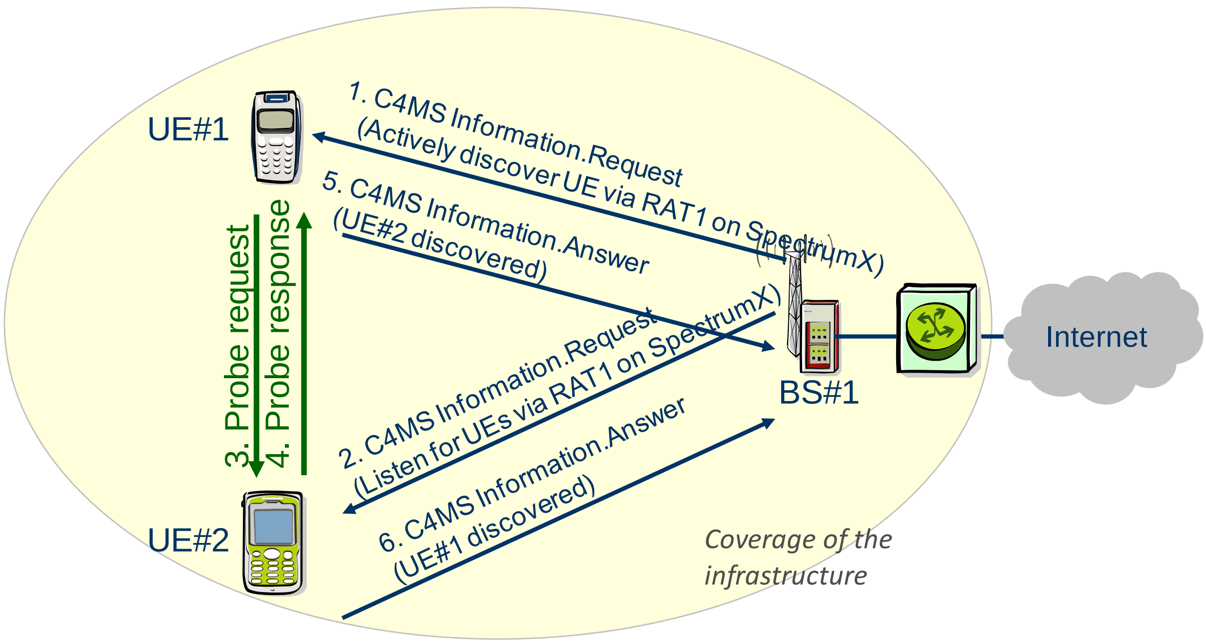


Figure 4: Infrastructure supported discovery

3.2.6 Algorithm evaluation

3.2.6.1 Evaluation Environment description

For the evaluation of this algorithm, three different methods are under implementation or investigation.

a. Analytical evaluation: In a first step, a theoretical analysis is made on how much information needs to be exchanged. This includes an analysis on the number of messages to be exchanged and the typical number of bytes for these messages.

b. Simulation: A comparison of the different algorithm options by using a simulation is under development. For this evaluation, the Opportunistic Network Environment (ONE) simulator [6] is used as base. The ONE Simulator allows to simulate when moving terminals are in a range that they can discover each other and to simulate when the discovery procedure is active or when the discovery procedure is switched off in order to save energy.
c. Validation: In cooperation with WP5, it is intended to validate these algorithms also in a prototype.

3.2.7 Requirements on the C4MS protocol definition & technical challenges

The infrastructure shall be able to retrieve discovery information from a terminal. If not already active, the terminal may have to activate discovery procedures (e.g. probing) for this procedure.

3.3 Spectrum opportunity identification and selection

3.3.1 Technical challenge addressed

Spectrum is one of the key resources in the creation of an ON. The suitability of a spectrum band for the creation of an ON can be measured with many different criteria. Some bands may be strictly restricted of such use e.g. based on policies or the node capabilities. There are also characteristics that may make some spectrum band more suitable for the creation of an ON than others. These characteristics may be related e.g. to the other services existing on the frequency band. The selection of the frequency band for the creation of an ON from a set of bands is illustrated in Figure 5 and further elaborated below.

Figure 5: Selection of the spectrum band for the creation of an ON and the necessary input.

A set of bands **X** consists of all possible bands that can be used for creating an ON. Restrictions to the set of bands come from policies which determine the allowed frequency bands. In addition, this set is restricted to the bands that nodes are able to utilize. Depending on the approach, the initial set of bands can include all the bands that are supported by all the nodes that have indicated to be available for the creation of an ON or only the bands that are supported by the node selected for the creation of an ON. This naturally depends on the order in which the selection is made, whether the nodes or the spectrum band is selected first. The selection of the nodes before the spectrum band reduces the amount of spectrum that needs to be checked for the availability and can reduce the delay significantly especially in the case that the number of nodes available for the creation of an ON is high and the supported frequencies diverse. On the other hand, in the worst case it can lead to a situation where none of the bands supported by the nodes selected for the creation of an ON is available and the node selection procedure has to be initiated again. Also the spectrum band can be used as one of the criteria for selecting the most suitable nodes for the creation of an ON and by doing this improving the throughput of the ON.

From the set of bands **X**, a subset $\mathbf{X}_i$ is selected based on the availability of the bands. The method used for checking the availability of the channel – cognitive control channel, local/global data base or spectrum sensing – is mandated by the policies on the different bands. At this stage there can be several bands on which the availability needs to be checked and methods for different bands can vary. Also a combination of the methods can be used e.g. cognitive control channel can be used for transmitting data from a data base or spectrum sensing results. In case spectrum sensing is used, the selection of the most suitable sensing method based on the operational SNR, available time, the amount of a priori information and required detection probability can be made using an algorithm further described in Section 3.3.5.1. In case spectrum sensing results are gathered from several nodes in the vicinity, by combining these results additional information can be obtained on how reliable the information on the availability is on different bands.

From the available bands, the spectrum band for the creation of the ON is selected. The selection may be influenced by factors such as channel idle time prediction based on history information, policies and channel conditions. Channel prediction is done by using channel occupancy information from the past time periods. This history information about channel usage can be obtained e.g. from local database and gathered by sensing nodes that sense the spectrum. The period over which the history information is gathered may vary significantly e.g. over one week or couple of seconds. Channel prediction can be considered as a form of learning which gives an approximation of the length of the idle time in the vacant channel. This approximation can be used as a criterion for selecting the most suitable spectrum band for the creation of an ON. The longer the idle period, the less channel changes need to be performed during the lifetime of an ON. Channel changes introduce additional delay and control signalling at the ON and may result to a decreased QoS experience of the user or even a break in the delivered service in case new spectrum band is not immediately available.

There are also other factors than the length of the idle period that may cause operator to favour some bands over the others. Operators may have and update a preference list of the bands and place priority based on e.g. the price of the usage. One simple example would be to use own bands whenever available. Also this list may be updated based on learning from the past experience.

Policies also influence the decision on the most suitable band for the creation of an ON. Policies mandate e.g. the allowed transmission power, time and bandwidth on different spectrum bands and by doing this make some bands more appealing candidates for the creation of an ON than others. Policies may also indicate how often a channel should be sensed to avoid excess interference to the existing services. In principle, the period after which the spectrum needs to be sensed again depends on the existing services on that band and their interference tolerance time. Additionally, the operational SNR on different bands may play role in the selection of the most favourable spectrum band for the creation of an ON.

Under the above framework, this chapter presents some algorithms to address the spectrum opportunity identification and selection in the context of the ON formations. For that purpose, after stressing the mapping of this functionality with the scenario/use cases defined in deliverable D2.1 [2] and with the ON management stages presented in section 2, this chapter will present first in section 3.3.5 an algorithm based on a modular decision flow to select the adequate spectrum band as well as the spectrum sensing technique to enable the spectrum opportunity identification, and then in section 3.3.8 an algorithm for spectrum selection based on the fittingness factor concept.

3.3.2 Rationale

Based on the OneFIT concept, ONs are created in an infrastructure-less manner under the supervision of the operator with the main objective of ensuring application provisioning with an acceptable QoS level in the different scenarios identified in D2.1. Within the lifecycle of an ON, the technical challenge of spectrum opportunity identification and spectrum selection is necessary in the identification and selection of potential radio paths to establish the ON, as well as in the assessment of gains that can be achieved by the ON in accordance with the selected spectrum for each path.

More in detail, and focusing on the lifecycle that was presented in Figure 1, it is considered that the spectrum opportunity identification will be used in the suitability determination stage to check the availability of spectrum to enable the ON formation, while the specific spectrum selection will be made in the ON creation. Similarly, during the maintenance stage spectrum opportunity identification and spectrum selection will be executed to decide on possible reconfigurations of the ON.

3.3.3 Use cases mapping

The technical challenge of spectrum opportunity identification and spectrum selection is relevant to all the use cases identified in the scenarios of D2.1 [2], in which a spectrum needs to be selected to set-up the different links of an opportunistic network.

3.3.4 State Of The Art

In the context of Cognitive Radio (CR), Spectrum Selection refers to the functionality intended to choose the most adequate spectrum band to carry out a CR transmission. This selection should be made based on the characteristics of the channel in terms of e.g. the capacity that can be obtained by CR users, the CR user requirements and also taking into consideration the maximum interference that can be tolerated by other receivers. Interference considerations affect to other CR users and also to primary users in the particular case where CR addresses spectrum sharing between primary and secondary users in a Dynamic Spectrum Access (DSA) context. Spectrum selection process has to be executed either when a given CR transmission needs to be started or as part of the more general spectrum mobility procedures, in which an ongoing communication needs to be transferred to another channel (i.e. a spectrum handover procedure) due to e.g. the fact that the current channel becomes unavailable.

Spectrum selection functionality should be executed taking as input the frequency bands that are available for establishing a CR communication. These bands should be obtained by the Spectrum Opportunity Identification functionality. Following the classical cognition cycle defined by J. Mitola in [7] to enable the interaction with the environment and the corresponding adaptation of a CR system, Spectrum Opportunity Identification functionality can be understood as part of the "observation" stage in which the CR system achieves the necessary awareness level on its environment to make the appropriate decisions. The resulting "spectrum awareness" targeted by the Spectrum Opportunity Identification consists then in identifying the available spectrum bands and associated features that will allow evaluating the necessary elements for the spectrum selection, namely achievable capacity and generated interference.

From an initial perspective, spectrum awareness can be achieved by spectrum sensing mechanisms. A lot of different spectrum sensing techniques have been studied in the last years, such as the energy detector, which does not include any specific knowledge about the primary signal to be detected, the matched filter detection, which requires the knowledge of the specific primary signal formats, or the cyclostationarity feature detection. Also the possibility of combining sensing measurements from different sensors through appropriate fusion schemes has been considered in the so-called cooperative sensing. Surveys of different spectrum techniques can be found in references such as [8][9][10].

From a more general perspective, there has been a recent trend towards improving the awareness level of CR systems by strengthening their observation sub-systems beyond what can be obtained only by sensing techniques. Specifically, there has been an interest in recording, storing and accessing new relevant information about the external environment. For instance, Radio Environment Maps (REMs) have been proposed as new information sources that can assist cognitive operation by considering multi-domain environmental information [11][12][13]. REM is envisioned as an integrated space-time-frequency database consisting of multi-domain information, such as geographical features, available services, spectral regulations, locations and activities of radios, relevant policies, and experiences. By adequate query/answer procedures through control channels CR nodes can access to the REMs and receive the needed information to make their decisions.

The increase in the cognitive awareness level retained in the REM, particularly with respect to the temporal behavior of the different channels, can make the cognitive operation much more efficient.

In this respect, spectrum management tasks such as spectrum decision and spectrum mobility can substantially benefit from the knowledge stored in the REM. In particular, in [14] a set of statistics to capture temporal evolution of spectrum bands is proposed and the possibility to exploit them in the spectrum selection for a scenario with primary and secondary users is analysed. These statistics include not only the more intuitive elements such as averages of activity/inactivity periods and duty cycles, but also more advanced statistics to capture correlation structures in the temporal/frequency domain. In fact, recent measurement campaigns [15] have revealed that primary channel vacancy durations are not independently distributed over time, and that significant temporal, spectral and spatial correlations exist between channels of the same service. Focusing on the time perspective, other empirical measurements [16] have shown that, in addition to the expected daily/weekly periodicity of activity (ON) and inactivity (OFF) processes of the Primary Users (PUs), some correlation is observed between consecutive ON/OFF periods depending on the band of interest and the considered traffic conditions.

Focusing on the spectrum selection function, its optimization to avoid interference to legacy services has also received much attention in the last years. For instance, an analysis of the effect of multiple Primary Users (PUs) on the Secondary-User (SU) channel selection policy has been conducted in [17]. Considering heterogeneous PUs in terms of activity statistics and protection requirements, this work has determined the limits on successful SU transmission time, and evaluated the corresponding impact on the channel selection problem. The work in [18] has studied spectrum selection implications in a multi-channel radio network. Specifically, it has considered a general setting where PUs are un-slotted and may have different idle/busy time distributions and protection requirements, and has devised an optimal secondary access policy in the considered multi-channel scenario. In another proposal considering a multi-channel context [19], more attention has been paid to the challenging issue of the bandwidth selection. Specifically, the optimal bandwidth scheme that maximizes the secondary throughput has been determined for both the single and multiple secondary cases subject to channel switching cost. In [20], a more general channel aggregation capability where disjoint bands can be used has been considered. Specifically considering the Discontiguous OFDM (DOFDM) technology and assuming a maximum span for an aggregated channel, an aggregation-aware selection scheme that utilizes disjoint bands has been proposed and assessed.

Even though the aforementioned proposals have been proven to successfully deal with the issues they are meant to, most of them have assumed that SUs have strong knowledge about primary systems, which is not guaranteed in practice. In order to overcome this practical limitation, there has been a trend towards learning-based SU spectrum selection. More specifically, much attention has been paid to on-line RL (Reinforcement Learning) algorithms known to be suited for distributed problems as they could determine optimal policies without a detailed modeling of the environment. For instance, [21] has proposed a RL-based detection of spectral opportunities in an OFDM cognitive network subject to switching costs. The spectrum selection problem is subdivided in this paper in two steps, the detection of the spectral resources that generates a coarse overview of the available resources in the different frequency bands, and the detection of the PU’s system allocation that identifies the detailed available channels in a given band. RL mechanisms are applied to the first step, allowing the system to learn among three different actions, namely to continue transmission in the current band, to perform a detection phase in a different band while keeping transmission in the current band, and to switch transmission to a different band. In general, heterogeneity among the different channels needs to be taken into account in the spectrum selection problem. In that respect, elements such as channel diversity in terms of transmission range, packet error rate and primary utilization, etc have been considered in [22]. In this proposal, a RL heterogeneous channel selection scheme has been developed and proven to outperform the random assignment in terms of throughput and channel switching. Considering a different architecture where spectrum is modeled as an auction market, the work in [23] has proposed to make SUs compete for available channels using a Q-learning-based bidding strategy. Assuming multiple SUs and a single PU, results have shown that the proposed Q-learning-based auction can significantly improve SU's bidding strategies and, hence, the performance in terms of packet loss and transmission rate.

Most of these RL-based proposals do not require any a-priori knowledge about primary systems, but simply adapt secondary behavior based on the observed primary behavior, which solves the problem of practicality. Nevertheless, some basic knowledge about primary systems may be acquired in practice which would allow a better exploitation of the spectrum opportunities. Therefore, there has been a recent trend towards an intermediate approach that neither assumes perfect knowledge about primary systems, nor ignores useful information that may be available, in particular characterizing the primary activity. For instance, the work in [24] has proposed to assist the spectrum selection making process by an external database that provides information about the most probably un-occupied channels. It has been shown that by combining database queries and spectrum sensing reports, the proposed approach can outperform random channel search especially when there are a lot of occupied channels. It has been shown that by combining database queries and spectrum sensing reports, the proposed approach can outperform random channel search especially when there is a lot of occupied channels. However, as it has been identified by the authors, the obtained performances remain highly dependent on the validity of the information given by the database. In [25], multi-time scale predictive primary statistical models are built at different time scales based on sensing reports. Based on these models, "bad channels" are eliminated through a usability filter, and a pro-active spectrum access scheme that maximizes spectrum utilization while minimizing the occurrence of disruptions to PUs is proposed and assessed. In [26], renewal theory has been applied on past channel observations in order select channels with the longest expected remaining idle period. In [27], a statistical model that predicts lengths of primary spectrum holes is developed. Based on this model and on secondary service Quality of Service (QoS) requirements, a prediction-based spectrum decision algorithm has been proposed and has been shown not only to meet secondary QoS requirements but also to enhance the overall performance of CR networks. These works have been extended in [28] where primary randomness level is considered. Specifically, a simple classification method has been first applied to qualify primary traffic as periodic or stochastic. For each of the detected randomness levels, remaining idle times of primary channels have been estimated and a channel selection scheme that maximizes remaining idle times has been proposed and assessed. Results have shown that the proposed classification-based approach significantly reduces the amount of collisions with PUs compared to a system operating without classification. All these proposals exploiting primary activity statistics have considered a single secondary service type. Nevertheless, a joint optimization of spectrum selection for heterogeneous secondary applications has been considered in the spectrum decision framework proposed in [29]. Thanks to a joint consideration of primary activity statistics and secondary requirements, different spectrum selection criteria have been proposed for a set of heterogeneous secondary applications. Specifically, a minimum variance-based criterion is chosen for real-time applications while a maximum capacity-based criterion is selected for best-effort applications. Results have shown that the proposed criteria result in efficient bandwidth utilization while satisfying service requirements.

Apart from most of the aforementioned proposals that have independently optimized spectrum selection, others have jointly considered it with other challenging issues. For instance, many early proposals have considered a joint optimization of spectrum sensing and spectrum selection that intelligently schedules spectrum sensing and spectrum access events. To cite a few, [30][31] have developed a Partially Observable Markov Decision Process (POMDP) framework that formulates the sensing/transmission decision problem. Specifically considering a slotted PU network, optimal sensing and access decisions have been determined based on observation history. The proposed POMDP framework for sensing and access has been extended to un-slotted setting in [32]. Spectrum sensing and spectrum selection have also been jointly considered in [33] for minimizing energy consumption of cognitive sensor nodes. An energy-aware stochastic control problem has been formulated and proven to result in significant energy gains with respect to algorithms that sense all the available channels. In [34], sensing/transmission scheduling has been considered in multiband cognitive radio networks. It has been formulated as an optimization problem that jointly selects sub-channels and spectrum sensing times and has been solved by a semi-analytical optimization.

Apart from sensing issues, it has been argued that, given the specificities of cognitive radio networks, spectrum would be better selected along with all other transmission parameters. Therefore, many cross-layer resource allocation frameworks where all transmission parameters (channel, power, rate, etc.) are jointly determined have been developed [35]-[37]. Most of these proposals have assumed that the channel state information (CSI) over the interference link between SUs and PUs is fully available in order not to disturb PUs. However, such assumption does not hold in practice. In order to overcome this limitation, authors in [38] have developed a resource allocation algorithm that exploits location information in order to estimate the interference at PUs. Specifically considering OFDMA cognitive radio systems, it has been shown that near-optimal capacity can be achieved without any knowledge of CSI of interference links.

Another set of proposals have considered spectrum selection with an emphasis on resolving the spectrum sharing issues among SUs. In this context, game theory has been extensively used in order to manage spectrum resources among a set of competing SUs. To cite a few, the work in [39] has formulated a dynamic non-cooperative game among SUs that accounts for the time-varying primary activity, and has evaluated the quality of the corresponding Nash equilibrium. In [40], spectrum selection and power allocation have been jointly considered in order to control the aggregate interference caused to PUs in a cross-layer design. Specifically, a potential game model has been formulated to solve the allocation problem where each SU selects in a distributed way the operating channel and transmitting power to maximize a given objective function. Results have shown that the total throughput can be improved while introducing fairness in the cognitive radio network.

3.3.5 Description of modular decision flow based approach

At this section the combined carrier frequency, RAT and bandwidth selection mechanism which takes into consideration application requirements, policies, RAT capabilities, velocity, and spectrum has been studied. The situation where an opportunistic network is able to use all spectrum bands (e.g. ISM, IMT, TV-bands, GSM, 60 GHz) depending on the user equipment (UE) capabilities has been considered. To our knowledge this kind of setting is novel and has not been studied before.

The modular decision flow for selecting the best frequency, RAT and bandwidth combination for ON usage begins when the Cognitive management System for the Coordination of the Infrastructure (CSCI) starts the suitability determination phase.

Figure 6 presents the proposed framework. At the beginning a set of bands *X* which consists of all the possible bands that are allowed to be used for creating an ON is considered. Thus, it includes bands allowed by the policies, bands available according to a database, as well as bands that are supported by the nodes selected or candidates for the creation of an ON. Depending on whether the nodes or the spectrum band is selected first, the initial set of bands can include the bands supported by the nodes that have indicated to be available for the creation of an ON or the bands that are supported by the nodes selected for the creation of an ON. Information about possible available TV channels can be acquired from the database. This further diminishes the initial set of bands since only channels that seem to be available according to the database are kept in the initial set.

The set X is further limited by eliminating the bands that do not fulfil the power requirements as follows. A set of bands X_p is formed by rejecting all bands that do not support the required transmission power level. This is achieved by using Friis equation [41] and Shannon capacity equation. As a result the required transmission power is obtained. This required transmit power is compared with a transmit power constraint at each band. A band that does not support adequate transmit power is eliminated from the set of bands X and remaining bands form a new set of bands X_p.

The fast channel variations that depend on the speed of the UE have been taken into consideration. Supported UE velocity depends on used frequency. The faster the UE moves the larger is the Doppler shift [42]. The maximum allowed velocity depends on required transmitted symbol duration T_s. To avoid a fast fading distortion the used signalling rate $1/T_s$ has to be much greater than maximum Doppler shift f_d. A coherence time T_0 is the time that channel's response characteristics are considered to maintain unaltered. The relation between the coherence time and the Doppler shift is used to calculate the upper bound for the possible carrier frequency [43].

The upper bound for the acceptable center frequency f_c can be calculated if the UE velocity and the RAT symbol rate are known. Frequency bands that exceed this upper bound are eliminated and the rest of the bands form a set of bands X_v.

Candidate RATs are selected so that first a group of suitable RATs is formed by the RATs supported by the selected or candidate nodes to form the ON and the RATs that support a given application and fulfil the transmit power P_t requirement. The next step is to calculate a bandwidth that is required to fulfil the application bit rate. The application bit rate and the spectral efficiency of each RAT are known. Using these two parameters we can calculate the required bandwidth $W_{r,i}$, $i = 1,\ldots,M$ for each RAT denoted by R_i. Each required bandwidth is compared with each possible channel bandwidths $W_{s,k}$, $k = 1,\ldots,N$ of each band B_k, $k = 1,\ldots,N$ of set of bands X_v. Figure 7 shows how a required bandwidth $W_{r,1}$ of a RAT R_1 is compared with all possible bandwidths $W_{s,k}$. If a spectrum band's supported bandwidth corresponds to a required bandwidth, it forms a three parameter combination including a RAT and a required bandwidth as shown in the figure e.g. in upper part of the figure, for the requirement R_1, $W_{r,1}$, the spectrum bands that support the required bandwidth $W_{r,1}$ are marked with red circles. The possible bands are B_1 and B_{N-1}. The resultant RAT, bandwidth and band combinations are R_1,$W_{r,1}$, B_1 and R_1, $W_{r,1}$, B_{N-1} . In the lower part of the figure, for the requirement R_2, $W_{r,2}$, the spectrum bands that support the required bandwidth $W_{r,2}$ are marked with red circles. The possible bands are B_2, B_{N-1} and B_N. The resultant RAT, bandwidth and band combinations are R_2, $W_{r,2}$, B_2; R_2, $W_{r,2}$, B_{N-1} and R_2, $W_{r,2}$, B_N. These parameters are reserved and they form a set of three parameters combination. The bandwidth comparison is continued until every RAT and required bandwidth is compared with every band's possible bandwidth. As a result we obtain a set of RAT, bandwidth and spectrum band combinations that support both the required application bit rate as well as the required bandwidth.

The next step is to form a setting of possible carrier frequencies for RAT/bandwidth combinations. After carrier frequency selection a set of carrier frequency/RAT/bandwidth combinations for further processing on next step.

At the next stage the carrier frequency/RAT/bandwidth combinations are compared to the priority list parameters. These parameters are set by the operator and their priority order depends on a used scenario and a use case. The parameters include e.g., delay, session duration, predicted spectrum idle time, and cost. For instance, it may be preferable to use the operators own bands due to reduced costs. Another example is that delay sensitive applications could have better frequency (longer predicted idle period, wider bandwidth) and RAT combinations to avoid delay. Operators can also decide that certain kind of operation gets the best carrier frequency/RAT/bandwidth alternatives e.g. the scenario 5 where an operator backhaul network resources are aggregated.

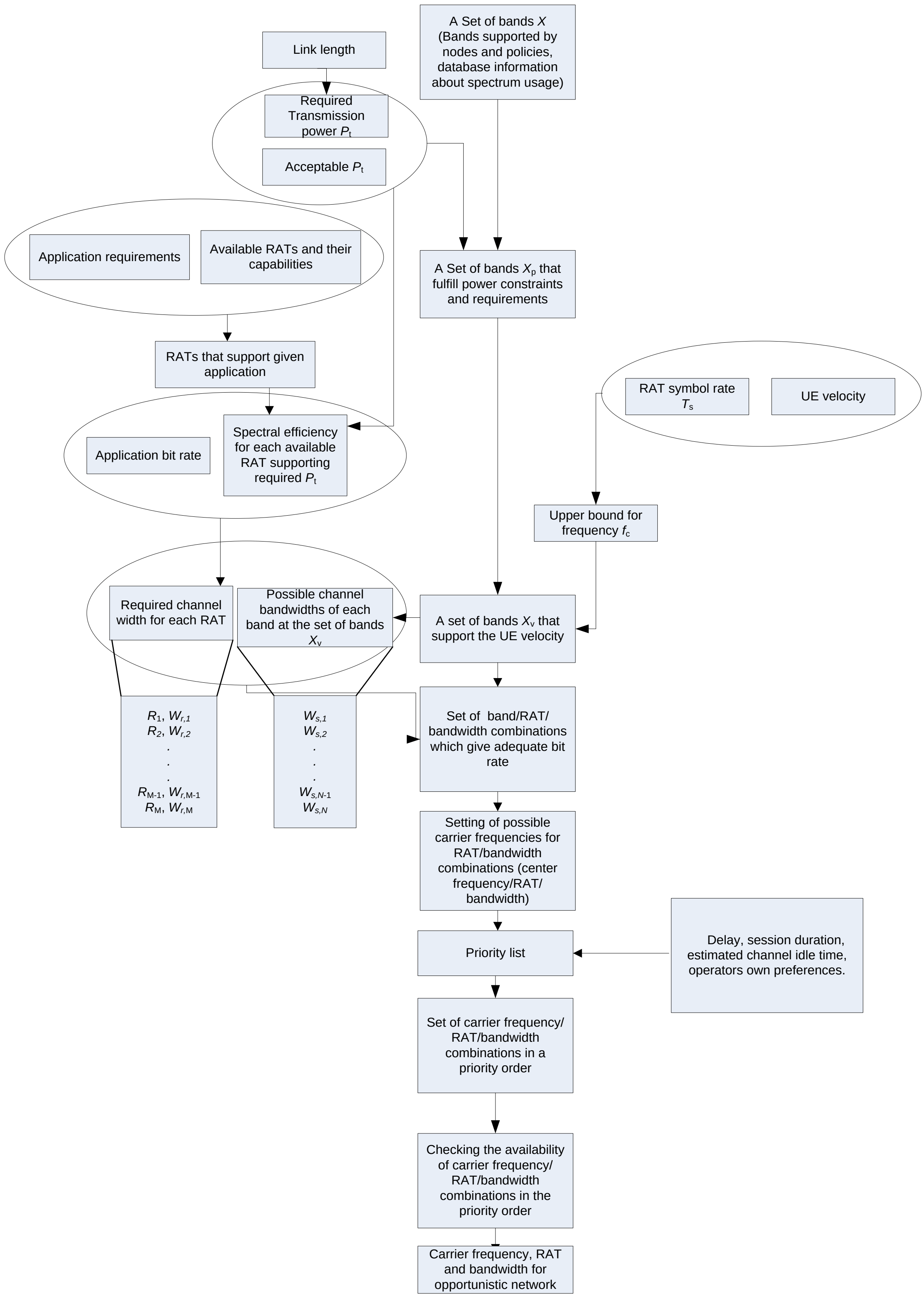


Figure 6: Framework for selecting one or more channels for ONs usage.

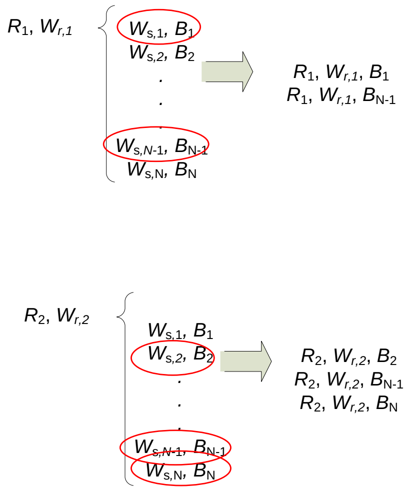


Figure 7: Formulation of three parameter combinations.

One criterion may be that bands that can rarely be used, e.g. 60 GHz band, will be used whenever possible in order to leave other spectrum free for other usage and by doing so be able to serve as many users as possible and increase the overall throughput.The priority list order and weighting of different parameters against each other can vary depending on the used scenario. At the priority list stage the carrier frequency/RAT/bandwidth combinations are arranged in a priority order corresponding to prevailing network conditions. The result is a set of carrier frequencies/RAT/bandwidth combinations in a priority order.

The last step is to check the availability of the carrier frequency/bandwidth combinations with the highest priority. The availability is examined by using spectrum sensing techniques, database or control channel depending on the policies on that band.

The outcome of this framework is selected carrier frequency, bandwidth, RAT and transmission power for the ON usage.

3.3.5.1 Decision making method for selection of spectrum sensing techniques

One of the key characteristics of cognitive radio systems is their ability to obtain knowledge of the operational environment e.g. the current state of the spectrum use. There are different techniques for obtaining this information e.g. cognitive control channels, databases and spectrum sensing techniques. The selection between these techniques is mandated by the policies and they may vary between different bands. Also a combination of techniques may be required by the regulation to guarantee the reliability of the spectrum availability information or to detect other cognitive radio systems. There are various classes of spectrum sensing techniques, such as energy detection, correlation based detection, waveform based detection, matched filter detection, and cooperative combining techniques. These techniques require different amount of a priori information, vary in complexity, and their performances are different in different situations and environments. The framework developed for the selection of a method to obtain information on operational environment has been introduced in [44] and it is illustrated in Figure 8.

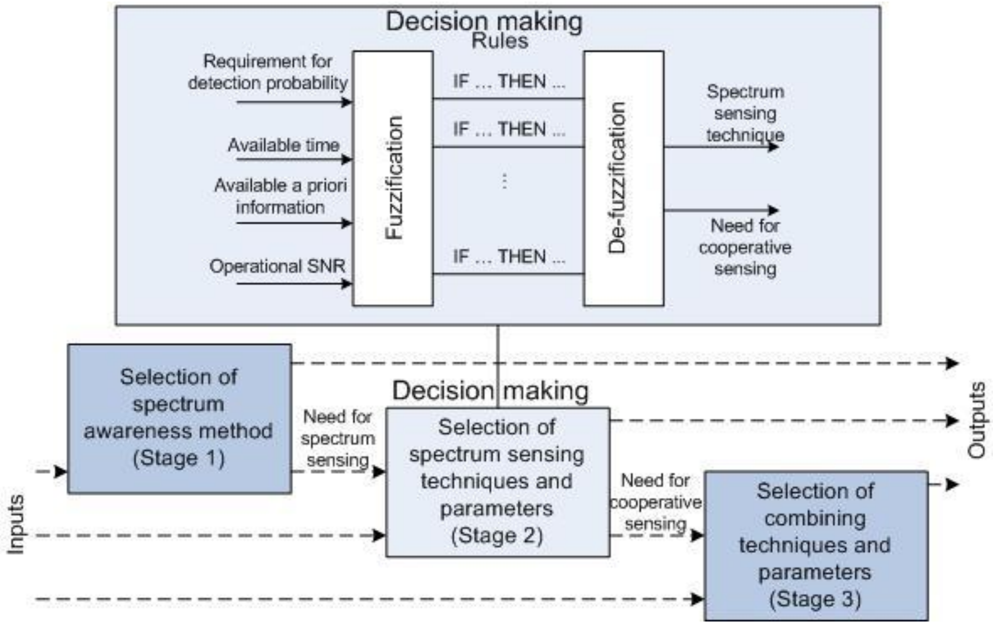


Figure 8: Decision making on the method used to obtain knowledge on the operational environment.

The algorithm considered in the research uses four input parameters to select the most suitable sensing method: requirement for detection probability, available time, available a priori information, and operational signal-to-noise ratio (SNR). One of the key performance metrics for spectrum sensing is the probability of detection, which guarantees adequate protection of other systems on the same spectrum bands. The output of the decision making is the most suitable spectrum sensing technique selected from three alternatives: energy detection, correlation based detection, and waveform based detection. In addition to these three algorithms, the output of the decision making can be that none of the considered spectrum sensing techniques is suitable for the given situation.

The heuristic decision making is done using fuzzy logic, see [45]. The process of fuzzy decision making consists three phases: fuzzification, decision making, and defuzzification. The input variables are first fuzzified using predefined membership functions (MBF). Two MBFs have been used for characterizing the input parameters, namely ‘low’ and ‘high’. Fuzzy numbers are then fed into a predefined rulebase that presents the relations of the input and output variables with IF-THEN clauses. The output of the fuzzy reasoning is a fuzzy variable that is composed of the outputs of the THEN clauses. The fuzzy variable is then changed into crisp number that is the actual result of the fuzzy decision making. Here we have used four MBFs for the output, each corresponding to a different sensing technique, i.e. energy detection, correlation based detection, waveform based detection, and no available technique. There are several methods for different phases of fuzzy decision making, and results dependent heavily on them. Additionally different kinds of shapes of MBFs affect on the decision making results. The rulebase of the fuzzy decision making system is shown in Table 1.

The development of the rule base has been based on the following assumptions. Energy detection is a fast technique, which does not need a priori information on e.g. the waveforms. On the other hand, it requires high operational SNR and is not able to fulfil high requirements for probability of detection. Correlation based detection is assumed to provide higher probability of detection than energy detection but it requires more time for processing. Operational SNR and a priori information requirements are the same for both correlation based detection and energy detection. Waveform based detection is assumed to provide high probability of detection and can operate at low SNRs. However it requires high processing time and a lot of a priori information.

Table 1. Rule base for fuzzy decision making.

Input				Output
Requirement for detection probability	**Available time**	**Available a priori information**	**Operational SNR**	**Spectrum sensing technique**
low	low	low	low	None
low	low	low	high	Energy detection
low	low	high	low	None
low	low	high	high	Energy detection
low	high	low	low	None
low	high	low	high	Energy detection
low	high	high	low	Waveform based detection
low	high	high	high	Energy detection
high	low	low	low	None
high	low	low	high	None
high	low	high	low	None
high	low	high	high	None
high	high	low	low	None
high	high	low	high	Correlation based detection
high	high	high	Low[2]	Waveform based detection
high	high	high	high	Correlation based detection

3.3.6 Implementation considerations for modular decision flow based approach

In the proposed framework, the inference is done in several separate phases. This ensures that the parameters can be managed separately.Feedback loops can be used to evaluate single input parameter influence. For instance, it is possible to use feedback loop to return from priority list to any parameter set in earlier stage. This will provide mechanism to adjust parameters either by restricting or loosening QoS requirements set at earlier stage. QoS requirements can also be restricted after each step depending on how large is the outcome set after previous elimination process. This ensures that the amount of possible outcomes is not exceedingly large and it will converge as the algorithm proceeds.

Figure 9 [3] shows how framework is mapped to the CSCI and a Cognitive Management system for the Opportunistic Network (CMON) blocks. All the input parameters related to the nodes, frequency, policy, RAT and an application are used in the suitability determination phase. Input parameters concerning node capabilities and characteristics are supported RATs, supported frequency bands, location information used to calculate the link length at the infrastructure node, and velocity. The input parameters related to frequency are estimated idle time in a frequency band, channel conditions, operational SNR, and available time for spectrum sensing. Parameters from used application are the bit rate, maximum allowed delay, and estimated session duration. The parameters from nodes, frequency, RATs and application are acquired from nodes and sent to infrastructure node. Input parameters from policies are allowed frequency bands, allowed transmission power, allowed bandwidth, and requirements set by the regulator for protecting legacy user (e.g. probability of detection). At the CMON block on the creation phase the algorithm output parameters are used to form the radio path between nodes. The selected parameters are bandwidth, frequency, RAT, and transmission power.

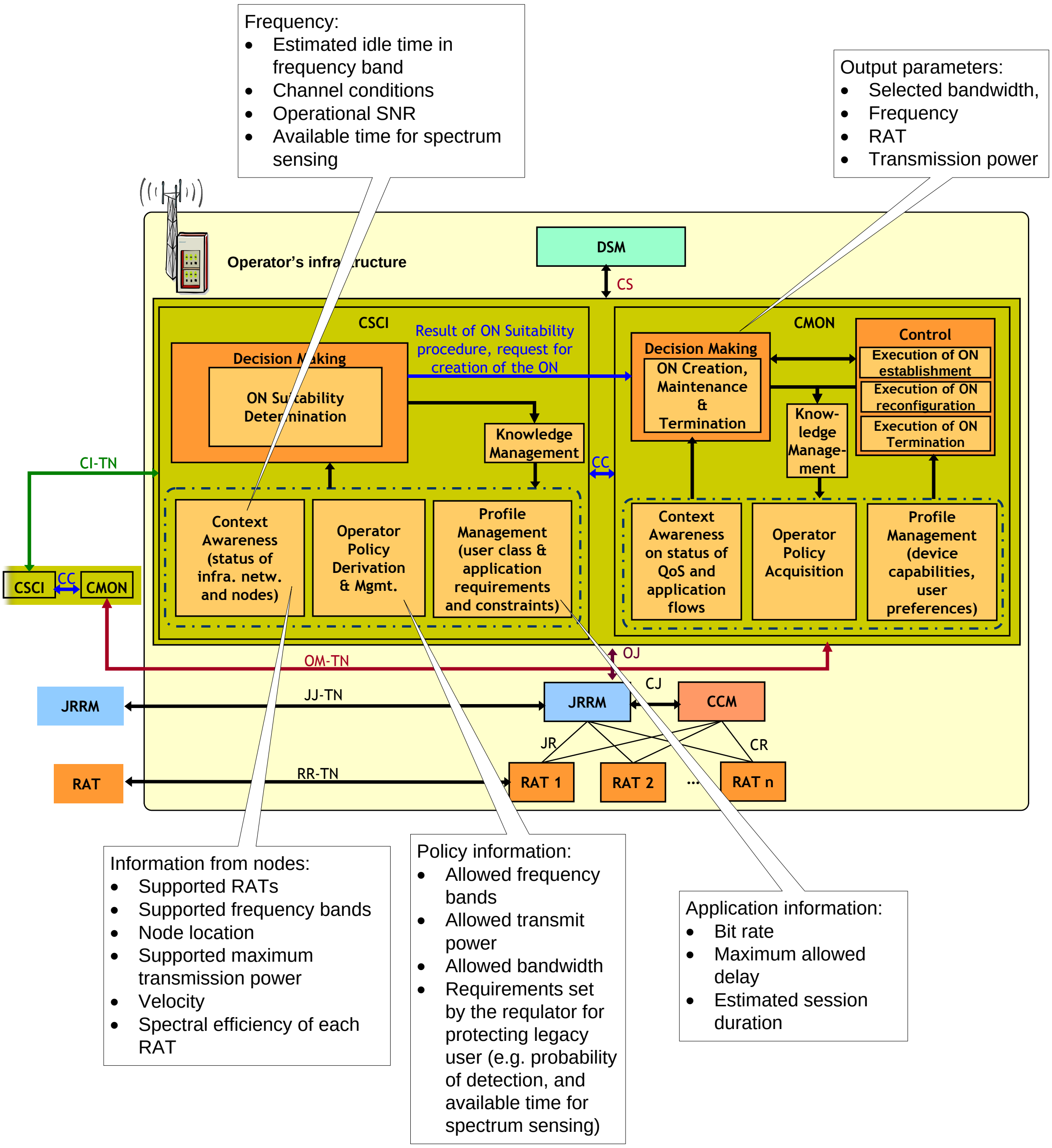


Figure 9: Algorithm mapping to CSCI and CMON [3].

3.3.7 Evaluation of modular decision flow based approach

The performance of proposed framework will be studied using Matlab simulation environment. We consider free space propagation model at the beginning but can add more realistic channel model considering also shadowing and path loss effects. At the simulations we use several spectrum bands like ISM, IMT, TV-bands, GSM, and 60 GHz. User velocity is divided into few levels e.g. statistic, pedestrian, etc. We consider several RATs and different application requirements. The performance of proposed framework will be studied by comparing the performance to the case where ON is not capable to use all frequency bands especially the 60 GHz or the TV-bands.

3.3.8 Fittingness factor based algorithm description

3.3.8.1 Problem formulation and characterisation

Let consider a radio environment in which a number of ONs need to be established or are already in operation. Among the different ONs, there exists a set of L different radio links to be established between pairs of terminals. Each radio link will belong to one ON, and one ON can be composed of one or several radio links. The purpose of each radio link is to support a certain CR application. The l-th application is characterized in terms of a required bit-rate $R_{req,l}$ and a temporal duration $T_{req,l}$. The maximum transmit power available at the terminals involved in the CR application is denoted by $P_{max,l}$.

The "spectrum selection functionality" aims at efficiently selecting a suitable spectrum bandwidth for each of the L radio links based on link requirements and characteristics of the spectrum. "Spectrum selection" will be supported by "Spectrum opportunity identification", which provides, for each radio link, a set of candidate spectrum bands that can be assigned to it.

The "spectrum opportunity identification" targets to provide the necessary awareness level of the radio conditions in different spectrum bands, in order to identify which are the frequency bands available for the communication. The characterisation of the frequency bands will be based on statistics capturing the temporal variations in the utilisation of each band. In that respect, it is envisaged to exploit also the potential correlations in the temporal and frequency domains that different channels may exhibit, as empirically identified in previous works such as [15][16].

