Formulations and identification of algorithmic solutions for enabling opportunistic networks - M4.1

Project Number:	ICT-2009-257385
Project Title:	Opportunistic networks and Cognitive Management Systems for Efficient Application Provision in the Future Internet - OneFIT
Document Type:	Deliverable

Contractual Date of Delivery:	31.05.2011
Actual Date of Delivery:	30.04.2011
Editors:	M.Bourdellès, S.Pega
Participants:	Please see the list of contributors
Workpackage:	WP4
Estimated Person Months:	PM
Nature:	PU[1]
Version:	1st version
Total Number of Pages:	
File:	OneFIT_M4.1_20110430.doc

Abstract

This document contains a detailed description of the algorithms to be implemented to manage the opportunistic networks.

There are defined according to the functional and system architecture (WP2) to fulfil the technical challenges.

These algorithms will implemented during the WP4.2 and validated during the WP4.3

Keywords List

Opportunistic networks, business models, algorithms, system requirements, technical challenges, opportunistic capacity extensions, opportunistic coverage extensions, infrastructure-less networks, traffic aggregation, mobile network operator.

[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 an 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 system architecture. The technical challenges are represented by a functional model and they are declined in functional modules.

The chapter 2 describes each part of this functional model.

The 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 interested. There is also a State of the art dedicated to each proposed solution. For each algorithm a simulation is performed, and a first result is presented and analysed. Finally, it is presented the list of system requirement, which are fulfilled by the algorithm.

The purpose of the chapter 4, is a table to present a synthesis of the cross reference mapping between all the algorithm and the system requirements (WP2).

Revision History

Revision	Date	Author(s)	Description
template	22.12.2010	TCF	template of the D4.1.
Template review	02.02.2011	UPC TCF	Structure review
Pre Draft	03.03.2011	TCF,	Pre Draft - Contribution to section 2, and SOTA on Route Pattern selection in mesh network TCF algorithm description.
v0.4	29.03.2011	M. Mustonen, H. Sarvanko, M. Matinmikko	Section 3.3. updated
V0.5	29.03.2011	ALUD	Section addition on “Algorithm on discovery of terminals”
V0.6	20.04.2011	UPRC	Section 3.1.6 – 3.3.6 “Mapping to CSCI-CMON Functional Entities”
V0.7	28.04.2011	LCI	Sections 3.10 and 3.11 added
V 0.8	29.04.2011	UPC	Section 2 updated Section 3.4 updated
V 0.9	29.04.2011	VTT	Section 3.4.5 updated
V 0.10	29.04.2011	UPRC	Sections 3.1 & 3.3 updated
V0.11	30.04.2011	TCF	Section 3.12 added
V1.00	30.04.2011	TCF	Section 3.5 updated Editorial changes

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Table of Acronyms

Acronym	Meaning
ANDSF	Access Network Discovery and Selection Function
BSCW	Basic Support for Cooperative Work (Tool)
C^4MS	Control Channels for the Cooperation of the Cognitive Management Systems
CCR	Cognitive Control Radio
CMON	Cognitive Management system for the Opportunistic Network
CPC	Cognitive Pilot Channel
CPE	Customer Premises Equipment
CSCI	Cognitive management System for the Coordination of the Infrastructure
E3	End-to-End Efficiency
EC	European Commission
FP7	7^{th} Framework Programme
GA	General Assembly
ON	Opportunistic Network
OneFIT	Opportunistic networks and Cognitive Management Systems for Efficient Application Provision in the Future Internet
QMR	Quarterly Management Report
PC	Project Coordinator
PMT	Project Management Team
RRS	Reconfigurable Radio Systems
TM	Technical Manager
STREP	Specific Targeted Research Projects
WP	Work Package

Table of Contents

List of Figures

List of Tables

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.

This document is the first deliverable of the work package 4.

The objectives of this work package are listed below:

- To conceptualize, formulate, develop and evaluate algorithmic solutions for the CMON and CSCI entities, in order to enable them to accomplish the management tasks suitability determination, creation, maintenance, forced termination handling.
- To synchronize with the C^4MS in order to pose requirements for the interface design, as well as fully exploit the information that is carried.
- To assess, through simulation campaigns and analytical models, the potentials of opportunistic networks and respective cognitive management systems in supporting Future Internet applications.

The D4.1 deliverable will address mainly:

- 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, listed by technical challenges.
- Preliminary implementations of the proposed simulated solutions with respect to identified parts of the scenarios, and performance analysis on potential existing results at the eleventh month of the project.
- First consistency evaluation with C^4MS interface definition expected as result at M9 on the deliverable D3.1.
- Traceability of the algorithms proposed with the requirements defined in the deliverable D2.1, and identification of the requirements potentially not covered.

2. High-level functional model

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 (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. 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.

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.).