Focusing on the temporal domain, the statistical characterisation of the different bands for the spectrum opportunity identification will be based on the activity (ON) and inactivity (OFF) periods. In that respect, potential statistics can be classified into first-order metrics such as means or conditional probabilities or higher-order metrics such as variances or correlation functions. In particular, a list of possible statistics of interest can be formed by (see [14] for details): (i) the average value and variance of ON and OFF periods, (ii) the empirical pdf (probability density function) of ON and OFF periods, (iii) The conditional probability between consecutive ON/OFF periods (i.e. the probability of observing a certain duration of the OFF period given a certain duration of the previous ON period), (iv) a measure of dependence level between successive ON/OFF periods (e.g. a value between 0 and 1 where 0 means ON/OFF period durations are independent and 1 means full dependence). Note that the identification of a certain degree of dependence between OFF and ON periods can be exploited to perform a better estimation of the remaining time that a given frequency band will be available for a CR transmission.

In turn, focusing on the frequency domain, the statistical characterisation will target the identification of inter-channel correlation structures potentially exhibited by the activity in the different bands. It is worth noting here that inter-channel correlation structures may be in general much more involved than the trivial clustered spectrum observed in some empirical measurements of legacy systems [16]. For instance, the new LTE-Advanced system is meant to support a new non-continuous channel aggregation feature [46], which makes inter-channel correlation patterns completely unexpected. The identification of high correlation degrees between different bands will be used by the spectrum opportunity identification to group different spectrum blocks into pools that can be assigned for CR communications.

Assuming that spectrum is modeled as a set of spectrum blocks each one with a certain bandwidth, the statistical characterisation of frequency correlation starts from binary time series representing the activity in a given block. It takes the value 1 whenever the channel is occupied and 0 otherwise. $T_i(k)$ denotes the time series of channel i in discrete time instants k. Then, a possible metric to capture the degree of correlation for two different blocks i,j is the so-called "similarity" defined in [47] as:

$$SIM_{i,j} = \frac{\sum_k \delta\left\{T_i(k) = T_j(k)\right\} - \sum_k \delta\left\{T_i(k) \neq T_j(k)\right\}}{\sum_k \delta\left\{T_i(k) = T_j(k)\right\} + \sum_k \delta\left\{T_i(k) \neq T_j(k)\right\}} \quad (1)$$

where $\delta\{A\}$ is the indicator function that takes the value 1 if condition A is true and 0 otherwise. Correspondingly, the similarity metric $SIM_{i,j}$ quantifies the concordance between the binary realizations of T_i and T_j.

Other possible metrics to capture inter-channel correlation are the joint probability density function of the time series associated to different channels or the correlation function between time series.

The output from the spectrum opportunity identification functionality and corresponding input to the spectrum decision will be a set of *P* spectrum pools based on the analysis of the statistical and correlation properties of the different blocks. The *p*-th spectrum pool is assumed to be formed by a number N_p of spectrum blocks. The *k*-th spectrum block forming the *p*-th spectrum pool is characterized by the 7-tuple ($f_{p,k}$, $BW_{p,k}$, $S_{p,k}$, $P_{max,p,k}$, $O_{p,k}$, $A_{p,k}$, $V_{p,k}$) where $f_{p,k}$ is the centre frequency, $BW_{p,k}$ the bandwidth, $S_{p,k}$ denotes the spectrum band where this block is located (e.g. ISM 2.4GHz, TVWS, etc.), $P_{max,p,k}$ denotes the maximum transmit power that can be used in this block, in case there exist regulatory limitations, and $O_{p,k}$ the spectrum opportunity factor (i.e. the fraction of time that the spectrum block enables spectrum access). Finally, $A_{p,k}$ and $V_{p,k}$ are, respectively, the average duration and standard deviation of the spectrum access opportunities offered by the spectrum block.

The decision on which spectrum blocks belong to each spectrum block can respond to different criteria, for instance by grouping blocks that present a high correlation or similarity level between them, or even in that are fully similar (i.e. $SIM_{i,j}$=1 for every pair of spectrum blocks). Just to illustrate this with a couple of examples let consider first Figure 10, where a primary user (PU) is occupying a certain bandwidth between frequencies f_1 and f_2 that is unknown to the CR system. In this case, the spectrum opportunity identification can subdivide the spectrum in blocks of bandwidth BW and analyse their temporal properties as well as their frequency correlations. As a result of the analysis, it will find that all the 4 contiguous blocks comprised between f_1 and f_2 experience exactly the same occupation (i.e. they are fully correlated) and thus they can be grouped as a spectrum pool. In such a case, a link of the ON can be allocated the whole bandwidth between f_1 and f_2 whenever it is not in use.

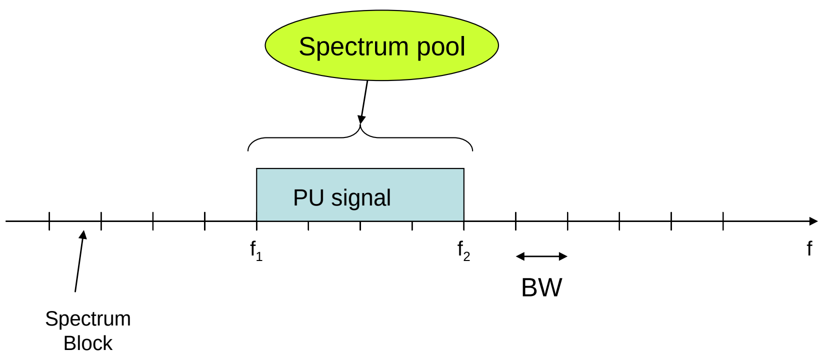


Figure 10: Example: spectrum pool formation to detect unknown bandwidth signals

As a second example to illustrate the pool formation, let consider Figure 11, in which there is a system that transmits making use of a frequency hopping technique using frequencies f_1, f_2 and f_3 in different time instants. In this case, the spectrum opportunity identification will observe a high degree of correlation between the blocks with centre frequencies f_1, f_2 and f_3 and thus it can consider them as belonging to a single spectrum pool. In this case, whenever this pool is assigned to a given link in the ON, some Medium Access Control (MAC) protocol will be needed to regulate how the transmissions of the link are carried out in each of the considered blocks of the pool depending on their utilisation.

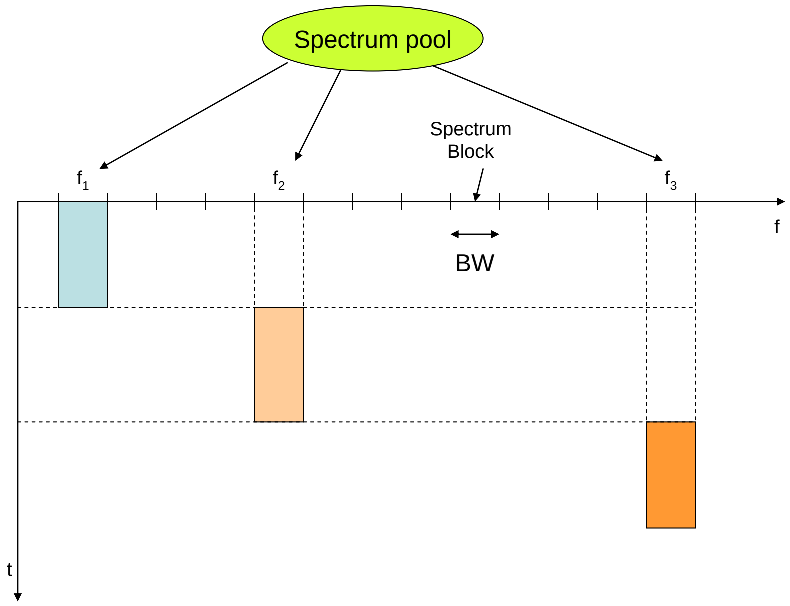


Figure 11: Example: spectrum pool formation with highly correlated signals

Based on all the above, the spectrum selection problem will take as inputs the results of the spectrum opportunity identification in the form of a set of P spectrum pools and will decide which is the adequate allocation of these pools to the L links of the opportunistic networks.

For the sake of simplicity, in the next sub-sections it will be initially assumed that all the spectrum blocks forming the *p*-th spectrum pool have the same bandwidth BW_p and that they are all fully similar, meaning that they offer exactly the same opportunities for spectrum access with $O_{p,k}$=1.

3.3.8.2 Fittingness factor definition

Given that the spectrum selection problem in general involves several radio links and several candidate spectrum pools, it is proposed to introduce the so-called “Fittingness Factor” as a metric to capture how suitable a specific spectrum pool is for a specific radio link that will support a specific application. $F_{l,p}$ denotes the fittingness factor for the *l*-th radio link (and associated application) with respect to the *p*-th candidate spectrum pool. The proposed fittingness factor will assess the suitability in terms of the bit rate that can be achieved operating in the spectrum pool versus the bit rate required by the application.

From a general perspective, the fittingness factor can be formulated as a function of the utility $U_{l,p}$ the *l*-th link can obtain from the *p*-th pool, where the utility is defined as [48]:

$$U_{l,p} = \frac{\left(R(l,p)/R_{req,l}\right)^{\xi}}{1+\left(R(l,p)/R_{req,l}\right)^{\xi}} \tag{2}$$

ξ is a shaping parameter that allows the function to capture different degrees of elasticity of the application with respect to the bit rate. In turn, *R*(*l*,*p*) denotes the achievable bit-rate using the *p*-th pool, which is given by the link capacity:

$$R(l,p) = N_p BW_p \log_2\left(1+\frac{\min\left(P_{\max,p},P_{\max,l}\right)}{L_{\max,p} I_p BW_p}\right) \tag{3}$$

where $P_{max,p}$, $L_{max,p}$ and I_p respectively denote the maximum allowed transmitted power (over a band BW_p), the maximum propagation loss and the noise and interference power spectral density in the *p*-th spectrum pool, assumed the same for all the blocks in the pool.

Based on the above concept, two different fittingness factor functions are defined. First one is the utility itself, that is:

$$F_{l,p} = f_1(U_{l,p}) = U_{l,p} \tag{4}$$

Let notice that with this function, the fittingness factor increases as *R*(*l*,*p*) increases with respect to $R_{req,l}$. In turn, a second function is defined as:

$$F_{l,p} = f_2(U_{l,p}) = \frac{1 - e^{-K \times U_{l,p} / \left(R(l,p)/R_{req,l}\right)}}{\lambda} \tag{5}$$

where K is another shaping parameter and λ is a normalization factor to ensure that the maximum of the fittingness factor is 1. Specifically, after some algebraic computations it can be easily obtained that:

$$\lambda = 1 - e^{-\frac{K}{(\xi-1)^{1/\xi} + (\xi-1)^{(1-\xi)/\xi}}} \tag{6}$$

Note that the second function (5) targets a more efficient usage of pools by penalizing fittingness factor if *R*(*l*,*p*) is much larger than $R_{req,l}$.

3.3.8.3 Fittingness Factor computation and update

According to the previous definition of the fittingness factor, (3) can be computed either by estimation of the different parameters involved in the equation or by an actual measurement of the achieved bit rate on the radio link. At initialization, the computation of $F_{l,p}$ needs to be based on estimated values of the different parameters. Nevertheless, the proposed approach is to take advantage of previous experience, when available, to update the value of the fittingness factor in accordance with the actual conditions experienced when a certain pool *p** is assigned. Therefore, the update of the fittingness factor can be based on a reward $r_{l,p*}$ capturing the actual bit rate $R_{meas}(l,p*)$ measured in the assigned pool *p** as follows:

$$r_{l,p*} = F_{l,p*}\Big|_{R(l,p*)=R_{meas}\left(l,p^*\right)} \tag{7}$$

Based on the obtained reward, a possible updating rule is:

$$F_{l,p*} \leftarrow F_{l,p*} + \beta\left(r_{l,p*} - r_{acc,l,p*}\right) \tag{8}$$

where $r_{acc,l,p*}$ is the accumulated reward computed as the exponential average of the series of reward values:

$$r_{acc,l,p*} \leftarrow \gamma r_{acc,l,p*} + (1-\gamma) r_{l,p*} \tag{9}$$

Next section will detail how the overall updating is carried out in the framework of the spectrum selection decision-making process.

3.3.8.4 Spectrum Selection decision making algorithm based on Fittingness Factor

The proposed fittingness factor function claims to have applicability in the spectrum selection decision-making process whose aim is to decide which spectrum pool is allocated to each application. In general, this decision is needed in different events: (1) when a new CR application starts, a spectrum pool has to be assigned for the corresponding wireless communication, (2) when a channel pool in use is no longer available to support the CR application (e.g. because the pool is exploiting secondary spectrum access and the primary user has appeared) a spectrum HandOver (HO) is required and, therefore, an alternative channel pool should be assigned to seamlessly continue the CR application or (3) when the quality perceived by the application in the spectrum pool currently in use is not satisfactory and, therefore, a spectrum HO is also required.

In any of the above events, the inputs needed and the procedure to establish a radio link for application *l* is detailed in the following.

Algorithm Inputs:

- Set of pools p=1,...,P, where the p-th pool is composed of k=1,...,N_p spectrum blocks and the k-th block characterised by:
  - frequency $f_{p,k}$
  - bandwidth BW_p
  - frequency band $S_{p,k}$
  - maximum power $P_{max,p}$
- - Link characterisation for each of the L links: l=1,...,L :
  - Information related to the application
    - Required bit-rate $R_{req,l}$
    - Value of ξ representing the elasticity of the application with respect to the required bit rate
    - Temporal duration $T_{req,l}$
  - Information related to the capabilities of the involved terminals
    - Maximum transmit power available at the terminals $P_{max,l}$
    - Supported frequency bands (e.g. ISM 2.4 GHz, ISM 5 GHz, 900 MHz, ...)
  - Information related to the radio interface
    - Propagation loss (it can be estimated based on a specific propagation model for the considered frequency band $S_{p,k}$ together with a distance associated to the terminals in the link or it can be directly measured e.g. from the received signal strength for a given known transmit power)
    - Noise and interference spectral density
    - Measured bit rate in the pool currently assigned $R_{meas}(l,p^*)$

Algorithm Procedure (for the *l*-th link):

1. Obtain from a spectrum opportunity identification functionality residing in the cognitive management system the set of candidate spectrum pools that can be assigned to this radio link. If there is no pool available, the request is rejected.
2. Obtain all fittingness factors $F_{l,p}$ for the different pools. If a given pool *p* has never been used yet by application *l*, the value of $F_{l,p}$ is computed based on estimations of the different parameters according to to (4) or (5). On the contrary, if pool *p* has already been used $F_{l,p}$ will result from the update based on the actual experienced bit rate as detailed in step 4.
3. Perform spectrum selection based on $F_{l,p}$ in accordance with some decision-making criterion. Here different possibilities arise, with some examples listed in the following:
   a. Greedy algorithm: This is the simplest case in which the spectrum pool *p** with the largest fittingness factor is selected.

   $$p^* = \arg\max_{p} F_{l,p} \tag{10}$$

   b. Softmax decision making: In this case the spectrum pool is selected on a probabilistic basis in accordance with the fittingness factor values of the different pools. The probability of selecting the p-th pool is given by:

   $$\pi_{l,p} = \frac{e^{F_{l,p}/\tau}}{\sum_{m=1}^{P} e^{F_{l,m}/\tau}} \tag{11}$$

where a tunable parameter τ (called temperature) can adjust how much probabilities to select the different pools would differ depending on the fittingness factor. Softmax decision making is usually used in reinforcement learning (RL) in order to enable a certain exploratory behaviour that would facilitate the updating of the knowledge database by experiencing new channel pools.

c. Multi-objective optimisation making: In this case the problem is addressed from an overall perspective involving all the currently active applications. Correspondingly, the trigger of the spectrum selection can be done by an application but this can lead to changes in the assignment to other applications. The idea would be to find the optimum mapping spectrum pools to applications that maximizes some metric such as the sum of fittingness factors in the allocated pools. Although this problem can be theoretically formulated, it is envisaged that the complexity in finding the solution can be very high when the number of applications and pools increases.

4. After having allocated pool p^*, the following steps are performed every ΔT until the application ends:

    1. Measure the actual obtained bit rate $R_{meas}(l,p^*)$.
    2. Update reward r_{l,p^*} according to (7) and $R_{meas}(l,p^*)$.
    3. Update fittingness factor F_{l,p^*} according to (8).
    4. Update r_{acc,l,p^*} according to (9).

Algorithm Output:

- Pool allocated to every link.

3.3.9 Fittingness factor based algorithm implementation considerations

The spectrum selection decision making algorithm based on the fittingness factor concept as explained in section 3.3.8 can be implemented either following a centralised approach, in which decisions are made by the infrastructure node, or following a decentralised approach, in which decisions are made by the terminals. Figure 12 reflects the allocation of both the spectrum selection and the spectrum opportunity identification in the functional architecture of OneFIT, taking into consideration both the centralised and the decentralised approaches. As it can be observed, spectrum opportunity identification will be carried out by the DSM entity in the infrastructure while the spectrum selection will be carried out by the CSCI/CMON entities of the infrastructure or the nodes, depending on the case. In order to get a more detailed view. Figure 12 and Figure 13 represent the allocation within the CSCI/CMON entities in the centralised and decentralised cases, respectively. In both cases, it is envisaged that the spectrum selection is associated to the CMON, dealing with the decision making for ON creation, maintenance and termination making use of the context awareness information about the QoS obtained by the application.

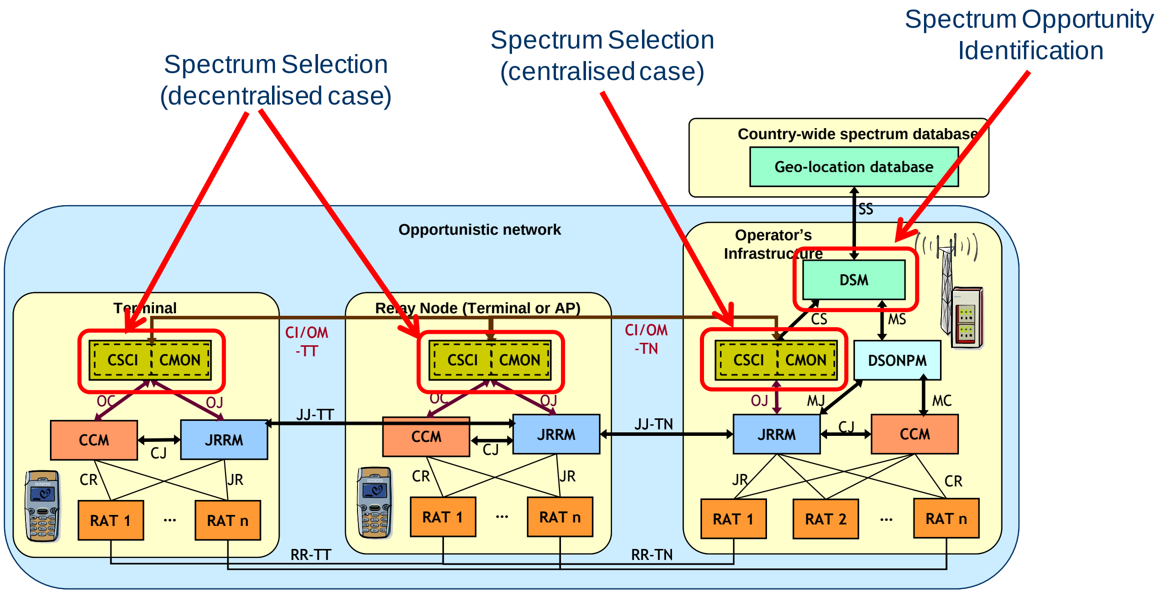


Figure 12: Mapping of Spectrum Selection and Spectrum Opportunity identification in the OneFIT Functional Architecture

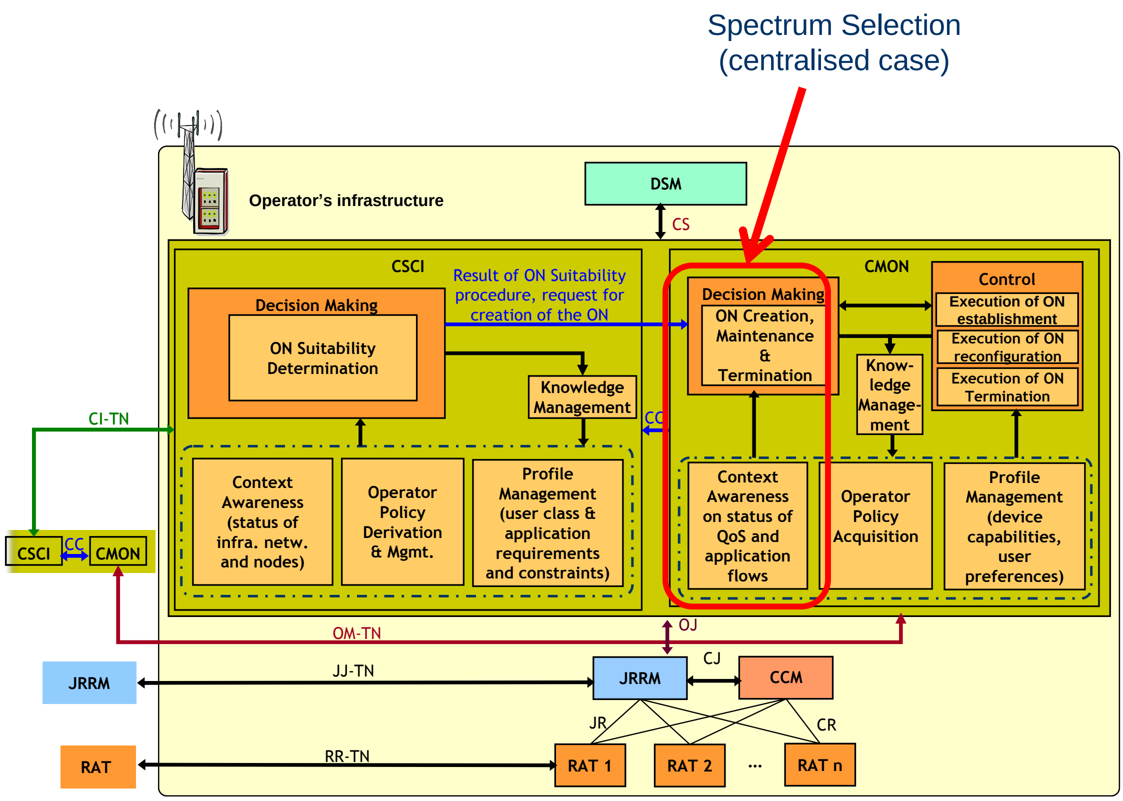


Figure 13: Detailed view of the allocation of the Spectrum Selection within the CSCI/CMON functionalities in the centralised case

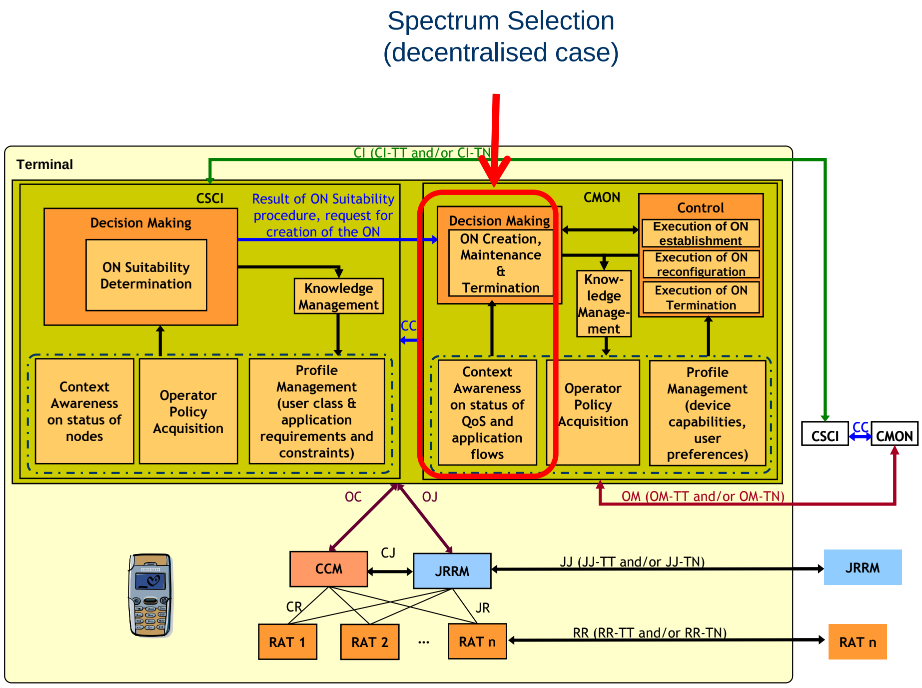


Figure 14: Detailed view of the allocation of the Spectrum Selection within the CSCI/CMON functionalities in the decentralised case

The choice of a centralised or decentralised implementation approach for the spectrum selection will be influenced by the following aspects, which will be further developed and analysed as part of future work:

- Information to be exchanged between nodes:

The execution of the decision making procedure explained in section 3.3.8.4 requires that a number of parameters related with the application requirements, the capabilities of the involved terminals, the radio interface and the available spectrum opportunities should be made available to the entity where the decision is made. Correspondingly, since not all these parameters can be collected or measured in the same node, it is necessary to transfer some of them through the C4MS. Later on in section 3.3.11 a detailed list of the specific parameters to be exchanged through C4MS protocol will be presented. In essence, in case a centralised approach is taken, the C4MS will mainly have to deliver information measured or collected by the terminals with respect to the application, capabilities and obtained QoS (e.g. bit rate). On the contrary, no information regarding the available spectrum opportunities will have to be sent through C4MS because this information will be generated by the DSM located in the same entity as the decision maker. Instead, the CS interface between DSM and CSCI/CMON can be used for the exchange of this information. In case that a decentralised approach is selected, the C4MS will have to deliver the information regarding the available spectrum blocks/pools to the terminals.

- Decision making point in case of a decentralised approach:

Given that the ON will be composed by at least two different terminals, when the spectrum selection is executed in a decentralised way, having separate decision making points at the different terminals could lead to inconsistencies in the spectrum selected for the different links. In such a case, it is envisaged instead that the decisions are made by one of the terminals that acts as master node of the ON. This will require that the information regarding the applications/capabilities/measurements made by other terminals is delivered to the master node through the C4MS, in addition to the information regarding spectrum opportunities delivered from the infrastructure.

- Context information acquisition and exchange strategies:

Even if the spectrum selection is centralised, the computation of the fittingness factor and the update procedure defined in section 3.3.8.4 to reflect the current context in a given link can be executed at the terminals or at the infrastructure. Since the update is based on the experience observed by a given terminal when using a certain spectrum pool, it seems a more natural and efficient approach that the update of the fittingness factor using expressions (7) to (9) is executed at the terminal side. In such a case, the actual value of the fittingness factor could be made available to the infrastructure on a request basis (e.g. because the infrastructure needs to execute a multi-objective optimisation and needs to collect information about the actual fittingness factor in the different links), or on an event-triggered basis (e.g. only when the observed QoS or the actual fittingness factor is below some threshold it would be reported). On the contrary, update of the fittingness factor at the infrastructure side would require more frequent exchange of measurements from the terminals, thus resulting in a larger signalling overhead. All these considerations also apply to the decentralised case with respect to how the fittingness factor updates are made available to the master node.

With respect to the spectrum opportunity identification based on the formation of spectrum pools (discussed in section 3.3.8.1) there are also some considerations to be made from a practical implementation perspective. In particular, trying to address the problem from an overall perspective without trying to limit the number of spectrum blocks could lead to large computation efforts since it is envisaged that with a high number of spectrum blocks the corresponding possible combinations to form pools would increase very quickly. As a result, it will be required to consider some constraints to allow reducing this computational effort. For example, one possibility would be to perform a subdivision into general bands, e.g. TV White Space (TVWS), Industrial Scientific Medical (ISM), etc., and consider pool formation only in a subset of the bands previously selected based on acquired experience. Similarly, the possibility to perform the pool formation at different levels could be envisaged, for example by performing first a rough analysis to get some basic pools and then to perform a more detailed analysis of some selected pools or bands.

3.3.10 Fittingness factor based algorithm evaluation

3.3.10.1 Simulation Environment description

The evaluation of the proposed spectrum selection framework based on the fittingness factor is evaluated by means of system-level simulations. The considered scenario assumes a set of P=4 spectrum pools. They are built from blocks of BW=200 kHz, and the number of blocks of each pool is N_1=N_2=2 and N_3=N_4=6. The maximum allowed power is P_{max}=$2W$ for all the pools and it coincides with the maximum power of the terminals (i.e. $P_{max,p}$=$P_{max,l}$=P_{max} for all l, p). The propagation loss is also assumed to be equal for all the pools and is computed using a free space model at distance 50m and frequency 2.4GHz.

Each pool is assumed to experience a different amount of interference I_p, following daily temporal patterns as described by Figure 15. Notice that a constant interference power spectral density (PSD) I_1=I_2=30.10^{-13} W/Hz is considered for pools 1 and 2 while a two-level PSD pattern is considered alternating between I_{3min}=I_{4min}=30.10^{-13} W/Hz and I_{3max}=I_{4max}=$70\cdot10^{-13}$ W/Hz for pools 3 and 4. With these interference levels it is obtained that $R_{meas}(l,1)$=$R_{meas}(l,2)$=512Kbps, while $R_{meas}(l,3)$=$R_{meas}(l,4)$=1536Kbps for low interference levels, and $R_{meas}(l,3)$=$R_{meas}(l,4)$=96Kbps for high interference levels.

L=2 radio links are considered. Link 1 is associated to low-data-rate sessions ($R_{req,1}$=$64Kbps$, $T_{req,1}$=$2min$) while link 2 is associated to high-data-rate sessions ($R_{req,2}$=$1Mbps$, $T_{req,2}$=$20min$). Independent traffic loads are considered for each link, λ_l being the arrival rate over the l-th link that is varied during the simulations.

As far as spectrum selection is concerned, the greedy decision making approach explained in Section 3.3.8.4 is considered in order to get a first insight into the problem. The focus is on the spectrum assignments at the initial access, so no spectrum HandOvers (HOs) are performed even if the quality perceived by the application in the pool currently in use is not satisfactory. Instead, a dissatisfaction metric is collected to benchmark the performance attained. It is measured as the probability of experiencing a bit rate below the requirement $R_{req,l}$.

Performance is obtained with a system-level simulator during a total simulation time of 2 days with a $\Delta T = 0.01s$. All updates/estimations are made using ξ=5, β=0.2, γ=0.2 and K=1.

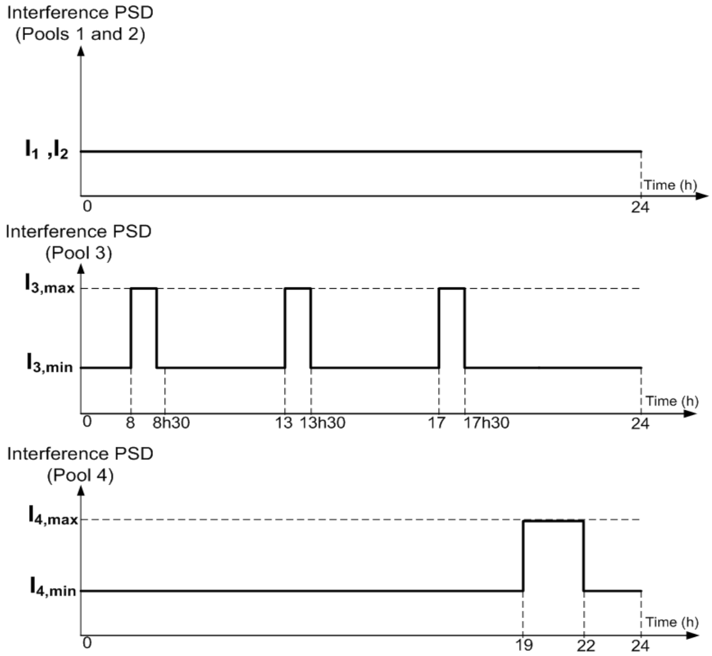


Figure 15: Daily pool interference patterns

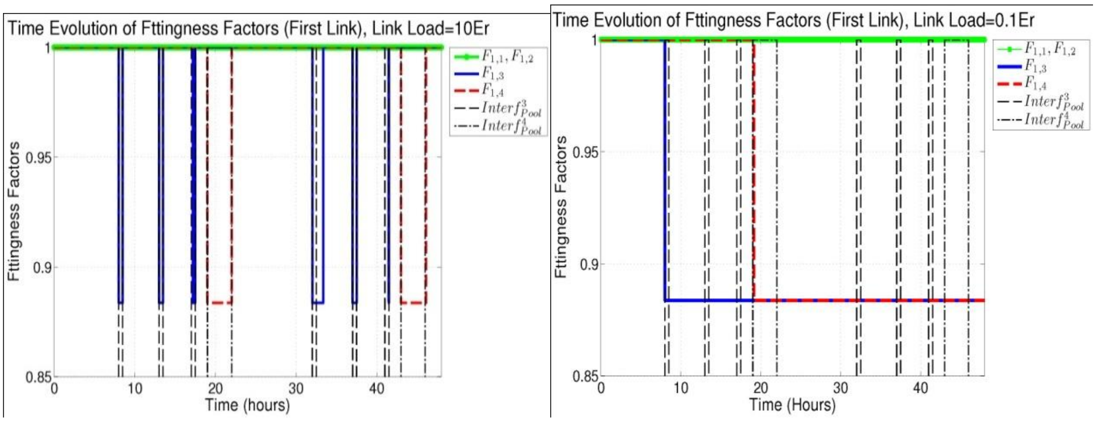
3.3.10.2 First performance evaluation

In order to illustrate the capabilities of the proposed fittingness factor functions, this section carries out an initial evaluation in the scenario presented in previous subsection. The analysis focuses first in the ability to capture interference variations in different pools. Secondly, a comparison between the two fittingness factor functions is performed from the perspective of the performance attained by the spectrum selection.

The analysis of the capability of fittingness factors to track changes in interference levels is carried out using the first function in which fittingness factor equals the utility. Figure 16 and Figure 17 respectively illustrate the time evolution of fittingness factors of each pool for the first and second links under different traffic loads. Discontinuous black lines represent the instants when the interference conditions change in the 3rd and 4th pools. For high load conditions -Figure 16 (a) and Figure 17 (a)- it is observed that fittingness factors of both links react fast to changes in interference levels. The reason is that, once interference level increases for one pool (e.g. at t=8h for the third pool), there is always an active link on that pool due to the high traffic load which makes the corresponding $F_{l,p}$ be quickly reduced. Then, once the interference burst is over, (e.g. at t=8h30m for the third pool), the pool would initially keep the low value of $F_{l,p}$ associated to the case when interference was present (i.e. $F_{1,3}$=0.88 for link 1 or $F_{2,3}$=0 for link 2) and correspondingly the greedy algorithm will tend to exclude it from the assignment. Nevertheless, due to the considered high traffic load, in a future spectrum decision it will happen that all pools with high fittingness factor values will be occupied and e.g. the third pool will eventually be assigned again to a given link. When this happens, the measured quality over the radio link will reveal that the third pool is again providing good performance and, correspondingly, its $F_{l,p}$ will get eventually increased. Notice that some interference change events of the third pool are missed by the second link meaning that they occur without any change in fittingness factor values (see e.g. Figure 17 (a) during the interference change at 13h that is missed during the first day while it is captured in the second day). This can occur whenever there is no active link during the periods when the interference increases in a pool.

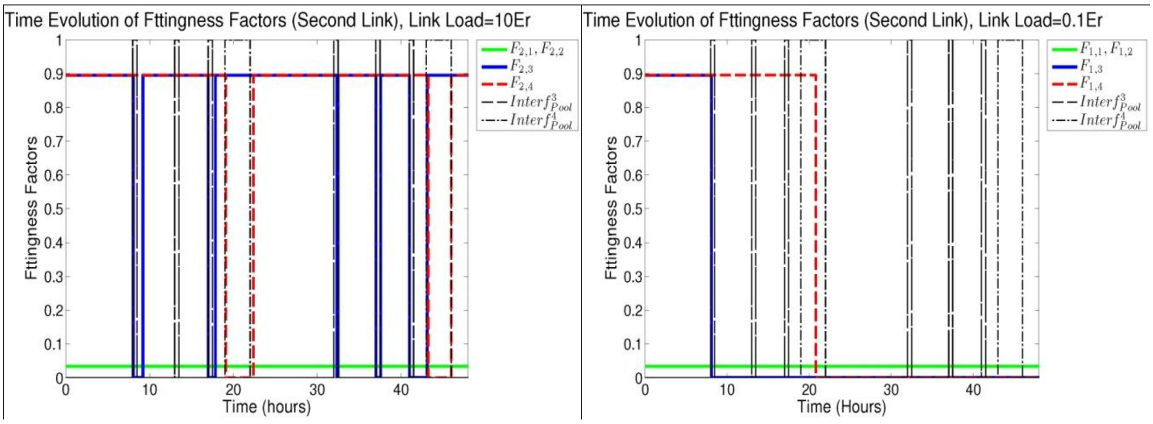
In turn, Figure 16 (b) and Figure 17 (b) illustrate the case of low traffic loads. The main observation is that, once interference level increases for the first time for a given pool, the fittingness factor associated to both links (both CR applications) is reduced and then kept unchanged during the remaining simulation time. The reason is that, under such low traffic load, the greedy approach is preventing accessing again the pool whose fittingness factor has been reduced since there is always another available pool with higher fittingness factor.

Even though the observed behaviour tracks well changes in interference levels, it does not efficiently manage available spectral resources. To illustrate this fact, let consider for instance the low traffic load case and the first link in Figure 16 (b). Before the interference increases, at t<8h the third and forth pools are preferred since $F_{1,3}=F_{1,4}>F_{1,1}=F_{1,2}$. Correspondingly, the low-data-rate sessions tend to be allocated in pools 3, 4 (that provide a bit rate of 1536Kbps), although their required bit rate of 64Kbps could also be achieved on pools 1 and 2 that provide 512Kbps. Such allocation will impact on the high-data-rate sessions of link 2 that can only be successfully served when using pools 3 and 4 and will find these pools many times occupied by link 1.



(a) (b)

Figure 16: Time evolution of fittingness factors of the first link (a) High Traffic load ($\lambda_1 T_{req1}$=10Erlang) (b) Low Traffic load ($\lambda_1 T_{req,1}$=0.1Erlang)



(a) (b)

Figure 17: Time evolution of fittingness factors for the second link (a) High Traffic load ($\lambda_2 T_{req,2}$=10Erlang) (b) Low Traffic load ($\lambda_2 T_{req,2}$=0.1Erlang)

Figure 17 illustrates a comparison between link dissatisfaction probabilities for the fittingness factor functions 1 and 2 as far as the second link is concerned. Link dissatisfaction probability is defined as the probability of observing a bit rate below the CR application requirement $R_{req,l}$. Results for the first link are not presented since it is all the time satisfied because the bit rate is always above the requirement of 64Kbps regardless the allocated pool and interference conditions. Results show that function $f_2(U_{2,p})$ is outperforming $f_1(U_{2,p})$ for all traffic loads with the gain reducing as traffic load increases. The observed reduction in the dissatisfaction probability ranges from 65% for medium traffic load (1Erlang) to 15% for high traffic load (5Erlang). This is basically justified by the intuition behind $f_2(U_{2,p})$ trying to assign just the required resources to a given link. As a matter of fact, $f_2(U_{2,p})$ tends to assign as much as possible pools 1 and 2 to the first link since they can support the required throughput ($R_{meas}(1,1)>R_{req,1}$) with the minimum resources ($R_{meas}(1,1)<R_{meas}(1,3)$). This tends to leave pools 3 and 4 available for the second link that would not be served adequately with the pools 1 and 2. This situation is clearly illustrated by Table 6 that gives the distribution of pool usage by both links for both fittingness factor functions for a traffic load of 1 Er. For $f_1(U_{l,p})$, the first link uses 70% of the time pools 3 and 4, which forces the second link to access pools 1 and 2 during 55% of the time. This significantly increases the dissatisfaction probability since $R_{meas}(2,1)<R_{req,2}$. As far as $f_2(U_{l,p})$ is concerned, the first link uses only 8% of the time the pools 3 and 4 which keeps them for the second link usage (84% of the time). This reduces the dissatisfaction probability since $R_{meas}(2,3)>R_{req,2}$.

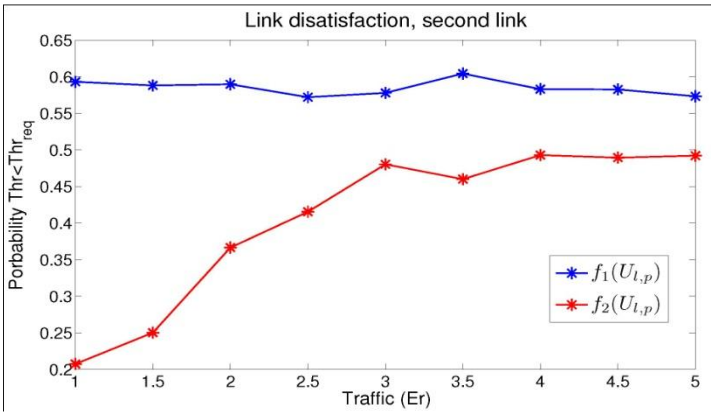


Figure 18: Link dissatisfaction of the second link

Table 2. Pool usage distribution for traffic=1Erlang

	$f_1(U_{l,p})$				$f_2(U_{l,p})$			
	Pool 1	Pool 2	Pool 3	Pool 4	Pool 1	Pool 2	Pool 3	Pool 4
link 1	0.14	0.14	0.25	0.46	0.45	0.46	0.03	0.05
link 2	0.31	0.24	0.34	0.10	0.1	0.06	0.37	0.45

3.3.10.3 Conclusions

This section has evaluated the new fittingness factor concept that has been proposed to capture the suitability of spectral resources exhibiting time-varying characteristics to support a set of heterogeneous CR applications. Two different fittingness factor functions have been proposed and analysed in a scenario with unknown interference variations in certain spectrum pools. The capability of these functions to track the fittingness of the spectral resources, thanks to the inclusion of a reward-based fittingness factor update, has been first analysed, obtaining that they efficiently capture interference variability for medium-to-high traffic loads. Then, the impact of fittingness factors over the spectrum selection decision-making process in a multi-service context has been evaluated. Results show that, even with a simple greedy approach, an efficient matching of spectral resources to the requirements of CR applications can be achieved, thus resulting in significant reduction in the dissatisfaction probability. Motivated by the proven usefulness of fittingness factor, as future work it is intended to explore other strategies for spectrum decision in addition to the greedy approach that has been considered.