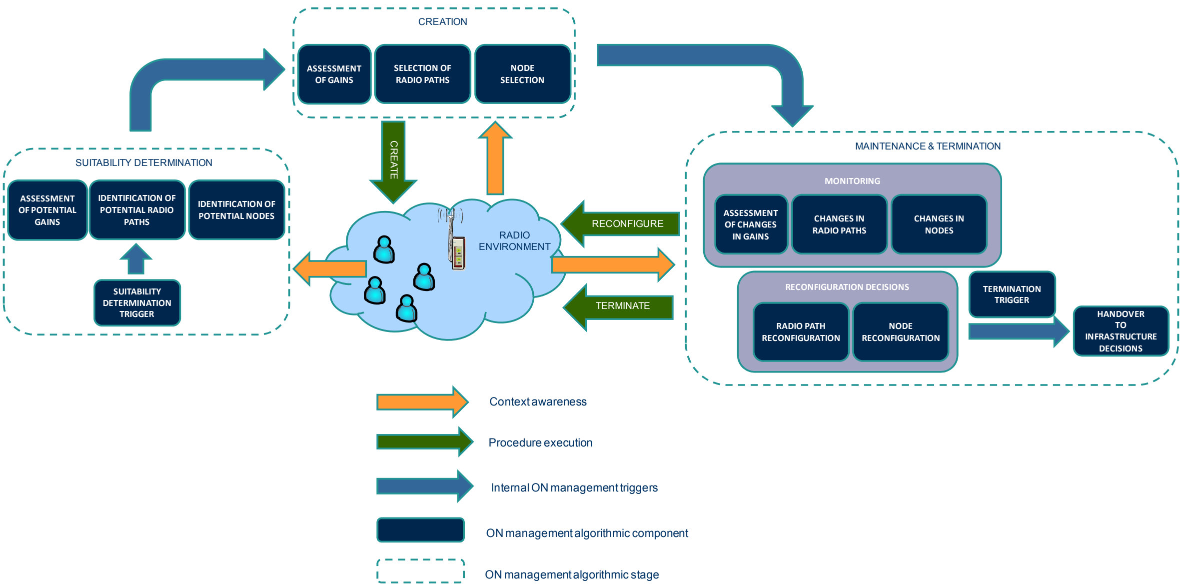


Figure 1: Sequential view of the ON management and decision making process

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.

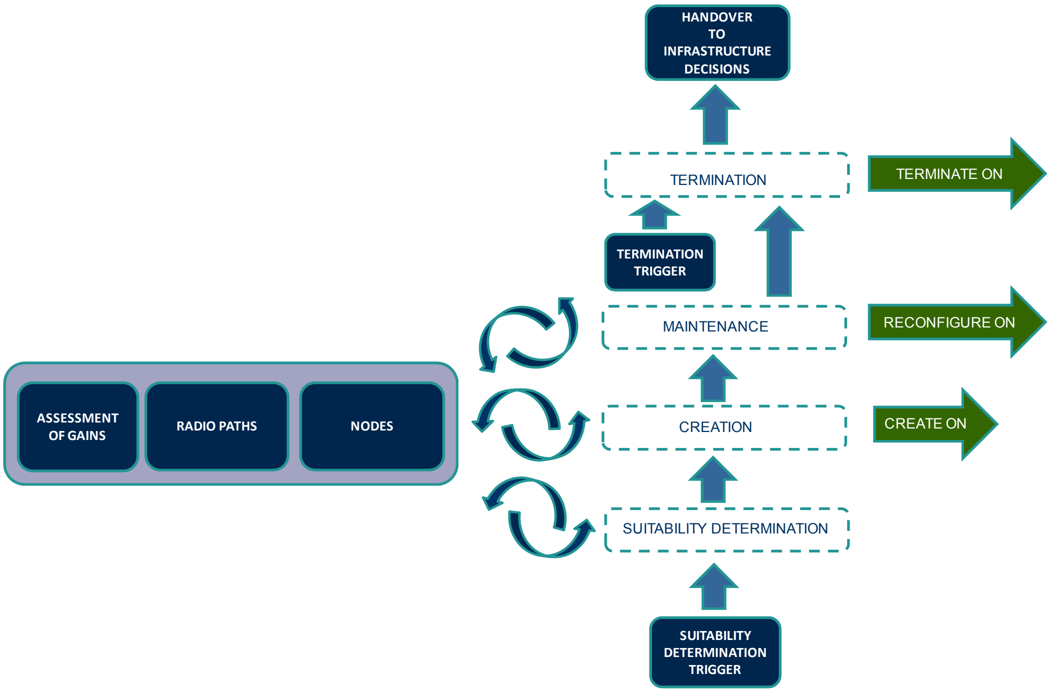


Figure 2: Functionalities along the ON life cycle

3. Algorithms description

3.1 Algorithm on knowledge-based suitability

3.1.1 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.

3.1.2 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, our approach 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.

3.1.3 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.

3.1.4 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 CWN access points and/or terminals and (ii) the ad hoc routing protocol that will be used for routing traffic between CWN and the infrastructure-less segments.

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 [20][21]. The outline of the described algorithm above is given in Figure 3.

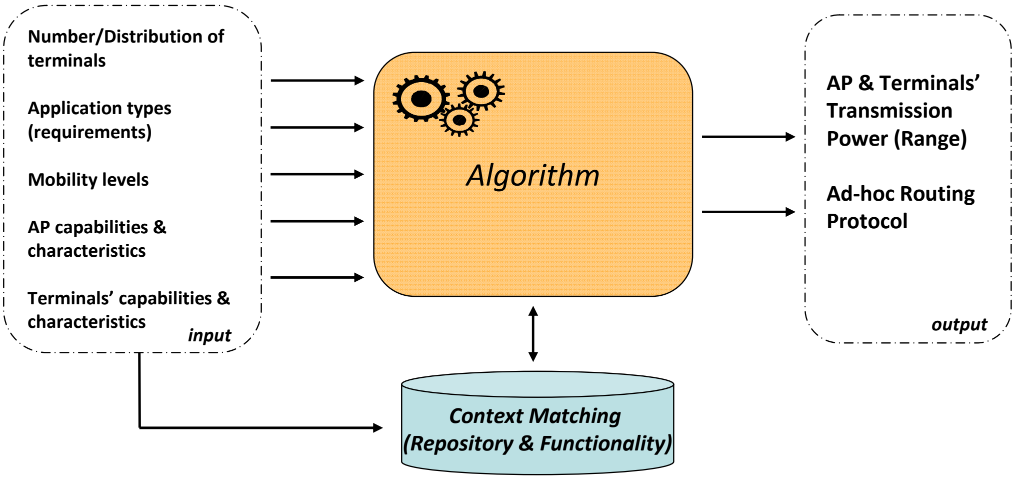


Figure 3. Outline of an algorithm

3.1.5 Mapping to CSCI Functional Entity

Figure 4 depicts the mapping to CSCI functional entity, in terms of parameters used by the Algorithm of Suitability Determination Phase. The CSCI involves the following entities: context awareness, policy derivation and management, profile management, decision making mechanism and knowledge management.