3.3.11 Requirements on the C4MS protocol definition & technical challenges

The "spectrum selection" functionality can follow a centralised approach where decision-making is held within CSCI/CMON functional entities on the infrastructure side. Spectrum availability information (e.g., channel pools) will be obtained by CSCI/CMON on the infrastructure side through CS interface from DSM functional entity, which will hold the "spectrum opportunity identification" functionality. Over such a basis, information exchange over the different interfaces to be supported over C4MS for the implementation of the proposed algorithm of spectrum selection based on fittingness factor as detailed in section 3.3.8 are:

- From Terminal to Infrastructure (through relay Node in case)
    - Information related to the application
        - Bit rate required for the application
        - Elasticity with respect to the required bit rate accepted by the application
        - Expected duration of the application

        Note: The characterization of applications might be available at the Infrastructure side by other means rather than flowing over CI/OM-TT and CI/OM-TN
    - Information related to the capabilities of the involved Terminals
        - Terminal maximum transmit power
        - Supported frequency bands (e.g. ISM 2.4 GHz, ISM 5 GHz, 900 MHz, ...)

        Note: Terminal's capabilities might be available at the Infrastructure side by other means rather than flowing over CI/OM-TT and CI/OM-TN.
    - Radio interface-related measurements
        - Measured Signal strength
        - Measured Noise and Interference level
        - Measured Propagation losses
        - Measured achieved Bit rate

        Note: The requirement on which types of measurements are needed depends on whether estimations of the bit rate or measurements are used in each case. For instance, in case that the actual bit rate is available then it is not needed to measure neither the signal strength nor the noise or the propagation losses. On the contrary, in case that the bit rate is estimated, measurements of the signal strength or alternatively the propagation losses (if transmit power is known) are needed. Note in particular that only one of the parameters "measured propagation losses" or "measured signal strength" is actually necessary.
- From Infrastructure to Terminal (through relay Node in case)
    - For each spectrum block k-th forming the selected spectrum pool
        - Central frequency fk
        - Bandwidth BWK
        - Transmission constraints (maximum transmit power in spectrum block)

It should be noted that in case that the "spectrum selection" functionality follows a decentralised approach it would be needed to transfer to the terminals information regarding the available pools and associated characteristics. Also, in case that the decision making is executed at a master terminal node, the rest of parameters related with application, terminal capabilities and measurements would need to be transferred.

With respect to the message exchange strategies currently under consideration for C4MS in WP3, it can be envisaged that all the above information is transmitted using dedicated signalling exchanged on-demand. In the case of measurements also the possibility to have event-triggered or periodical reporting could be considered.

Based on D3.1 [4], the C4MS messages and procedures to transmit the above parameters would be the Information Request/Information Answer or Negotiation Request/Negotiation Answer in the case of the information transmitted from terminals to infrastructure regarding application/capabilities/measurements. In turn, the information transmitted from infrastructure to terminals corresponding to the allocated spectrum would be sent using ON_Creation Request/ON_Creation Answer or ON_Modification_Request/ON_Modification_Answer.

3.4 Machine Learning based Knowledge Acquisition on Spectrum Usage

3.4.1 Technical challenge addressed

ONs will operate in a dynamically changing environment. In such an environment, dynamic spectrum use could lead to spectrum fragmentation which leads to wastage of spectrum. In order to enhance spectrum utilization and support more users' demands reliably, it might be useful if the allocated spectrum to users could be reallocated based on spectrum usage information.

3.4.2 Rationale

"Knowledge acquisition" on spectrum usage based on Machine Learning Algorithms/techniques (e.g. Bayesian networks, reinforcement learning) is aimed at providing a high-level, reliable picture of how spectrum has been and will most likely be utilized in the longer term. This will allow a proactive approach to dynamic spectrum assignment, i.e. to predict future spectrum demands in given time/location, based on past observations which will allow the opportunistic networks to appropriately use spectrum and further enhance utilization of available spectrum.

3.4.3 Use cases mapping

The approach considered here is applicable to use cases of all scenarios.

3.4.4 State Of The Art

In order to cope with the high fluctuation in the spectrum availability and diverse QoS requirement, the spectrum selection algorithm based on usage prediction with machine learning (Genetic Algorithm, Reinforcement Learning) has been investigated.

Genetic Algorithm (GA)

In [49], the genetic algorithm is used as a solution approach to the cell-by-cell dynamic spectrum allocation with the centralized control. For an ad-hoc cognitive radio networks, the distributed version of the genetic algorithm is investigated in [50].

Reinforcement Learning

In [51], RL is applied in dynamic channel selection scheme for a centralized CR network. And the RL algorithm for the joint selection of optimal spectrum and the transmit power in the CR ad-hoc networks with decentralized control is proposed in [52]. In [53], the distributed approach to decide the spectrum assignment based on RL in primary cellular networks is investigated. Each cell is allowed to autonomously decide the best frequencies to use in order to maximize spectral efficiency and to preserve QoS.

3.4.5 Algorithm description

The detailed specification of algorithm will be presented in future deliverable D4.2. In this section a high level overview of requirements addressed by the algorithm is presented. The algorithm will use current & historic spectrum utilization information to predict future spectrum demands. It is capable of providing spectrum usage prediction based on measurements (if available/obtainable) or the statistical models. For example Beta distribution of duty cycle seems to accurately represent cases of fully loaded or completely idle channels in most systems, or exponential –like distributions for channel vacancy distribution (not idd). In order to meet the required QoS for ON nodes, the algorithm will consider channel conditions such as channel PER, noise level and bit-rate as well as the interference effect on primary users. In addition to generate opportunities, the algorithm will be used to enforce spectrum reallocation i.e. to release portions that could then be temporarily assigned for the formation of the opportunistic network or improve on QoS of ongoing services, or in anticipation of PU activity. Whilst the spectrum is being vacated, spectrum mobility/vertical HO procedures are expected to minimized impact to QoS (keeping the interference & signaling overheads).

Algorithm including reallocation procedure consists of monitoring, predicting, decision making and execution phases in Figure 19. Monitoring (M) data may include spectrum occupancy information (allocated bandwidth, PU utilization level) and spectrum demands. Based on monitoring phase, the algorithm can formulate spectrum usage pattern and predict the future spectrum demands in the predicting (P) phase. The decision making (D) process would be initiated by the predicting phase. If reallocation of spectrum bands would be operated whenever the status of spectrum occupancy is changed, the system overhead could be highly increased. Thus, it is expected that the decision making process would be triggered when the future spectrum demand is predicted to be highly increased from predicting (P) phase and spectrum opportunities generation is required and/or relocation could contribute to improving QoS of ongoing services highly. In the decision process, the radio links and its new spectrum bands will be identified to optimize spectrum use and system capacity. The execution (E) phase mainly includes the processes of dynamically and autonomously reallocating spectrum bands. In order to do, it will send messages to force spectrum bands change to target nodes. In M-P-D-E cycle, since prediction performance might depend on the learning technique, many different learning techniques such as Bayesian, Reinforcement Learning, and Genetic Algorithm will be implemented to choose the most proper technique for each scenario.

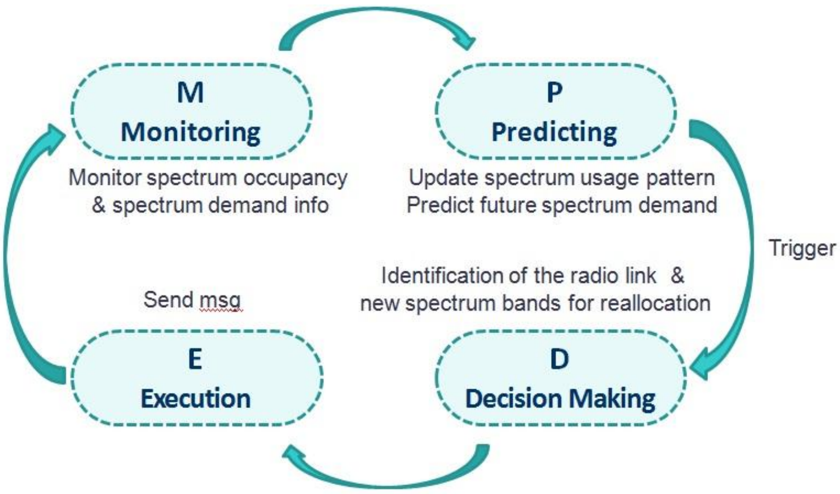


Figure 19: M-P-D-E cycle for spectrum reallocation

3.4.6 Implementation considerations

In order to decide to reallocate spectrum bands, the node who decides to reallocate spectrum bands needs to know historical spectrum usage pattern, all the current spectrum allocation made and spectrum occupancy information and to predict future spectrum demands. Based on that information, the node will decide to reallocate spectrum bands to improve spectrum efficiency and capacity in the network level. To do this, the reallocation of the spectrum will be centralized and managed by the BS. Figure 20 presents the mapping of the algorithm in the functional architecture of the infrastructure side. It is expected the main entity to decide spectrum reallocation would be CMON in network side and relevant information of changing wireless links would be delivered to the target nodes.

Figure 21 represents the placement of proposed algorithm in the high level functional model. After creating an ON, M-P-D-E cycles of the proposed algorithm will be operated. Based on prediction of traffic demands and spectrum usage information, the algorithm will identify the radio links and new spectrum bands for the links for reallocation so that the spectrum utilization can be optimized and/or the QoS of the ON could be improved.

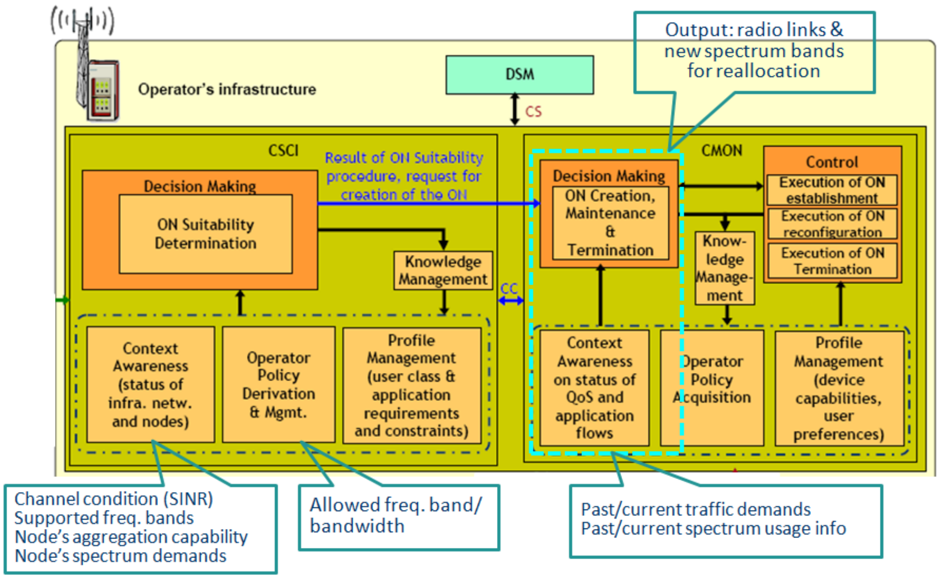


Figure 20: Machine Learning algorithm on Spectrum Usage in OneFIT Functional Architecture

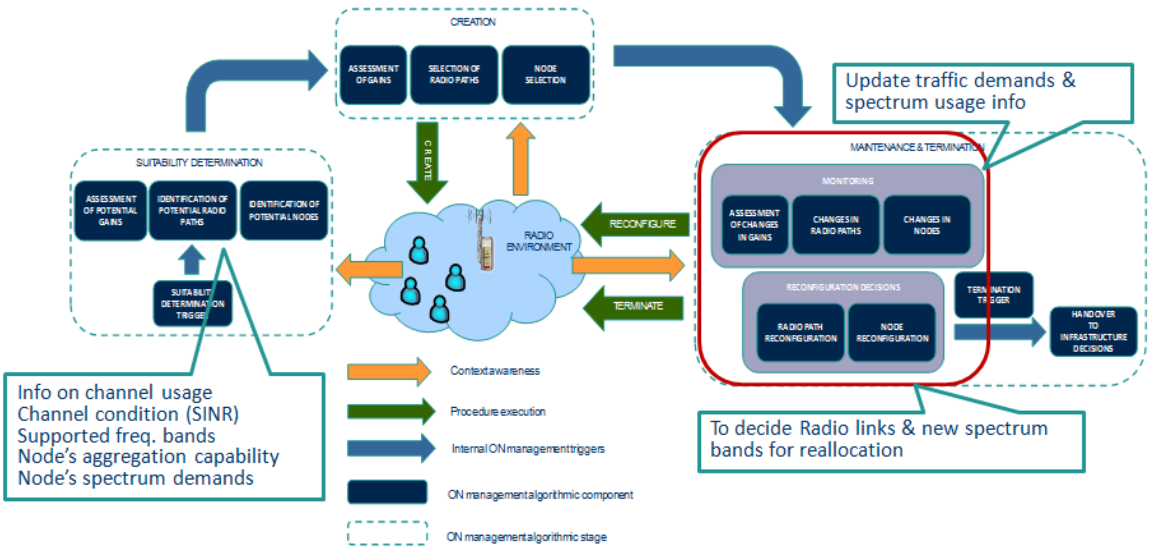


Figure 21: Placement of Machine Learning algorithm in OneFIT high level functional model

3.4.7 Algorithm evaluation

The design and implementation of the algorithm is currently at an early stage. Evaluation results shall be reported in D4.2.

3.4.7.1 Simulation Environment description

A GUI-based simulator/tool is currently being developed.Past/current traffic demands, past/current spectrum usage information (occupancy, PU utilization level), channel condition (SINR), user's required QoS, service time, allocated BW (center frequency, BW) and context data (channel PER, neighbour nodes, PU utilization level in each channel) will be used as inputs.

The learning algorithms under consideration include Genetic Algorithm, Reinforcement Learning, Bayesian learning, PSO (Partial Swarm Optimization) and HMM (Hidden Markov Models). Algorithm specific input parameters (e.g. chromosome length for Genetic Algorithm) will be supplied through user-interface front-end of the simulator. Predicted spectrum demands, new spectrum arrangement (including forced reallocation), spectrum usage information (utilization, fragmentation, the number of users, user satisfaction degree) will be shown as outputs, and outputs from each learning algorithm will be compared.

3.4.7.2 First performance evaluation

First set of performance evaluation results shall be reported in D4.2. Performance evaluation will be against following selected key performance indicators:

- Achieved Throughput
- Spectrum utilization
- Delay as an indicator of fast discovery and number of channel switches

3.4.8 Requirements on the C4MS protocol definition & technical challenges

When the message of Spectrum_Assignment.Request (SAR) is sent via C4MS, the supported frequency information should be passed to the algorithm. It is expected that the other necessary information such as spectrum usage, traffic load and context data (channel PER, noise level, bit-rate, and spectrum utilization level in each channel) is provided from the systems.

3.5 Techniques for Aggregation of Available Spectrum Bands/Fragments

3.5.1 Technical challenge addressed

Since dynamic spectrum use could lead to spectrum fragmentation, the techniques to aggregate separated spectrum bands efficiently are required to improve spectrum utilization. In order to find the proper aggregated spectrum blocks, device's aggregation capability needs to be taken into consideration.

3.5.2 Rationale

Spectrum aggregation refers to the creation of virtual blocks of spectrum through the aggregation of disjoint bands. It is expected that spectrum aggregation will result in higher spectral utilization and user throughput.

3.5.3 Use cases mapping

Algorithms proposed in this section are applicable to use cases of all scenarios.

3.5.4 State Of The Art

This section describes the state of the art solutions, addressing PHY/MAC dependent and independent solutions separately.

3.5.4.1 PHY/MAC dependent solution

In order to meet the IMT-Advanced requirements, LTE-Advanced and IEEE 802.16m is considering the spectrum aggregation scheme in their standard version.

- **LTE-Advanced**

In LTE-Advanced standard, the terminology of carrier aggregation is mentioned for spectrum aggregation. Carrier aggregation is defined that two or more component carriers (CCs) are aggregated in order to support wider transmission bandwidths up to 100MHz. While both contiguous and non-contiguous cases are considered, three cases mentioned are considered; intra band contiguous component carrier aggregation, Intra band non-contiguous component carrier aggregation and inter band non-contiguous component carrier aggregation [54].

- **IEEE 802.16m**

In 802.16m standard version, “multi-carrier operation” is mentioned as the terminology that allows operation in any bandwidth as wide as 100MHz by aggregating contiguous and/or non-contiguous RF carriers [55].

- **IEEE 802.22**

In 802.22, two types of aggregation of adjacent channels, channel aggregation and channel bonding was considered and It is concluded that channel bonding is a better solution at least in the contiguous case [56].

3.5.4.2 PHY/MAC independent solution

Since the following algorithms are not system-specific, they can operate independent of PHY/MAC layer specification.

- AASA (Aggregation Aware Spectrum Assignment)

Considering device’s spectrum aggregation capability, this algorithm searches for disjoint spectrum blocks from left to right (from low to high frequency). Once it finds out spectrum blocks of requested bandwidth within the spectrum aggregation region, AASA assigns them to a node. By using a simple greedy algorithm that search for and assign channels from low to high frequency, it tries to avoid generating new fragments that cannot be aggregated.

- MSA (Maximum Satisfaction Algorithm)

The aim of the MSA is to satisfy as many user bandwidth requirements as possible to improve the spectrum efficiency. It is utilizing the worst spectrum band which can just satisfy the bandwidth requirement of the user in consideration of the upcoming users [57].

- LCS (Least Channel Switching)

In order to minimize the channel switching times (due to appearance of PUs) at sensing moments, the outage probability is introduced. Based on prediction of primary activities and the corresponding channel state transitions, this algorithm chooses the spectrum blocks with the lowest outage probability, which means the probability that primary users will be shown up in that blocks is lowest [57].

3.5.5 Algorithm description

The detailed specification of the proposed utility-based spectrum aggregation algorithm will be presented in D4.2. In this section a high level overview of the algorithm is presented. To accommodate bandwidth requests, a utility function is defined to rank available spectrum blocks within the aggregation range of the device. The possible range for spectrum aggregation depends on the device's H/W capability. The utility function will consider channel throughput, PU activity level, user preference based on locations, and the possibility of creation of new fragments within aggregation region. After calculating ranks for all spectrum blocks, the algorithm will allocate the spectrum block with the highest ranking to a given bandwidth request.

3.5.6 Implementation considerations

The proposed utility-based technique can be implemented based either on a centralized approach or a decentralized approach. Figure 22 illustrates the mapping of the algorithm to the functional architecture. While the algorithm is operated and the most appropriate spectrum blocks will be chosen in the infrastructure node in a centralized approach, it would be operated in the terminals in a decentralized approach. Based on information on channel conditions, node's H/W capability and the request, the main entity to manage spectrum selection is expected to be a CMON entity.

Figure 23 represents the proposed algorithm in the high level functional model. During the creation phase of ON, the proposed algorithm needs to be operated to find the most appropriate aggregated spectrum blocks. After creating ON with a chosen virtual channel, it is expected that the algorithm needs to be run to find a proper virtual channel since the channel condition and spectrum occupancy is expected to be changed dynamically.

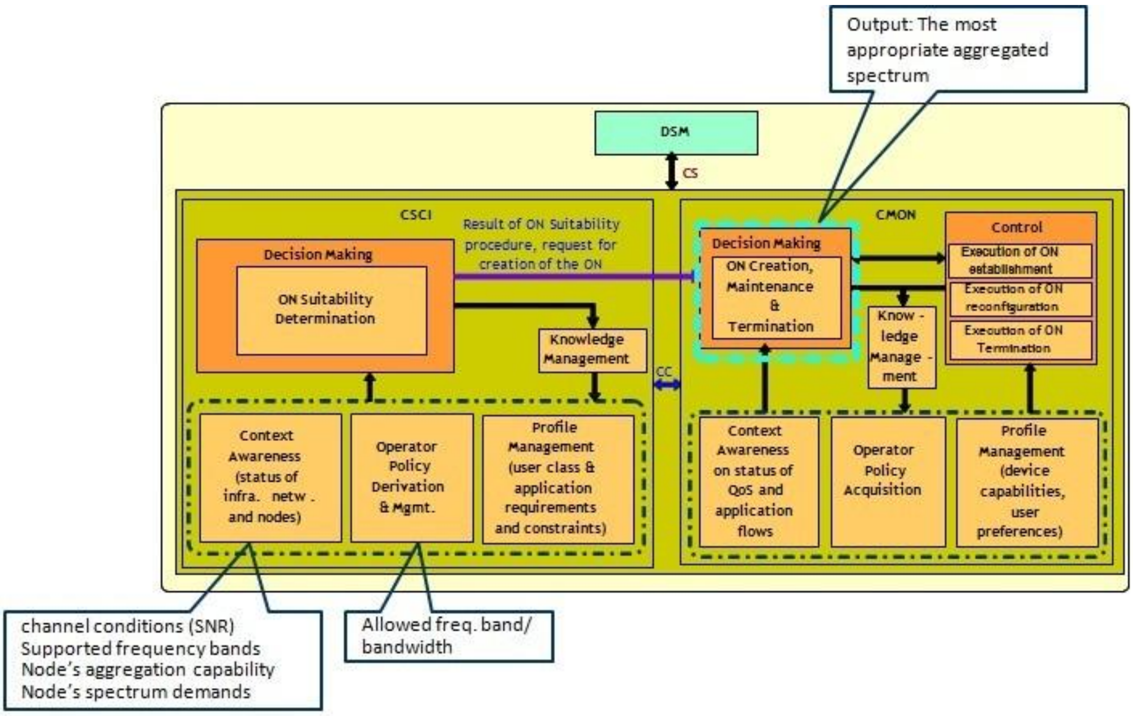


Figure 22: Aggregated spectrum allocation algorithm placement in OneFIT Functional Architecture

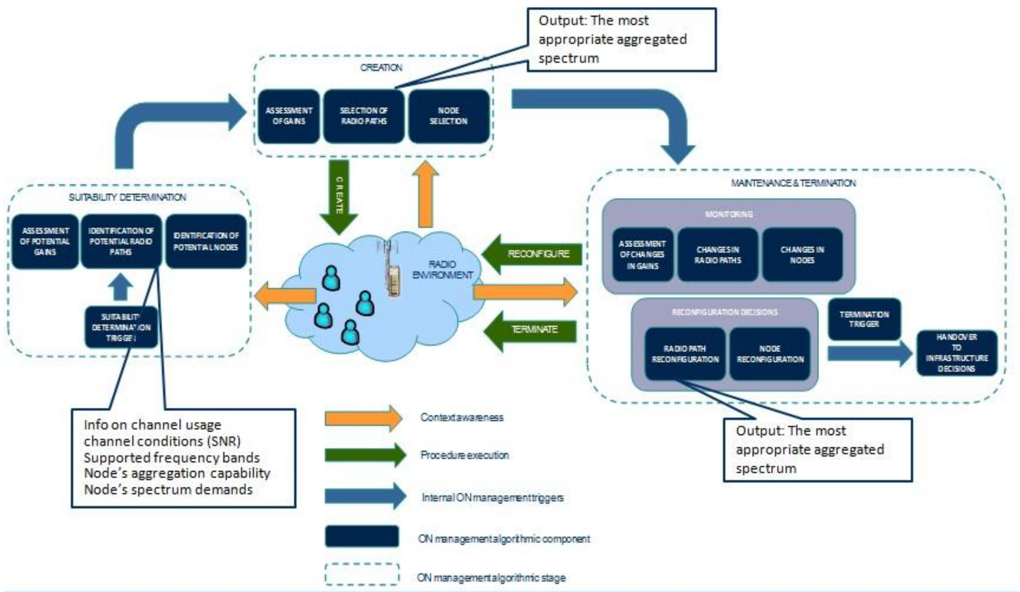


Figure 23: Aggregated spectrum allocation algorithm placement in OneFIT high level functional model

3.5.7 Algorithm evaluation

3.5.7.1 Simulation Environment description

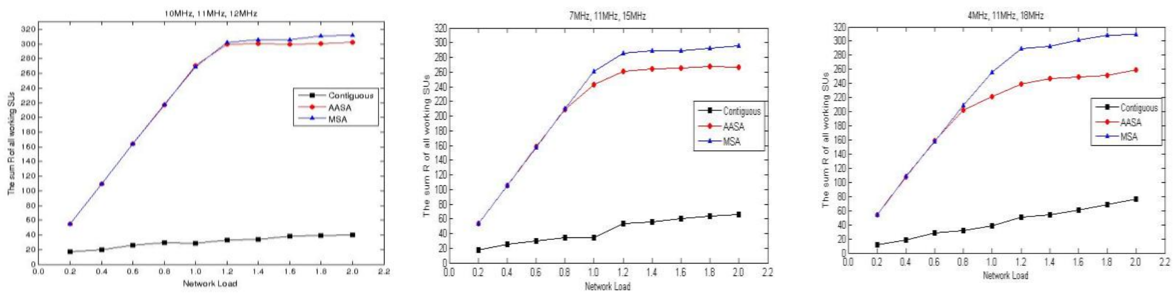
The initial simulation model developed in Matlab is not specific to particular PHY/MAC layer specifications. In addition, user mobility has not been considered in simulations.

The following assumptions are made. The considered total width of spectrum is set to 600MHz and the spectrum aggregation range is 40MHz. The bandwidth requirements of users are randomly chosen from three predefined sets, {10MHz, 11MHz, 12MHz}, {7MHz, 11MHz, 15MHz} and {4MHz, 11MHz, 18MHz}. 120 simulation scenarios with fixed random spectrum availability are used for achieving average performance.

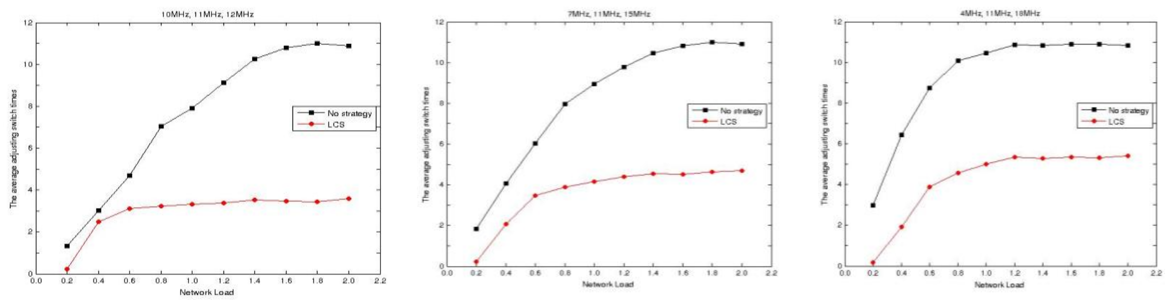
3.5.7.2 First performance evaluation

Figure 24 depicts some of the initial results of comparisons between aforementioned STOA algorithms. Figure 24.(a) indicates superiority of MSA over other techniques (AASA and contiguous band allocation) in terms of satisfaction of user requested bandwidth. In Figure 24(b), it is shown that LCS outperforms an algorithm with no strategy in terms of minimization of channel switching. Finally, both MSA and LCS show better performance for a predefined set of bandwidth request which has the biggest difference between the requested bandwidth.

The proposed utility-based spectrum aggregation algorithm will be compared to MSA and LCS and will be also evaluated in terms of spectrum utilization as well as the degree of spectrum fragmentation.



(a)



(b)

Figure 24: Comparison of performance of spectrum aggregation algorithms

3.5.8 Requirements on the C4MS protocol definition & technical challenges

The output of the algorithm is the chosen virtual channel consisting of many spectrum fragments for a specific request. This will be sent in the message: Spectrum-Assignment-Answer (SAA) via C^4MS.

3.6 Algorithm on knowledge-based suitability determination

3.6.1 Technical challenge addressed

The algorithm focuses on the technical challenges of the Suitability Determination phase as analyzed in D2.1. Specifically, the challenge of the decision whether or not it is suitable to set up an ON or not, at specific time and place is addressed.

3.6.2 Rationale

According to the OneFIT concept, ONs are created in an infrastructure-less manner under the supervision of the operator and include numerous network-enabled elements. Main objective of the ON according to the defined scenarios of D2.1 is to ensure application provisioning in an acceptable QoS level by providing opportunistic coverage extension, opportunistic capacity extension, infrastructure supported opportunistic ad hoc networking, opportunistic traffic aggregation in the radio access network or opportunistic resource aggregation in the backhaul network. To ensure this creation a feasibility analysis is required. This can rely on off-line simulations, which are conducted a priori so as to evaluate candidate solutions against multiple, disparate input parameters and assessment criteria. The results of such simulations will be then used to derive recommendations covering various, disparate contexts of operation. As a result, Knowledge-based suitability determination Algorithm proposes a first decision towards the creation of an ON, giving as an output a request for the creation of ONs, associated with a pre-selected set of candidate nodes.

3.6.3 Use cases mapping

The algorithm is potentially implemented to all use cases as defined in D2.1, due to the fact that the decision whether or not it is suitable to set up an ON is addressed in all scenarios.

3.6.4 State Of The Art

The concept of extending the infrastructure in order to achieve better resource provisioning and utilization is not new. Well known approaches have been proposed in the past mainly with the aim to increase the cellular coverage and/or capacity and decrease costs, thus abandoning the traditional worst-case (peak-hour) based planning that used to lead to over-provisioning of expensive resources in non-peak times. These approaches include the well-known WiFi hotspots [58], and Femto Cells e.g. Home Node-Bs [59] that are now aggressively used by operators in order to offload large portions of the traffic from the wide area networks of their infrastructure. This can be seen as the conservative version of the solution of ONs, exhibiting minimum or totally absent dynamics. The possibility of exploiting infrastructure-less segments in order to increase the efficiency of the infrastructure-based network in a more dynamic manner has also been considered under the legend of the so-called “hybrid networks”. A good overview and comparative study of numerous hybrid networks and different example scenarios can be found is given in [60].

3.6.5 Algorithm description

The algorithm will be responsible for making decisions upon the feasibility of the creation of ONs when judged as appropriate. The delineation of such an algorithm-strategy is the objective of this section.

In particular, at the input level, a properly defined algorithm will need to read context information, which according to the preceding analysis, comprises (i) the number and/or spatial distribution of terminals, (ii) the type (requirements) of applications requested, (iii) mobility levels and (iv) access point and terminal capabilities and characteristics, such as supported applications, routing protocols etc. In the output, the algorithm must select (i) the transmission power (range) of the Access Points (APs) and/or terminals and (ii) the ad hoc routing protocol that will be used for routing traffic between the infrastructure and the ONs.

Additionally, in order to fulfil the requirement for more proactive and faster response to changes, the algorithm can be enhanced with context matching functionality. First the currently captured context is identified and then it is matched against a set of pre-existing reference context-action pairs so as to identify the best way to handle it i.e., select the power to be transmitted by the AP and/or terminals, the routing protocol to be used. Context matching can be based on well-known techniques with the k-Nearest Neighbour(s) (k-NN) algorithm being a firm candidate. A pertinent solution, which is based on k-NN and also exhibits non-prohibitive complexity has been provided in [61][62]. The outline of the described algorithm has been introduced in [63] is given in Figure 25.

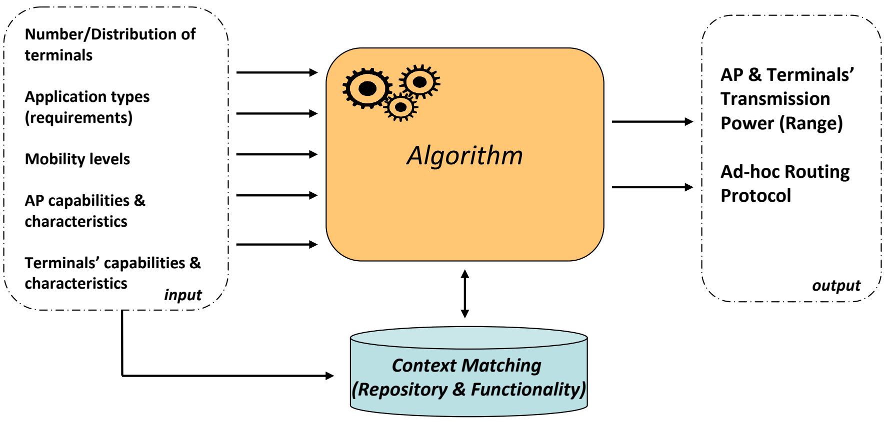


Figure 25: Outline of the algorithm

3.6.6 Implementation considerations

This section includes considerations, in terms of platform and algorithm implementation with the use of a multi-agent environment. Within such a multi-agent environment/system, every component (such as a network infrastructure element, a user device or management software) can be represented by one or more intelligent agents that act as a mediator between the components' functionality and the rest of the system. Thus, each system component is loosely coupled to other components and can interact by exchanging messages through a high level interface. In such a context, C4MS can be seen as a RAT-agnostic, upper layer logical communication channel (mainly over TCP/IP) between distributed agents/agent platforms residing in both terminal and network sides and used for the conveyance of context information. The corresponding information flow can be formulated as an ontology that can be easily extended or modified.

JADE [64] is a robust, fully Java and FIPA compliant framework for developing distributed agent systems and can run on both PCs and wireless devices that support Java Micro Edition (Java ME) using the package developed by the Lightweight Extensible Agent Platform (Leap) Project. JADE components exchange messages which are serialized and transmitted over TCP, according to the FIPA Agent Communication Language (ACL) message structure specification.

The JADE messaging architecture differentiates between intra-platform and inter-platform communication. In the case of intra-platform communication, agents reside in the same platform and JADE uses its IMTPs for implementing delivery services. In order to minimize delivery time, JADE selects the most appropriate transport mechanism further distinguishing between the case of communicating agents that reside in the same container and agents that reside in different containers. A container, which is hosted by a Java Virtual Machine, provides the run-time environment and the services for one or more agents.

Figure 26 depicts the components (devices&agents) that are going to be used for the implementation and demonstration purposes. The Knowledge-based Suitability Determination Algorithm can be assumed as a centralised approach so the decision-making is located in the CSCI Agent of the BS on the infrastructure side.

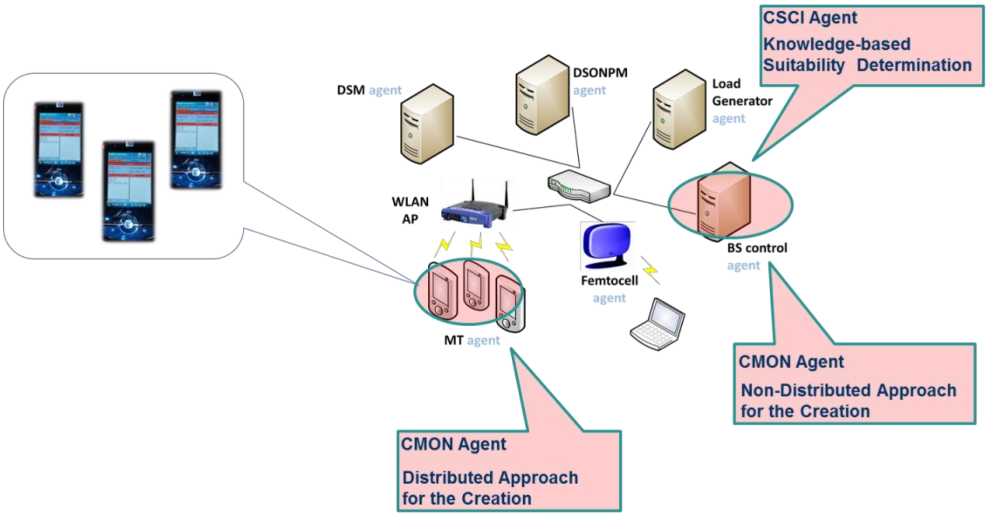


Figure 26: Components of the Agent-based Approach

Figure 27 depicts the mapping to CSCI functional entity, in terms of parameters used by the knowledge based Suitability Determination Algorithm. The CSCI involves the following entities: context awareness, policy derivation and management, profile management, decision making mechanism and knowledge management.

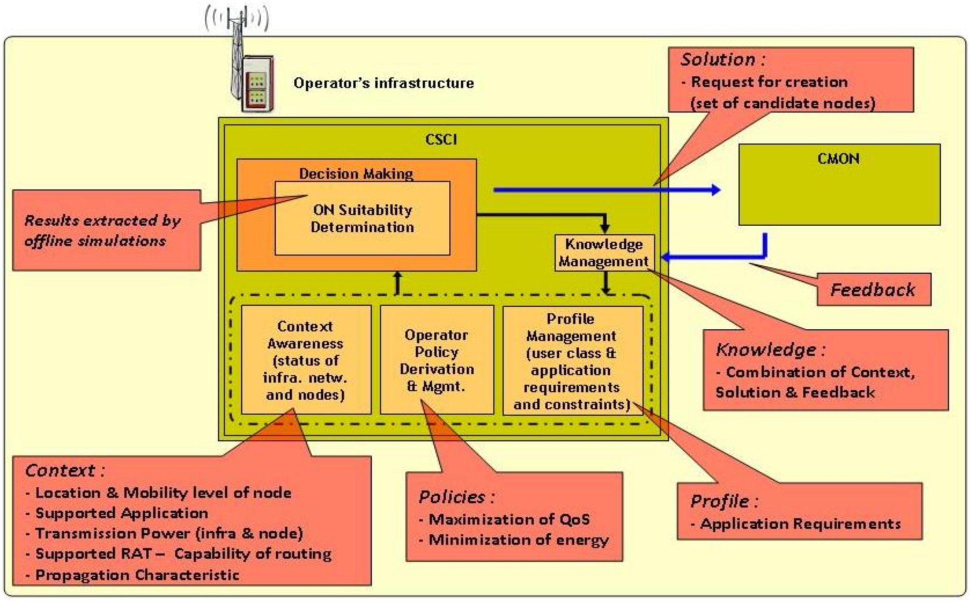


Figure 27: CSCI Functional Blocks

Context awareness. The context awareness functional entity of the CSCI involves the monitoring of the status of the nodes and the infrastructure network. The context is consisted of the location and mobility level of each node, supported application, transmission power of the AP/BS and nodes, supported RAT for each node, propagation characteristic of the environment and capability of the node for the routing.

Policy Derivation/Management. This entity designates high level rules that should be followed in context handling. These rules are related to the maximization of the QoS levels, and the minimization of cost factors (e.g. minimization of energy consumption).

Profile management. This functional entity includes requirements and preferences of the supported applications of the nodes (e.g. max end2end delay and packet loss).

Suitability Determination. This entity provides the process for the decision making located typically in the infrastructure side. This decision relies on off-line simulations and gives as an output to CMON functional entity a request for the creation phase, associated with a pre-selected set of candidate nodes.

Knowledge Management. The knowledge management entity combines the context, the solution of the decision making and the feedback from the CMON entity, in order to create the knowledge for making better decisions in the future, according to the learned results.

3.6.7 Algorithm evaluation

In order to evaluate the performance of this algorithm several simulations have been performed prior to its integration in the platform described in section 3.6.6. In the following the simulation environment used is described in detail followed by indicative results derived from these simulations.

3.6.7.1 Simulation Environment description

A large set of scenarios and test cases were executed in the simulation environment, which was based on the widely used OMNeT++ network simulation environment [65] and ran on an Intel Pentium - 4 3,0 GHz with 1,5 GB of RAM.

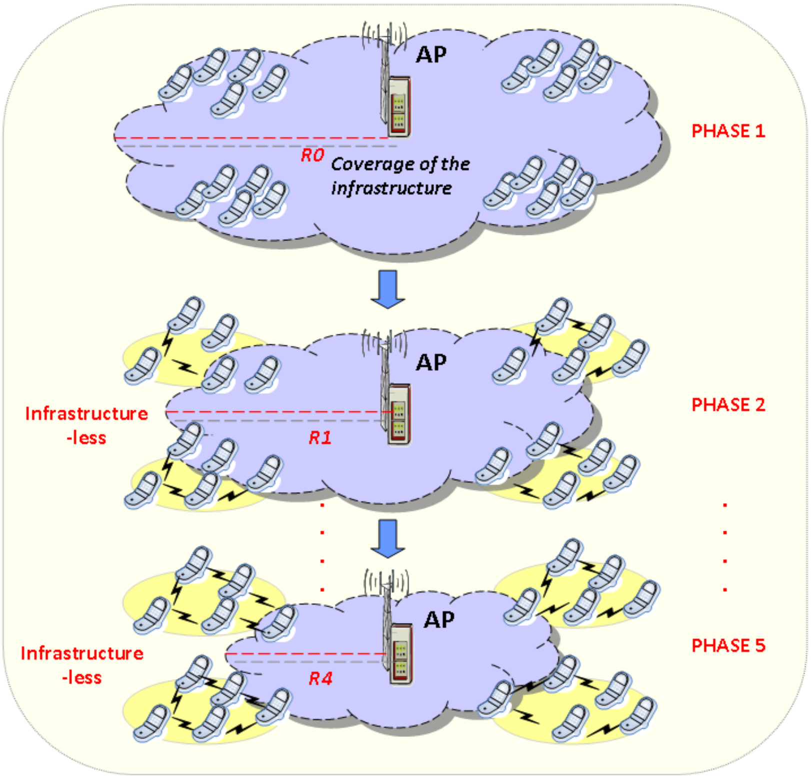


Figure 28: Considered Scenarios

The topology, as also depicted in Figure 28 comprises a single Access Point (AP) operating at IEEE 802.1b technology and a total set of *20* terminals which are served by this AP. The propagation model is set to Free Space, with no effects from the environment and the terrain profile is flat with the elevation of the AP set to *20*m. The initial transmission power of the AP is set equal to *0.03*W. Moreover, terminals are assumed to be static. Table 3 summarizes the general input parameters of the considered simulation enviroment. A set of applications are considered to be offered to the terminals through the AP and further analyzed in the following. The terminals are uniformly distributed in the cell around the AP.

Table 3. General parameters of the simulation enviroment

Area	*250 x 250 m*
Simulation Time	*60 min*
Physical Characteristics	*802.11b, Direct Sequence Spread Spectrum (DSSS)*
Physical Layer Data Rate	*11Mbps*
Total Number of Terminals	*20*
Reception Power Threshold	*-95 dBm*
Initial AP Trx Power	*0,03 W*
Terminals Trx Power	*0,02 W*

Three types of applications are considered in the simulation scenarios, which were selected so as to exhibit varying and scalable resource requirements and sensitivity e.g. with respect to bandwidth, delays, jitter, packet loss etc. These are a) Internet browsing b) Voice over IP (VoIP) and c) Video conference. All important properties for the applications are listed in Table 4.