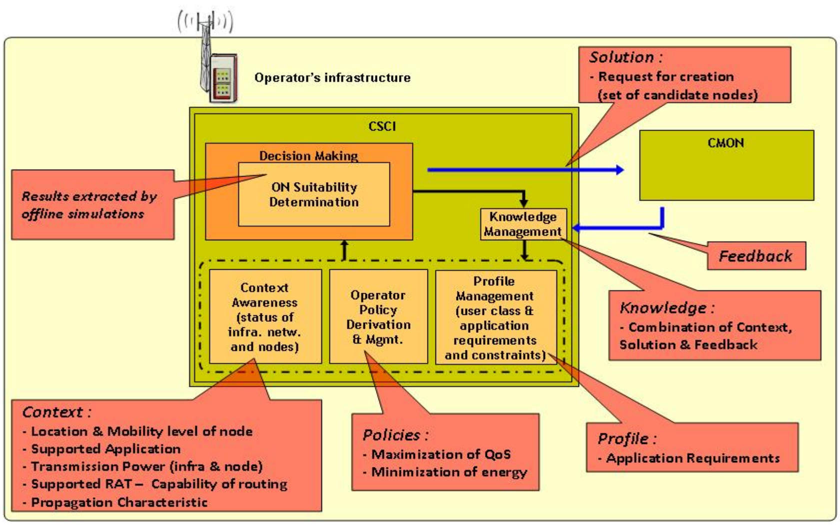


Figure 4 Mapping to CSCI Functional Entity

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.

3.1.6 Algorithm evaluation

3.1.6.1 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 and ran on an Intel Pentium - 4 3,0 GHz with 1,5 GB of RAM.

The topology comprises a single Access Point (AP) operating at IEEE 802.11b 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, thus resulting in a cell with a radius equal to about *250*m. Moreover, terminals are assumed to be static. Table 1 summarizes the general input parametrs of the considered simulation enviroment. Last but not least, a set of applications are considered to be offered to the terminals through the AP and further analyzed in the following.

Table 1. General parameters of the simulation enviroment – Cases 1 & 2

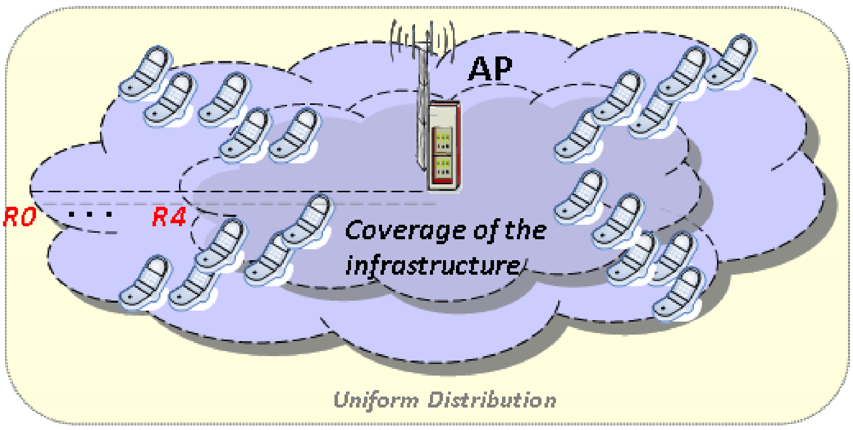
Area	*250 x 250 m*
Simulation Time	*60 min*
Physical Characteristics	*802.11b, Direct Sequence Spread Spectrum (DSSS)*
Physical Layer Data Rate	*11Mbps*
Total Number of Terminals	*20*

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.

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 5 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.*

(a)



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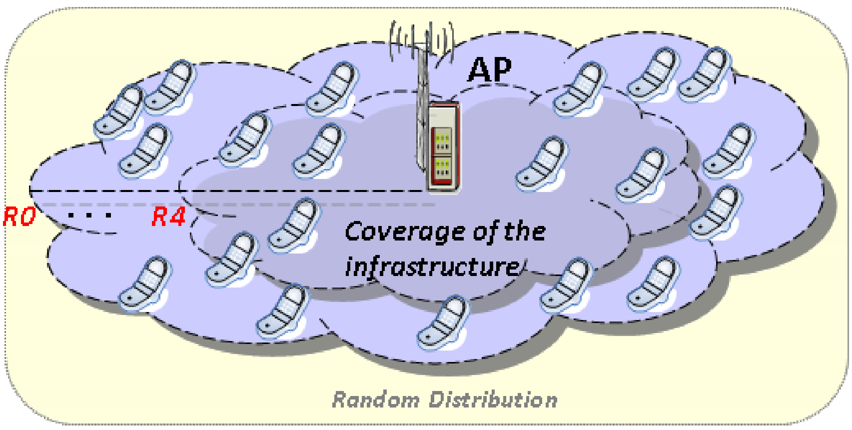


Figure 5. Considered area (a) Case 1 (Uniform Distribution) and (b) Case 2 (Random Distribution)

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 infrastructure-less networks among them in an ad-hoc manner and operating in WLAN 802.11b as well. It should be noted that the issue of interference between the transmitting terminals is not taken into account and is left out for future study. The exact number of nodes connected in ad-hoc mode in each of the phases and for both scenario cases is shown in Table 2. 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. On the contrary, in the random distribution case the number of the ad-hoc connections increases in a rather irregular way, leading for example in situations like the ones observed in Table 2, where the same number of ad-hoc nodes appear in both phases 4 and 5. 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.