Table 4. Traffic Input Parameters

Browsing	*Light, Protocol Version : Http 1.1*	
	Page Interval Time : Exponential 720 sec	
	Pages Per Server : Exponential 10	
	Page propeties:	*1 constant part : 500 bytes*
		5 Small Images : 250 bytes each
VoIP	*Encoder Scheme G.711 (silence),*	
	Compression / Decompression delay 0.02 sec	
	1 voice frame per packet	
	Incoming and outcoming Conversation environment : Land Phone – Quiet room	
	No control signalling(e.g. for setup/release) included	
Video Conferencing	*Low Resolution Video : 128X120 pixels, 9 bits/pixel*	
	10 frames/sec	

The examined simulation scenarios evolve as follows. The initial TRx power of the AP is gradually decreased. Five steps (phases) are considered, each one corresponding to a specific percentage of the initial TRx power, namely: 100% (initial), 90%, 80%, 70% and 60% , thus resulting in ranges *R0, R1*, *R2*, *R3* and *R4*, respectively. This is depicted in Figure 29 in which it is also shown how the initial coverage of the AP is being reduced to a smaller one as a result of the gradual decrease of its transmission power. Apparently, it holds that *R0>R1 >R2>R3>R4.*

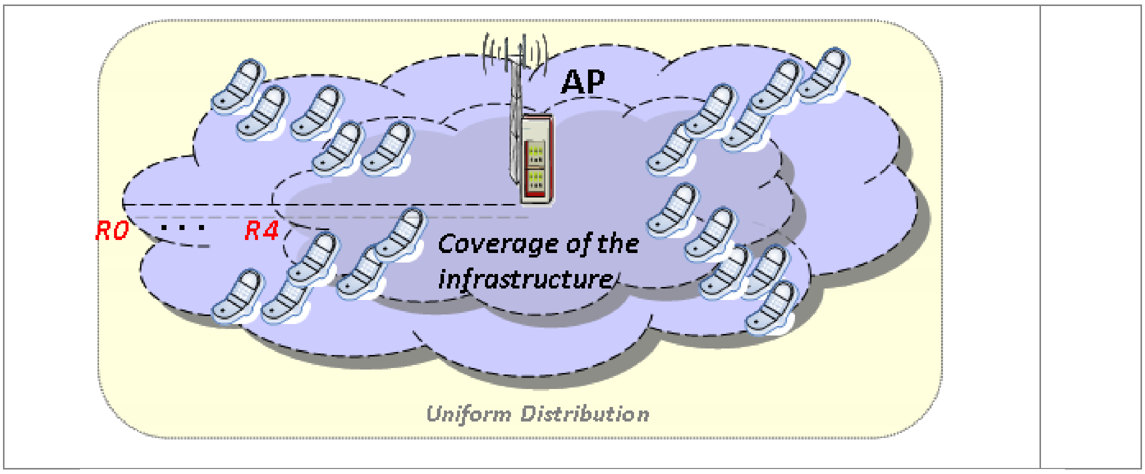


Figure 29: Considered area Case 1 (Uniform Distribution)

During the gradual reduction of the AP's TRx power, a number (percentage) of terminals are left out of the APs' range. These terminals are then supposed to create ONs among them in an ad-hoc manner and operating in WLAN 802.11b as well. The exact number of nodes connected in ad-hoc mode in each of the phases is shown in Table 5. In the uniform distribution case, as the initial range of the AP decreases, the number of the terminals that are out of this range increases in a constant way.

Finally, we also experiment on the routing protocol which will be used to route traffic to terminals that are found out of range during the AP's transmission power reduction. For completion reasons, we conduct all the simulation scenarios assuming 3 different kinds of ad-hoc routing protocols, namely Ad hoc On-Demand Distance Vector routing protocol (AODV) [66], Optimized Link State Routing protocol (OLSR) [67] and Geographic Routing Protocol GRP [68].

Table 5. Number of out of range terminal nodes per phase

Phases	Ranges	Number of out of range terminal nodes
		Uniform Distribution Case
1	R0	*0*
2	R1	*4*
3	R2	*8*
4	R3	*12*
5	R4	*16*

3.6.7.2 First performance evaluation

The major concern of these simulation studies is to investigate the QoS provision potentials of such a scheme and thus, assist in the definition of these criteria.

Accordingly, in each of the phases we focus on specific QoS metrics, which are used to evaluate conditions and assist in coming up with useful recommendations with respect to the creation of the infrastructure-less networks. Particularly, in this simulation study, quality of service evaluation is carried out by the following performance metrics:

a) *Delay (sec)*: which is the one way, end to end delay of data packets from the sending to the receiving node. It includes a) processing delays e.g. voice packet compression/decompression, packetization etc. b) queuing and medium access delays in the AP as well as in the intermediate nodes, c) TRx delay of the AP and the intermediate nodes and d) the propagation delay for each connection between the AP and the destination node.

b) *Data received (Kbps)*: which corresponds to the total number of the successfully received packets (including PHY/MAC headers) by a wireless node per unit of time, regardless of the destination of the received frames.

c) *Data Dropped (Kbps)*: which is defined as the rate at which data is dropped due to full higher layer data buffers or because of too many retransmission attempts

d) *Throughput (Kbps):* which corresponds to the total data traffic in bits per sec, successfully received by the destination excluding packets for other destination MACs, duplicate and incomplete frames.

e) *Jitter (sec)*, which is used to denote the average time difference between the arrivals of two consecutive packets at any destination node.

All the above metrics are averaged to the set of terminals in the simulated network. Moreover, Table 6 summarizes the requirements for specific QoS metrics [69] and for each of the considered applications. This table will be used as a reference throughout the rest of this paper and will assist in extracting conclusions and recommendations from the derived statistics.

Table 6. QoS requirements per application type

Applications	**Technology**	**QoS Metrics**			
		Delay (ms)	*Jitter (ms)*	*Bit Rate (Kbps)*	*Packet Loss*
Browsing	Non real time and Asymmetric	<400	N/A	<30	0%
VoIP	Real Time and Symmetric	<100	<400	64	<1% (lasting 2-3 sec)
Video Conferencing	Real Time and Symmetric	<150	<150	1382,4	<1%

Next results focus on the case with uniform distribution of terminals. Figure 30 depicts the average end-to-end delay that the packets of each terminal nodes see and which, as already said, is estimated by summing up processing, queuing, MAC, transmission and propagation delays as well. It should be noted here that the end-to-end delay that is measured by the network simulator, actually assumes a terminal node in the one end and the AP in the other end. That is to say, in order to obtain the actual end to end values, we should first double the obtained simulation measurement (reach the other terminal node) and add a worst case delay of about *65*ms [70] corresponding to the extra delay due to the packets traversing the public internet. Therefore, Figure 30 depicts exactly these elaborated results.

For the Internet browsing application the average delay (averaged in all phases and routing protocols) is about *67,09*ms. In the case of VoIP application, the average value for the delay is about *126,82*ms. Finally, the Video conferencing application exhibits an average delay of about *188,12*ms and as the number of the terminals that are out of the range is increasing, there is a big rise in the delay.

As a general observation, since the number of the intermediate, out of range nodes is increasing, while the AP's range is shrinking from *R0* to *R4 (phase 1 to 5),* the overall delay is also increased as more terminals are responsible for routing and forwarding the received packets. Nevertheless, the end-to-end delay increases in a non linear manner in contrast with the number of out of coverage terminals, which increases linearly, due to the uniform kind of terminals' distribution (see Table 5). In particular, this increase is almost inexistent in the case of Internet browsing application, keeping the delay values negligible in all phases. The increase is made clearer in the case of VoIP, but still remains at low levels in the first 4 out of the total 5 phases and in almost all cases of routing protocols. Finally, it is rather considerable in the case of Video conferencing in almost all the phases, especially in phases 4 and 5.

Similar results can be derived when examining Figure 30 with respect to the used routing protocol. For instance, there are negligible differences in the produced delays for the three protocols, when using the internet browsing application. On the other hand, OLSR seems to clearly outperform its competitors in the case of VoIP application giving an average delay (for the 5 phases) almost *30*ms less than the ones collected in the case of AODV and GRP, respectively. However, it should be noted that this variation is mainly ascribed to the last two phases, 4 and 5. While in phases 1 to 3, no significant differences exist. A quite similar situation appears in the Video conference application, but with the AODV being the winner this time, resulting in *75*ms and *30*ms less delay values compared with the OLSR and GRP, respectively.

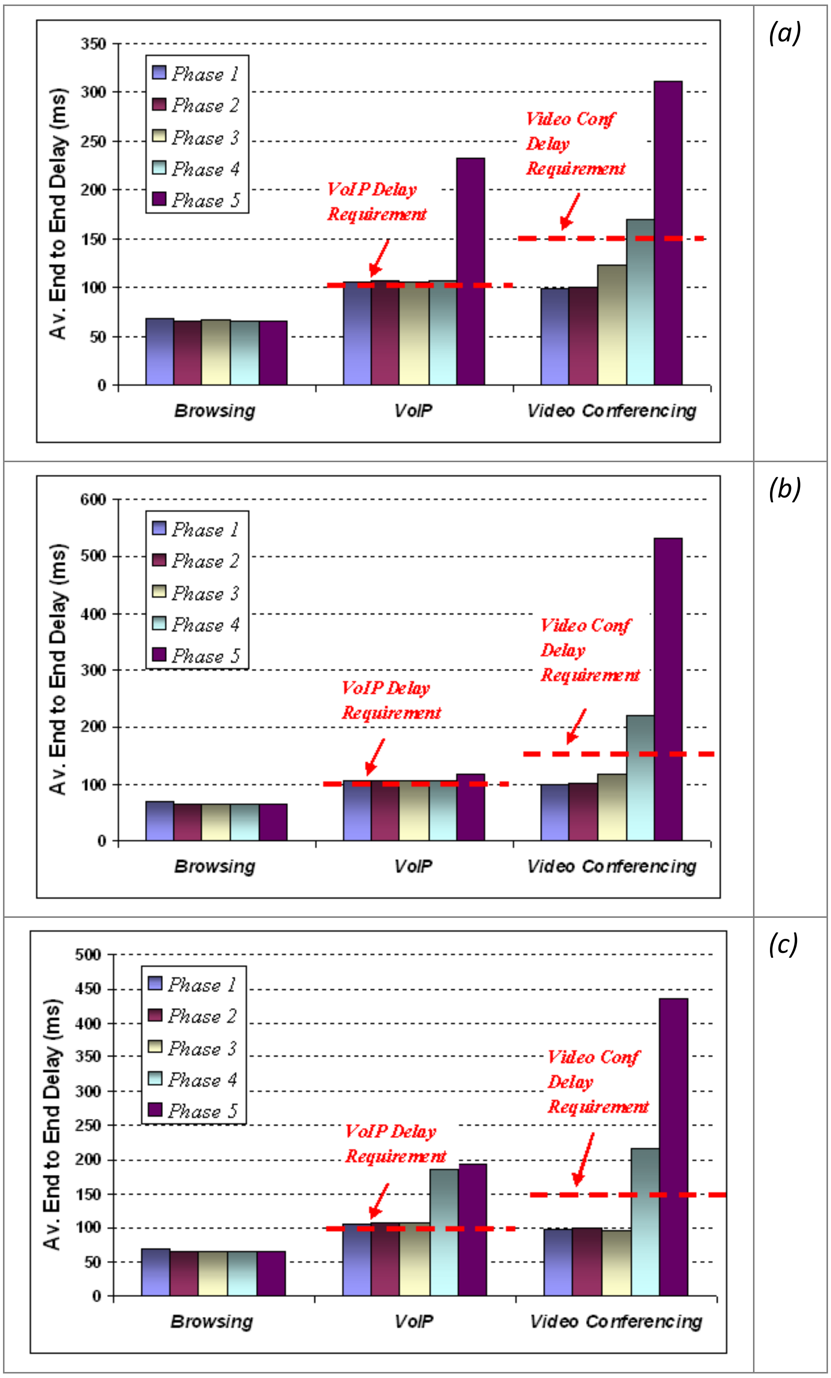


Figure 30: Average. End to End Delay per Node vs Application type for (a) AODV (b) OLSR (c) GRP routing protocol

In the sequel, we examine the obtained results against the set of predefined application requirements given in Table 6. By advising the table, it is assumed that the one way acceptable end-to-end delay for VoIP and Video conferencing applications are *100*ms and *150*ms, respectively [69]. The results are also depicted in Figure 30, where single dotted lines corresponding to the delay requirements for the two time-sensitive applications are also drawn for readiness purposes. The delay requirement for web browsing (< 400ms) is not depicted, since it is far away from being violated in all the examined cases. Phase 5 seems to be a prohibitive state for the network, when considering VoIP and Video conference applications. Moreover, phase 4 can also result in intolerable delays e.g. when OLSR and GRP routing are deployed.

Accordingly, the above designate cut-off values for the transmission range (or transmission power), which in the majority of the combinations of the tested application and routing protocol can be found somewhere between the 70% and 60% (fine-tuning might be needed) of the initial one. A 30% or 40% reduction of the AP's transmission power while offering applications with tolerable values of delays is very promising with respect to power/energy savings and gives a positive feedback to the suitability question upon creating the infrastructure-less network.

Figure 31 depicts the % percentage of packet loss which arises after dividing the number of dropped data with the data sent by all clients.

In the same figure, single dotted lines are used to depict the requirements posed for guaranteeing the flawless reception of the application. For both applications, internet browsing and especially for VoIP, packet loss remains at acceptable levels i.e. not exceeding or extremely slightly exceeding a value of 1%, for all the phases of the reduction of the AP's transmission power and for all three routing protocol options. This is not the case for video conferencing. As depicted in Figure 31, in the three last phases the average data dropped packets result in a non acceptable value, which is actually far away from the minimum allowable threshold as defined in Table 6 and also depicted as a dotted line in the same figure.

Last but not least, Figure 32 depicts the average downlink throughput in Kbps estimated for all terminals, bit infrastructure-based and infrastructure-less. Although the delay in general increases, we observe that in browsing and VoIP applications the average downlink throughput per terminal node increases, even though this happens at non significant levels. A first, immediate explanation behind this observation would be as follows: In the first phase there are terminals that are in the edge of the cell and the achieved physical data rate is not the maximum supported by the technology i.e. 11Mbps, whereas this is restored with the reduction of the range that causes a corresponding reduction in the average distance among terminals using ad-hoc connections as well. However, the network simulator does not support scaling back of the physical data rate (i.e. among 1, 2, 5,5 and 11Mbps) and as a result, it might be safer to ascribe this throughput increase to the relative increase of the total data received per terminal.

When it comes to video conference application, we observe a significant decrease in the throughput when moving from phase 1 to phase 5. This can be justified if seen in conjunction with the corresponding increase in both the dropped data rate and the end-to-end delay metrics that the application suffers.

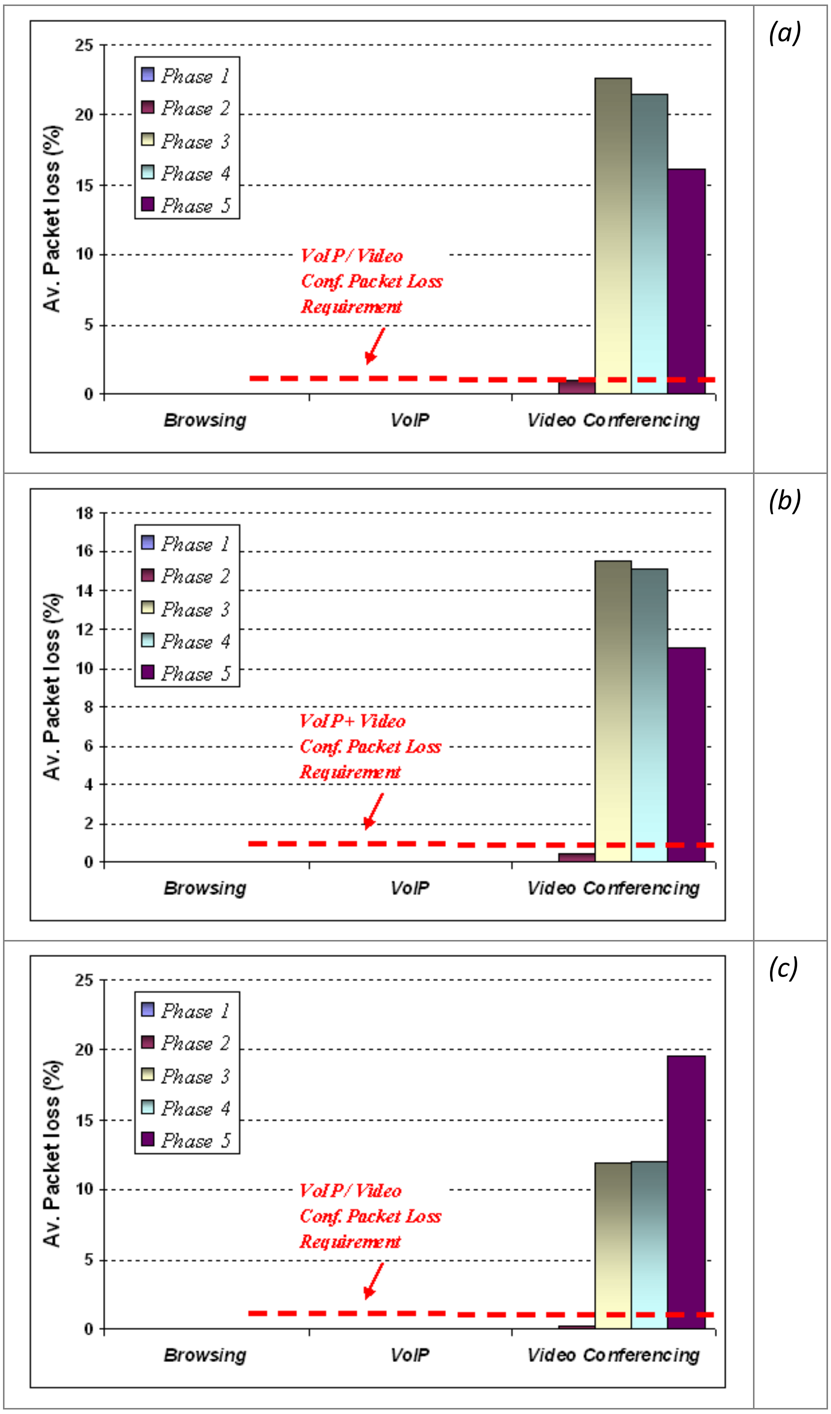


Figure 31: Average Packet Loss per Node vs Application type for (a) AODV (b) OLSR (c) GRP routing protocol

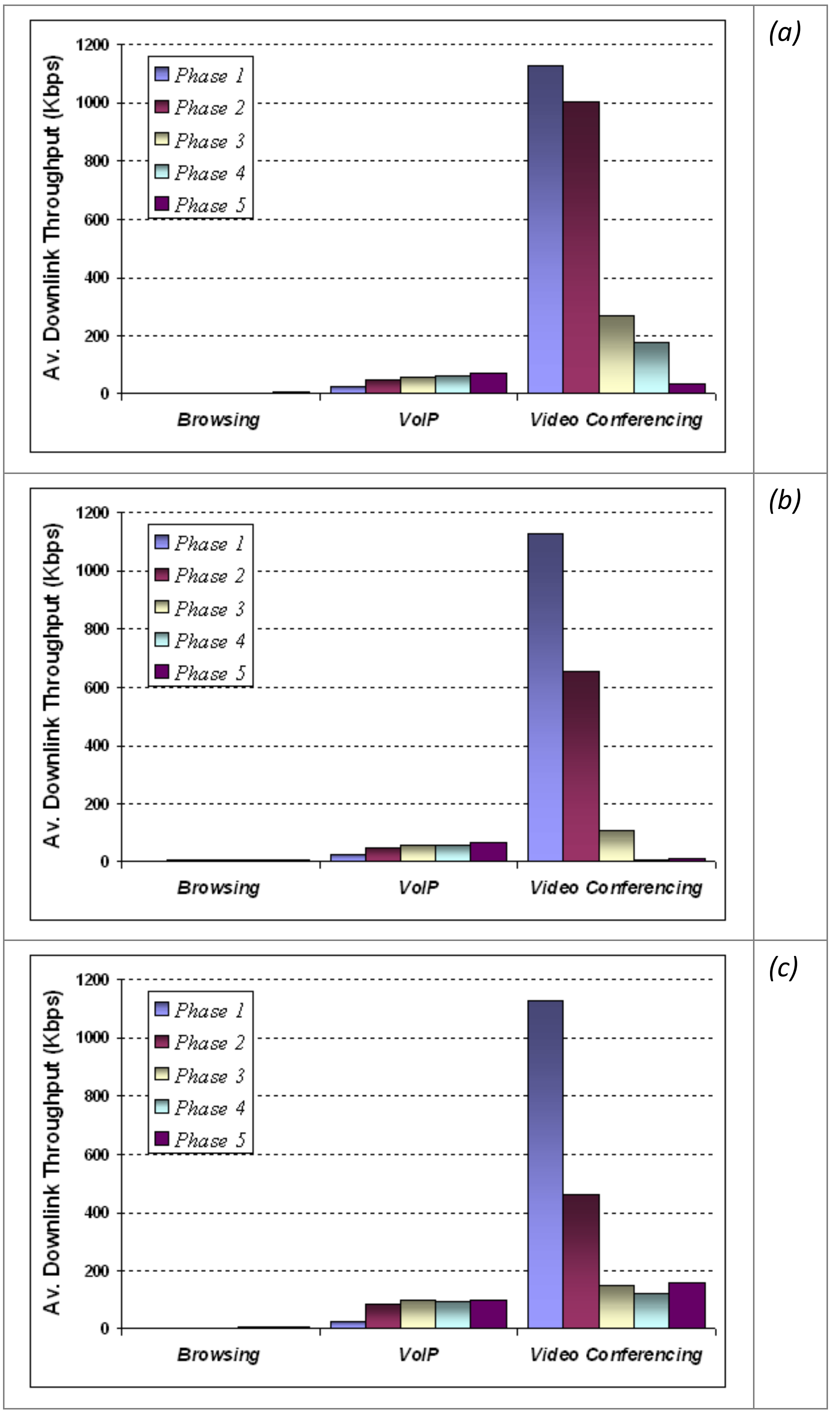


Figure 32: Average Downlink Throughput per Node vs Application type for (a) AODV (b) OLSR (c) GRP routing protocol

Focus now is placed on results observed from Figure 32 with respect to the used routing protocol. In the case of internet browsing there are insignificant differences. In the case of VoIP, GRP seems to outperform its competitors, giving an average throughput *28*Kbps and *27*Kbps more than OLSR and AODV, respectively. Also in case of video conferencing AODV outperforms its counterparts in terms of achieved throughput giving almost *141*Kbps and *117*Kbps more than OLSR and GRP, respectively.

When the traffic is uniformly distributed, transmission range reductions of X% (e.g., 70) can be done without impacting too much the service provisioning. In this case a “small” transmission range reduction means that “several” devices are left out of range (see Table 5).

In addition, by comparing the obtained results for the whole set of QoS metrics, it is easy to realize that the measured values exhibit big similarities in all phases ranging from 1 to 4. However, this does not happen in phase 5. Going one step further and checking the actual number of terminals that are left outside the range in all these phases (Table 5), we may come up with great certainty in the conclusion that the absolute number of terminals which are left out of the range and form the infrastructure-less network is a very crucial factor to take into account and therefore it calls for further investigation.

In general, what can be deduced from the above scenarios and results is that there appear cut-off levels of the AP transmission power (AP coverage) which if they are not infracted, applications can still be satisfactorily supported and provided at adequate QoS levels, with less AP power resources. In case more devices are concentrated away from the AP, then the cut-off value will be high, near to the default AP transmission range. This will result in small, yet important, savings in the total transmission power. If more devices are concentrated near the AP, then the cut-off value will be significantly lower than the default AP transmission range. This will result in larger savings in the total transmission power.

Of course, there is also the other side of the coin, according to which the cut-off levels designate that below them, some applications cannot be adequately supported. In particular, although an application such as internet browsing can continue to be satisfactorily provided after the reduction steps, this is compromised in the case of applications which are much less tolerable in time slips. This calls for special caution when thinking of the fact that future internet applications are expected to combine high quality video and voice in a real time fashion.

Moreover, one thing that should be realized and should be put into practice while seeking for cut-off levels is that QoS is a rather complex commodity and in most of the cases it cannot be provided after optimizing a single or even a few parameters. Therefore, it is required to take into account the whole or major set of the defined QoS metrics in a joint manner and try to guarantee that they will provide satisfactory values at the same time.

In order to further evaluate the performance of the algorithm as well as to demonstrate its feasibility this algorithm will be integrated into the overall platform described in section 3.6.6. Results from such evaluation will be presented in forthcoming deliverables. Furthermore experiments with alternate simulation assumptions (e.g propagation models) will be done and presented in D4.2.

3.6.8 Requirements on the C4MS protocol definition & technical challenges

The Knowledge-based Suitability Determination Algorithm can be assumed as a centralised approach where the decision-making is located in the CSCI functional entity on the infrastructure side. The C4MS will support the transportation of the information needed from the terminals to the Infrastructure. Particularly the information exchanged is the following:

- Location of the nodes
- Mobility level
- The supported application
- Transmission power of the nodes
- Supported RAT for each node
- Capability of routing

3.7 UE-to-UE Trusted Direct Path

3.7.1 Technical challenge addressed

This algorithm focuses on the user plane path control between UEs belonging to an ON. The algorithm considers the handover of the UE to UE data path from a situation where the UE to UE data path is established through the infrastructure (i.e. the situation without an ON established), to the situation where a direct path is established between the UEs without going through the infrastructure (i.e. the situation with an ON established).

Considering the fact that the architecture of the ON is 3GPP based, the technical challenge resides mainly in having a UE to UE direct communication with the same security and trust as if the path was established through the 3GPP infrastructure. The addressing scheme (L2/MAC address or L3/IP address) on the direct UE to UE infrastructure network has to be resolved, keeping in mind the legacy 3GPP architecture.

3.7.2 Rationale

Direct UE-to-UE communication between ON members is a key feature of the Opportunistic Network. Such communication will allow to realize new services due to the high speed of local communication between UE (i.e 802.11 technologies), and to the traffic offloaded in the infrastructure. The benefit of direct UE-to-UE communication is obvious for the operator as it allows saving infrastructure resources and the creation of new services.

On the user’s side, the benefit of the ON as defined by OneFIT largely lies in the operator-grade level of security offered to the peer users in the case of direct communication. Adding the Operator print in security field for Ad-Hoc communication extension will increase End Users confidence. Then the ability to provide these trusted paths over multiple hops using different RAT is one of the keys to deliver OneFIT’s promises.

The algorithm study has to identify the terminal address problem from application layer’s identities to routing addresses at MAC and IP level, and the handover of the user plane data path form the UE-to-UE case to a UE-to-infrastructure case and vice-versa.

3.7.3 Use cases mapping

This algorithm is a core requirement for Scenario 3 “opportunistic ad hoc networking” (see Figure 33), but it will also be required for supporting all scenarios where UE-to-UE direct the situation may appear in other scenarios. The algorithm is also expected to applied and extended to support the Scenario 1 coverage extension and the scenario 4 “Traffic aggregation”.

The algorithm will be studied for the use case where the Opportunistic Social Network is based on Wi-Fi technologies and where the wireless operated network will be based on the 3GPP technologies.

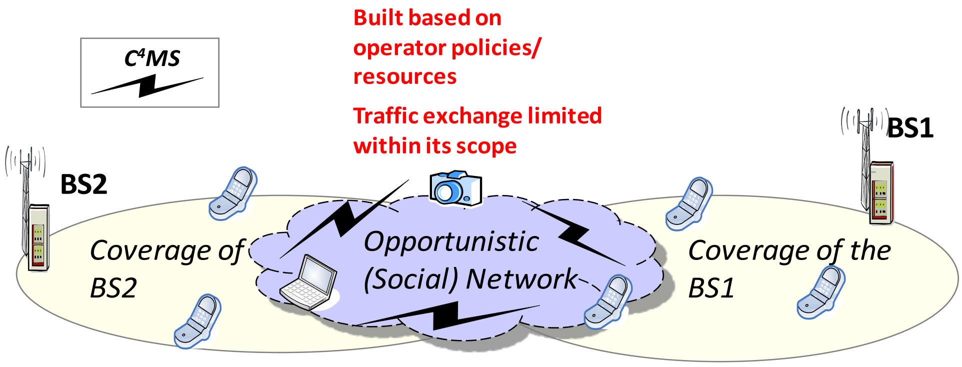


Figure 33: Scenario 3: Operator-governed cost-efficient localized application/service/content provision scenario.

3.7.4 State Of The Art

Although 3GPP has not defined specific use cases for UE to UE traffic optimization, 3GPP has defined various network infrastructure configurations combining 3GPP and Wi-Fi radio technologies, and network offload traffic techniques that are useful to report.

Regarding the wireless network selection, 3GPP has defined the Access Network Discovery and Selection Function (ANDSF) for supporting multi-access network scenarios with intersystem-mobility between 3GPP-networks (GSM, UMTS, LTE) and non-3GPP networks (e.g. WiMAX, WLAN). This has been described in D3.1.

Regarding the user plane 3GPP has specified two different schemes for managing the mobility.

Inside the 3GPP RAT, the 3GPP provides mobility at the layer 2. A layer 2 is established from the UE to the serving PGW, and the mobility (i.e change of user plane path, due to a change of node B) is managed by a L3 IP tunnel (i.e GTP) transporting the UE L2 traffic. On top of this layer 2, the terminal has an IP address allocated by a PDN Gateway depending on the Access Point Name (APN). When 3GPP interact with non 3GPP RAT, like Wireless LAN, then the mobility is managed at the IP layer with mobile IP protocol like DSMIP-V6 (cf [71]). Regarding the user plane path in 3GPP, a UE user plane data path is usually established between the UE and the PDN Gateway. In our case we would like to communicate between 2 UEs. 3GPP has defined specific procedure to perform shortcut or offload in the infrastructure that are interesting to report.

- SIPTO, LIPA (cf [72]) ; LIPA refer to the traffic breakout in a Home NodeB for accessing to local IP resource (ex : access to a local printer on the enterprise network); SIPTO (Selected IP traffic offload) refer to the offload of traffic in the Home NodeB for accessing to the internet.
- IFOM ([73]). IFOM (IP flow mobility) refer to the routing of IP flow in a UE attached simultaneously to the 3GPP RAN and to WLAN.

In terms of security, a 3GPP UE is identified by information stored in the SIM card. Over non-3GPP RAT ([74]), the UE is authenticated via SIM/USIM and EAP-SIM/EAP-AKA protocols.

3.7.5 Algorithm description

The algorithm will take as foundation the new ON-specific 3GPP LTE procedures studied in WP3 for ensuring that each UE in the ON has a trusted relationship with the infrastructure network whatever the RAT used for the hops between the UE and the RAN.

Figure 34 illustrates the UE-to-UE trusted direct path concept.

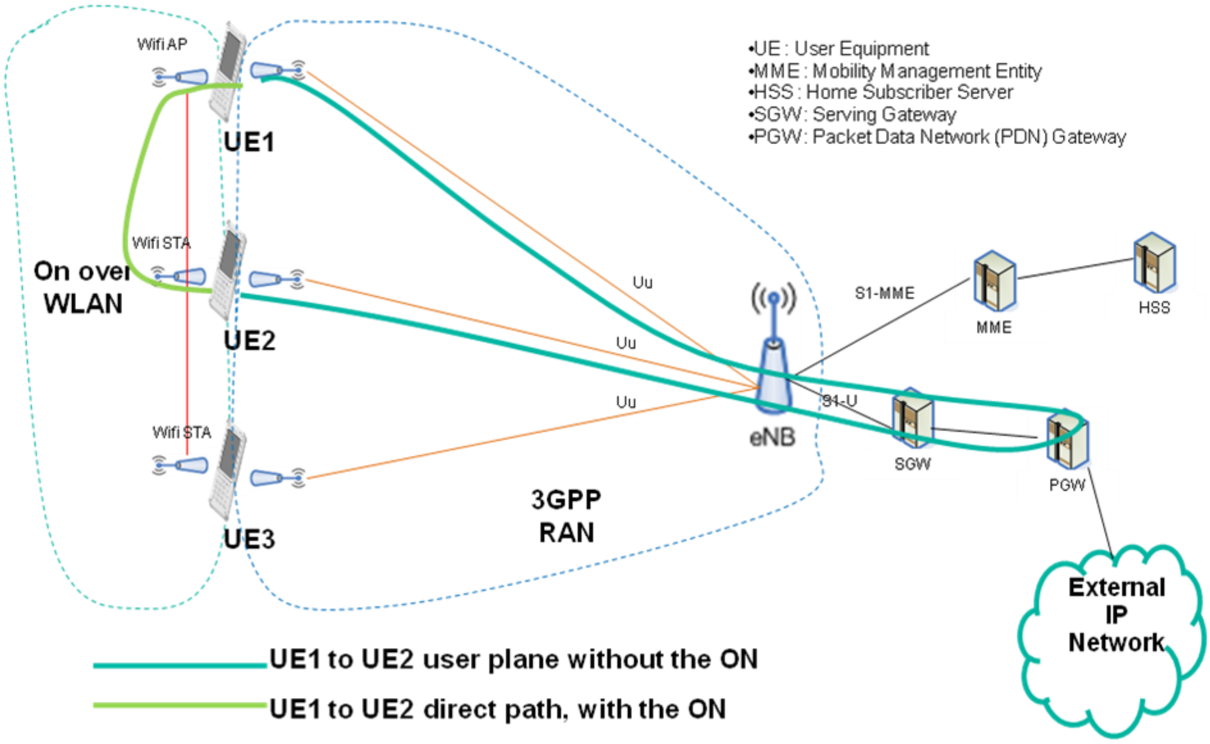


Figure 34: UE-to-UE Trusted Direct Path

The algorithm uses input parameters obtained from the UEs to be considered for the ON. Such parameters encompass the UE WLAN capabilities: (e.g.: WiFi direct, Security, QoS, ...), and other UE capabilities related to the ON.

The algorithm will determine primarily the role of the UE in the ON regarding the Wi-Fi access. For example in case of coverage extension scenario, the algorithm will determine whether a UE has to use the Wi-Fi access or not. This could result in different cases if the UE is under the 3GPP network coverage, or if the UE is not under 3GPP coverage.

Secondly the algorithm will establish the addressing scheme used on the ON (Layer 2 or Layer 3).

Finally, the algorithm will determine the data path of the UEs that will be optimized from a UE-to-infrastructure-to-UE to a direct UE to UE path.

During the 2nd step the algorithm will determine all the security elements that will be required. For establishing a secure direct UE to UE path, the algorithm will have to determine the secure element, like the data link ciphering key.

3.7.6 Algorithm evaluation

The algorithm evaluation will consider different criteria such as the amount of traffic signalling exchanged over the different C4MS protocol, the energy efficiency or the transmission delay.

3.7.6.1 Simulation Environment description

The evaluation environment is under study and will possibly consist of a dedicated simulation or prototype environment based on a 3GPP architecture simulating UEs with both 3GPP and Wi-Fi RAT and ON functions.

The simulation environment will be able to identify the algorithm performance for selected OneFIT use cases.

3.8 Algorithm on selection of nodes and routes

3.8.1 Technical challenge addressed

The algorithm focuses on the technical challenges of the creation phase as analyzed in D2.1. Specifically, the challenge of the selection of nodes which will participate to the ON is addressed.

3.8.2 Rationale

According to the OneFIT concept, ONs are created in an infrastructure-less manner under the supervision of the operator and include numerous network-enabled elements. Main objective of the ON according to the defined scenarios of D2.1 is to ensure application provisioning in an acceptable QoS level by providing opportunistic coverage extension, opportunistic capacity extension, infrastructure supported opportunistic ad hoc networking, opportunistic traffic aggregation in the radio access network or opportunistic resource aggregation in the backhaul network. To ensure this, the selection of the proper nodes, among all discovered nodes in the vicinity is rather essential. As a result, our approach proposes a mechanism for selecting nodes that will participate to the ON.

3.8.3 Use cases mapping

The algorithm is potentially implemented to all use cases as defined in D2.1, due to the fact that the selection of proper nodes to participate within the created ON affects all possible scenarios.

3.8.4 State Of The Art

Various approaches concerning node selection for ad hoc, wireless sensor or mesh networks are already available. For example, random node selection in unstructured P2P networks is discussed in [75] while authors in [76] address the relay selection problem in cooperative multicast over wireless mesh networks. Also, in [77], analytical and simulation approaches are used in order to investigate the relationship between the lifetime of sensor networks and the number of reporting nodes and to provide the trade-off between maximizing network lifetime and the fastest way to report an event in a wireless sensor node. In [78], the selection and navigation of mobile sensor nodes is investigated by taking into consideration three metrics including coverage, power and distance of each node from a specified area. In [79], a grid-based approach for node selection in wireless sensor networks is analyzed, in order to select as few sensors as possible to cover all sample points. In [80], the issue of server selection is being investigated by proposing a node selection algorithm with respect to the worst-case link stress (WLS) criterion. These works are proposing specific node selection algorithms by taking into consideration attributes such as the area of coverage, the navigation/ mobility issues of moving sensors, or the minimization of the number of relays.

3.8.5 Algorithm description

The algorithm will be responsible for the creation of ONs taking into consideration multiple parameters. Two approaches are assumed in this direction, distributed and non distributed. The delineation of such algorithm-strategies is the objective of this section.

3.8.5.1 Distributed Approach

The algorithm introduces a set of steps which are taken into consideration for the efficient selection of the ON nodes that will constitute the created network. Aligned with this statement, initially, each discovered node is being checked whether it is legitimate according to the policies of the network operator to participate to an ON. If the result is negative the discovered node is rejected by default, else if the result is positive, then the evaluation of the discovered, candidate node continues according to a fitness function. The fitness function is based on a weighted, linear formula which takes into consideration the following:

- Candidate node's energy level

- Candidate's node availability level including:
  - capabilities (available interfaces, supported RATs, supported frequencies, support of multiple connections, relaying/ bridging capabilities);
  - status of each node in terms of resources for transmission (status of the active links), storage, processing;
  - node's location
  - supported applications (according to node's capabilities and application requirements)
- Candidate node's delivery probability

The proposed fitness function is the following:

$$Fitness\ Function = x_i * [(e_i * w_e) + (a_i * w_a) + (d_i * w_d)] \quad (12)$$

where e_i denotes the energy level of node i and w_e is the weight of the e_i variable to the fitness function. Also, a_i denotes the availability level of node i at a specific moment and w_a is the weight of a_i, while d_i denotes the delivery probability of packets of node i and w_d is the respective weight. Also x_i acts as multiplier according to relation below:

$$x_i = \begin{cases} 1, e_i > 0 \cap a_i > 0 \\ 0, e_i = 0 \cup a_i = 0 \end{cases} \quad (13)$$

According to the previously mentioned characteristics, each candidate node obtains a fitness value. If the fitness value is higher than a pre-specified threshold, then the candidate node is added to a subset of accepted nodes. Otherwise, it would be added to a subset of rejected nodes. This procedure continues until all discovered nodes have been evaluated and added to the respective subsets of the accepted or rejected nodes. Figure 35 illustrates the aforementioned opportunistic node selection algorithmic approach.

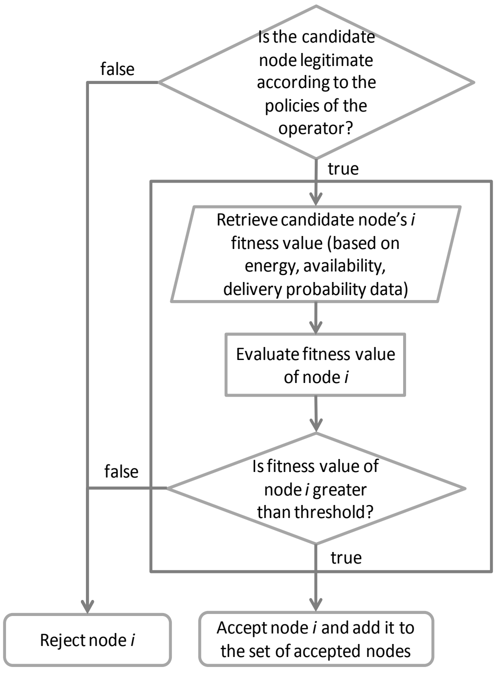


Figure 35: Opportunistic node selection algorithmic approach

Moreover, various routing schemes are considered in our approach. Specifically, a flooding-based opportunistic routing protocol is considered, where nodes replicate and transmit messages to neighbouring nodes that do not already have a copy of the message. A representative example of such a protocol is the Epidemic protocol [81]. The other implemented protocol is the Spray&Wait

[82] which sets a maximum allowed number of copies per message in the ON. For example that upper bound could be set to 10 copies of the original. As a result, lower overheads of replicated messages are observed (compared to Epidemic).

3.8.5.2 Non - Distributed Approach

Initially, a BS identifies a congestion situation and non-congested BSs are identified. The set of BSs is sent to the terminals in the congested area and the terminals in the congested area find paths to non-congested (and congested) BSs according to a “breadth-first search” type. Each terminal should find a set of paths to some of the indicated BSs. Each path has a set of nodes, the capacity of these nodes, and the cost of the links between the nodes.

The algorithm with the non-distributed approach is based on Ford-Fulkerson flow control algorithm [83]. Figure 36 depicts a given network - directed graph, in which every link has a certain capacity c, a starting point (the source) and an ending point (the destination). A value f (the flow of a link) satisfying f ≤ c for each link is associated. As long as there is a path from the source to the destination, with available capacity c on all links in the path, flow f is sent along one of these paths. Then another path is found and so on. The maximum flow of the ON is calculated.

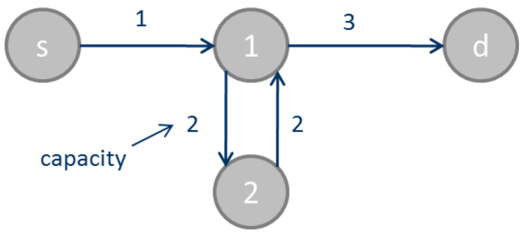


Figure 36: Source and Destination with intermediate nodes and the Capacity of the links

Figure 37 depicts an indicative topology, which consists of 7 ON nodes and 2 Base Stations. Also 2 virtual nodes are assumed in our topology, in order to define the flow in the ON (from source to the destination). Particularly:

- N0 is the “Virtual” super source to which the nodes of the congested area are connected. The capacity of the link from N0 to terminal is set to one.
- N1-7 are the ON nodes
- N8-9 are the 2 Base Stations of our topology
- Finally N10 is our “Virtual” super destination to which the BSs are connected. The capacity of the link from BS to N10 is set equal to the capacity of the BS (estimate on number of terminals that can be served).