Table 2. Number of out of range terminal nodes per phase – Cases 1 & 2

Phases	**Ranges**	**Number of out of range terminal nodes**	
		Uniform Distribution Case	**Random Distribution Case**
1	**R0**	*0*	*0*
2	**R1**	*4*	*3*
3	**R2**	*8*	*7*
4	**R3**	*12*	*11*
5	**R4**	*16*	*11*

3.1.6.2 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, 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 3 summarizes the requirements for specific QoS metrics 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 3. 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%

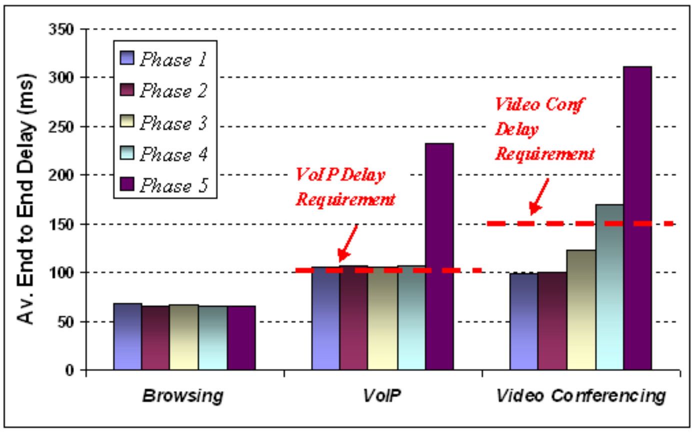
Figure 6 depicts the average end-to-end delay that the packets of each terminal nodes see and which, as already said, is estimated by summing up processing, queuing, MAC, transmission and propagation delays as well. It should be noted here that the end-to-end delay that is measured by the network simulator, 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 corresponding to the extra delay due to the packets traversing the public internet. Therefore, Figure 6 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 2). 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 6 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.

(a)



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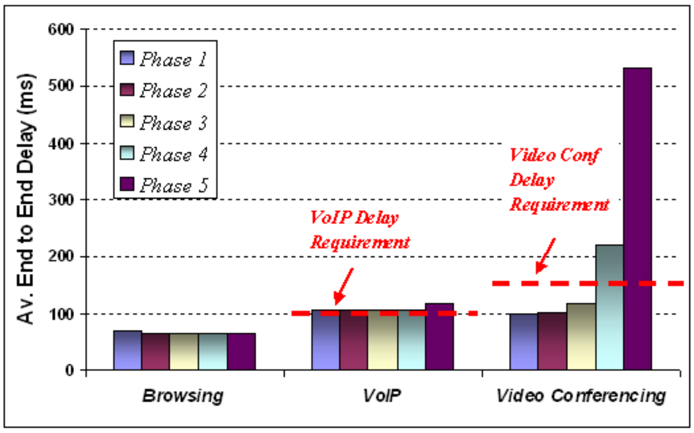

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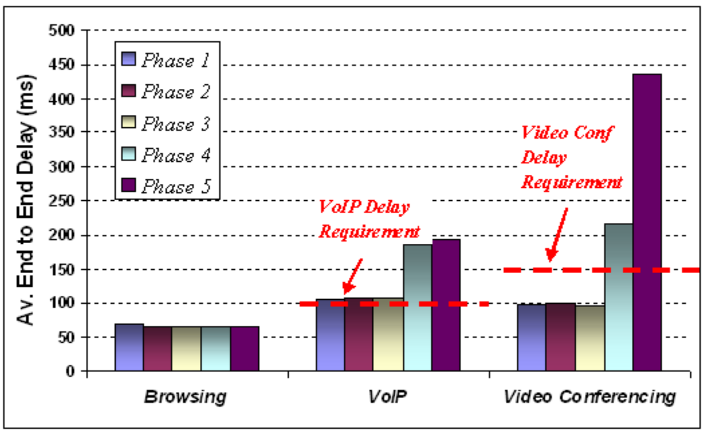


Figure 6. Av. End to End Delay per Node vs Application type for (a) *AODV* (b) *OLSR* (c) GRP *routing protocol – Case 1*

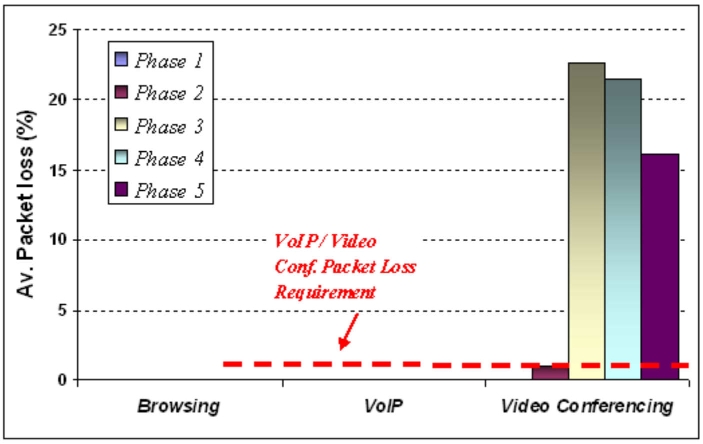
In the sequel, we examine the obtained results against the set of predefined application requirements given in Table 3. By advising the table, it is assumed that the one way acceptable end-to-end delay for VoIP and Video conferencing applications are *100*ms and *150*ms, respectively []. The results are also depicted in Figure 6, 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 7 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 7, 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 3 and also depicted as a dotted line in the same figure.

(a)



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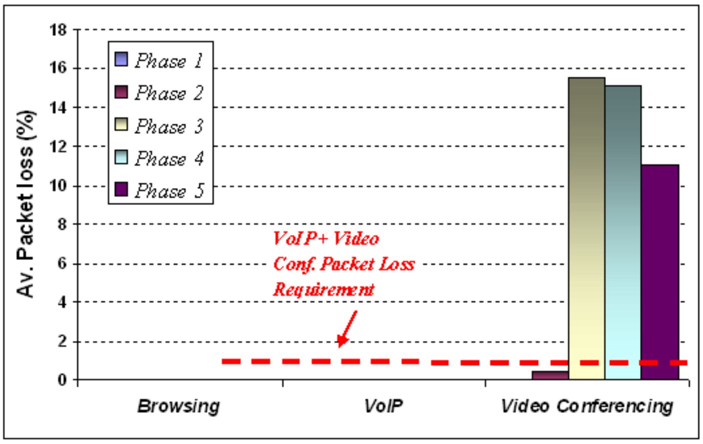

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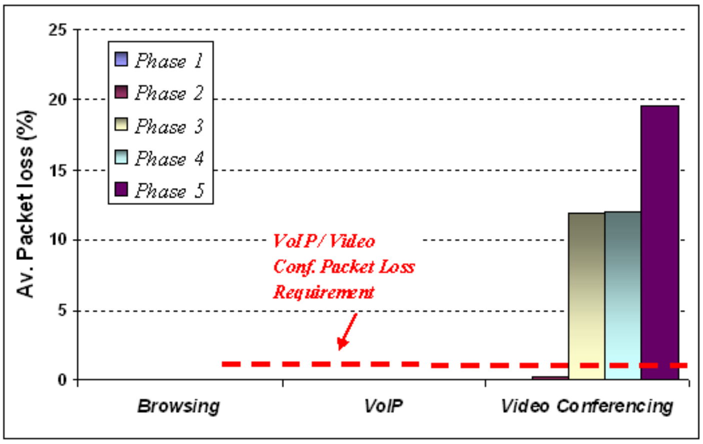


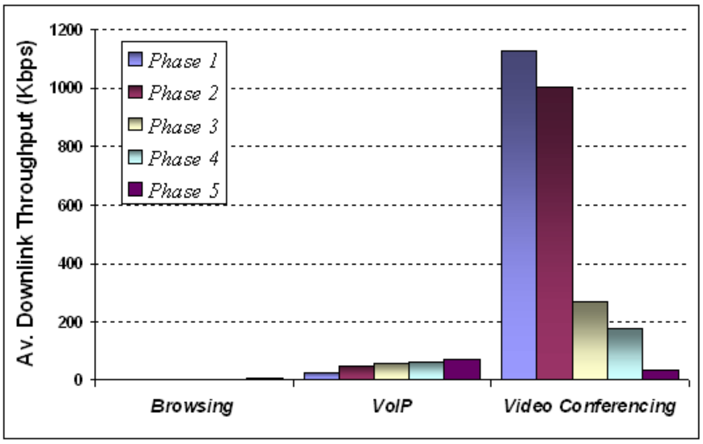
Figure 7. Av. Packet Loss per Node vs Application type for (a) *AODV* (b) *OLSR* (c) GRP *routing rotocol – Case 1*

Last but not least, Figure 8 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.

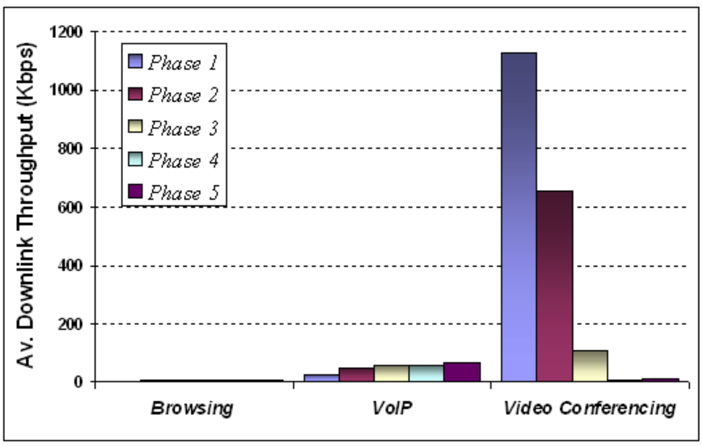
When it comes to video conference application, we observe a significant decrease in the throughput when moving from phase 1 to phase 5. This can be justified if seen in conjunction with the corresponding increase in both the dropped data rate and the end-to-end delay metrics that the application suffers.

Focusing now is placed on results observed from the Figure 8 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.

(a)



(b)



(c)

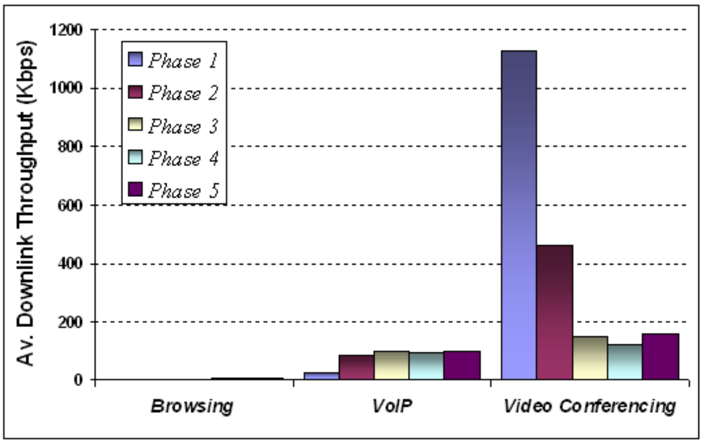


Figure 8. Av. Downlink Throughput per Node vs Application type for (a) *AODV* (b) *OLSR* (c) GRP *routing protocol – Case 1*

3.1.7 Requirements for Global Consistency

3.1.7.1 Requirements on the C^4MS protocol definition & Technical challenges

<u>Input</u>

- location
- 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
- capability of the node for the routing
- QoS levels

<u>Output</u>

- Candidate Nodes

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 [REF802.11] 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 1 (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 9 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.