The capacity of the links between ON nodes is small (e.g. 1, 2) since we do not want an ON node to serve too much traffic. The value of the capacity would depend on the requirements of the application (e.g. video would need higher values than browsing) or the fitness of the nodes (fitter nodes, as described previously will be capable of handling higher capacities).

The procedure, as depicted in Figure 38 starts by getting the input consisting of the full paths from source (nodes that need to be served, e.g., terminals) to destination (to serving nodes, e.g., BSs or other serving terminals of an ad-hoc communication scheme etc.). A path consists of many links which are distinguished by starting and ending points, cost and capacity (associated with cost) and the utilized RAT. Finally, the terminal and BS parameters are also needed. Once, the input is fulfilled, the algorithm picks one of the discovered paths according to the breadth-first search method [84] which yields the shortest path. From the selected path, it finds the link with the smallest capacity (associated with the link cost). Then, it sets the flow of the path equal to the smallest link capacity (associated with the link cost) and updates the residual capacities of the rest of the links. The algorithm continues until there is no unchecked path from source to destination. Once all paths are checked, a vector containing all selected links from source to destination is created.

Figure 39 depicts an indicative solution, where the actual flows that derived from the algorithm are shown in yellow color.

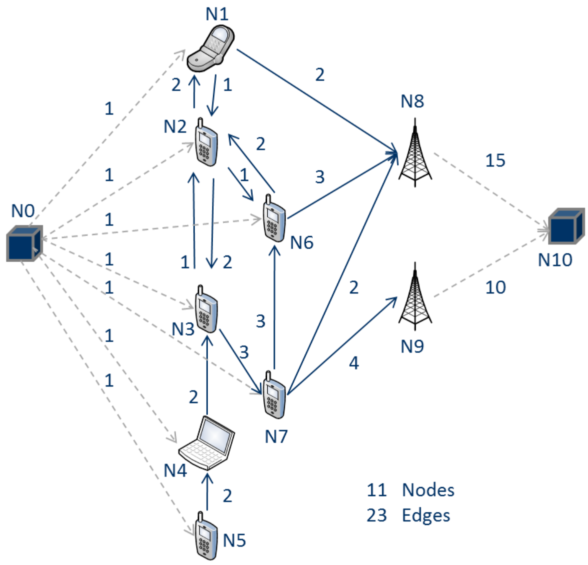


Figure 37: Directed-graph of an ON, illustrating ON nodes (N1-N7), BSs (N8-N9), super source (N0), super destination (N10), links, capacities of each link

3.8.6 Implementation considerations

The implementation considerations for both approaches of the algorithm are the same as previously presented in section 3.6.6. However, as depicted in Figure 26, the distributed approach Algorithm for the creation is located in the CMON Agent of the node, whereas the non-distributed approach in the CMON Agent of the BS.

Figure 40 depicts the mapping to CMON functional entity, in terms of parameters used by the creation Algorithm.

The context awareness functional entity of the CMON uses the information obtained from nodes such as the fitness value, including energy level of the node at a specific moment, available RATs/ interfaces of the node, the quality of links, the available buffer size, the actual location of the node and the mobility level (if it is moving) and the serving BS along with the route to the serving BS. Also, ON-related device capabilities and context information from specific monitoring mechanisms are taken into account, such as whether the node has direct connection with the Macro BS or not.

The operator policy acquisition functional entity is responsible for obtaining operator's policies such as: allowed nodes, allowed frequency bands and transmission bandwidth, allowed transmission power on different bands, allowed mechanisms to obtain information on the spectrum usage (control channel, database or spectrum sensing). In general, this functional entity specifies a set of rules that the CMON must follow.

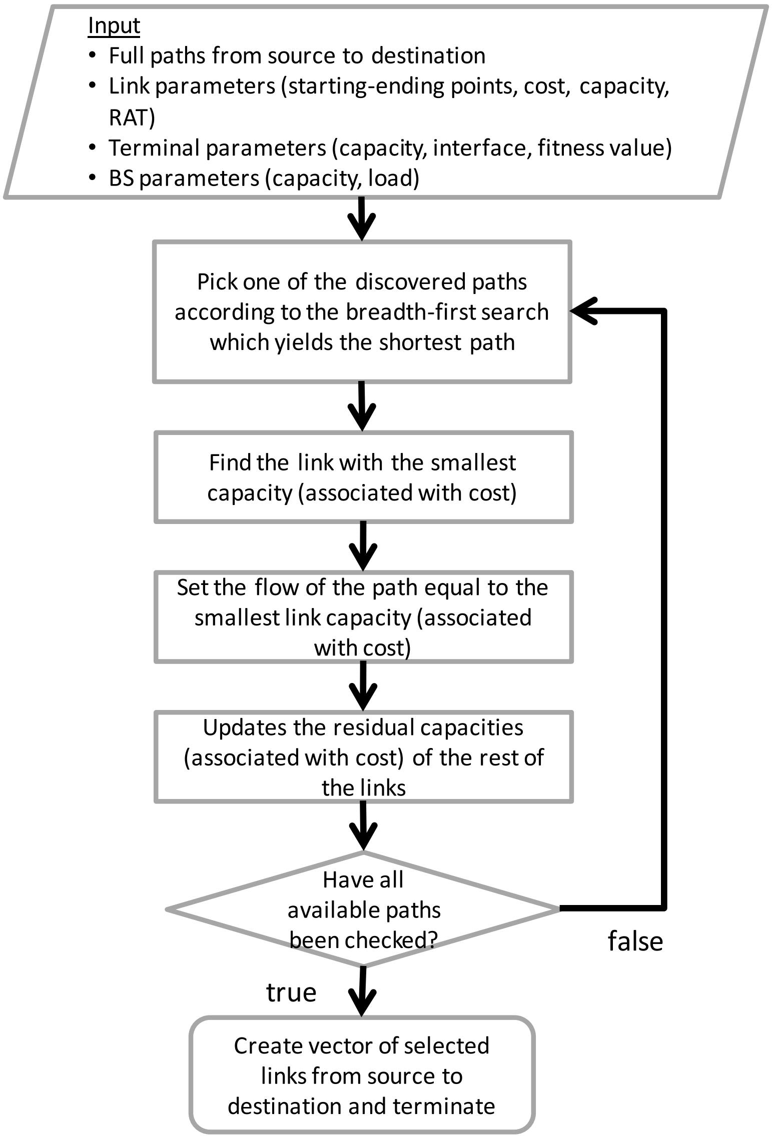


Figure 38: Flowchart of the proposed Algorithm

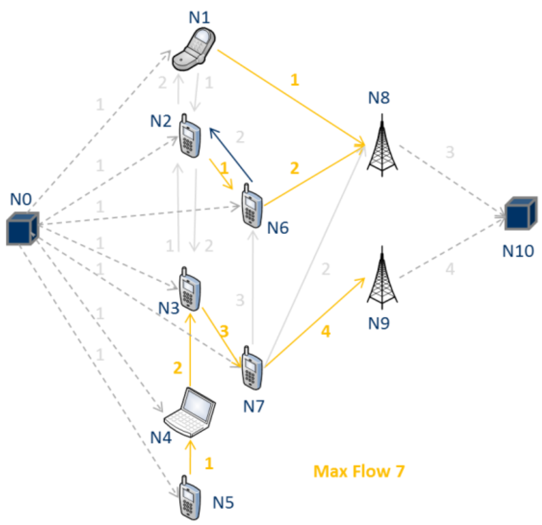


Figure 39: Directed-graph of an ON after the result of the algorithm, illustrating actual flows (yellow) of each link and max flow of the ON

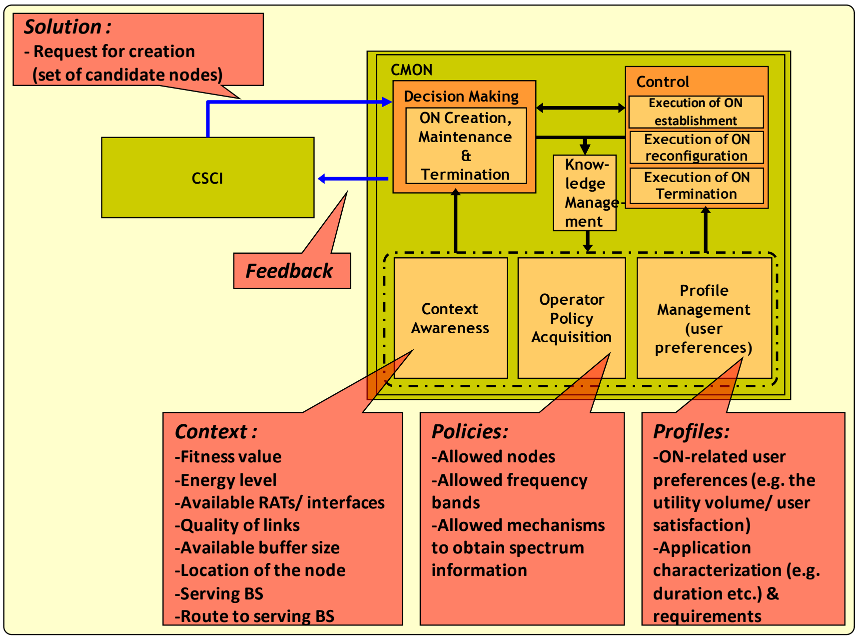


Figure 40: CMON functional blocks

The profile management functional entity considers the ON-related user preferences such as the utility volume/ user satisfaction associated with the use of an application/service at a particular quality level. Also, the application characterization (e.g. the expected duration etc.) and the application requirements are included as well.

Context, policies and profiles functional entities along with the suitability determination output from the CSCI provide the input to the decision making mechanism that will decide on the creation, maintenance or termination. Additionally, the decision making mechanism provides the input to the control entity of the CMON which is responsible for the execution of the decision. Knowledge management entity uses the output of the decision making and control mechanisms in order to make better decisions in the future in terms of performance and provide learning capabilities to the CMON. The acquired data are passed onto the CSCI for improving the governance functions/logic hosted by the CSCI.

3.8.7 Algorithm evaluation

In order to evaluate the performance of these algorithms several simulations have been performed prior to their integration in the platform described in session 3.6.6. In the following the simulation environment used is described in detail followed by indicative results derived from these simulations.

3.8.7.1 Simulation Environment description

For the evaluation of the distributed approach of the ON creation, the Opportunistic Network Environment (ONE) simulator is being used [6]. ONE simulator is the outcome of research projects and it is released under the GPLv3 license. The program has the ability to simulate traffic between nodes and provide results regarding overall delivery probability of the network, delivery latency (from source to destination), number of hops (from source to destination) etc. Also, the user controls the transmission range of the nodes, the transmission speed of the links, the number of interfaces of each node, the buffer size of each node, the TTL of each data packet, the size of each data packet, the creation interval of the data packets, the total time of running of each scenario etc. Finally the non-distributed approach is going to be evaluated in future work.

3.8.7.2 First performance evaluation

Indicative, preliminary performance evaluation is provided in the following section. The delivery latency has been measured for an ON consisting of 3 source nodes, 3 destination nodes and 18 intermediate nodes. Also, the top 70% includes the first 12 ON nodes according to their fitness value and the top 30% includes the first 6 ON nodes. The simulation runs until there is a loss of all paths towards one destination node. As Figure 41 suggests, the estimated delivery latency tends to decrease as fewer but better opportunistic nodes are accepted to the ON for both the Epidemic and Spray&Wait routing schemes.

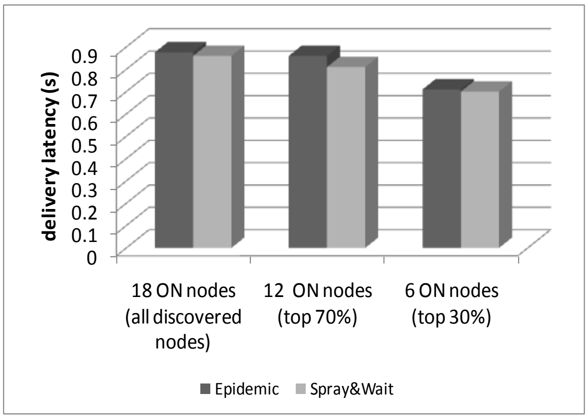


Figure 41: Estimated delivery latency

Also Figure 42 illustrates the number of aborted packet transfers. This number corresponds to the packets which were aborted if the connection was lost before the packet transfer had successfully finished. It is estimated that as fewer but better nodes are accepted by the ON, the number of aborted packet transfers tend to decrease.

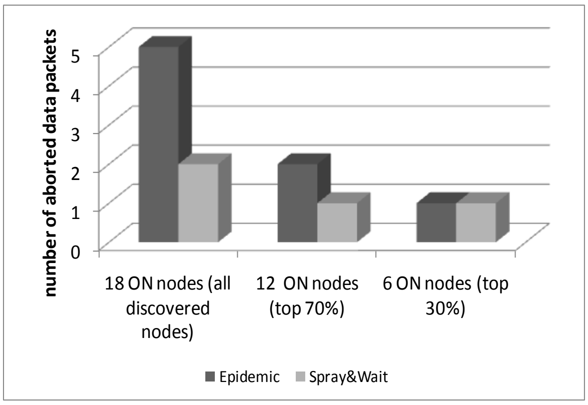


Figure 42: Estimated number of aborted data packets

A drawback of the fitness function is that the expected ON lifetime (i.e. the time until there is a loss of all paths towards one destination node) tends to decrease. Specifically, Figure 43 shows that an ON with fewer nodes tends to obtain lower levels of lifetime, due to the fact that fewer nodes are more stressed as they have to accommodate more transmission load. Nevertheless, the ON tends to perform better with the Spray&Wait routing protocol due to the fact that the replicated messages that are circulated in the ON are limited to an upper bound.

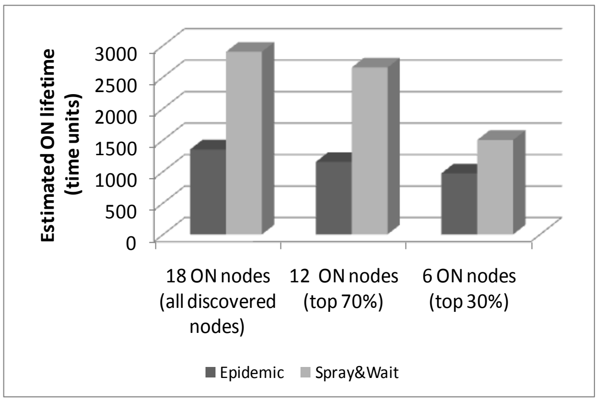


Figure 43: Estimated ON lifetime

This is also depicted in Figure 44 where the overhead ratio of replicated messages circulated in the ON is relatively lower in the Spray&Wait protocol compared to the Epidemic one.

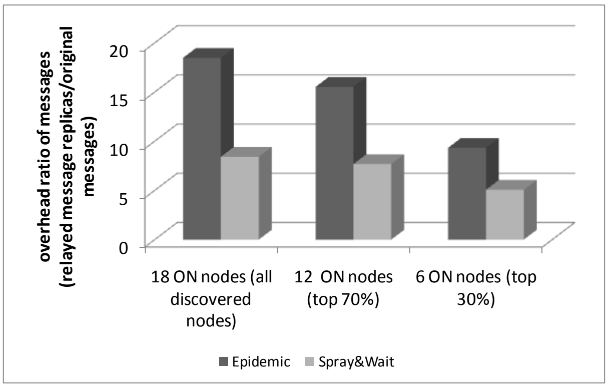


Figure 44: Overhead ratio of replicated messages circulated in the ON

In order to further evaluate the performance of these algorithms as well as to demonstrate their feasibility these algorithms will be integrated into the overall platform described in section 3.6.6. Results from such evaluation will be presented in forthcoming deliverables.

3.8.8 Requirements on the C4MS protocol definition & technical challenges

The two algorithms can be assumed as distributed for the first one and non- distributed for the second (Based on Ford-Fulkerson flow Control Algorithm), assuming the decision-making for the creation of ONs to be located in the CMON functional entity on the terminals and infrastructure side, respectively. The C4MS will support the transportation of the information needed between the terminals and the Infrastructure. Particularly the information exchanged is the following:

Distributed Approach

- Fitness value
- Serving BS
- Path to Serving BS

Non - Distributed Approach

- Terminal Parameters (e.g. Capacity)
- BS Parameters (e.g Load)
- Full path from source (e.g. Terminal) to destination (e.g BS), including link information, such starting node ending node, cost, RAT.

3.9 Route pattern selection in ad hoc network

3.9.1 Technical challenge addressed

The algorithm focuses mainly on the Suitability Determination and Maintenance the technical challenges as they have been analyzed during WP2. This algorithm is related to the ad-hoc network. It is a response to the QoS management technical challenge.

3.9.2 Rationale

The plurality of user applications implies different constraints for data transfer in order to guaranty the QoS. The characteristics associated to the main types of supported services in a wireless network have been identified and enumerated in [85] and [86]. In an opportunistic network composed of heterogeneous equipments having different characteristics, it is necessary to take into account the specificities of these equipments and the characteristics of the supported radio access technologies to determine the way to transmit and to receive data. Depending on the service requested, the routing behaviour shall be adapted, and the routing protocol shall consider specific metrics.

3.9.3 Use cases mapping

The general objective of scenarios is to relay a node or a set of nodes to an infrastructure. The constraints and the processing to apply may be very different depending of the number of hops to consider.

The challenge of route pattern selection feature applies mainly when multi-hops between terminal equipment are necessary to reach the infrastructure.

Another challenge is to realise algorithms to perform this scenario is to take in account that the different nodes are heterogeneous and that some nodes are mobile and others not mobile.

Scenario 1 Opportunistic coverage extension

The main challenge of this scenario, from routing pattern selection point of view, is mainly described in the Use Case 4, when several hops are necessary to relay the infrastructure. In that case, we can consider 2 different approaches. The first is to create a point-to-point connection for each hop. In that case the route is implicitly unique and there is no necessity of route selection algorithm. But, if we consider a second approach, where a self organised opportunistic network is created and managed, as an ad hoc cloud, connected to an infrastructure, then this use case becomes an application of the general function of route selection pattern.

Scenario 2 Opportunistic capacity extension

In this scenario the use cases are related only to 1-hop connectivity from the infrastructure. The functions to apply could be considered more as access selection than route selection. Functionally, these use cases can be considered as particular cases of the routing pattern selection algorithms, with a limit of 1-hop distance in the opportunistic network.

Scenario 3: Infrastructure supported opportunistic ad-hoc networking

This scenario is dedicated to self-organised opportunistic networks. The different equipments composing this network may be connected to different infrastructures, even if these infrastructures do not belong to the opportunistic network. The accessible infrastructures are various and they provide different capabilities in term of QoS. The routing pattern selection algorithms will determine the routes among a set of heterogeneous RATs.

3.9.4 State Of The Art

For state-of-the-art, please refer to section 3.10.4 of this deliverable.

3.9.5 Algorithm description

The proposed algorithm is an enhancement of the routing protocols to take into account the constraints associated to user applications, by selecting appropriate metrics for each service class and to compute these metrics in order to determine the most adapted route to exchange data.

The core of the algorithm is located in the CMON module identified in the functional architecture. But the algorithm also includes an important initialisation part, which would be located in the CSCI, in order to identify the available routes.

The core algorithm takes into account that the routing function behaves differently depending of the user application (i.e. a conversational class service shall not be multi-path routed).

According to [86], the algorithm considers the 4 following service classes:

- Conversational class
- Streaming class
- Interactive class
- Background class

Each one has specific constraints and characteristics. The end user applications require also a minimum throughput to be satisfied. This information is provided by the upper layers of the protocol stack.

- The algorithm uses numerous metrics to determine the most adapted route to transfer the data. These metrics come from 2 sources (see Figure 45): the information related to the neighbouring nodes is provided by the C4MS, and the information dedicated to the local node is mainly provided by the lower layers (e.g.: available RATs).

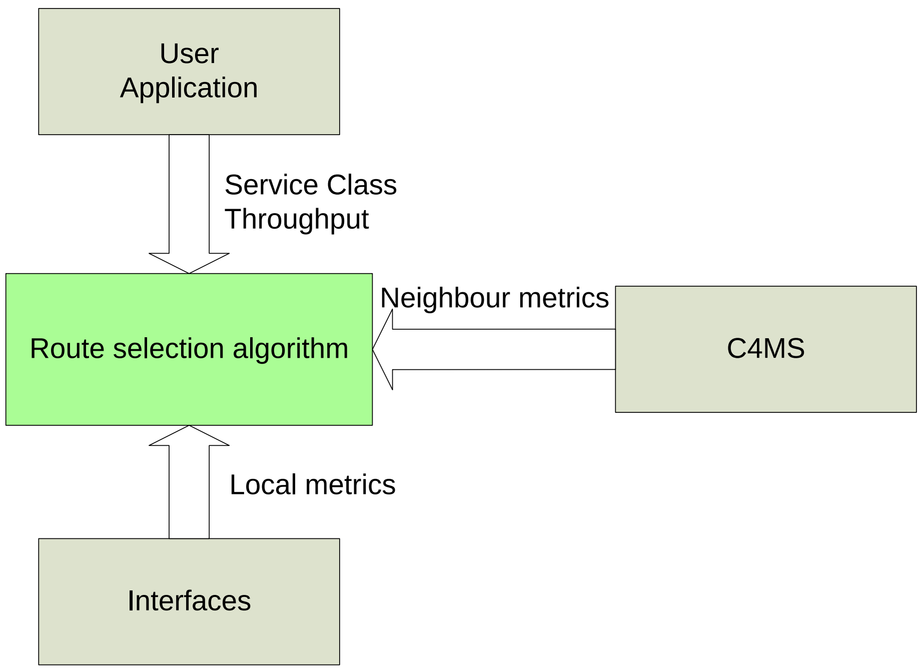


Figure 45: Inputs for Route selection algorithm

The metrics to be considered to process the algorithm are:

- Supported RATs
- Available throughput per RAT
- Reception quality per RAT (RSSI, SINR)
- Reception/Transmission delay (latency, jitter)
- Node power capabilities

- Mobility/Velocity

Different functions of computation for the route selection are implemented, using different sets of metrics selected according to the requested end user application. The calculation to qualify each available route applies also a weight for each considered metric depending of its importance related to the service class.

It has to be noticed that some information have to be correlated between them, for example, the mobility constraint is different depending on the used RAT because the capability to reach RATs is different.

3.9.6 Implementation considerations

The algorithm is located in the CMON module (see Figure 46 and Figure 47). It is a distributed algorithm located on each terminal. It runs as a distributed algorithm. It is activated during the ON negotiation procedure. It is triggered during the ON negotiation stage, the ON creation stage and during the ON reconfiguration procedure.

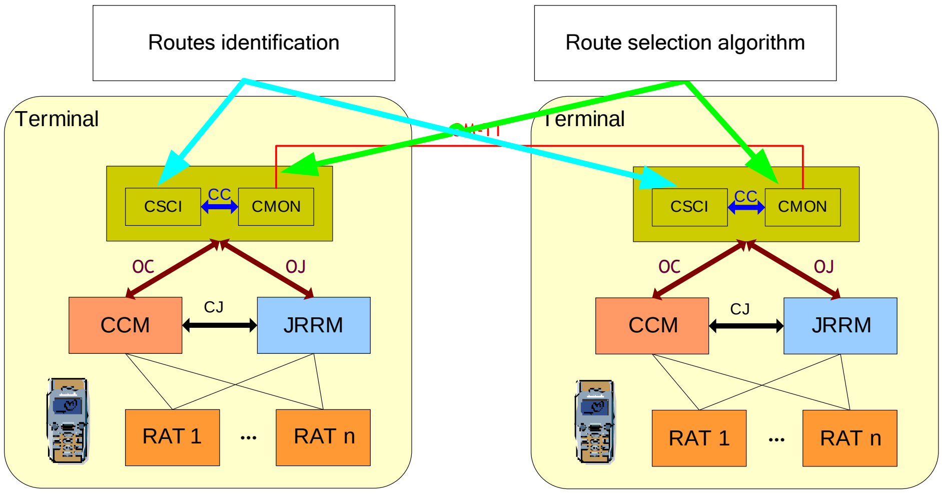


Figure 46: Mapping of routing pattern selection in the OneFIT Functional Architecture

During the suitability determination, the radio path to reach the gateways to the infrastructure has to be identified. The initialisation part of the route pattern selection algorithm determines the exhaustive available routes in advance of phase, before the opportunistic network creation, in order to allow the selection of the most adapted route by the CMON during the ON creation stage.

The routes identification procedure uses the C4MS protocol messages to exchange information between the nodes which will potentially compose the opportunistic network.

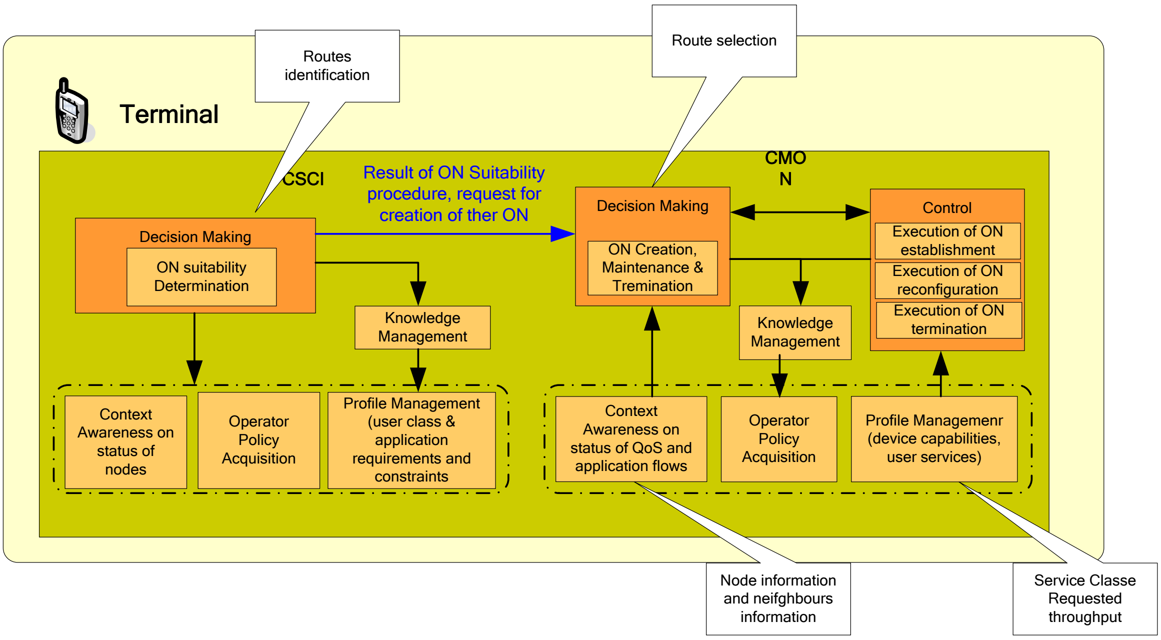


Figure 47: Detailed view of routing pattern selection

3.9.7 Algorithm evaluation

3.9.7.1 Simulation Environment description

The simulation is performed under OMNET++ environment, using the framework [87]. The protocol stack used to perform the simulation is based on the WiFi protocol stack (802.11), with the DYMO routing protocol. The OneFIT enhancements are simulated by modification of the routing protocol.

The simulated nodes support 2 interfaces that can be configured with different characteristics. The structure of the simulated protocol stack is depicted on the figure below (Figure 48).

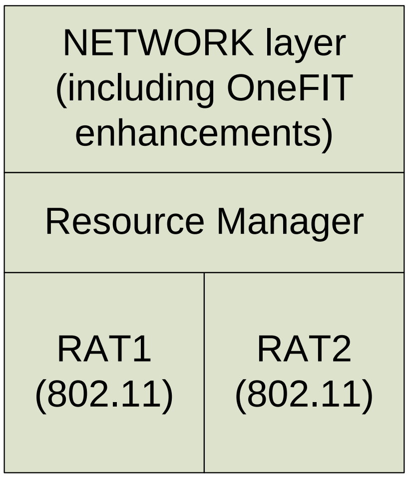


Figure 48: Simulation Protocol stack overview

The NETWORK layer contains the routing protocol (DYMO) modified to include the OneFIT enhancements, it also emulates the C4MS message echange. The Resource Manager controls the dispatching between the different RATs. The RATs are Wifi based but they have been adapted to provide metrics requested to compute the OnFIT algorithms.

3.9.7.2 First performance evaluation

The algorithm is under development on the simulator, the first evaluation of results will be given in the D4.2 deliverable.

3.9.8 Requirements on the C4MS protocol definition & technical challenges

The algorithm requires different inputs to be executed:

- Node characteristics
  - Supported RATs
  - Power capabilities
- Radio link metrics from each RAT
  - Available throughput
  - Link quality (RSSI/SINR)
- Other information
  - Mobility (GPS)
- Application information
  - User service class
  - Requested throughput

The information locally determined by the node need to be transmitted/received over the C4MS protocol to provide the information to the neighbouring nodes.

The algorithm provides the selected route information (i.e.: the selected next hop).

3.10 QoS and Spectrum – aware Routing Techniques

3.10.1 Technical challenge addressed

The algorithm focuses on the technical challenges identified in sections 4.2 and 4.3 of Deliverable D3.1 [4] addressing spectrum and route identification and selection.

3.10.2 Rationale

The main issues with routing in opportunistic networks are the movement of users, managing spectrum opportunities and QoS assurance. To address the spectrum awareness we have used a layered graph approach. In our routing algorithm, each spectrum opportunity is represented by a layer of the graph and routes are represented within each graph layer; this results in a structured graph based framework for managing routes within the network which results routes to be treated as graph edges and manage their structure by graph based optimization techniques. The QoS assurance is provided by the QOLSR (QoS Optimized Link State Routing) protocol which supports many aspects of QoS assurance within the route decision making. Depending on the movement pattern of the users in mobile MANETs, spectrum awareness and QoS assurance can become complicated so that our algorithm needs to go through many levels of optimization considering different network environments and movement patterns.

3.10.3 Use cases mapping

The following three OneFIT scenarios are applicable:

- Scenario 1: Opportunistic coverage extension

  Whenever a device is out of the coverage of the infrastructure, an opportunistic network will be created in order to serve it. The routing protocol should be able of routing the data between the extended coverage and infrastructure network with taking into consideration the spectrum opportunities and the level of QoS.

- Scenario 2: Opportunistic capacity extension

  In this scenario, the routing protocol should integrate the spectrum opportunities and route patters to add extra opportunistic users and extend the capacity of the network.
- Scenario 3: Infrastructure supported opportunistic ad-hoc networking

  The routing protocol should be capable of routing the data between the opportunistic users in an infrastructureless manner, which means that in case of creation of opportunistic network between the users that are near to each other, the routing protocol should be able to route the data between them without the need for infrastructure.

3.10.4 State Of The Art

3.10.4.1 QoS based routing Protocols

All the QoS based protocols mentioned here provide different frameworks for handling the traffics that require a level of Quality of Service but none of them have spectrum aware capability defined in them which is a vital need for a Cognitive Mobile Ad hoc Networks. The tree shown in the Figure 49 is extracted from the work of [88] which shows the categorization of different QoS-based routing protocols. From all the routing protocols shown in Figure 49, in this section we give a general idea about the most popular and efficient QoS based routing protocols which are QOLSR, CEQMM and AODV.

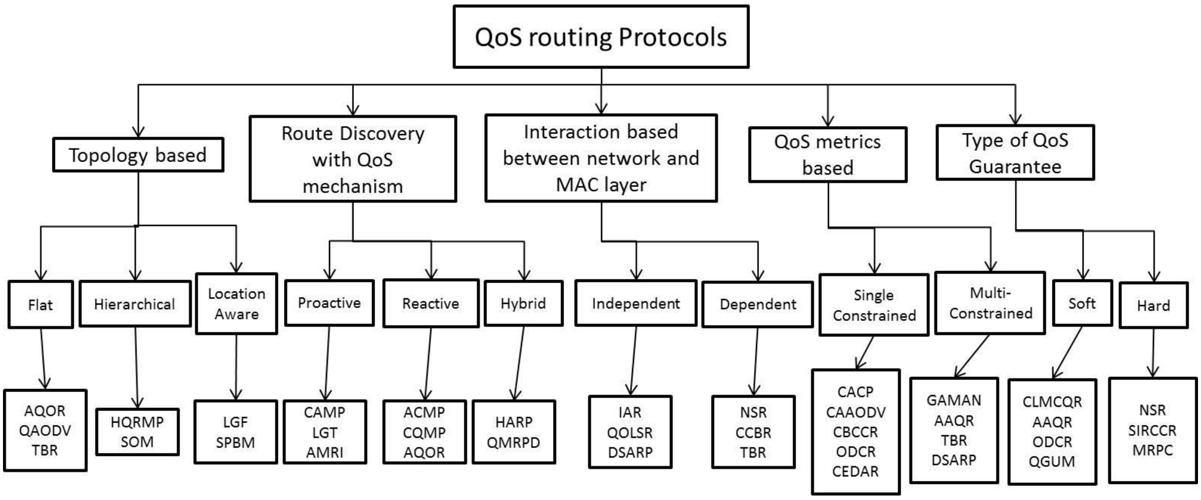


Figure 49: Taxonomy of the QoS routing protocols

OLSR (Optimized Link State Routing) [89] is an optimization of the classical link state algorithm of MANETs. *Multipoint relays:* OLSR introduce the concept of multipoint relays (MPRs) to mitigate the number of messages sent in the network discovery and route information maintenance process. In OLSR only nodes selected by neighbours as MPRs are responsible for forwarding control traffic and link state information declaration (bi-directional, unidirectional or lost link), to minimize the overhead from flooding of control traffic by using these specific nodes. Each node in the network selects a set of nodes in its symmetric 1-hop neighbourhood which may retransmit its messages. This set of selected neighbour nodes is called the "Multipoint Relay" (MPR) set of that node. Each node maintains information about the set of neighbours that have selected it as MPR from periodic *Hello* messages. This set is called the "Multipoint Relay Selector set" (MPR selector set) of a node.

QOLSR (Quality of service for Ad hoc Optimized Link State Routing) was introduced as an extension to OLSR to provide a Quality of Service (QoS) framework for it [90]. QOLSR defined a multiple metrics framework to provide a guaranteed QoS between the source and destination; the QoS metrics such as bandwidth, Delay, Jitter, Probability of Loss and etc. are provided by the new fields added to

HELLO and TC messages and so that there is no need for flow of extra messages in the network, resulting reduced signalling. With having the QoS metrics ready, QoS-MPRs (Multipoint Relays) are calculated and flooded in the network within the TC messages which results calculating the QoS-based routing tables. The QMPRs always generate the TC messages containing the QoS metrics and the rest of relaying process for the messages is done through the MPRs which existed in the base specification of the OLSR protocol. Knowing the QoS requirement of all paths from sources to destinations is enough to arrange routing tables so that QoS within the paths are supported.

CEQMM (a Complete and Efficient Quality of service Model for MANETs) is based on the IntServ (Integrated Service) and DiffServ (Differentiated Service) QoS models [91]. By combining the positive points of these two QoS models, per-flow and per-class provisioning is implemented in the base architecture of the CEQMM. The highest priority is given per-flow provisioning and the lowest priority is given per-class provisioning. For prioritizing the packets and providing different provisioning based on their QoS criteria, priority classifier, active queue management and packet scheduler are the modules implemented to provide this framework. QOLSR is the protocol that has been applied to CEQMM to provide a multiple metric routing mechanism which due to the efficiency can respond quickly to the changes in the network topology. Congestion avoidance due to either high load or mobility of the users is another important implementation of CEQMM.

AODV (Ad-hoc On-Demand Distance Vector Routing) is an on-demand routing protocol that has taken very much attention because of its simplicity and less signalling traffic compared to other routing protocols [92]. It allows mobile nodes to obtain routes quickly for new destinations, and does not require nodes to maintain routes to destinations that are not in active (on demand) communication. AODV allows mobile nodes to respond to link breakages and changes in network topology in a timely manner. AODV uses destination sequence numbers created by the destination and included to requesting nodes, to assume loop freedom, and help to define the more recent path to a destination at a node. The base structure of the AODV protocol does not support QoS provisioning but because of the extendibility in the structure of this protocol, there has been added many enhancements to support different aspects of QoS; such as RAODV (Reliable AODV) which continuously (on a regular timing basis) differentiates the two types of well-behaving and misbehaving nodes to provide 25% better goodput [93][94].

AODV-RD (AODV Reliable Delivery) is another enhancement to the main protocol that provides a level of QoS based on measurements of the nodes signal power, packet delay and transfer rate[95].

AODV-BR (AODV Base Routing) uses a mesh technique to support more reliable routes from sources to destinations; at the time that any route is broken due to the mobility issues, the node on the broken path reroutes the message by locally broadcasting to its immediate neighbours. qAODV (Quality of service AODV) [96] is enhanced by the carrier sensing mechanism of IEEE 802.11b for measuring the available bandwidth. The idea behind this method is that the idle time when the nodes are note transmitting, plays an important factor on calculating the available bandwidth of the channel that the node is willing to start sending packet now. QoS AODV, QAODV and SQ-AODV are the other enhancements based on the AODV protocol to provide QoS framework.

SWAN (Stateless Wireless Ad Hoc Networks) [97] proposes a stateless network model using distributed feedback based control algorithm, in particular explicit congestion notification (ECN) from the additive increase multiplicative decrease (AIMD), which is a rate control mechanism to dynamically regulate admitted real time traffic.

3.10.4.2 Spectrum-aware routing Protocols

Cognitive radio networks are differentiated from the normal types of multichannel networks in the sense that the multiple channels are provided to the network equipment opportunistically, meaning that the channels used are not static. Due to this dynamic spectrum changing, new aspects of routing should be considered in implementation of a routing protocol for the cognitive radio networks. This new aspect should consider spectrum awareness because not only messages are routed through different routing paths in the network but also routed through dynamic spectrum opportunities within it. Since these spectrum opportunities are provided by the idle operation time of the Primary Users (PU) so that there is no fixed Common Control Channel (e.g. CCC) for the Secondary Users (SU) to provide a guaranteed signalling channel for management of the SUs. There are many challenges in the routing domain for such networks consisting of, how to vacate the current spectrum band/opportunity upon PU re-appearance, periodic route maintenance and repair, unpredictable route failure etc. These challenges can be addressed by the spectrum aware routing protocols that are designed specifically for operation in such opportunistic networking environments.

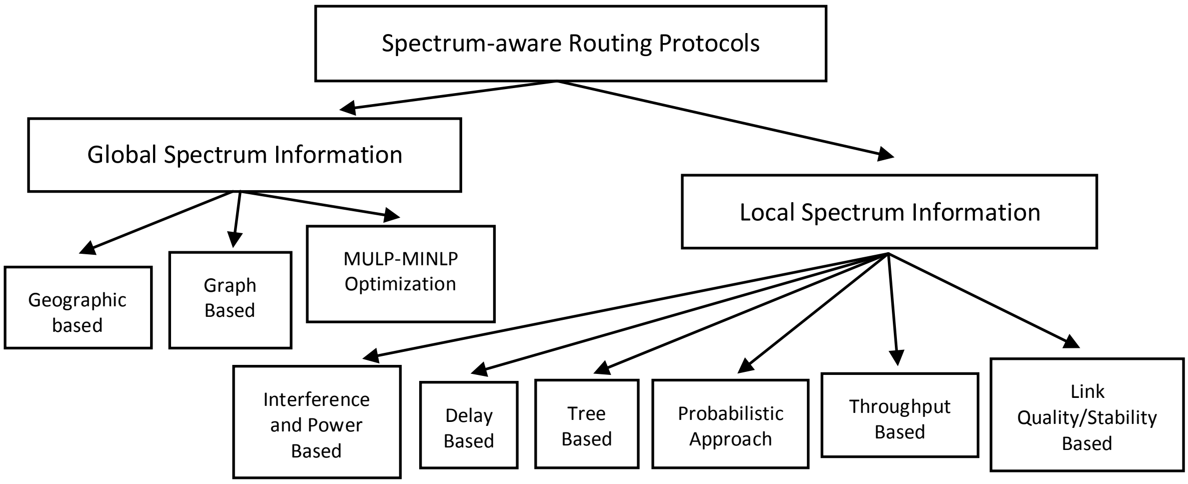


Figure 50: Taxonomy of spectrum aware routing protocols

The diagram shown in the Figure 50 depicts the two ways that the spectrum awareness can be achieved, which are through Global Spectrum Information and Local Spectrum Information. We have tried to give a brief description of the important spectrum aware protocols falling under these two categories.

3.10.4.2.1 Global Spectrum Information

Geographic based routing

These types of routing protocols require the geographic location of the SUs to be able to predict future movement. By having the geographic location of a user, routing decisions can be made much more accurately and efficiently.

- **GPSR (Greedy Perimeter Stateless Routing)**

GPSR [98] is a routing protocol for wireless datagram networks that uses the positions of routers and a packet's destination to make packet forwarding decisions. GPSR makes greedy forwarding decisions using only information about a router's immediate neighbours in the network topology. When a packet reaches a region where greedy forwarding is impossible, the algorithm recovers by routing around the perimeter of the region. By keeping state only about the local topology, GPSR scales better in per-router state than shortest-path and ad-hoc routing protocols as the number of network destinations increases. Under mobility's frequent topology changes, GPSR can use local topology information to find correct new routes quickly.

- **SEARCH (SpEctrum Aware Routing protocol for Cognitive ad-Hoc networks)**

SEARCH [99] is a spectrum aware routing protocol that uses the geographic forwarding method for path and channel selection for reducing the probability of interference with the Primary Users (PU) as well as occupying their unused channel during idle time slots. Routing is based on the geographic forwarding that is partly specified in GPSR (Greedy Perimeter Stateless Routing). Under normal condition SEARCH follows a Greedy forwarding of message, but when a void region (a region with absence of nodes to continue forwarding the message) is reached, the Perimeter forwarding mode uses the Geographic information of the node to create spanning tree and this way it can pass around the void region. SEARCH does not have any QoS framework which is vital for a routing protocol in cognitive ad-Hoc network.