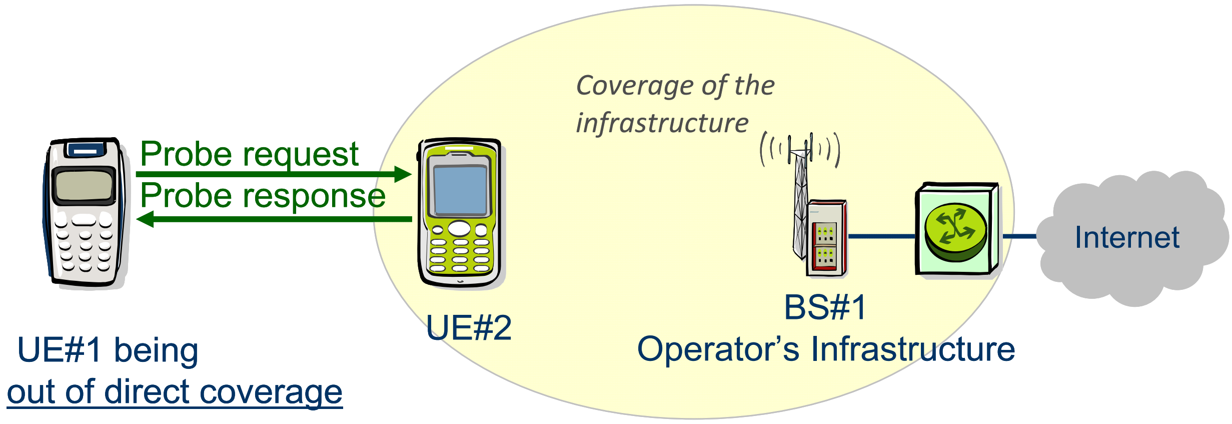


Figure 9: Traditional discovery procedure using probes

Figure 10 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 UE`s report the results back to the infrastructure so that the infrastructure can make further decisions for the creation of an opportunistic network.

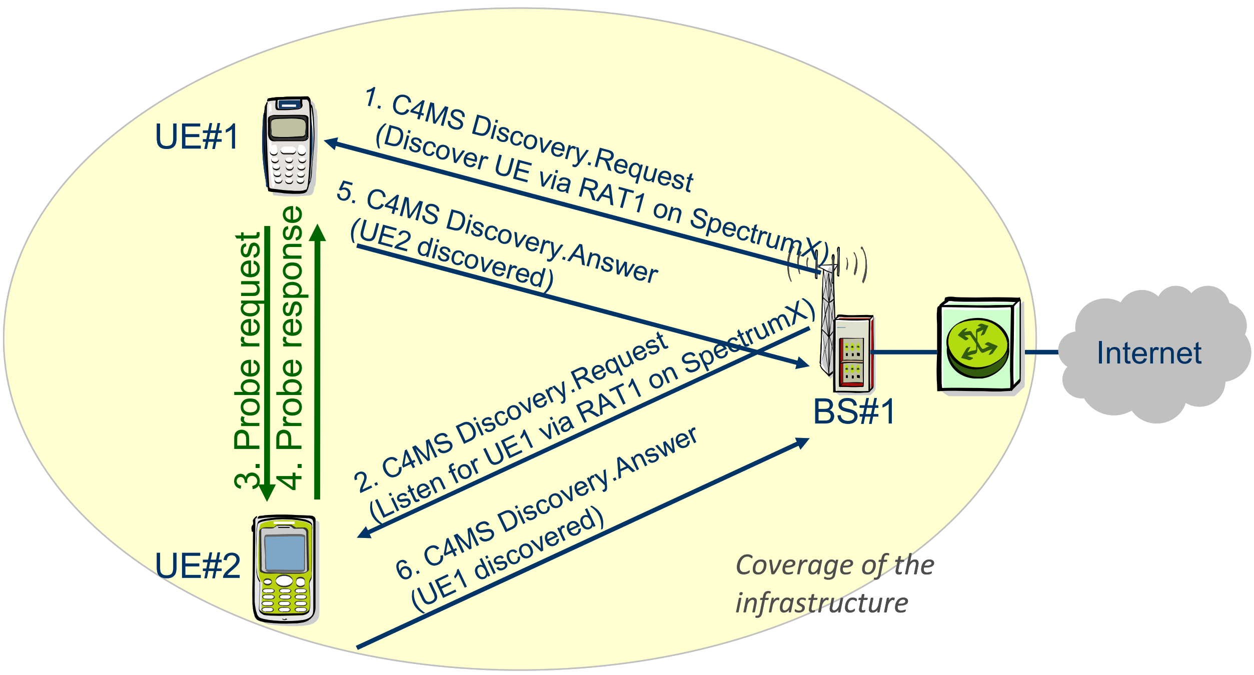


Figure 10: Infrastructure supported discovery

3.2.6 Algorithm evaluation

3.2.6.1 Simulation Environment description

Not available.

3.2.6.2 First performance evaluation

Results are currently not available.

The goal is compare for the different cases explained above on

- How much information is exchanged
- How much time is needed for the discovery procedure.

3.2.7 Requirements for Global Consistency

3.2.7.1 Requirements on the C^4MS protocol definition & Technical challenges

The C4MS shall support the transport of guidance information from the infrastructure to a terminal executing the discovery procedures.

3.2.7.2 Requirements for inter Technical challenges consistency

It shall be possible to extend existing discovery procedures with additional information indicating capabilities related to opportunistic networking.

3.3 Algorithm on selection of nodes and routes

3.3.1 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.

3.3.2 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.

3.3.3 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.

3.3.4 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 [22] while authors in [23] address the relay selection problem in cooperative multicast over wireless mesh networks. Also, in [24], 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 [25], 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 [26], 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 [27], 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.

3.3.5 Algorithm description

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 shown in Relation (1):

$$\text{Fitness Function} = x_i * [(e_i * w_e) + (a_i * w_a) + (d_i * w_d)] \quad \textbf{(1)}$$

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 (2):

$$x_i = \begin{cases} 1, e_i > 0 \cap a_i > 0 \\ 0, e_i = 0 \cup a_i = 0 \end{cases} \quad \textbf{(2)}$$

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 11, illustrates the aforementioned opportunistic node selection algorithmic approach.