Graph Based routing

The general approach for designing routes in wireless multi-hop networks consists of two phases: graph abstraction and route calculation. Graph abstraction phase refers to the generation of a logical graph representing the physical network topology. The outcome of this phase is the graph structure G = (N, V, f(V)), where N is the number of nodes, V is the number of edges, and f(V) the function which allows to assign a weight to each edge of the graph. Route calculation generally deals with defining/designing a path in the graph connecting source destination pairs. Classical approaches to route calculation widely used in wired/wireless network scenarios often resort to mathematical programming tools to model and design flows along multi-hop networks.

- **Layered-Graph Routing**

Spectrum Aware routing is a method proposed by [100] which defines multiple layers in the graph of source destination routes to represent a range of spectrum opportunities; the number of layers corresponds to the number of available channels, which are found and updated through the signalling defined for this protocol. The main problem with this method of routing is the high load of network centric signalling which can congest the network in long term. The other method of graph based routing in [101] (Colored Multi-Graph Model) follows the same methodology as the layered graph above with other approaches used for updating the layers in the graph.

Optimization in Routing Protocols

In the work demonstrated by [102], [103] the focus is on designing a spectrum sharing technique for Cognitive Radio Networks. They introduce a Mixed Integer Non-Linear Programming (MINLP) formulation whose objective is to maximize the spectrum reuse factor throughout the network, or equivalently, to minimize the overall bandwidth usage throughout the network. Another mathematical programming is leveraged also in [104], where a Mixed Integer Linear Programming (MILP) formulation is derived for the problem of achieving throughput optimal routing and scheduling for secondary transmissions. The objective function aims at maximizing the achievable rate of source–destination pairs, under the very same interference, capacity and routing constraints as defined above. The authors directly use the formulation to design route/channel assignment patterns for small-to-medium size network scenarios by resorting to commercial solvers.

3.10.4.2.2 Local Spectrum Information

Interference and Power based Routing Protocols

The consumed power is the main source for calculation of the routing metrics and interference in this category of routing protocols.

- **Minimum Power Routing**

The work of [105] has discovered how to manage minimum weight paths in cognitive wireless ad hoc networks. A routing weight based on the required power to reach a specific destination is associated with different wireless systems. The proposed routing protocol locally finds the path to minimize the routing weight between a source and a destination. The route discovery procedure is very similar to link state routing algorithms where this newly introduced weight is used. The model does not take into account the PUs, their behaviour, or the interference caused by/to other CR nodes. However, such information is implicitly incorporated into routing decisions during neighbour discovery stage.

This work introduces a very nicely outlined system model based on multiple interfaces. The performance of the proposed system is highly dependent on the neighbour discovery procedure and its refresh rates as there are no other maintenance or recovery procedures defined in the routing protocol to react to PU activity. Furthermore, the power-level based cost metric is not sufficient to address challenges of multi-hop CRNs.

- **Controlled Interference Routing**

Interference constraints are at the basis of the work in [106] where the authors analyse the trade-off between single-hop and multi-hop transmission for SUs constrained by the interference level that PUs can tolerate. Authors analyse the potentialities of a multi-hop relaying by deriving the geometric conditions under which a SU is admitted into a spectrum occupied by a PU. On the basis of these geometric results authors propose two routing methods termed Nearest-Neighbour Routing (NNR) and Farthest-Neighbour Routing (FNR).

Delay-based Routing Protocols

The quality of routing protocols can also be measured in terms of delays to establish and maintain multi-hop routes and to send traffic through the very same routes. Besides ‘‘classical” delay components for transmitting information in wireless networks, novel components related to spectrum mobility (channel switching, link switching) should be accounted for in multi-hop CRNs. Delay-aware routing metrics are proposed in [107] to [109], which consider different delay components including:

- The *Switching Delay* that occurs when a node in a path switches from one frequency band to another;
- The *Medium Access Delay* based on the MAC access schemes used in a given frequency band;
- The *Queuing Delay* based on the output transmission capacity of a node on a given frequency band.

Tree-based Routing Protocols

The original Tree-based Routing (TBR) protocol only works on a single wireless system such as IEEE802.11a or 11b, rather than multiple wireless systems. To address this problem, an efficient and practical protocol is proposed, called Cognitive Tree-based Routing (CTBR) protocol, which extends and significantly enhances the ability of the known TBR protocol to enable the TBR to handle multiple wireless systems. To adapt the cognitive environment, they introduce a new cognitive-aware link metric to indicate the link quality, and propose global and local decision schemes for the route calculation, in which the global decision is to select the route with the best global end-to-end metric, whereas the local decision is for that a forwarding cognitive terminal selects a interface with the least load. A Spectrum-Tree base On-Demand routing protocol (STOD-RP) is proposed [110] and [111] which simplifies the collaboration between spectrum decision and route selection by establishing a “spectrum-tree” in each spectrum band. The formation of the spectrum-tree addresses the cooperation between spectrum decision and route selection in an efficient way. The routing algorithm combines tree-based proactive routing and on-demand route discovery. Moreover, a new route metric which considers both CR user’s QoS requirements and PU activities is proposed. In addition, their work provides a fast and efficient spectrum-adaptive route recovery method for resuming communication in multi-hop CRNs.

Probabilistic Approaches

A routing approach based on a probabilistic estimation of the available capacity of every CR link is proposed in [112]. A probability-based routing metric is introduced; the metric definition relies on the probability distribution of the PU-to-SU interference at a given SU over a given channel. This distribution accounts for the activity of PUs and their random deployment. This routing metric is used to determine the most probable path to satisfy a given bandwidth demand *D* in a scenario with

N nodes that operate on a maximum of *M* orthogonal frequency bands of respective bandwidths W_1, . . . ,W_M (in Hz).

Throughput-based Routing Protocols

Throughput maximization is the main objective of the routing protocols described in the following section.

- **Path Spectrum Availability based Routing**

Throughput maximization by combining end-to-end optimization with the flexibility of link based approaches to address spectrum heterogeneity is proposed in SPEctrum-Aware Routing Protocol (SPEAR) [113] a robust and efficient distributed channel assignment and routing protocol for dynamic spectrum networks based on two principles: integrated spectrum and route discovery for robust multi-hop path formation, and distributed path reservations to minimize inter- and intra-flow interference. Through simulations and test bed measurements, they show that SPEAR establishes robust paths in diverse spectrum conditions and provides near-optimal throughput and end-to-end packet delivery latency. SPEAR performs extremely fast flow setup and teardowns, and can maintain interference-free flows in the presence of variance in channel availability.

- **Spectrum Utility based Routing**

Achieving high throughput efficiency is the main goal of protocol ROSA [114]. Opportunities to transmit are assigned based on the concept of spectrum utility and routes are explored based on the presence of spectrum opportunities with the objective of maximizing the spectrum utility. The proposed routing protocol is further coupled with a cooperative sensing technique which leverages both physical sensing information on spectrum occupancy and virtual information contained in signaling packets exchanged by SUs. The exchange of additional virtual information is performed through a common control channel and is used by the local spectrum/power allocation algorithm.

3.10.4.3 Stability based routing

The stability based routing protocols are dedicated to Mobile Ad hoc Networks (MANET), they are mainly derived from the family of the "on demand protocols". They are adaptive according to the topology changes. Here are presented the most significant routing protocols based on the link stability. The objective of these protocols is to maximise the duration of the discovered routes.

The specificity of this family of protocols is the algorithm, which determines the selected route. The principle is to consider that the less stable links are the bottleneck of transmission.

- **MABR (Multipath Associativity-Based Routing Protocol)**

The MABR protocol [115] is an extension of the ABR protocol. It is based on the link age. The age is determined by counting the number of received beacons. When the number reaches a threshold, the link is declared stable. The threshold is variable and it is calculated depending on the relative velocity between the 2 nodes.

The routes are established by broadcast requests, the selected routes is the route having the most stables links; in case of equality in the number of stable links between several routes to reach the destination, this router selects the shorter distance route, it means the route with the less number of hops.

This protocol assumes that each node is able to get dynamic information about its mobility, as the velocity is required to perform the algorithm of route selection.

- **SSA (Signal Stability-based Adaptive Routing)**

The purpose of the SSA [116] routing protocol is to consider the most stable route is the route for which the links have the strongest signal reception. This routing protocol is optionally able to take into account the location stability, defined as a configuration parameter.

The SSA protocol is composed of the 2 protocols FP (Forwarding Protocol) and DSR (Dynamic Routing Protocol), which work together to route the packet data.

As for the ABR protocol, the SSA protocol requires the knowledge of the node location and the velocity of each node in the network.

- **AOSV (Ad-hoc On-demand Stability Vector routing protocol)**

The purpose of the AOSV [117] routing protocol is to propose an algorithm to predict the route stability in the future. It uses a stochastic approach to calculate the link stability as the probability to receive a signal strength with an higher value than a predefined threshold, by using calculations based on radio propagation equations.

3.10.5 Algorithm description

The detailed specification of algorithm will be presented in D4.2. In this section a high level overview of requirements addressed by the algorithm is presented. The route identification and selection in ONs is challenging due to availability of multiple node and spectrum opportunities at each time frame and the fact that the users are mobile so that at each new time frame new data should be fetched to represent the current state of the network. By arrival of the data to each hop, before it can be routed to the next hop, the routing algorithm decides about the next hop for routing the data and the available spectrum opportunity to provide the routing medium.

The algorithm covers three vital requirements of routing in Opportunistic Networks, which are:

- Spectrum awareness
    - Indication of nodes spectrum sensing
    - Indication of node channel measurement
    - Indication of frequency bands and the way of recognizing them
    - Geographic-location information for spectrum availability sensing
    - Spectrum characterisation
    - Decision making regarding QoS based on spectrum opportunity
    - Information received from the infrastructure such as Signal strength, Noise and interference level, propagation loss, achieved Bit rate, Transmission constraints, etc.
- Quality of Service (QoS)
    - Throughput
    - Delay
    - Jitter
- Route Selection
    - The routing algorithm to rely the route selection on it
    - Integrating spectrum opportunity with the route selection

Spectrum aware routing is based on utilizing a multi-layer model for routing protocols. According to Figure 51, we can map each spectrum opportunity to a layer of the graph and by doing so each layer represents a route map between all network nodes by using each of the SOPs. As time goes on, each spectrum opportunity is updated and layers are re-configured. There are two ways of routing the data within the network, vertically and horizontally. Routing the data vertically represents passing the data through the best available spectrum opportunity and routing the data horizontally represents the normal routing of data between nodes within the network. Our algorithm integrates both horizontal and vertical routing of data to provide spectrum awareness as a complement to the QoS-based of routing of data within the network.

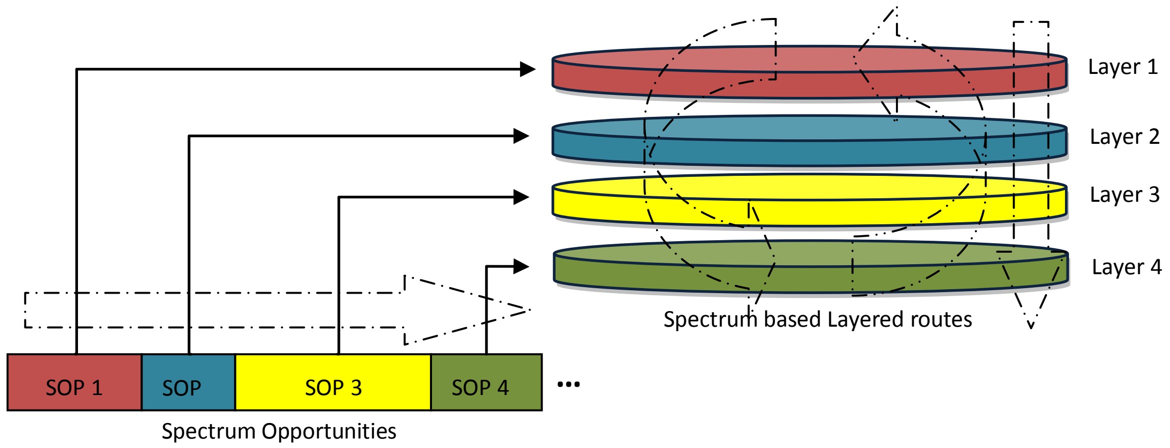


Figure 51: Depiction of the Spectrum opportunity in a layered graph

Each layer of the spectrum opportunity contains the updated route of the opportunistic network between the nodes as shown in Figure 52 (the figure represents routing of the data between three example nodes A, D and B using a cross layer approach). Routing is both possible between the nodes within a sub-layer and in cross-layer fashion, across different spectrum opportunities. Furthermore routing is based on a modified version of the QOLSR (QoS-based Optimized Link State Routing) routing protocol , so that routes within the layers should guarantee the level of QoS that users have negotiated for it.

Figure 52 shows a complete picture of the layered graph, including access, horizontal, vertical, and internal edges. Based on the layered graph, a hybrid algorithm is proposed to integrate spectrum awareness with route selection in Mobile Ad-hoc networks. As depicted in Figure 52, there are three nodes C, D and B that are allocated three spectrum opportunities Ch1, Ch2 and Ch3 and at each layer the same set of nodes are replicated and only the route decision making (within the layers) are different. The cross layer routing (vertical) across different spectrum opportunities and the routing within the layers (horizontal) is clearly shown in Figure 52.

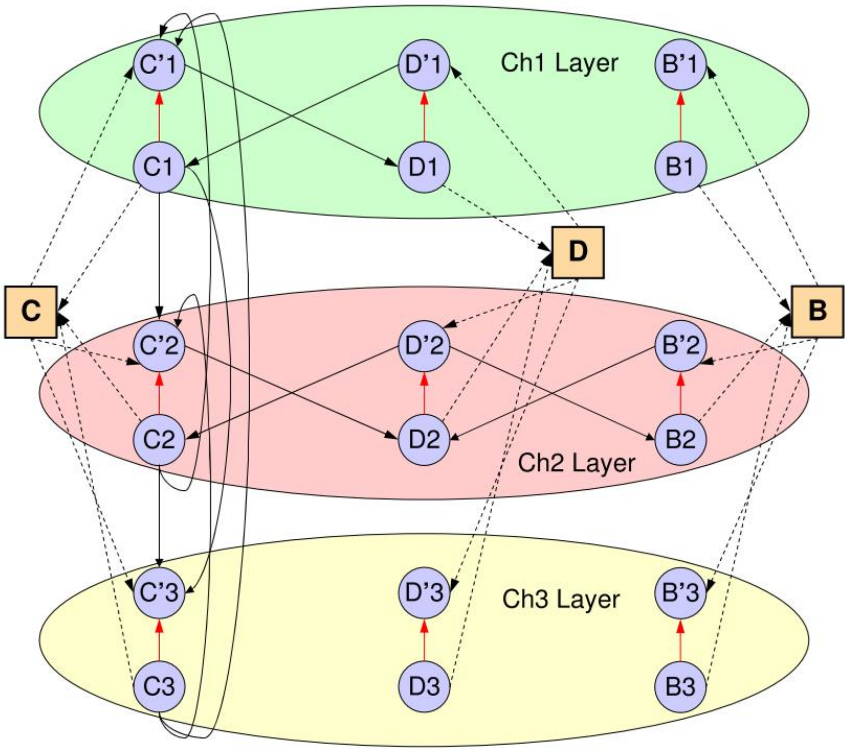


Figure 52: Routes within the layer of SOPs

When a spectrum opportunity becomes available, there is no way of knowing the future state for that specific range of spectrum except by utilizing a probabilistic (or learning based) approach. By knowing movement model of the opportunistic users and using that model in a probabilistic approach to expect the future state of the spectrum, our routing algorithm would be able to guess the future state of the channel.

3.10.6 Implementation considerations

Figure 53 shows the modules providing a variety of inputs to the algorithm. The context awareness module provides the essential information for routing such as Spectrum Opportunity, Status of the Routes, Location, Velocity, etc. Operator Policy derivation and management should provide the information that we need to acquire from the operator point of view and simply the infrastructure related information such as the free spectrum band of primaries, range of availability, etc.

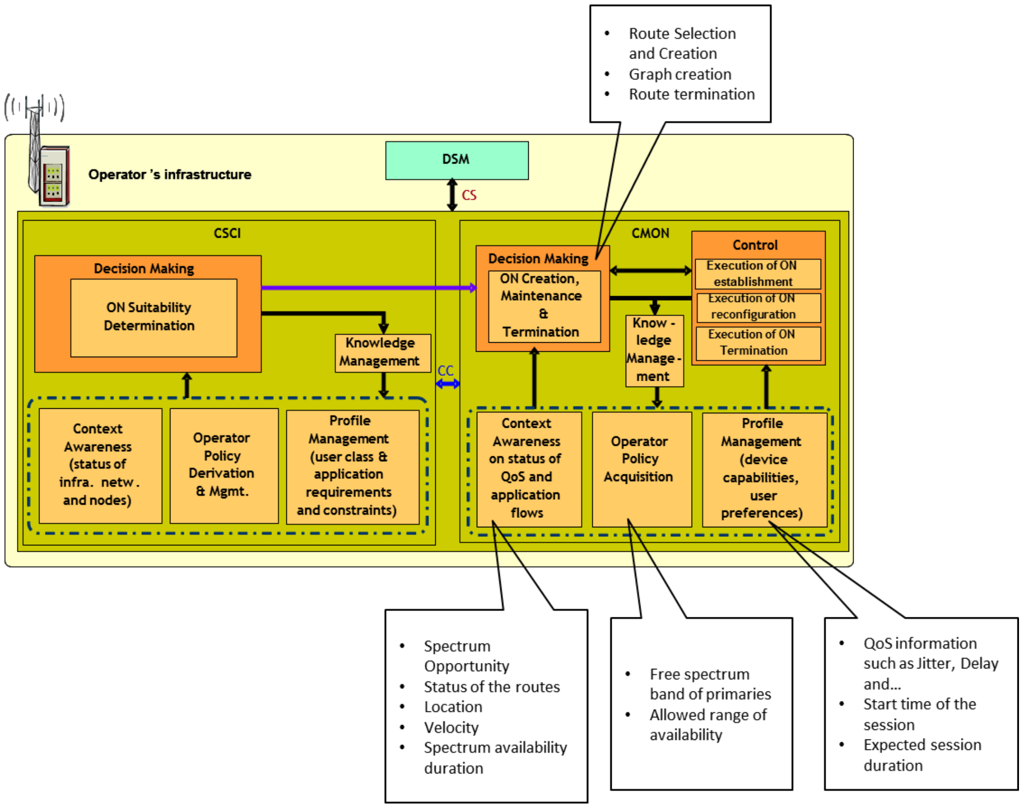


Figure 53: Placement of the routing algorithm in OneFIT Functional Architecture

The profile management module provides the information regarding the upper layer requirements; this module should provide the QoS constraints, session start time/end time and other information that is helpful in decision making about application requirement of routing algorithm.

Through the information that the functional architecture of OneFIT provides the routing algorithm, three main requirements of routing in ONs are addressed – these are: a framework for spectrum awareness, provision of QoS (based on QOLSR) and spectrum availability. Graph theory is used for modelling of spectrum opportunities and route selection and is considered a very powerful tool that can result in stable configurations and a valuable method for managing re-configuration and maintenance of the routes within the network. Furthermore, routing decision at each network node together with considerations of the spectrum availability and topology can result in more structured routes (in cases of failure, there may be many alternative supporting routes available)

Figure 54 shows three phases of route determination and evaluation, route creation and route maintenance based on the ONFIT architectural model. In the suitability determination phase the spectrum opportunities and nodes are identified and managed; In the creation phase the graph based vertical (Spectrum Opportunities) and horizontal (sub-layer routes) are created; in the maintenance and termination phase changes in spectrum opportunities and node configurations are identified regularly so that the edges of the graph are updated.

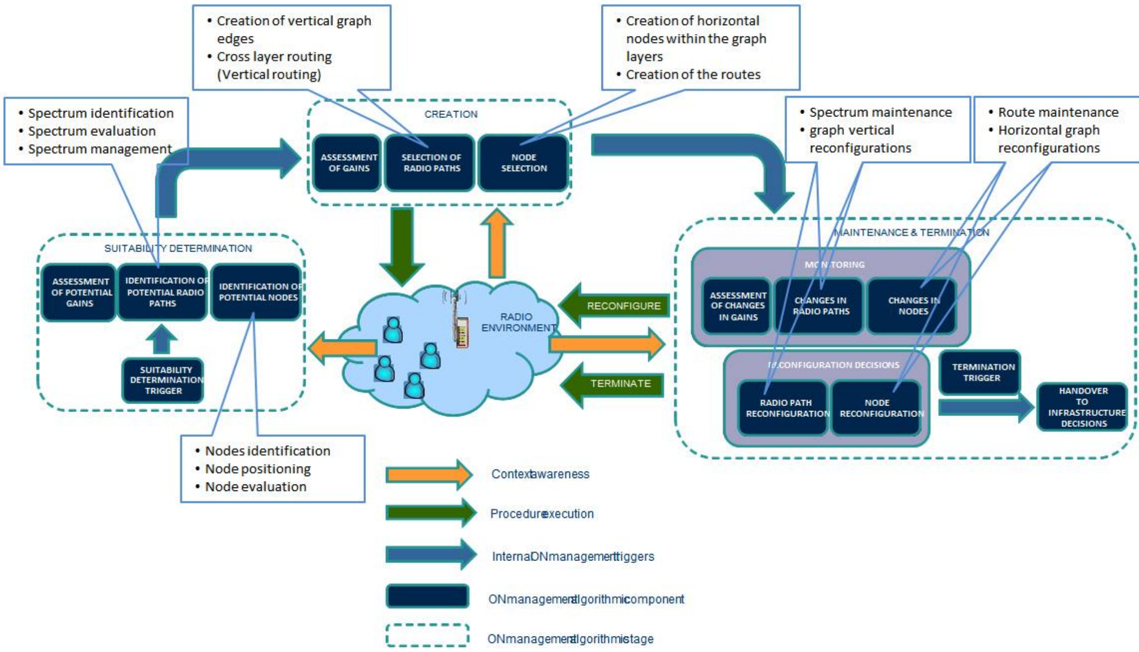


Figure 54: Placement of the routing algorithm & components in OneFIT Functional Model

3.10.7 Algorithm evaluation

The design and implementation of the algorithm is at an early stage. Evaluation results shall be reported in D4.2.

3.10.7.1 Simulation Environment description

The simulation environment is based on the OMNeT++ network simulator. Furthermore two packages of INET and INETMANET in OMNeT++ are two main packages used in simulations. The link layer protocol of the simulation is 802.11; and OLSR, DSR and AODV routing protocols will be the first to be tested in the network topology. Three mobility models will be used to simulate the movement of the users within the opportunistic network (i.e. Chiang, Gauss Markov and Tracl mobility models [118]). The initial propagation models will be Log normal shadowing and Rayleigh fading [119].

3.10.7.2 First performance evaluation

First set of performance evaluation results shall be reported in D4.2. The main purpose of the performance evaluation is to determine performance of the hybrid routing protocol in a cognitive opportunistic network setting. Performance evaluation will be against following selected key performance indicators:

- Packet delivery ratio
- Average End-to-End delay / jitter
- Throughput
- Route quality (reliability & stability)
- Scalability of algorithm
- Convergence time
- Control overhead

3.10.8 Requirements on the C4MS protocol definition & technical challenges

To provide a global consistency a number of parameters have been identified that will be required from network side, through the signalling protocol (C4MS). The exact composition of of parameters is dependent on the final implementation of the routing protocol but in brief the parameters can be classified as:

- The parameters regarding the Geographic position of the users.
- The QoS parameters such as, Delay, Jitter and etc.
- The power and interference related parameters.
- Simple route discovery, setup, maintenance and teardown signalling related parameters.
- Spectrum related parameters.

3.11 Application cognitive multi-path routing in wireless mesh networks

3.11.1 Technical challenge addressed

In this section the description of cognitive multi-path routing algorithm for the wireless mesh networks will be given. This routing algorithm will address the use case from the OneFIT scenario 5 regarding backhaul bandwidth aggregation and specifically in the environment of wireless mesh access networks.

3.11.2 Rationale

OneFIT scenario 5 proposes backhaul bandwidth aggregation as one of its use cases. To achieve bandwidth aggregation a proper multi-path routing algorithm has to be developed. This routing algorithm will be used by the ON created with purpose of bandwidth aggregation of multiple routing paths. By using this technique, OneFIT system will be able to create properly configured ONs across access points (base stations) in order to resolve problems in backhaul links (congestion, need for more bandwidth, broken link) that may arise during the network lifecycle. This multi-path routing algorithm can be used for load balancing as well. In this way better bandwidth utilization could be achieved.

New routing metrics need to be developed in order to enable cognitive side of routing mechanism. This cognition should address specifics of wireless links and of WMNs as well as knowledge about the application that is used and the QoS that this application requires.

3.11.3 Use cases mapping

Proposed multi-path routing algorithm is being developed for the purpose of backhaul bandwidth aggregation use case (Multi-path routing in licensed and unlicensed spectrum) of the scenario 5. It will be designed for use in wireless mesh networks. However this algorithm could be used with different routing metrics and therefore could be used for other OneFIT scenarios, which require multi-path routing.

3.11.4 State Of The Art

Specific nature of the WMNs (static nodes, shared wireless medium, limited number of non-interfering channels, paths with multiple wireless hops, limited capacity of gateway connections) require careful development of appropriate routing metrics and algorithms. Routing metrics have to be developed specifically for wireless mesh network environment in order to be able to correctly determine the link cost. Among most important wireless mesh network characteristics that need to be addressed by the routing metrics are inter and intra-flow interference between wireless links in order for routing metric to be isotonic [120].

Selection of routing protocol is also very important. Different routing protocols have different signalling overheads and different path establishment/discovery speed. Among two major types of routing protocols, proactive and reactive, proactive type is more preferable in wireless mesh access networks [120]. Reactive routing protocols discover paths on demand (when needed) and therefore impose less signalling overhead for fast changing wireless networks like mobile ad-hoc networks. Proactive routing protocols are based on the fact that every network node have the complete image of network graph and can easily and faster accommodate to changing environment but with bigger signalling overhead than reactive routing. Therefore these protocols can be used in networks with less frequent network topology changes. Wireless mesh networks are composed of static wireless mesh routers and changes in network link topology are less frequent. In these networks frequency of flow arrivals is much bigger than the frequency of link breaks. These facts lead to conclusion that proactive routing protocols are more appropriate for use in WMNs than reactive routing which will impose much overhead for flooding of route request messages for every flow and path establishment would be slow. Proactive routing can be divided into source routing and hop-by-hop routing. When source routing is used packets contain the whole routing path in their header which combined with small size of wireless packets lead to big communication overhead. Hop-by-hop routing requires that every packet has only destination address in its header. Every node in the network knows next hop for every destination. For this type of routing protocol it is very important for the routing metric to be isotonic (aware of inter and intra-flow interference) in order for loop-free packet forwarding and for fast and optimal path selection (by use of Dijkstra or Bellman-Ford algorithms) [120].

Multi-path routing algorithms for WMNs are heavily studied in [121]. Appropriate routing metrics for WMNs are proposed (CATT, LAETT, CARTA, AAC) as well as multiple paths selection algorithm. Previous work concentrated on selection of previously determined number of routing paths for multi-path routing which could lead to aggregated throughput degradation as described in [121]. Reactive route management procedure that heavily uses DSR (Dynamic Source Routing) is used in [121]. Routing metric AAC (Average Available Capacity) is proposed in [121]. This value is obtained from a set of paths by combining their long term availability with their achievable capacity. Further improvement of the multi-path routing over wireless mesh network is achieved with network coding and algorithm for gateway selection [121].

3.11.5 Algorithm description

Multi-path routing algorithm will be capable of identifying and simultaneously selecting multiple paths from one wireless mesh access point to more than one gateway in order to achieve aggregation of backhaul bandwidth. It includes metrics and path selection algorithm that will be application cognitive. This means that path cost will depend on application, which generated the packets. Depending on application QoS requirements routing paths to a destination will be sorted and appropriate set will be selected for packet forwarding. When some links in a wireless mesh backhaul become unavailable, or experience high congestion, ON creation is triggered in order to solve the presented problem by means of load sharing between other paths in the wireless mesh network. Alternate paths will be discovered and established by multi-path routing algorithm incorporating special metrics. Packet forwarding mechanism will be directed to send all packets from one group of applications (i.e. delay and/or jitter sensitive applications) over one alternative path and other packets over other paths. This classification of the traffic, based on applications from which it originated, allows a cognitive multi-path routing to be used.

Figure 55 depicts the building blocks of the application cognitive multi-path routing algorithm. Input parameters are source and destination nodes and profile of the application. Other input parameters depend on used routing metrics and routing protocol. As mentioned in SOTA section, both proactive and reactive routing protocols are used in wireless mesh networks for route discovery and establishment. Proposed multi-path routing algorithm will use different routing protocols for these purposes depending on a network status (frequency of link breaks, mobility of nodes, traffic patterns…) and type (ad-hoc network where data flows only among network nodes, ad-hoc network with data flows mainly going to and from infrastructure, WMN where majority of the traffic goes to and from gateways, WMN where majority of the traffic is exchanged between directly connected users…). Discovered paths from source to destination will be forwarded to path selection mechanism, which includes path cost derivation by using appropriate metrics and selection of appropriate number of paths for achieving the best performances and resource utilization. Selected paths will be used by the packet distribution mechanism, which selects appropriate paths for different packets based on a path cost and profile of the application that generated each particular packet. In this way all packets from one application will take the same path (or subset of paths previously selected in a way that respects application demanded QoS), which will result in avoidance of out of order packet situation and minimization of jitter in packet transmissions.

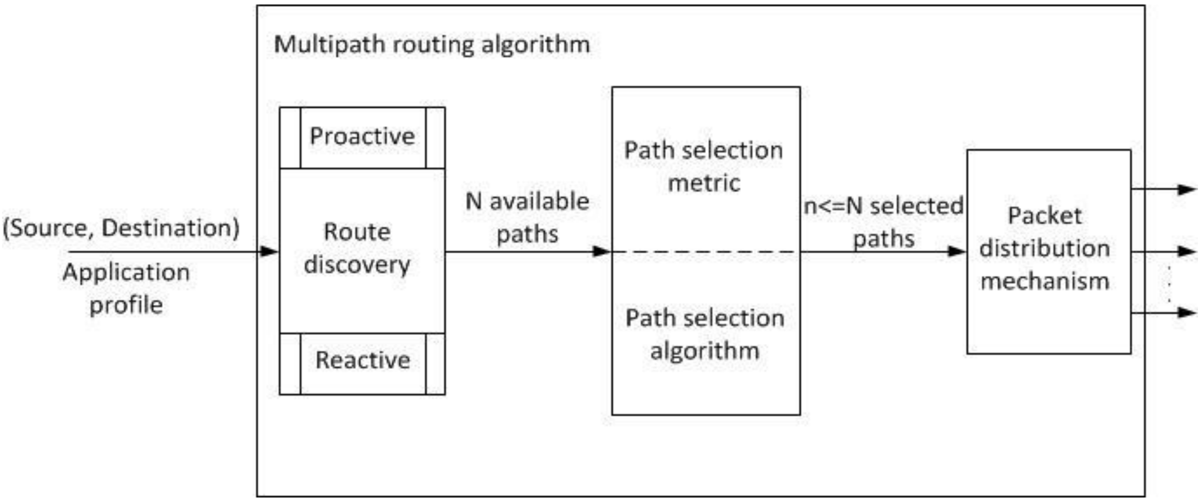


Figure 55: Multipath routing engine

The most important part of the routing algorithm is application cognitive routing metric that is aware of WMN environment specifics. Routing metric should satisfy the following requirements:

- It has to be isotonic-aware of inter and intra-flow interference;
- Aware of multi-channel nature of WMNs;
- Aware contention for share media which is specific for wireless communications;
- It has to be load aware (aware of remaining capacity of the links) in order to allow resource utilisation control and in particular load balancing among WMN backhaul links;
- It has to allow gateway prioritisation (standard in WMNs) and classification;
- It has to incorporate different link characteristics for different application profiles (delay, jitter, number of lost packets and retransmissions, interference levels, security...).

Giving different weights to different link characteristics for packets originated from applications belonging to different profiles is important in order to enable new routing metric to be application aware. For example:

$$LinkCost = a * LinkDelay \oplus b * LinkJitter \oplus c * NumberOfLostPackets \oplus d * LinkCapacity$$

By combining different values of coefficients *a, b, c* and *d* we can calculate appropriate link cost for different application profiles. If the application is delay sensitive (VoIP, video conferencing...) then parameter *a* will be more important in the link cost calculation process than, for example, parameter *d*.

By using a centralised controller of the wireless mesh access network (wireless controller), centralized analytical approach to route discovery and classification can be achieved. Modern wireless controllers gather enough contextual data about access network environment and have enough processing power to be able to construct graph of current access network status and to use analytical models to determine optimal or near optimal multiple paths. As the size of access network grows and the number of required contextual data that needs to be processed grows, combinatorial complexity of analytical approach grows and time needed for solution derivation goes up. This type of WMN network configuration (with centralized control) requires less signalling among APs. Contextual data are already sent by APs to wireless controller who has good picture about current status of the whole access part of the network. This approach will be taken into account for benchmarking the results obtained by regular approach where access points are treated as routers.

Algorithm placement in the light of the OneFIT high level functional model is shown in Figure 56.

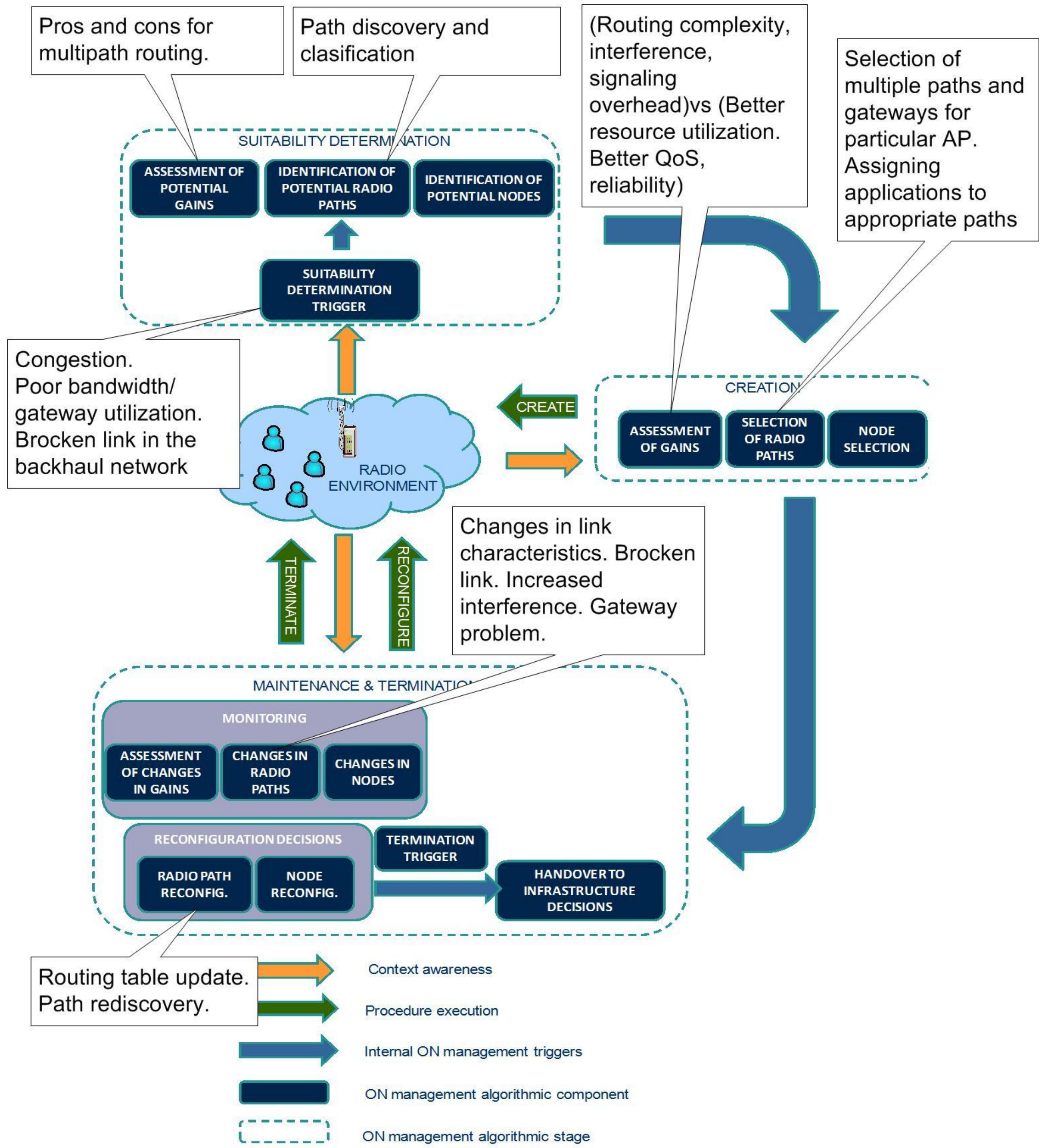


Figure 56: Algorithm placement in OneFIT high level functional model

3.11.6 Implementation considerations

Application cognitive multi-path routing algorithm will be developed for and evaluated on WMN environment. Implementation with “fat” and “thin” APs should be tested. In case of the “fat” APs all management and control of WMN is done on autonomous APs. One of the possible approaches is that APs should have one routing table for every mesh gateway in access network. In case of the "thin" APs all management and control is done by wireless mesh controllers. These controllers gather data about access network environment and performance and have a clear picture about access network status and capabilities. Multi-path route detection and selection will be done on these network devices and distributed to APs.

In the light of OneFIT functional architecture, the multi-path routing algorithm will be mapped to the CMON and CSCI management entities as shown in Figure 57.

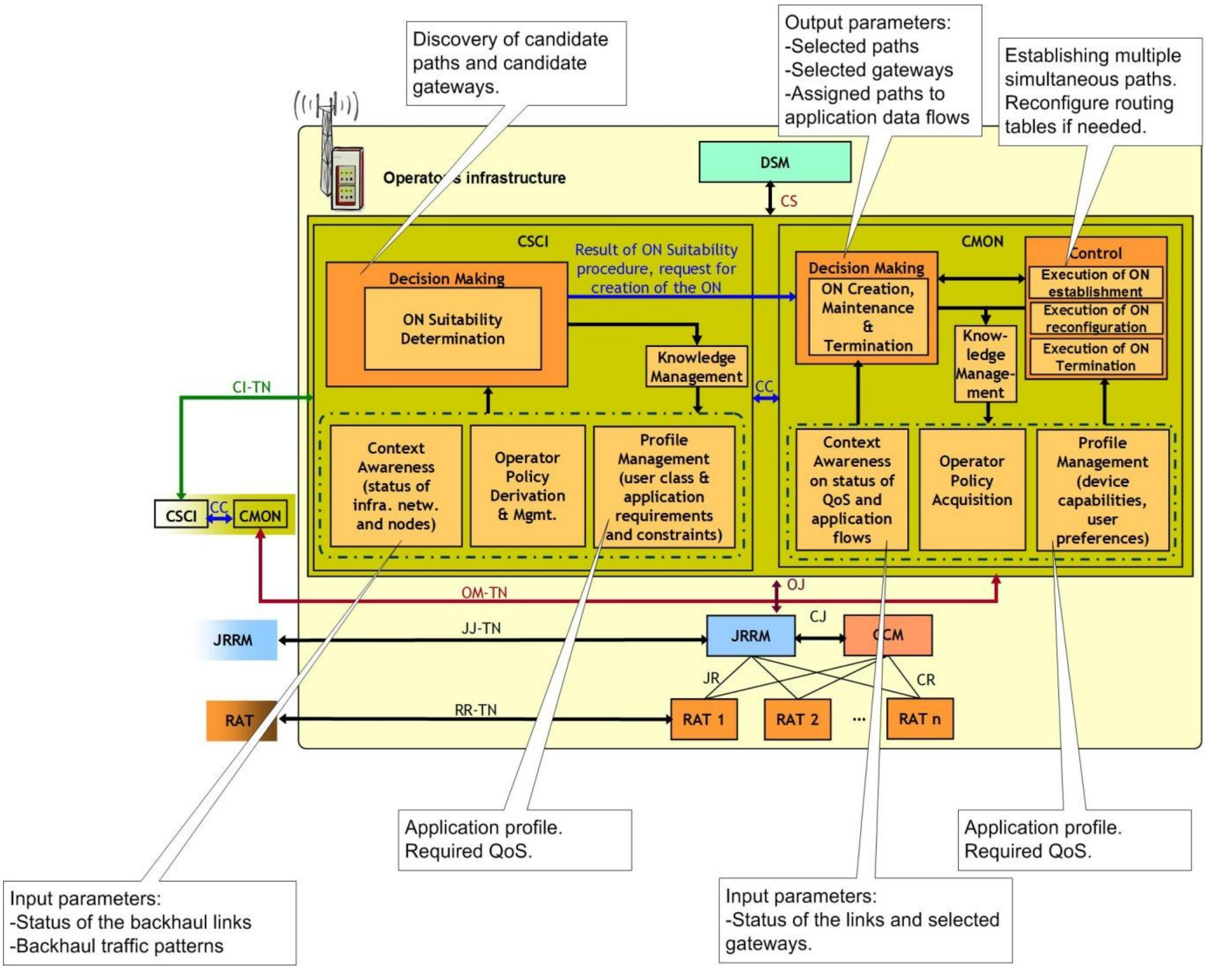


Figure 57: Mapping to CMON and CSCI functional entities

3.11.7 Algorithm evaluation

3.11.7.1 Simulation Environment description

Application cognitive multi-path routing algorithm will be tested in network simulator environment and in real time test-bed representing open platform wireless mesh network with distributed and centralized control and management. LCI will develop this WMN platform for the purpose of WP5.

Different routing metrics and routing protocols (proactive and reactive) will be tested in different testing environments. This will provide initial performance estimation of different routing approaches in various network situations as well as suitability and performance of selected metrics for multi-path routing.

Simulator and real testbed based simulations will be based on WMN whose APs have the ability to be connected to more than one gateway at the same time (multi-homing [1]). Different proactive and on-demand routing protocols will be tested with the developed metric. Packets will be recognisable by the application that generated them (or type of application-profile) which will be used in multiple path discovery and their cost derivation. Traffic that is made of packets generated by an application of the certain profile will be sent over the path with minimal cost regarding the application cognitive routing metric.