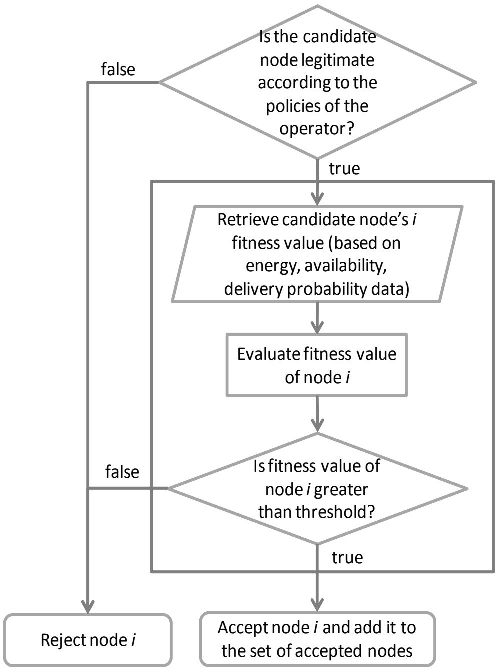


Figure 11: Opportunistic node selection algorithmic approach

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 [28]. The other implemented protocol is the Spray&Wait [29] 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).

3.3.6 Mapping to CMON Functional Entity

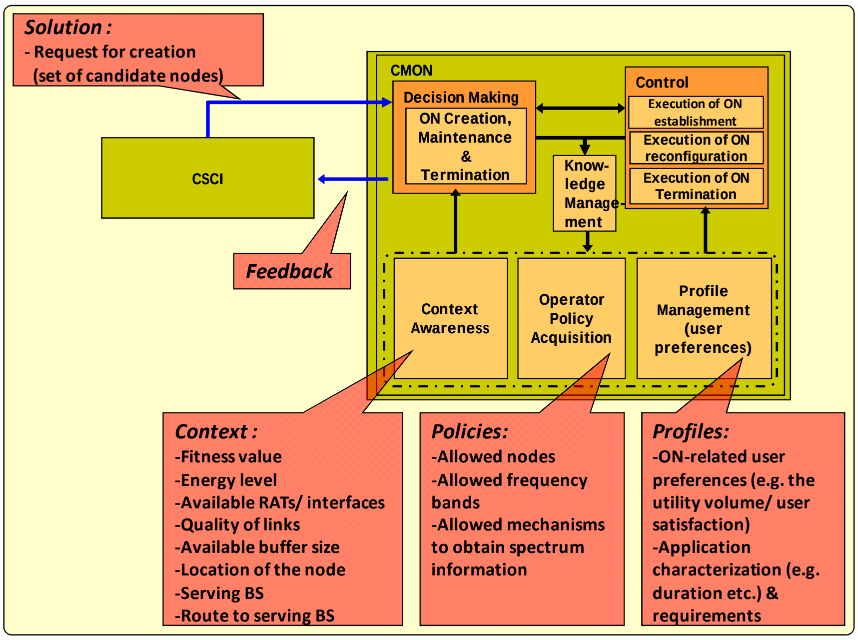


Figure 12: CMON functional blocks

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.

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.

3.3.7 Algorithm evaluation

3.3.7.1 Simulation Environment description

For the evaluation of the proposed approach of the ON creation, the Opportunistic Network Environment (ONE) simulator is being used [30]. 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.

3.3.7.2 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 13 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.

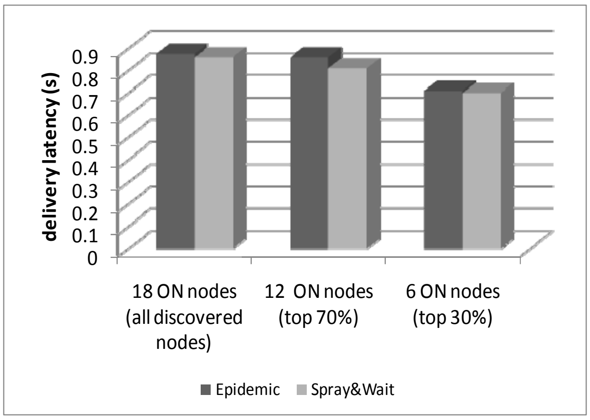


Figure 13: Estimated delivery latency

Also Figure 14 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.

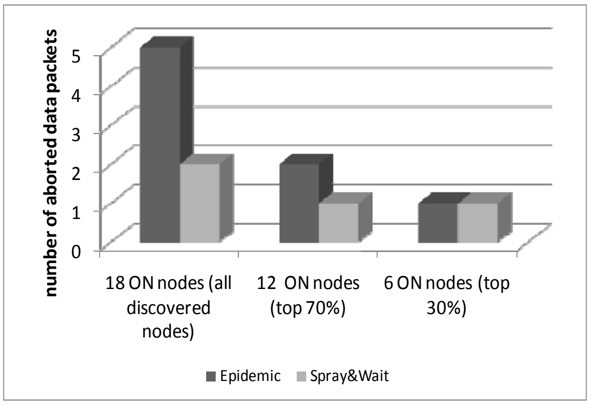


Figure 14: Estimated number of aborted data packets

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 15 shows that an ON with fewer nodes tends to obtain lower levels of lifetime, due to the fact that less 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.

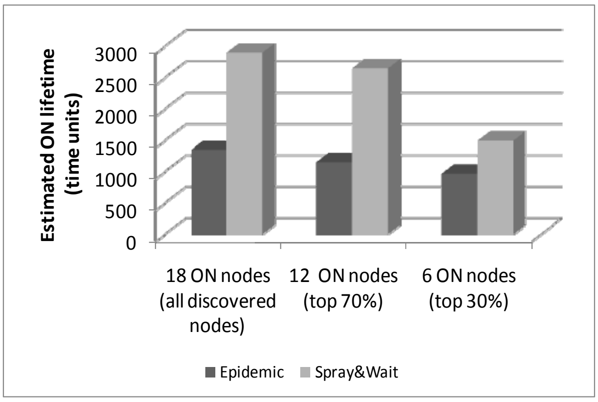


Figure 15: Estimated ON lifetime

This is also depicted in Figure 16 where the overhead ratio of replicated messages circulated in the ON is relatively lower in the Spray&Wait protocol compared to the Epidemic one.