3.11.7.2 First performance evaluation

Routing algorithm is still in early stage of development. For the performance evaluation of this algorithm, multi-path and single-path routing approaches will be compared in the light of:

- QoS provided to the end user;
- Resource utilisation in the backhaul of the WMN;
- Signalling overhead for control messages used by routing algorithms;
- Speed of route discovery and establishment;
- Speed of route reconfiguration and routing table update;
- Size of the routing tables.

The same comparison will be made for different routing protocols that will be used in multi-path routing algorithm.

3.11.8 Requirements on the C4MS protocol definition & technical challenges

For enabling and supporting application cognitive multi-path routing algorithm proposed in this section, C4MS protocol should support exchange of cognitive data needed by the routing engine. Reactive routing (with message flooding processes) and proactive routing (with exchange of routing tables) should be supported. Routing algorithm requires the following input data:

- Status of network links (available capacity of link, channel used, interference levels, expected delay, jitter, packet drop…);
- Operator policies (required resource utilization levels, required QoS levels for different applications and groups of users, security for protection of data, end users and network…);
- Traffic patterns (most used gateways, spatial and time distribution of traffic…);
- Application profiles and corresponding QoS requirements.

While multi-path routing algorithm is used C4MS needs to gather the following cognitive data in order to evaluate performance of established ON:

- End user envisaged QoS;
- Utilization of network resources;
- Stability of selected paths;
- Speed of path establishment and reconfiguration;
- Data about packet routing performance (delay, jitter, packet loss, out of order packets, retransmissions…).

3.12 Multi-flow routes co-determination

Further information on multi-flow routes co-determination can be found in [123] and is the object of the patent taken out in [124].

3.12.1 Technical challenge addressed

In the general case of opportunistic networks, and more particularly on the scenarios described in [2], these scenarios integrate (even if most of the networks descriptions are operator governed) self-organizing networks whose management is similar to the one of MANET networks.

The issues to be raised in terms of routing enhancement are manifold. One of these issues is the Quality of Service management, and in particular the routing based throughput optimization including resource allocation optimization.

The algorithms proposed to optimize routing protocols for the specific mobile networks are proactive OLSR, OLSRv2 [125],[126], reactive AODV, DYMO, [127]. FEQMM [128], SWAN [129], QOLSR [130] and CEQMM [131] extensions integrate to these protocols a quality of Service management to maintain and adapt a QoS of established traffics. These extensions mainly focus on an adaptation of resources provision, applying QoS metrics for the route path selection [130], combining both per-flow state property of IntServ for highest priority flows, and service differentiation of DiffServ for lowest priority flows [130],[131] or applying an explicit congestion notification from a rate control mechanism to dynamically regulate admitted real time traffic [129].

We propose in this section protocol elements which complete these optimizations. This protocol focuses on gains that may be provided by the specific characteristics of this kind of networks: decentralized management of resources allocation, self traffic flows route (re)configuration including broadcast and multi-route establishment, and opportunities due to node mobility. The proposed algorithm combines the (re)routing of traffic flows on ad-hoc network with a throughput optimization technique called network coding. This optimization technique proposes to use the common routing paths of multi-flows to reduce the information to transmit on these paths, benefiting by the information transmitted on other paths for these flows.

3.12.2 Rationale

The rationale of the algorithm proposed is described as a first section of the algorithm description.

3.12.3 Use cases mapping

As for the Route pattern selection in mesh network section, the algorithm is related to the optimization of the communication of the ad-hoc part of the opportunistic network:

- Scenario 1: Opportunistic coverage extension,
- Scenario 2: Opportunistic capacity extension
- Scenario 3: Infrastructure supported opportunistic ad-hoc networking.

3.12.4 State Of The Art

The concept of *network coding* was first introduced for satellite communication networks in Yeung and Zhang [132] and then fully developed in Ahlswede et al. [133].

The principle of network coding is described in the following picture, applied on the butterfly topology. This picture presents two traffic flows, one from S_1 to D and F, the other one from S_2 to D and F. Moreover each one of the common egress node may receive from one path one of the traffic flow, and from one part of one another path (which may be restricted to only one node), the two traffics are relayed using the same relaying nodes resource. The principle is to code the two traffic flows with a common smaller one, using a coding function *Nc()*, the traffic flow relevant from this flow being decoded by the use of the other flows already received. In the example the coding function is the bitstream *xor* of the two flows (considered of numbered packets of the same size). In D(resp.F), receiving X1 (resp.X2) and X1 or X2, it easily deduces X2 (resp. X1). The Figure 58 shows the differences between the use of network coding and a classical independent flow route allocation. The gain in terms of throughput and number of message sent between the two alternatives are of 1/3 (from 6 emission to 4), with means also a gain in radio resources and in power consumption in the relay nodes. In particular in the first situation the node E receives two packets and sends two packets (and causes a bottleneck in the flows, impacting the QoS) whereas in the second one, it receives and sends only one packet (with a more homogeneous traffic load between the nodes in the topology).

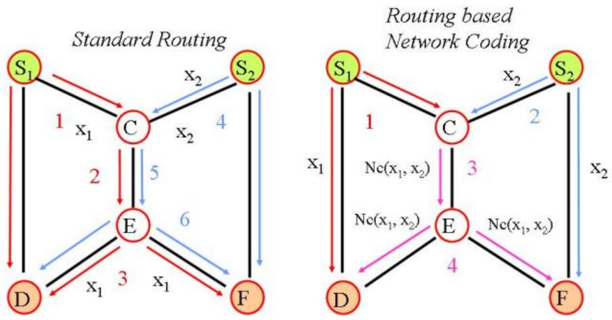


Figure 58: Network coding principle from the butterfly topology

The Figure 59 presents the application of the network coding optimization on a 2 sides flow relay topology. The optimization in terms of throughput and number of messages sent is of n + 2 [134], with n as number of relay nodes. The examples provided present network 2 inter-flows coding optimizations. The principles presented here may be extended to n-flows optimization, with *Nc()* defined as a linear combination of n flows.

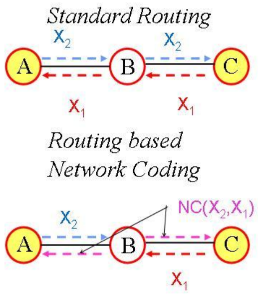


Figure 59: Network coding principle from the 2 sides flows relay topology

3.12.5 Algorithm description

3.12.5.1 Rationale on a concrete example

The following figure (Figure 60) presents the issue to be solved on the butterfly (or Manhattan 2x3) topology as presented previously in the network coding description. In this example a flow X1 is already established from the ingress S1 to the egress D and F. The traffic route (which is optimal) is established with respect to the path S1-D-E-F. A new flow is requested from the ingress S2 to the same egress nodes D and F.

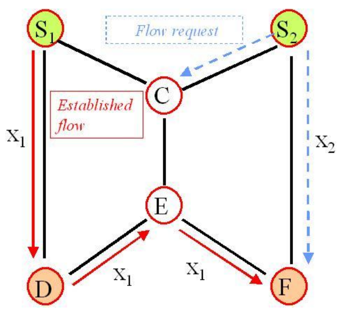


Figure 60: Routing path application example

Figure 61 describes a potential routing path definition using a "classical" routing algorithm (called Routing X) which allows optimizing the flow paths, independently from one to each other, or more precisely not modifying current flow established in the new flow route determination. An example of such a flow route defined is presented, and compared with the optimal route, using the full power of network coding optimization.

As shown in Figure 61, to go from the first routing situation (routing X) to the second one (routing based NC), the following operations need to be applied: 1) link cut on the X1 flow on D-E and E-F; 2) X1 multicast at node S1 to C and D; 3) coding decision on node C; 4) relay of the coded flow from the node E to the nodes D and F; 5) decoding decision on the egress nodes D and F. These modifications are illustrated on Figure 62.

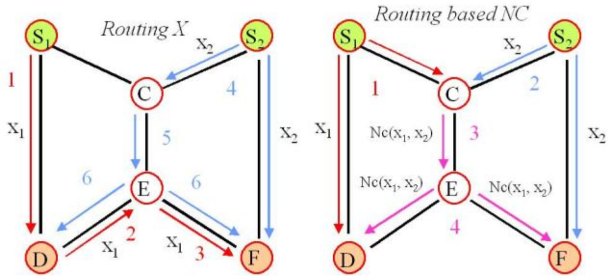


Figure 61: Comparison between a classical routing and a routing based NC

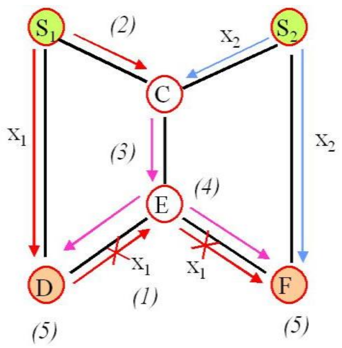


Figure 62: Modifications to be applied to go from Routing X to Routing based NC

The issue to solve remains to collect at a node the information needed to define a decision of network coding. This information is in one hand knowledge of the topology close to this node, and in the other hand the information of flows on this topology. Note that these flows can be not relaying through this node (as shown in the example in Figure 62 on node C for the flow X_1).

The algorithm described in the following section proposes to generalize the modification to be applied on existing established flows in order to optimize the flows in using the network coding flows optimization capabilities.

3.12.5.2 Protocol steps description

In order to illustrate the protocol steps, we will take the classical routing flows situation described in Figure 60 as starting situation in which the algorithm will be applied.

Flooding of traffic route information over the network

The first work will be applied to each traffic flow. It consists on the memorization, for each node in the neighborhood of a traffic path coming from the ingress node, of the distance in a number of nodes to the traffic ingress, and of the precedent nodes identifier to access to this originator ingress node.

This first step can be done on a bounded distance Dijkstra algorithm [134]. The selection of short paths to the ingress node traffic can be considered as a restriction, to restrict the flooding to n-hops distance, potentially dependant on quality of service requirements such as latency. The application on our example is shown on Figure 63 on a 3 hop bounded flooding exploration.

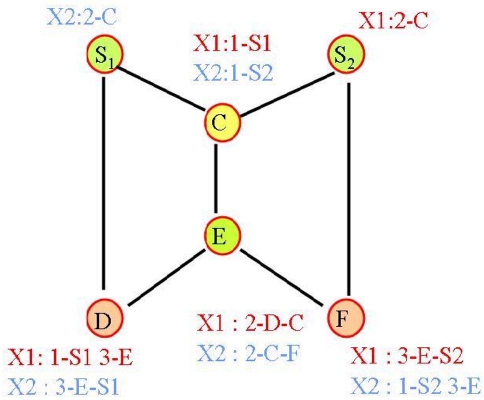


Figure 63: Step 1

Detection from egress nodes of potentially “pivot” nodes candidates.

This step consists, periodically from candidate egress nodes by sending specific messages, to send information on these flows. These messages, called Mtopo messages contain the following fields:

- a **Lf** flows list,
- a **Lp** list of list of optimisable flows with network coding
- a **Firstcod** list of the first node identifier the network coding may be applied, and the distance **Ldp** of the path the network coding will be applied,
- a **Nd** list of egress nodes,
- a **Ln** list encoding the tree of the paths explored,
- a **Lft** list indicates, for each path of the Ln tree, the flow id of path including the ingress node of the flow.

In the next figures the symbol  represents Mtopo messages.

As illustrated in Figure 64 a node (in the example the node E) receiving such message from different egress node has the sufficient information to determine if it can be such a potential “pivot” node. The egress nodes that can send such messages are nodes egress of several flows.

Messages relay from potential “pivot nodes”.

The pivot node identification is “pushed” to the nodes that potentially transfer the (in the example 2) flows.

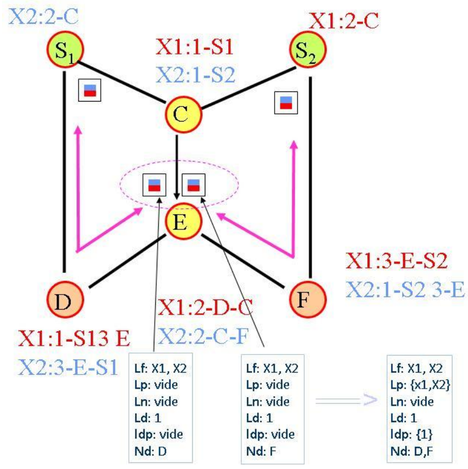


Figure 64: Step 2

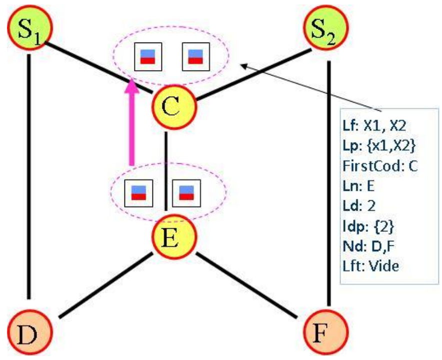


Figure 65: Step 3

Decision function on ingress nodes

The messages are finally sent to the ingress nodes. From the information received from the different paths of this information, network coding is applicable only if one path is common with another flow (i.e. with a message coming from a node identified as a potential network coding pivot node) and one another. The network coding decision will be applied taking care of the different constraint required for the traffic flow (latency, resource allocation capabilities, link stability). In case of network coding application decision, the flow is reinitiated with the information of network coding application sent to the respect nodes). The network coding is actually applied on a “pivot” candidate node if the node receives information from the two originator nodes. Protocol between the ingress nodes and the pivot node may be defined to know if the ingress nodes decide or not to apply network coding.

The Mtopo messages transmitting to the ingress nodes provide the sufficient information to detect the topology information to decide if a network coding is applicable.

In the example, the ingress node S1 (resp. S1) has the knowledge:

- of a path S1-D (S2-F) the traffic flow X1(resp.X2) may be transmitted
- of a tree S1-C-E-D;F the flows X1 and X2 may be transmitted, with a 2 nodes encoding of the two flows from the node C.
- of a path transmitting the X2 (resp.X1) flow from the ingress node to the egress node F (resp.D).

The S1 and S2 nodes have the sufficient information to (re)establish the optimal traffic routes as depicted in Figure 60 and labeled “Routing based NC”.

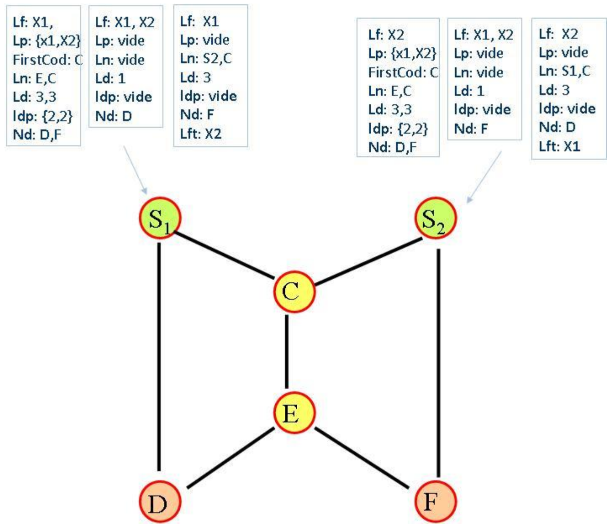


Figure 66: Step 4

Traffic paths re-establishment

The fifth step is the network coding application on common path and decoding on the egress nodes. The ingress nodes assign the route establishment in transmitting to the next hop nodes of the traffic path defined, MEstab messages including:

- the flow identifier, and any other parameters needed to initiate the traffic
- flows coding authorization, with the flows identifiers
- the first node identifier the coding will be applied
- the nodes tree to access to the egress nodes.

Each node receiving the MEstab message:

- allocate the resources needed to initiate the traffic,
- suppresses its id in the nodes tree
- transfers the message to the neighbour nodes of the tree

If the first node identifier in which the coding will be applied is the current node, the node memorizes the information and will proceed with the coding of the flows at the receipt of packets of the flows.

3.12.5.3 Topology extensions by definition of delegated nodes and multi paths optimization

The algorithm presented is restricted to the ingress nodes from originator of independent paths. The ingress nodes are also restricted to ingress nodes of several traffics. The following figure introduces the notion of:

- delegated ingress nodes, on which the capability to stamp the **Lft** field of the MTopo messages is delegated.
- delegated egress nodes, on which the capability to send the MTopo messages are delegated (in the following figure we suppose the node F is the ingress node of the traffic flow X2).

The definition of the set of delegated ingress and egress nodes is the object of future work.

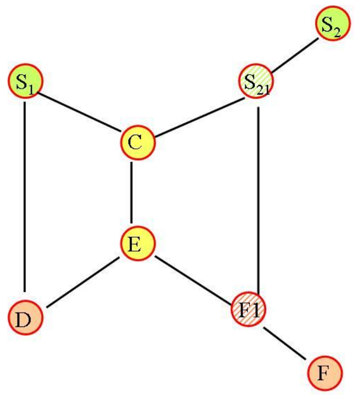


Figure 67: Ingress and egress delegated nodes

The Decision function on ingress nodes may define the paths the network coding is applicable. One solution is to deterministically select one of the paths (for example from an ordered function from the identifier of the coding nodes candidates). The other solution is to use the opportunity of these paths to transmit several flows from these paths.

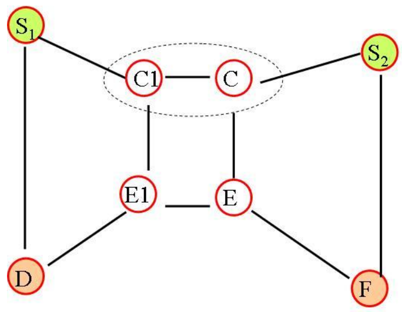


Figure 68: Multi paths optimization determination

3.12.5.4 Application on 2 sides relay topology

This section describes the application of the proposed protocol on a 2 sides flow relay topology. Practically, this topology is the one of PMR vehicles running along a road.

The particularities of these particular topologies are the following:

The ingress node of a flow is also the egress node of this flow. These nodes are considered as both initial and egress nodes.

The relay nodes have to encode and decode the data at each data packet receipt. These decodings are applied with respect to the data packets previously received.

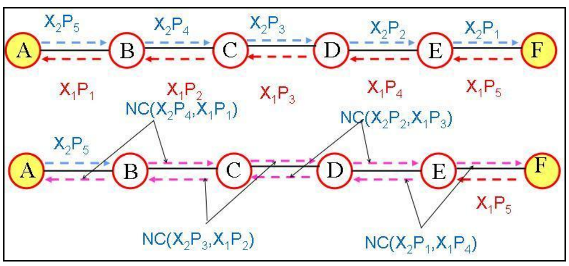


Figure 69:2 bi-directional flows with 4 relay nodes with standard routing and network based routing

The algorithm based on MTopo message transmission from egress node to ingress nodes is applied, with a specific field indicating the flows are bi-directional, as illustrated in Figure 70.

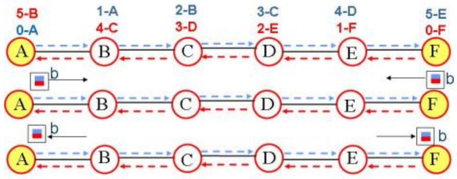


Figure 70: MTopo messages go through within the network

When receiving MTopo messages from the two egress nodes, the relay nodes allocate resources to memorize 2 packets of the two flows (as shown in Figure 71).

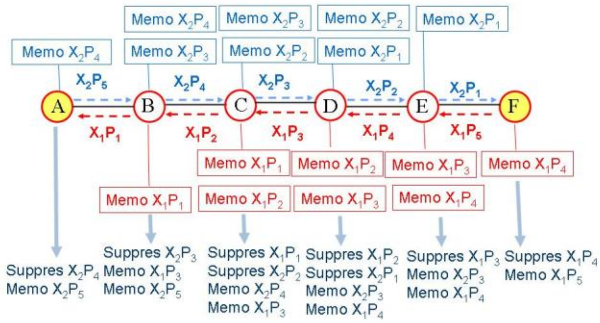


Figure 71: First step of memorization after receipt of the mTopos messages from both sides for each node

The ingress nodes, at receipt of the `Mtopo` messages, transmit `Mestab` nodes, with the next hop as first hop realizing the coding. The particularity of the coding/decoding process is that each relay node encodes and decodes the data packets

The dissemination of the coding steps from the first encoding nodes to the others is illustrated in Figure 72 and Figure 73.

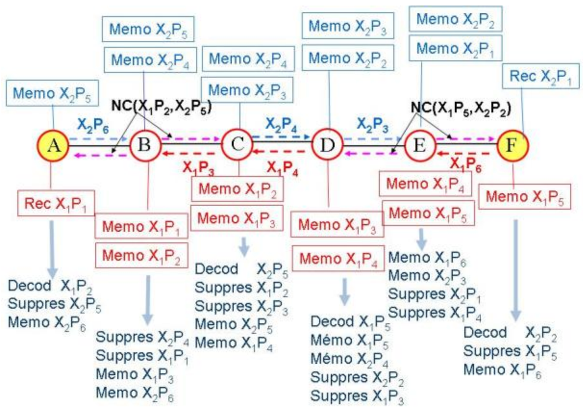


Figure 72: The relay nodes close to the in/ingress nodes are the last to receive the MTopo messages, all the other are ready to decode the data they encode, from MEstab message from e/egress nodes

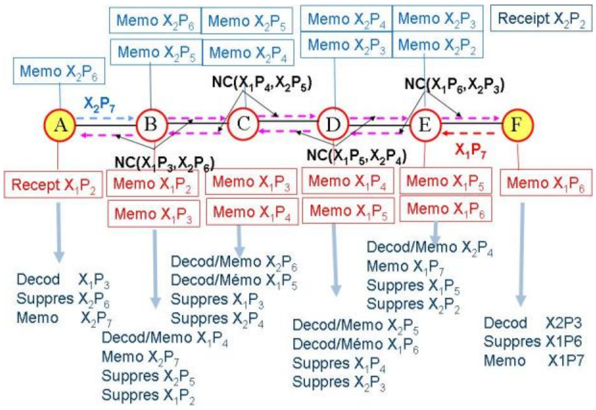


Figure 73: Nominal situation, all nodes coding and decoding packets received.

3.12.6 Implementation considerations

The algorithm is located in the CMON module. It is a distributed algorithm located on each terminal. It runs as a distributed algorithm. It is activated during the ON creation stage and ON maintenance procedure.

3.12.7 Algorithm evaluation

3.12.7.1 Simulation Environment description

The simulation is performed under OMNET++ environment, using the framework [87]. The protocol stack used to perform the simulation is based on the WiFi protocol stack (802.11), with the DYMO routing protocol. The OneFIT enhancements are simulated by modification of the routing protocol.

3.12.7.2 First performance evaluation

The algorithm is under implementation with respect to the following implementation guidelines:

- A flow is usually identified by the tuple (source IP address, destination IP address, source port number, destination port number). For sake of simplicity, in the simulator the flow is identified by the uint32_t value of the IP source address. It follows that only one flow can be established by the same source node.
- Even if multicast is supported at the application layer, no multicast ad-hoc routing algorithm is implemented in the actual version of the simulator. As an example, assuming to use reactive ad-hoc routing protocols, to find a single route for the first flow from Node 0 to Node 2 and Node 5, a routing algorithm like the Multicast-DYMO algorithm would be required. Since this is not available, two unicast communications have to be established toward the two destinations of the same flow: a first one between Node 0 and Node 2 and a second one between Node 0 and Node5.
- The Network Coding solution can be simulated using Constant Bit Rate (CBR) traffic only and not with video streaming. Indeed, the Network Coding solution assumes that discovery messages are flooded at the flow initialisation from the source to the destination in order to discover the network topology. However, when considering video streaming, the client requests the video to the server via the RTSP handshake: if follows that the topology discovery is triggered by the client and not by the server. This has a non negligible impact of the NC table construction.
- The network coding can be disabled setting a parameter NC=0 in the OMNET configuration files.

3.12.8 Requirements on the C4MS protocol definition & technical challenges

As related in the algorithm description, the C4MS protocol shall have the capability to implement the information to memorize and to exchange the `MTopo` (to be flooded in the network) and `MEstab` messages (directed emission of messages). It shall be able to memorize tables associating flows to entries storing a list of path distance (or other QoS metric values) and the identifier of node.

3.13 Techniques for Network Reconfiguration – topology Design

3.13.1 Technical challenge addressed

The topology control focuses on the technical challenges associated with the creation, maintenance and termination of ON. Here, the main challenge is finding effective trade-offs, as the focused area involves multi- objective optimization Problem formulation.

3.13.2 Rationale

Topology Control in Network Design is provided to enable coordination in decision making among the nodes regarding their respective parameters (e.g. Transmission range) to generate a network with desired global properties. As the scenarios of OneFIT involve the coverage extension, capacity extension and traffic rerouting, it calls for an effective topology control. The efficient creation, maintenance and termination of ON's depends on how the network topology control acts. A proficient topology control, will provide Opportunistic networks with:

- reliability and stability (Reduction in rerouting)
- reduction of energy consumption (Critical Transmission Range assignment)
- increase in network capacity (Capacity assignment/ optimization)
- effective cost (Lowest possible cost /trade off focusing the desired network-wide perspective)

3.13.3 Use cases mapping

Scenario 1: Opportunistic coverage extension

Here in all use cases the optimization criteria for topology control algorithm is "Optimal Coverage". The use case 3 with connectivity optimization via an access point, invokes the topology control based on the "High standard information" as the position of the access point will be known to the network. Like vice, the use case 4 calls for k connectivity optimization topology control.

Scenario 2: Opportunistic capacity extension

Given that capacity aware topology control functionality will be at work in scenario 2, the QoS and spectrum aware topology control can be considered to remove the congestion and solve the edge users capacity shortage.

Scenario 3: Infrastructure supported opportunistic Ad-Hoc networking

The use case 1 of infrastructure offload calls for cost effective links, thus the topology control top priority will become: to enable the least cost link topology with desired QoS. The presence of BS coverage may enhance the efficient energy communication of nodes, as the high standard information in the form of BS exact position will be known. Use case 2: infrastructure-governed home networking involves indoor application, thus topology control with limited information can be more useful as it will be less expensive than using High information based topology control.

Scenario 4: Opportunistic traffic aggregation in the radio access network

Given the nature of the application, by using QoS aware topology control the use case 1: Handling cases of users with poor quality towards the infrastructure can be resolved. The other use cases can be handled well by energy and cost efficient linking specially the use case 4: cooperative handling.

3.13.4 State Of The Art

The topology control has been classified into various categories depending on the criteria under focus.

In [135] based on the transmission range property of the network nodes, the topology control is divided into two main categories: Homogeneous and Non-Homogeneous Topology Control, as depicted in Figure 74.

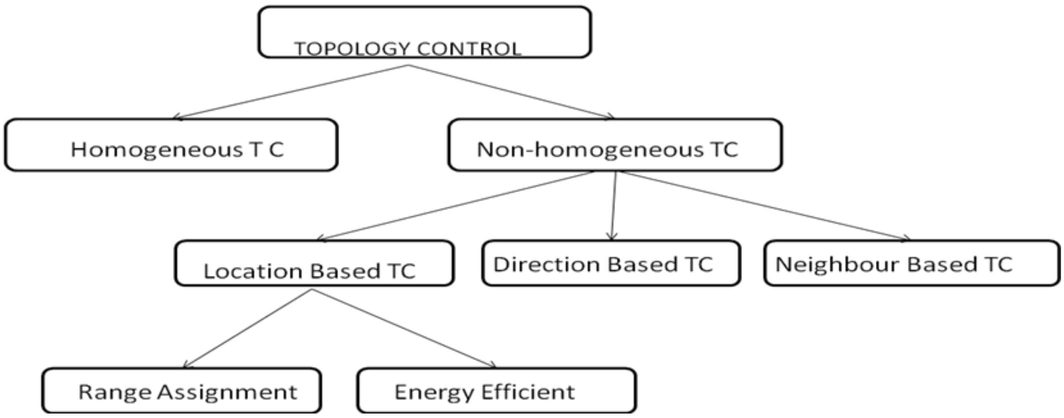


Figure 74: Taxonomy of topology control protocols

1. **Homogeneous TC**

As the name suggests the transmitting range of all the nodes is the same. While the transmitting range of an individual node is always kept the below the maximum allowed range (also called the Critical Transmitting range CTR) [137]. The minimum possible transmit range is the target that can enable effective topology control.

2. **Non-homogeneous TC**

In non-homogeneous the nodes can have different transmit ranges as long as they are below CTR [138]. The non-homogeneous Topology control is further classified into three topology control approaches:

Location based TC: establish the topology on the assumption that exact position of the node is known. The Range Assignment is modified (to optimize desired criteria) [139] if centralized approach is followed while energy efficient communication is triggered if decentralized approach is adopted [139].

Direction based TC: Each node in the network doesn't know its respective position, instead it estimates the direction of its neighbours.

Neighbour-based Topology Control: Each node knows the number and identity of their neighbours.

Beside the above taxonomy, another approach for topology control taxa is given in [136]. The main categories are: Centralized and Distributed approaches.

1. **Centralized TC**: The topology is optimized considering the position and transmitting range of the nodes.
2. **Decentralized TC**: The neighbour information is mainly utilized in various manners to ensure topology control. The utility of the information lead to the following two types.

   Connectivity Aware TC: The number of neighbours is monitored such that the connectivity is ensured and stabilized.

   Capacity Aware TC: The interference level from the neighbours in taken into account to ensure the optimized network capacity.

In contrast to the above taxonomies, here the classification on the bases of transmitting range is avoided, as the environment dealt in OneFIT consists of heterogeneous nodes. Despite the fact that the simplicity of classification criteria in [135] reduces the complexity of the problem, the entire division is made on one parameter of transmit power adjustment which is rather seen as optimization criteria here. On the other hand, the taxonomy based on centralized and decentralized nature of the technique in [136] is annulled here. This is due to the fact that most of the centralized methods can be modified to follow a decentralized approach.

Given that the resources, optimum parameters and environment for ON's creation, maintenances and termination is varying, the information available for building the topology along with the main target of creating the ON (optimize coverage and/or capacity etc) also varies. The taxonomy for topology control suggested for OneFIT is "optimization criteria based topology" and "provided information based".

The provided information is classified as: High Standard information, Standard information, Limited information. While keeping in view the OneFIT scenarios Optimization criteria are: Coverage optimization and Capacity optimization.

High Standard information based: The provided information is accurate and vast, it mainly encircles the topology control algorithms as

- R&M [140] optimizing capacity and connectivity
- LMST (Local Minimum Spanning Tree) [141] optimizing criteria is 1-connectivity and capacity
- and CLTC (Cluster based Topology Control) [143], [144] optimizing criteria is k-connectivity

Standard information based: The information in hand is not vast. It include algorithms as

- Mob-CBTC (Mobility Cone Based Topology Control) [145] ,PBTC (Prediction Based Topology Control) [145] and DistRNG (Distributed Relative Neighbourhood Graph) [147] with connectivity optimization

Limited information based: The information provided is vivid and element of uncertainty is present. This includes algorithms such as,

- LINT (Local Information No Topology) [148] with capacity optimization
- and K-Neigh [149] with coverage optimization.

3.13.5 Algorithm description

The detailed specification of algorithm will be presented in D4.2. In this section a high level overview of requirements addressed by the algorithm is presented. The topology control (TC) algorithm will enable topology formation and control during ON creation, maintenance and termination phases. The algorithm is executed in two main stages: the topology construction and then the maintenance of topology. While the topology construction phase will output the connectivity ensuring energy efficiency, the topology maintenance phase will focus on reduction in rerouting and increasing lifetime of ON. The routing protocol is expected to run above topology control scheme/protocol.

A multi objective/constraint approach is selected for the design of TC enabling adaptive topology control. For opportunistic coverage extension (via support user) scenarios, approach based on optimum neighbour is used, while opportunistic coverage extension (via an access point) scenarios call for *k*-connectivity with location-based TC. The main focus will be on building a QoS and spectrum aware, interference resistant topology control. By taking into account the following contextual data, the cognition necessary for topology control can be realized:

- Position/Directionality/orientation of a node
- Capabilities of the node
- Mobility patterns and link life time.

- Traffic patterns and QoS requirements
- Available resources and their variation patterns

Given the fact that computational power of an individual network node is limited, all the parameters and information cannot be collected and evaluated in a node. Here, depending upon the node capabilities/behaviour, based on the probability of change in formation content, some evaluated information will be delivered to the node (e.g. over mechanisms by Radio Access Technologies or through C^4MS). Thus, the level of cognition will differ in different network nodes/terminals.

Inputs

The following are considered as inputs common to all ON management stages:

- Node capabilities: Maximum power, Achievable levels of power, Energy consumption at power levels (or Battery drain) Position orientation sense, Directional Mobility, Speed.
- Radio environment: Propagation loss, interference levels per channel, noise, variation profile
- Policies

However, phase-specific inputs have been identified as described in the following.

For creation:

- Node capabilities: Node type/ standing role in the network.
- Radio environment: RATs available, number of channels/ RAT, number of interfaces/ RAT, Energy consumption/RAT
- Performance criteria/ Metrics: QoS Class indicator, Maximum bitrate on uni/bidirectional link, Guaranteed bitrate on uni/bidirectional link
- Neighbouring environment: Nodes Lists, Nodes ID, Energy level per node, Neighbour's ID per RAT. Delivery probability per node, Relaying traffic limit per node, Supported traffic class indicators of nodes
- Spectrum Availability indicators, Radio Interface performance indicators, Transmission constraints related to available spectrum resource
- Application (type and duration) requirements
- Patterns: Mobility, utility

For maintenance:

- Variation in Information about: Node Status, Number of nodes, Resources, QoS/QoE requirements, Traffic/congestion requirements, Radio link parameters, Mobility.
- Patterns: effect of changing Mobility, changing utility

For termination

- Release of assigned resources information flag, Handover information flag, Statistics provisioning information indicators.

Procedure

The decision of ON creation from CSCI will reach CMON, triggering the first phase of the algorithm. It will start building the topology against the maximum power graph. The selected paths shall have low stretch factor, will be energy efficient and fulfil the optimization criteria (the reason ON is created for). Once the topology has been created, the routing protocol will be triggered (route discovery/ method to route data packets). The topology construction phase will perform the following:

- Analysis of the available information to determine the optimization criteria:
    - Stretch factor to create a spanner

  - Optimal node degree
  - Weights calculation
- Neighbour environment consultation and orientation development:
  - Through the real-time analysis and feed
  - Through cognitive/context information
- Analysis of available routes:
  - Through the real-time analysis and feed
  - Through cognitive/context information
- Nodes and path selection on the metrics parameters
  - Optimization function: Distributed construction of Stretch factor-spanner. Global Connectivity, Trade offs such as between worse case connectivity and node degree.
  - The weight calculation and the influence of previous experience to the current time reading will be determined by heuristic approach.
  - Determine the cost per link
- Removal of redundant nodes, determine the path redundancy
  - Update cognition, update weights

After topology has been created, the topology maintenance phase will start. Monitoring the available context data (e.g the variation in application flow, node status etc) or triggers from other layer (e.g. in the case the routing protocol, indications of route or candidate node unavailability/disappearance) will trigger execution of the topology control to reconfigure topology and to restore connectivity. To check the need of reconfiguration, information of neighbours will be collected periodically. The local/global mobility patterns will be sent to update context too. The topology maintenance will involve periodic monitoring of:

- Node and radio link parameters and requirements (updates from the neighbourhood/ enhanced node)
- Node entrance/departure triggers (link availability predictions based on cognition, will be used)
- Variations in QoS/QoE/Traffic (Redundant routes based on cognition are evaluated)

Finally, the weights and cognition are updated and a new topology formation is produced.

3.13.6 Implementation considerations

Since the cognition and topology control algorithm based on the multi objective optimization function (spectrum awareness, QoS and interference awareness, context awareness) is on the node/ terminal level, topology will be implemented in distributive manner, although the centralized topology control can also be chosen, e.g. the network node identifying it self as of high capabilities can lead to clustering, assuming the role of cluster head. As, the CMON is the main entity involved in the decision making and control for ON creation, maintenance and termination phases, it will be the main entity where topology control will reside. CMON-to-CMON communication will be via OM – TT to enable relaying, while OM-TN interface will be used in case of direct BS service. The direct feed will be taken from CSCI, JRRM and DSM entities. The CSCI will provide CMON with candidate nodes once ON suitability decision has been made by CSCI. The JRRM will provide neighbourhood information (through C4MS) and conditions regarding network, cell load etc while the spectrum resource availability is obtained from DSM.

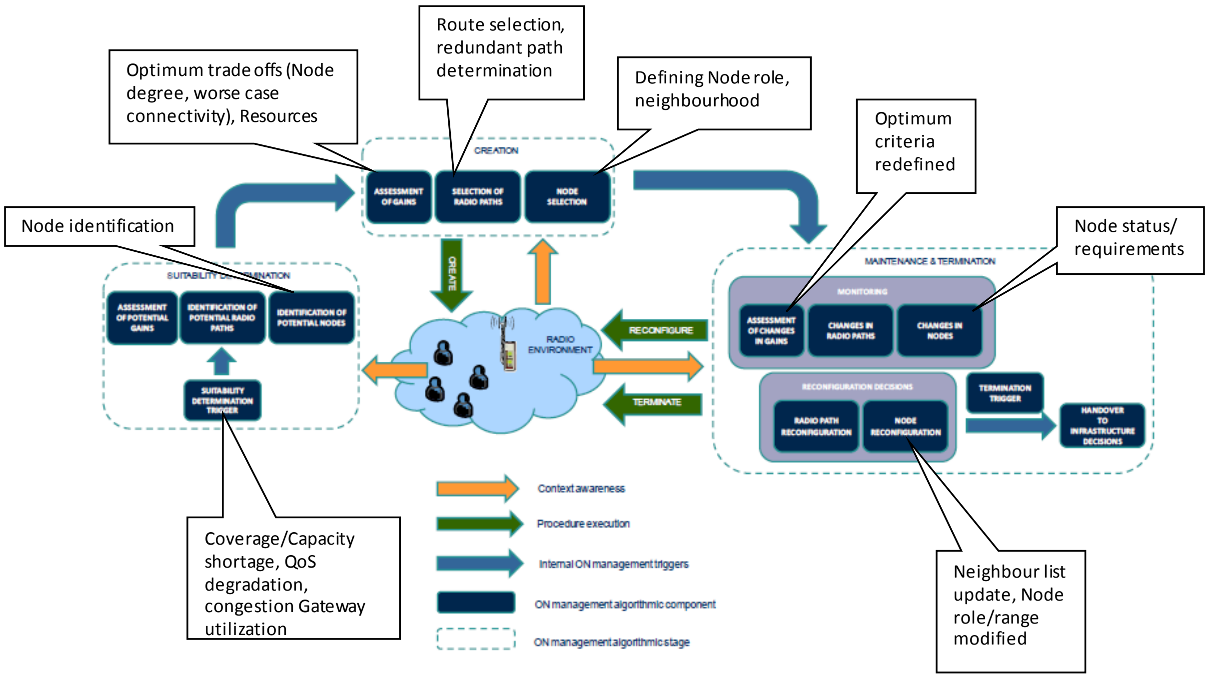


Figure 75: Placement of the TC algorithm & components in OneFIT Functional Model

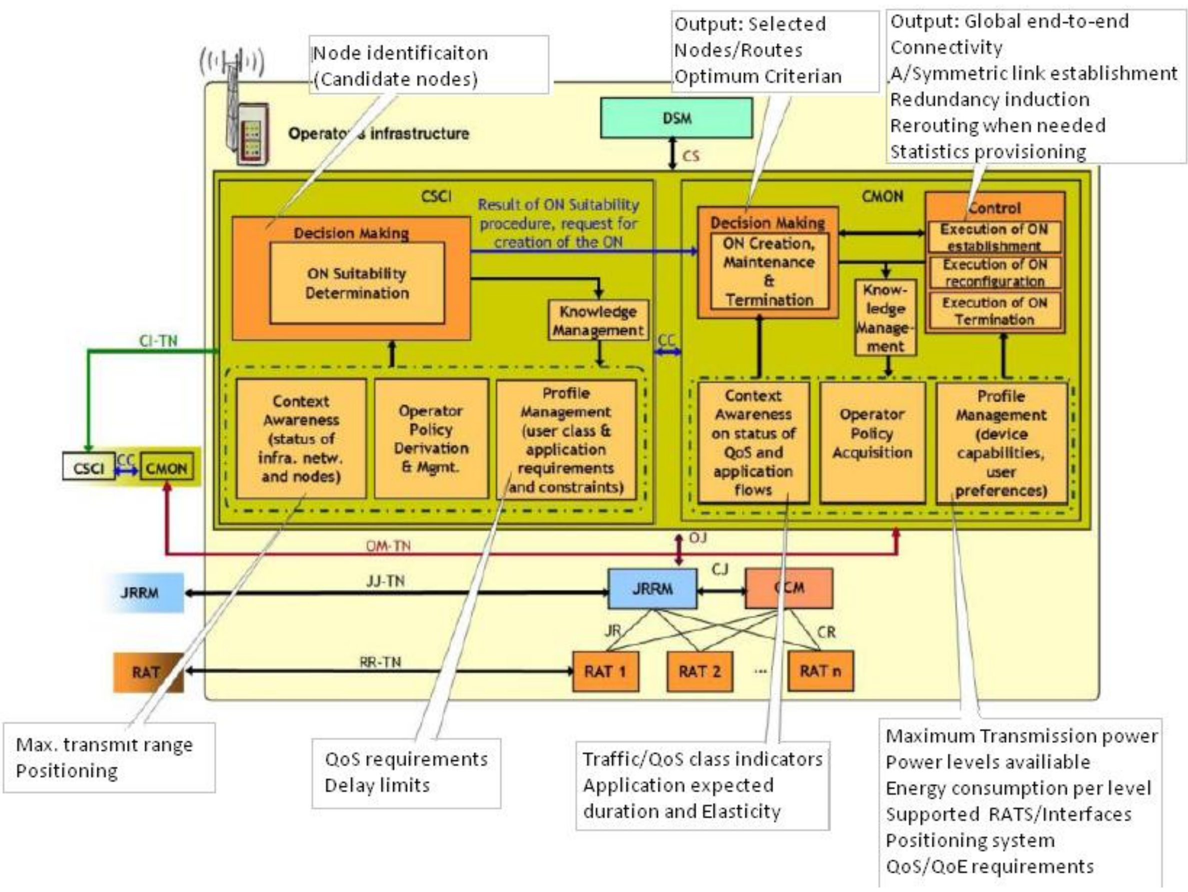


Figure 76: Placement of the TC algorithm in OneFIT Functional Architecture

3.13.7 Algorithm evaluation

The design and implementation of the algorithm is at an early stage. Evaluation results shall be reported in D4.2.

3.13.7.1 Simulation Environment description

A complete description shall be provided in D4.2. Algorithm implementation and validation will be performed on a network environment simulator, and based on the aforementioned multi objective optimization metrics. The most suitable types/approaches for topology control will be tested and optimized for operation under diverse environmental conditions. Performance of the algorithm will be evaluated based on simulated OneFit scenarios.

3.13.7.2 First performance evaluation

Performance evaluations will be conducted (and reported in D4.2) against the following selected key performance indicators:

- Packet delivery ratio
- Scalability of algorithm
- Convergence time
- Network/topology cost
- Average delay
- Sensitivity to changes in design variables

3.13.8 Requirements on the C4MS protocol definition & technical challenges

The C4MS shall support the transport and provision of *Localized information*: Node positions, accessible neighbours, as well as *Global information*: Cell loading, interference level, and Traffic type/ QoS requirements, as required by TC algorithm.

3.14 Content conditioning and distributed storage virtualization/aggregation for context driven media delivery

3.14.1 Technical challenge addressed

The algorithm that is described in this section will address the technical challenge of suitability determination, creation, maintenance and termination of an ON overlay network in order to meet requirements of the scenario 5 “Opportunistic backhaul bandwidth, storage and processing resource aggregation”. More specifically, this algorithm will dynamically calculate and implement control and management functionalities as related to content caching on access network elements in order to improve media delivery performance of the overall network. Cognitive proactive and reactive caching algorithms and media aware routing (Application cognitive multipath routing algorithm) will be developed and evaluated in order to improve utilization efficiency of the backhaul resources. ON will be established over infrastructure nodes in order to achieve the best coordination among them and the best performance of cognitive caching algorithms so that the end users can receive the best QoS/QoE of media streaming.

3.14.2 Rationale

Scenario 5 of the OneFIT project proposes aggregation of backhaul resources. These resources can be bandwidth, storage space and processing power. In order to achieve aggregation of backhaul storage resources, proper caching algorithms must be introduced. Caching algorithms are a variant of node selection problem that is identified as part of an ON lifecycle. These algorithms have to be able to process gathered contextual data about radio environment, available backhaul resources, user profiles and application profiles. By using these data, caching algorithm will be able to address all the problems that arise in media streaming over wireless networks and to provide the best QoS/QoE to the end user as well as the best network resource utilization (bandwidth, storage and energy consumption).

3.14.3 Use cases mapping

Algorithm proposed in this section will address use case of scenario 5 that considers opportunistic backhaul storage aggregation.

3.14.4 State Of The Art

For purpose of quality and efficient media delivery various approaches are used. The best known are content delivery networks (CDN) [150][151] which use strategically placed content replica servers in order to bring the media content closer to the end users and to off-load the source servers. In this way users experience better QoS and network resources are better utilized. There are proposals for peer to peer (P2P) CDN solutions [152][153][154][155] that will include end user's equipment into caching and media streaming process. These solutions tend to use contextual data in order to incorporate the most efficient caching and media streaming strategies. More contextual data taken into account means greater processing burden on management nodes and greater delay in decision making, but on the other hand it will mean better reaction to real network environment and situations which lead to better resource utilization and end user perceived QoS/QoE.

Caching of content in networking equipment (routers, proxy servers, access points…) will provide better network resource utilization (most of all power consumption) [156] and it will bring content closer to the end users and avoid usage of user equipment in caching and streaming process. By avoiding usage of the end user equipment, list of the contextual data needed for decision making will be shortened (caching on the end user equipment require data about equipment usage patterns, caching and streaming capabilities and user motivation to participate in these processes) and decisions will be derived more efficiently and more precisely.

Access points and base stations represent infrastructure equipment that is the closest to the end users. By caching on these devices, the multimedia content will be brought as close as possible to the end users. These network nodes work all the time, whether or not they are used for streaming/caching and their base power consumption will not impact the overall content delivery system power consumption which leads to better energy efficiency.

3.14.5 Algorithm description

The algorithm that will be developed and evaluated during the WP4 course will provide a framework for node selection during ON suitability determination, creation and maintenance phases in order to support proactive and reactive caching mechanisms for video content delivery/streaming over pervasive wireless mesh networks (WMN). This type of WMN requires for all APs to be able to cache certain amount of media data.

Proactive caching will provide initial network access node selection for placement of video files. To be able to achieve cognitive placement of files, proactive caching mechanism must take into account the following contextual data:

- Video content popularity (on local and more broad level);
- Spatial and time distribution of user requests;
- Profile of end users (their mobility patterns, viewing patterns, equipment capabilities, QoS requirements);
- Operator policies (protection of content, end users and network, QoS requirements, resource utilization requirements…);

- Status of backhaul nodes (available storage in APs, popularity of currently cached data and available bandwidth for streaming…);
- Backhaul traffic patterns.

By processing above mentioned contextual data, proactive caching mechanism will select appropriate network access nodes (wireless mesh network access points) and place certain number of copies of video file (video file's chunks) into their storage space.

Reactive caching mechanism will constantly monitor status of the network and changes in user requests in order to dynamically re-cache data in order to address these changes. Contextual data that will be taken into account for this mechanism are:

- Changes in backhaul traffic (in order to avoid congestion on some backhaul links);
- Changes in spatial user request distribution (more requesting users move from one AP to another);
- Changes in status of backhaul nodes (links congested, node down…);
- Popularity of files ready for proactive caching (if very popular file has to be cached in access points then storage space for it has to be freed).

Collected contextual data will be stored in databases and used for derivation of cognition about network environment and system performance. By using this cognitive information, algorithm is able to derive appropriate response to previously encountered situations and to predict best response for newly encountered problems.

When the algorithm detects a user request for file *f* which contains *N* chunks (*k*) and if that particular file is not locally cached in WMN access points, then the algorithm has to decide whether or not to cache new file or to proceed with streaming from source server (see Figure 77). If decision is made to cache new file in WMN APs, then candidate nodes have to be detected and selected. During the streaming process to the end user, chunks of video file *f* will be cached on selected APs and at the same time contextual data about system performance and resource utilisation will be collected.

If requested video file is stored on access points, algorithm needs to determine candidate nodes for streaming chunks of video file to the requesting user. Previously collected contextual data and derived knowledge will be used for selection of candidate nodes and derivation of streaming schedule that will provide the best system performance and network resource utilisation. During the streaming process algorithm will monitor system status by gathering contextual data and if changes in system environment reach some threshold (event triggered change) re-caching possibilities should be examined. If re-caching is not possible or is not expected to solve current problem, then streaming will be continued from source server. During streaming session from the source server, system will be monitored and streaming will be continued from APs if system environment status allows it. If re-caching is selected as the solution for the encountered problem, then appropriate APs will be selected and some chunks of the video file will be moved among APs. When re-caching process finishes the new streaming schedule will be derived and streaming session will continue. Contextual data about system performance, resource utilisation and end user perceived QoS/QoE will be gathered during algorithm cycle and saved in contextual database for further knowledge derivation.

For every user request ON will be created among selected WMN APs to support algorithm execution which will provide aggregation of storage resources in order to locally stream as much chunks of requested video file as possible. ON will provide support for reactive caching mechanism by enabling gathering and exchange of contextual data which will enable detection of any changes in access network environment. When values of gathered contextual data change above certain threshold, reactive caching mechanism will start the re-caching process over the created ON.

The proposed algorithm has specific roles in ON suitability, creation and maintenance stage as shown in Figure 78.

3.14.5.1 Suitability determination

When user sends request for particular video file, OneFIT system will check to see if this file (or number of its chunks) is stored locally in access network to which end user is connected. If not, system will decide what to do with user request. It can be forwarded to the origin server or to the other access network's manager. In this case ON will not be created. If requested video file (or number of its chunks) is locally stored on WMN APs, status of these APs will be inspected to see whether or not they are able to stream parts of particular video file on time and with requested quality. Depending on user requested QoS (acceptable delay, jitter and quality of presentation) management entity will decide whether or not to create ON. If decision is made to proceed with ON creation, candidate APs are found such that they can provide all parts of the requested video file and that they are able to do that on time (when requested).

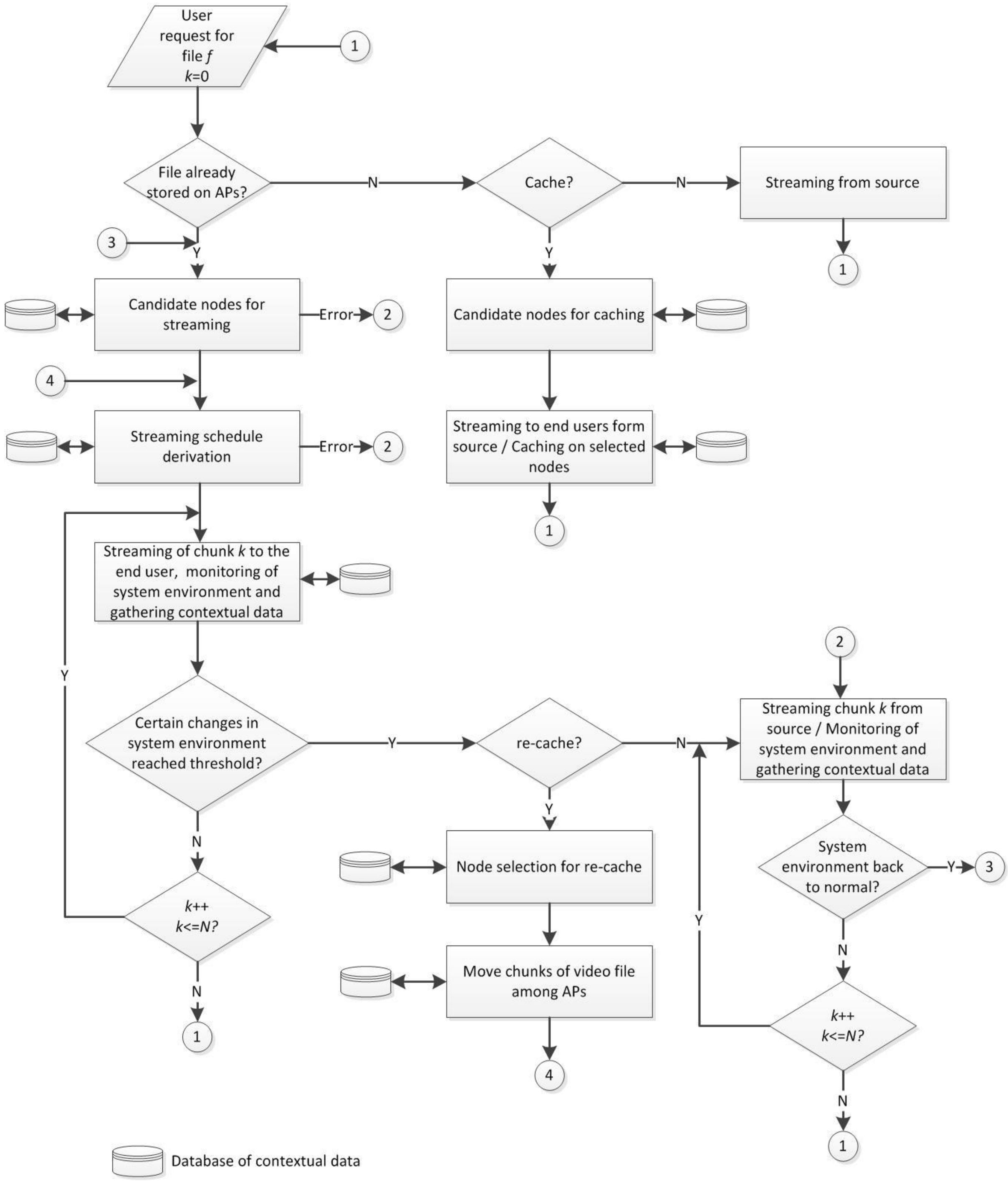


Figure 77: Algorithm for contextual backhaul storage aggregation

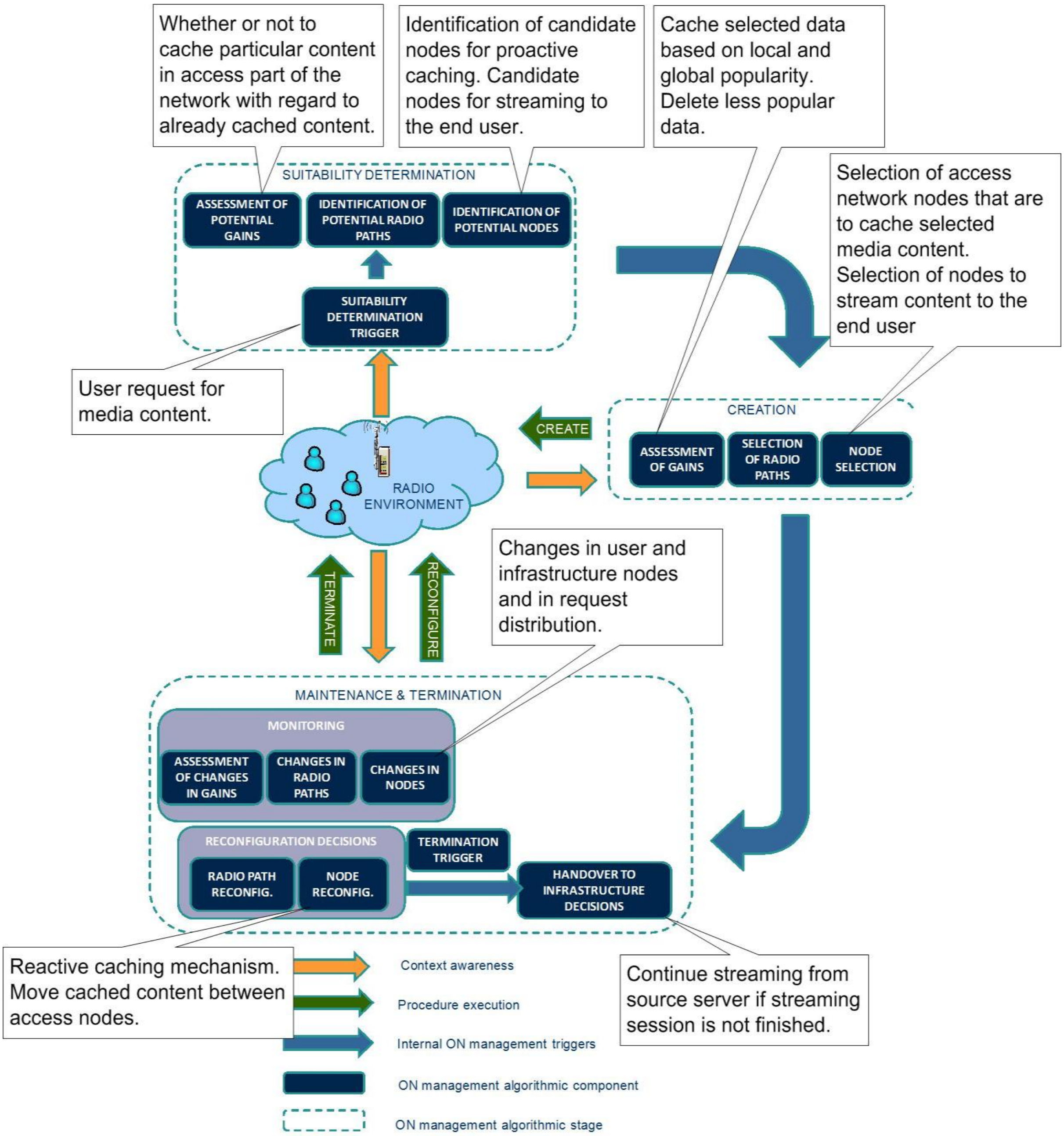


Figure 78: Algorithm placement in OneFIT high level functional model

3.14.5.2 Creation

When candidate nodes are derived, creation phase has to choose among the candidate nodes those that are most appropriate for addressing the user request for the particular video file or those that are most appropriate for proactive caching of video content. For this decision to be made, appropriate backhaul traffic patterns have to be recognized and anticipated and user profiles have to take into account all characteristics that can impact the quality of candidate node selection (mobility, viewing patterns…). Selected APs have to address different system performance metrics (interference level, resource utilization, QoS maximization, power consumption minimization) which can be of more or less importance to the decision making process.

3.14.5.3 Maintenance

During the video streaming session reactive caching mechanism will be constantly processing contextual data about network environment and requesting users. When changes in these data have reached some threshold reconfiguration is required. This reconfiguration process will use reactive caching mechanism to reorder caching of video content or to include additional APs (previously indicated as candidates) and all of that in order to provide as much constant streaming session (the same QoS, resource utilization…) as possible. When changes in ON environment exceed some other previously determined threshold then ON has to be terminated and streaming session has to be handovered to the source server.

3.14.6 Implementation considerations

Centralized and distributed versions of the proposed algorithm will be developed for pervasive WMNs. APs of this type of WMN have the ability to cache content proactively (in advance) and reactively (as it passes through them). In centralized approach the algorithm will reside on wireless controller on which ON suitability, creation and maintenance decision making will take place. In decentralized approach APs will run the algorithm and ON logic.

Regarding the OneFIT functional architecture, proposed algorithm should be provided by the CSCI and CMON management entities in infrastructure access nodes as shown in Figure 79.

3.14.7 Algorithm evaluation

3.14.7.1 Simulation Environment description

Mathematical model in form of mixed integer linear program is derived. Currently this model provides optimal file replica placement for proactive caching. This caching mechanism takes into account user request distribution (spatial) and file popularity as well as storage capacity of network nodes and their power consumption in order to derive optimal selection of candidate nodes that are to store particular video file. Objective function is given in form of the aggregation function of two optimization criteria. The first criterion is minimization of average delivery tree length (expressed in number of router hops) and the second is minimization of total system power consumption. Importance of these two optimization criteria is depicted with the value of weight parameter introduced in the objective function.

Mathematica program package is used for creation of WMN environment and equations of mathematical model based on input parameters. Model is presented in form of equation matrices. These matrices are loaded into the Matlab program package where the MILP solver code is used to derive optimal solution of the problem.

Wireless mesh network for this experiment is shown in Figure 80. This is the mesh network with the k-connectivity between 1 and 4. This type of connectivity with multiple paths can be expected in practice since a good wireless mesh structure requires for every access point to be able to connect to at least two neighbouring APs. Blue rectangles represent wireless access points and all of them are candidates for replica placement. Red circles depict users that are requesting the video file. The green circle represents optimal connection for video server for the case of centralized video streaming. This solution is used for benchmarking the solutions gained when streaming is done only by the access points. Normalized power coefficients are used. Base power consumption for the typical mesh AP is around 18 Watts and additional 5 Watts (pessimistic point of view) will be required in order for AP to be CDN ready (implement streaming engine, maintain cached content…). Because APs work all the time, whether they are streaming or not, we don't need to include their base power consumption into the overall system power consumption.

Experimental environment will be further developed in order to support dynamism in WMN environment so that reactive caching part of the algorithm can be implemented and evaluated. First we will introduce stochastic mathematical model for system environment and heuristics for solving it. Then simulations will be continued in available network simulators and at the end on real WMN testbed.

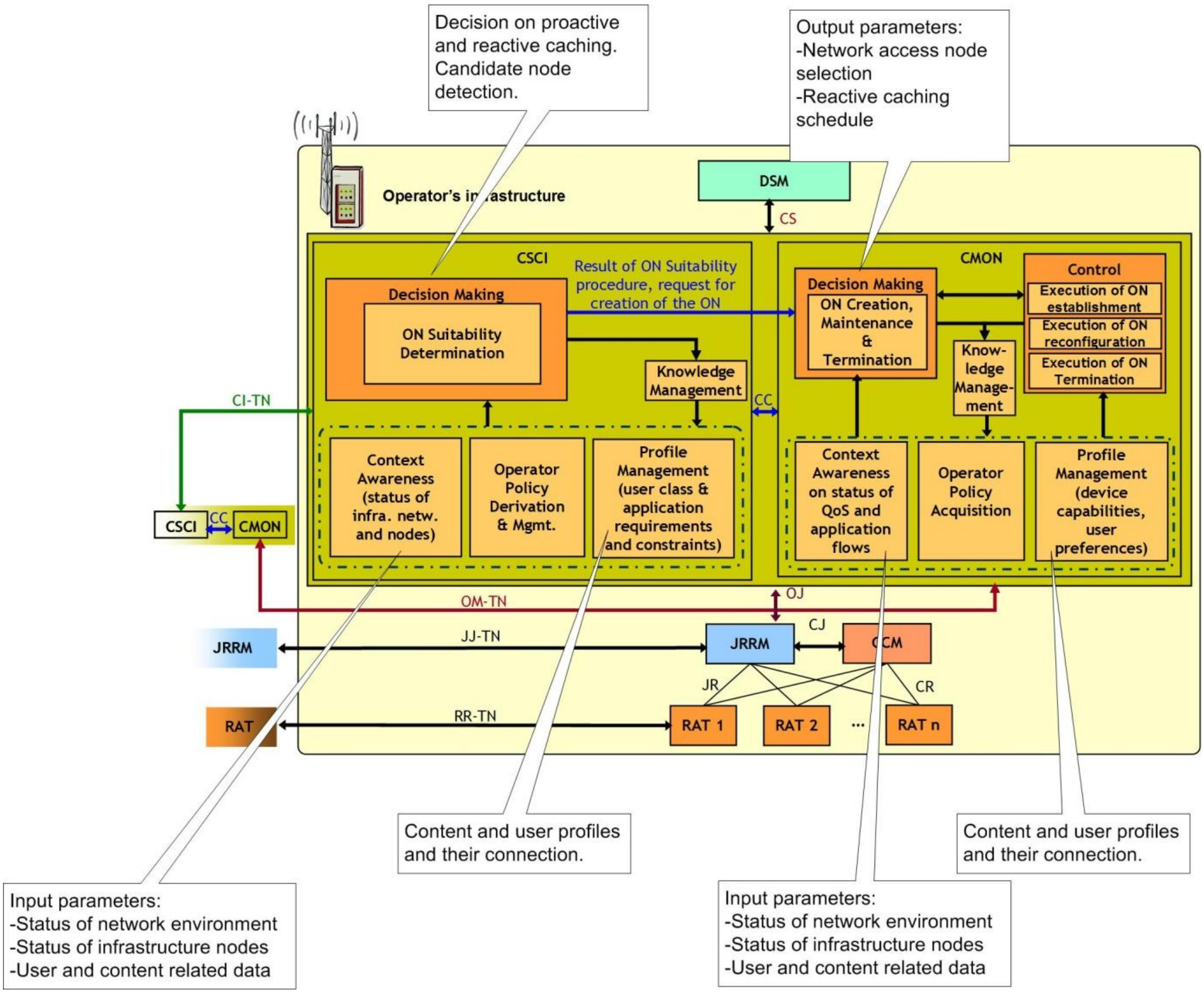


Figure 79: Algorithm placement in OneFIT functional architecture

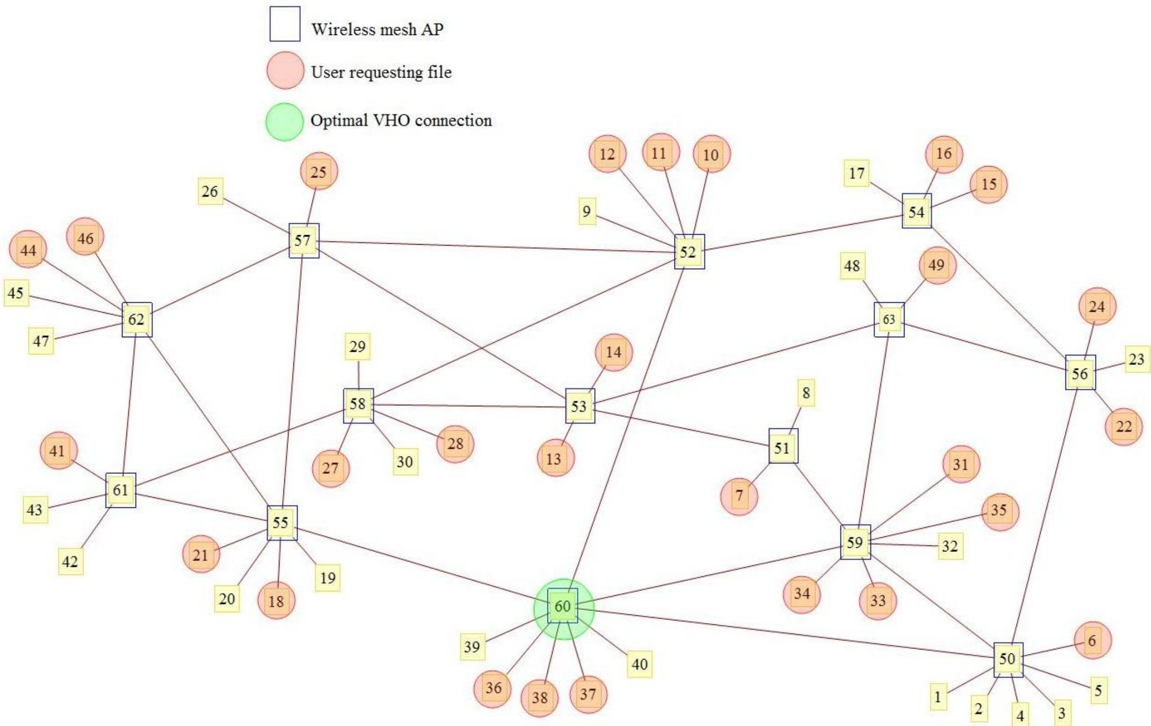


Figure 80: Topology of wireless mesh network used for the experiment

3.14.7.2 First performance evaluation

Experimental results, for the example network graph depicted in Figure 80, show that the two optimization criteria mentioned before are mutually opposing. Minimization of power consumption criterion tends to centralize streaming approach and average delivery tree length criterion tends to distribute streaming process among as much APs as possible. This trade-off is shown in Figure 81. Parameter W is weight parameter in objective function that gives different priority to both optimization criteria. When W=1 we want to minimize average delivery tree length (ADTL) and when W-0 all we want to do is to minimize system power consumption.

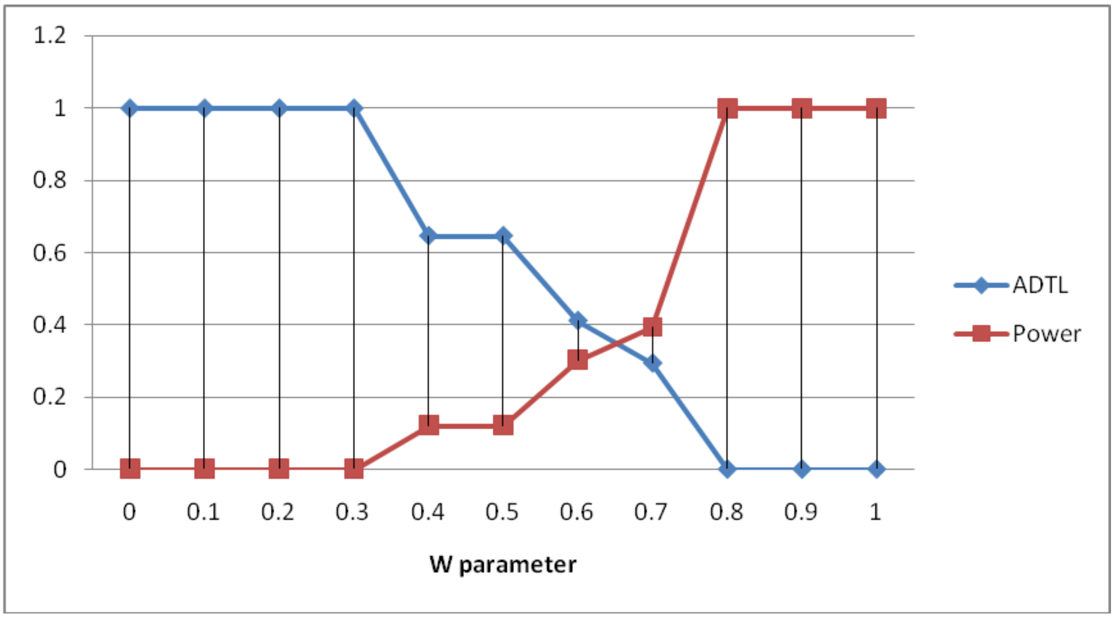


Figure 81: Average delivery tree length and power consumption are two opposed optimisation criteria

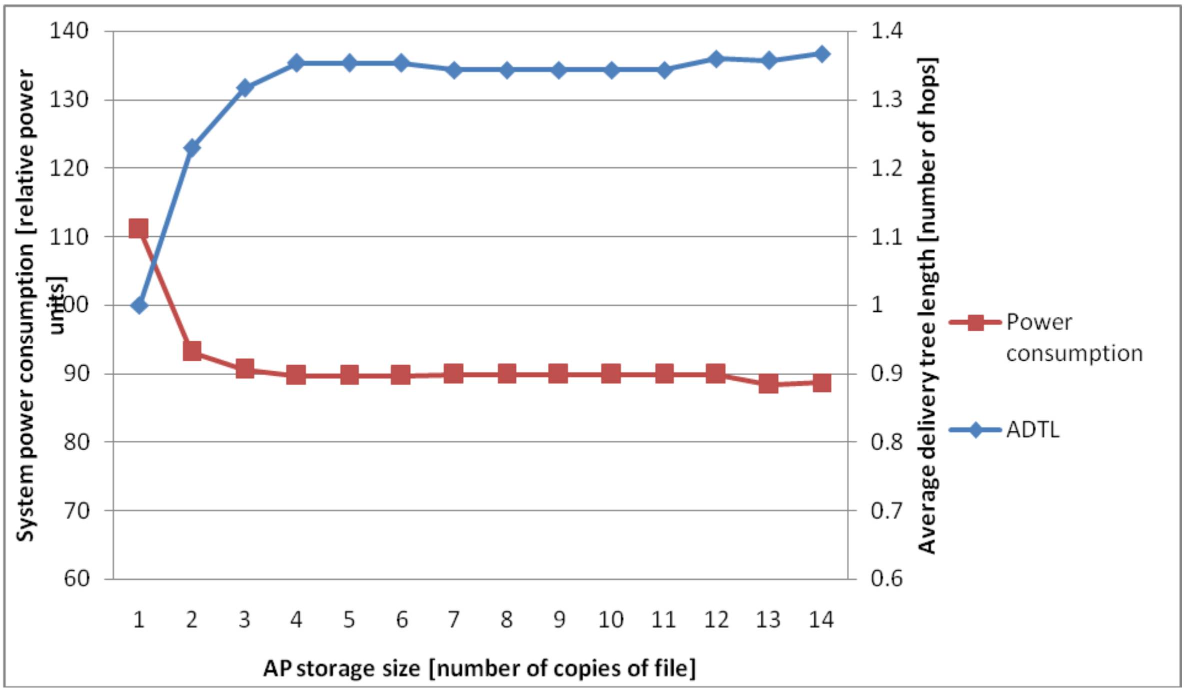


Figure 82: Impact of the increasing storage capacity of the APs in terms of ADTL and consumed power metrics

In Figure 82 it is shown how AP storage size impacts previously mentioned optimization criteria. We can see that increase in AP storage size tends to minimize system power consumption but on the other hand by minimizing power consumption it tends to increase average delivery tree length (ADTL).

Finding optimal replica placement for one case of input parameters (user request distribution, set of candidate nodes for file replica placement, file popularity and caching storage limitation of APs) takes around 2 sec for the example graph shown in Figure 80. These experiments are conducted on laptop with 4GB of RAM and Intel CORE i5 processor on 2.5GHz. This execution time is acceptable for proactive caching mechanism. For reactive caching where speed is of great importance we will need to implement some heuristics for the MILP model solving which will speed up the calculations but we will not be able to guarantee that the obtained solution is optimal.

Reactive caching can be achieved with developed MILP model. Reactive caching mechanism will constantly monitor network environment and user request distribution and when changes in system reach some threshold, MILP model will be used to derive new near optimal replica placement in order to address newly introduced changes.

Further improvement of replica placement MILP model will follow. Model needs to take into account more contextual data (user mobility, specifics of wireless mesh environment, better bandwidth utilization…).

3.14.8 Requirements on the C4MS protocol definition & technical challenges

C4MS protocol should be able to support exchange of contextual data between WMN APs and between WMN APs and centralized management (i.e. wireless controller). Contextual data that needs to be captured from the system in order to implement ON that will achieve cognitive caching (proactive and reactive) is:

- User request distribution (spatial and in time);
- User equipment capabilities (storage size, screen resolution, processing power, available bandwidth);

- User viewing patterns (stopping the video stream, for how long, more interested in certain parts of the video);
- User mobility patterns;
- Access point's capabilities (supported caching and streaming of video, ON capability);
- Access point's current status (free space in caching storage, files in caching storage, expected load in particular interval of time, free bandwidth available for video streaming);
- Traffic patterns (statistical data about usage patterns of different links for other network services);
- Power consumption of different network nodes (in order to use power consumption minimization optimization criteria when selecting candidate nodes to store replica of video file);
- Operator and service provider policy exchange (minimal QoS requirements, network utilization requirements, protection of content and user's requirements).

Data that will be sent during and after algorithm execution:

- Streaming schedule needs to be sent to the requesting user;
- Capture data about QoS/QoE envisaged by the end user;
- Gather data about end user behaviour during streaming session (mobility, viewing patterns, device capabilities-speed of battery drain);
- Capture information about network resource utilization during the streaming process;
- Transfer cached data across access points when reactive caching demands it.

4. Conclusions

This deliverable reports the first 6 months of the WP4 activities and presents a first version of the algorithmic solutions for enabling opportunistic networks. In particular, the deliverable has identified the high-level functional model that captures the technical challenges associated to the management of ONs, namely suitability determination, creation, maintenance and termination. The different functionalities are mainly related to the nodes forming the ON, the radio paths to establish the communications in the ON and the assessment of gains to determine when and where the observed conditions advice the formation of an ON. Based on this functional model, the deliverable has presented the different algorithmic solutions to cover the identified management tasks. Each algorithm has been mapped to the use cases and scenarios in deliverable D2.1, and a state-of-the-art associated to each technical solution has been presented, prior to the description of the algorithm, including considerations on implementation. Also performance evaluation plans have been described, including initial performance results when available.

Further WP4 activities will focus on the performance assessment and synergic operation of algorithmic solutions enabling opportunistic networks (deliverable D4.2) and on the comprehensive evaluation of performance of synergic operation of integrated algorithms enabling opportunistic networks (deliverable D4.3).

Particular conclusions on the different proposed algorithms are given hereafter.

- **Discovery of terminals supporting opportunistic networks**

This algorithm focuses on the efficient discovery of candidate nodes for an ON (in particular terminals) in a given geographical area. The goal is to improve existing discovery procedure by providing guidance from the infrastructure, e.g. about other terminals in the vicinity, their location and supported/active frequencies.

- **Spectrum opportunity identification and selection**

Concerning spectrum opportunity identification and selection, this deliverable has presented an algorithm based on the fittingness factor concept to be used in the spectrum selection process based on the available spectrum pools that have been found by the spectrum opportunity identification. Pool formation can respond to different criteria such as grouping spectrum blocks with high correlation formation or even that are fully similar. The fittingness factor is a metric that tries to capture the suitability of spectral resources exhibiting time-varying characteristics to support a set of heterogeneous CR applications in an ON. After defining the different steps of a spectrum selection decision making algorithm based on the fittingness factor concept, an initial evaluation has been carried out considering two different fittingness factor functions in a scenario with unknown interference variations in different pools. First, it has been analysed the capability of the fittingness factor to track interference variations and second the impact of the considered functions over the fulfilment of CR application requirements has been studied. Results have shown that even with a greedy approach, an efficient matching of spectral resources to CR application requirements can be achieved.

- **Machine learning based knowledge acquisition on spectrum usage**

A machine learning base “knowledge acquisition” technique is proposed to provide a high-level, reliable picture of how spectrum will most likely be utilized in the longer term. This will allow a proactive approach to dynamic spectrum assignment i.e. to predict future spectrum demands in given time/location, based on past observations which will allow the opportunistic networks to appropriately use spectrum and further enhance utilization of available spectrum. The algorithm (detailed in D4.2) is expected to also support the logic necessary for forced reallocation of spectrum through monitoring, predicting, decision making and execution phases. The quality of predictions is naturally subject to the choice of learning technique deployed and therefore a number of state-of-the-art learning techniques shall be evaluated. A high level description of requirements and key performance indicators has also been presented.

- **Techniques for aggregation of available spectrum bands/fragments**

A utility-based spectrum aggregation algorithm is proposed and a high level overview of the algorithm is presented. The details will be further elaborated in deliverable D4.2. To accommodate bandwidth requests, the proposed utility function is required to rank available spectrum blocks within the aggregation range of the device. The possible range for spectrum aggregation depends on the device’s H/W capability. The utility function will consider channel throughput, PU activity level, user preference based on locations, and the possibility of creation of new fragments within aggregation region. After calculating ranks for all spectrum blocks, the algorithm will allocate the spectrum block with the highest ranking to a given bandwidth request. First performance results of state-of-art techniques have also been provided and discussed.

- **Knowledge based suitability determination**

A Knowledge based suitability determination algorithm has been presented. The algorithm relies on off-line simulations, which are conducted a priori so as to evaluate candidate solutions against multiple, disparate input parameters and assessment criteria. The algorithm will investigate under which circumstances the creation of the ON is suitable and beneficiary for the overall network. The evaluation will be performed for 3 different cases. The first two are differentiated with respect to the way that terminals are distributed around the WLAN AP (Uniform/Random) and the third one has mobility assumptions.

- **UE to UE Trusted direct path**

Creating optimised data paths between UEs is a main goal of an opportunistic network. The change of data path has to be controlled by a dedicated algorithm in order to maximise the benefits for the network operator, and to keep the required level of security. The studied algorithm is designed for a 3GPP network architecture, and aims to determine the optimal data path for UE to UE direct communication. It aims to determine the physical data path the associated addressing scheme (L3/IP or L2/MAC level) and the security parameters associated. The evaluation will be performed for different use cases with the aim of measuring mainly the signalisation traffic.

- **Selection of nodes and routes**

The proposed algorithms take into account a distributed and a non-distributed approach. Both approaches are responsible for the creation of ONs taking into consideration multiple parameters. The delineation of such algorithm-strategies is the objective of this section. The algorithm of the distributed approach introduces a set of steps which are taken into consideration for the efficient selection of the ON nodes that will constitute the created network. Aligned with this statement, initially, each discovered node is being checked whether it is legitimate according to the policies of the network operator to participate to an ON. If the result is positive, then the evaluation of the discovered, candidate node continues according to a fitness function. The fitness function is based on a weighted, linear formula which takes into consideration energy, availability and delivery probability of the node. On the other hand, the algorithm of the non-distributed approach is based on the Ford-Fulkerson flow control algorithm. Initially, a congestion situation in a BS is identified and then non-congested BSs are found. The set of BSs is sent to the terminals in the congested area and the terminals in the congested area find paths to non-congested (and congested) BSs. This approach will lead to a solution which takes into account the flows that will pass from each terminal of the congested area till they find a non-congested BS.

- **Route pattern selection in ad hoc network**

Concerning route pattern selection in ad hoc network, the algorithm described proposes to enhance the routing protocols to take into account the constraints associated to user applications, by selecting appropriate metrics for each service class and to compute these metrics in order to determine the most adapted route to exchange data. This algorithm is currently under implementation. First results will be presented in the D4.2 deliverable.

- **QoS and Spectrum aware routing techniques**

A hybrid QoS and Spectrum aware routing techniques is proposed to simultaneously address challenges of spectrum availability (for secondary use) and route selection, in ONs. A high level description of requirements and key performance indicators has been presented. The proposed techniques (that will be further detailed in D4.2) will combine QoS assurance capability of QOLSR with a graph-theoretic based approach.

- **Application cognitive multipath routing in wireless network**

Initial idea for the application cognitive multi-path routing algorithm has been presented. Routing algorithm will be developed and tested in wireless mesh network environment. Legacy proactive and on-demand routing protocols will be tested with newly introduced routing metric. This routing metric will be the main part of the proposed routing algorithm. It will address the WMN environment characteristics and it will be able to determine link cost based on profile of the application from which particular packet originated. Multiple paths will be detected and appropriate number will be selected and established. Packet forwarding mechanism will be responsible for sending packets belonging to particular application over appropriate subset of multiple paths. Evaluation will be done on software simulators as well as WMN testbed with open platform APs.

- **Multi-flow routes co-determination**

Concerning Multi path Co-Determination, this deliverable presented protocol elements which combine “classical” ad-hoc routing protocol and network coding optimization in reasoning in terms of independent multi-flows (some of them being potentially established) routes co-determination, instead of single traffic route determination. This protocol offers the capability to catch the information needed in terms of topology and flows in order to decide at the ingress node level the best routes to benefit of network coding capabilities. Adaptation to particular topologies and traffic flows were explored, with the extensions to 1) multi-paths optimization determination, 2) application on the specific case of 2 flows bidirectional flows and 3) the definition of delegated ingress and egress nodes to extend the set of topologies the protocol may be applied. Simulations are currently under development to evaluate the process described on different topologies and flows situations.

- **Techniques for network reconfiguration - topology design**

A technique for Topology Control is proposed to enable coordination in decision making among the ON nodes to generate a network connectivity map with desired global properties. Since the scenarios in OneFIT involve the coverage extension, capacity extension and traffic rerouting, it calls for an effective topology control. An efficient topology control mechanism will provide ONs with reliability and stability (Reduction in rerouting), reduction of energy consumption (Critical Transmission Range assignment), increase in network capacity (Capacity assignment/ optimization) and reduced cost. The proposed technique (detailed in D4.2) is based on multi objective/constraint approach for the design of TC enabling adaptive topology control.

- **Content conditioning and distributed storage virtualization/aggregation for context driven media delivery**

An algorithm for cognitive proactive and reactive multimedia content caching in pervasive wireless mesh network environment is presented in this deliverable. This algorithm considers backhaul storage resource aggregation through means of cognitive caching on WMN APs. Proactive caching algorithm will be based on knowledge statistically derived from gathered contextual data about multimedia content popularity, user request distribution and WMN capabilities. Second part of the cognitive caching algorithm is reactive caching whose task is to monitor changes in system environment and when those changes reach some threshold to initiate re-caching process among

WMN APs. First evaluation on performance and impact of proactive caching on WMN APs is presented. Reactive caching will be developed and tested in WMN environment in software simulators as well as WMN testbed with open platform APs which are capable of content caching. Joint performance of cognitive proactive and reactive caching will also be evaluated.

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