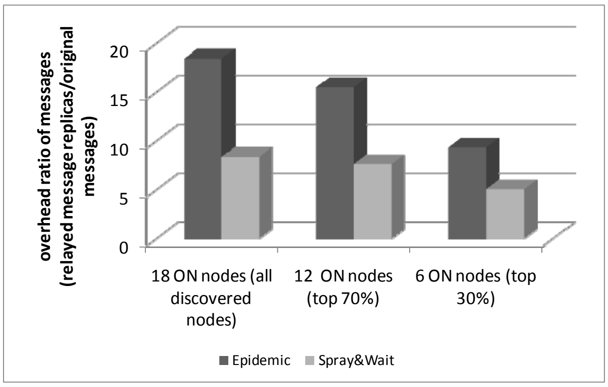


Figure 16: Overhead ratio of replicated messages circulated in the ON

3.3.8 Requirements for Global Consistency

3.3.8.1 Requirements on the C^4MS protocol definition & Technical challenges

Input:

The following requirements are taken into account for the opportunistic node selection:

- Measured energy level of node
- Measured availability level of node
  - Supported RATs
  - Supported frequency bands
  - Support of multiple connections
  - Supported applications
  - Gateway capability
  - Status of active links
  - Location
- Serving BS
- Route to serving BS

Output:

- Selected nodes and routes that will create the ON

3.4 *Spectrum opportunity identification and selection*

3.4.1 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. 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 17 and further elaborated below.

Figure 17. 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 improve 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 3.4.5.1. 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 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. Longer the idle period, 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. Operator 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 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.

3.4.2 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.

3.4.3 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 an opportunistic network.

3.4.4 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 [48] 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 [49][50][51].

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 [52][53][54]. 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 that respect, in [55] 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 [56] 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 [57] 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 [58]. 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 [59] 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 [60], 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 [61], 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, [62] 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 [63]. 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 [64] 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 and would be better exploited. 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 this context, many proposals have characterized primary activity for the sake of optimizing spectrum selection. For instance, the work in [65] 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 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 [66], 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 [67], renewal theory has been applied on past channel observations in order select channels with the longest expected remaining idle period. In [68], 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 enhance the overall performance of CR networks. These works have been extended in [69] 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 [70]. 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, [71][72] have developed an 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 [73]. Spectrum sensing and spectrum selection have also been jointly considered in [74] 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 [75], 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, there 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 [76]-[78]. 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 [79] 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 [80] 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 [81], 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.

3.4.5 Algorithm 1 description

3.4.5.1 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 [85] and it is illustrated in Figure 18. Decision making on the method used to obtain knowledge on the operational environment.

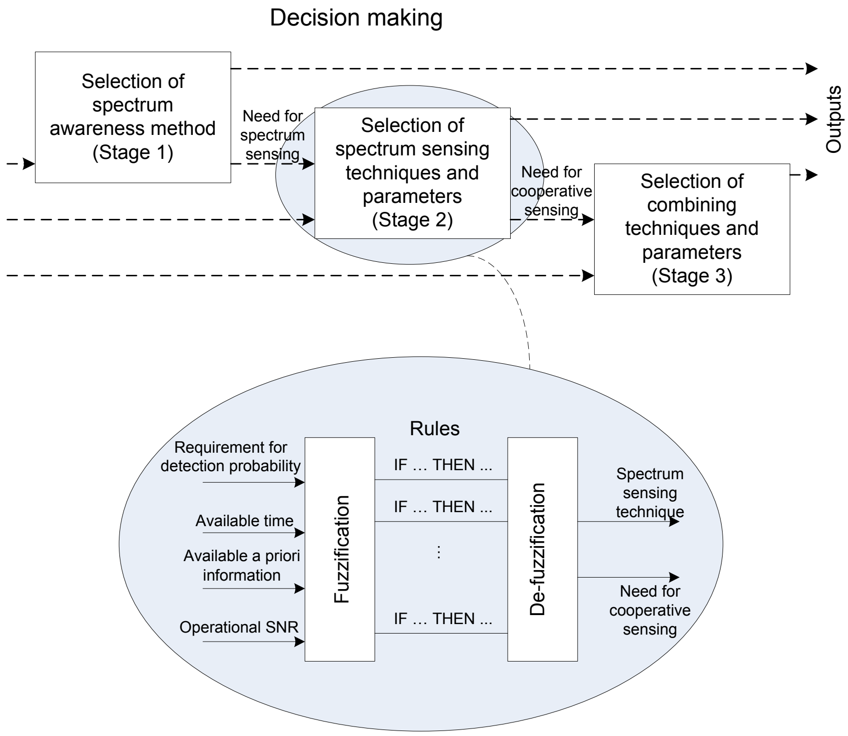


Figure 18. Decision making on the method used to obtain knowledge on the operational environment.

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 [86]. 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 4. Rulebase for fuzzy decision making.Table 4***.

Table 4. Rulebase 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	Waveform based detection
high	high	high	high	Correlation based detection

The development of the rulebase 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 fulfill 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.

3.4.5.2 Mapping to CMON and CSCI functional entities

Nodes:

- Supported RATs
- Supported frequency bands
- Link length
- Transmission power
- Mobility/velocity
- Available time for spectrum sensing
- Available a priory information about waveforms of other users

Frequency:

•Estimated idle time in frequency band

•Channel conditions

•Operational SNR

RAT:

•Maximum supported velocity

•Maximum data rate suppoted by each RAT

Application:

•Minimum allowed bit rate

•Maximum allowed delay

•Estimated session duration

Output parameters:

Selected:

•Bandwidth

•Frequency

•Transmission power

•Selected technique for obtaining spectrum availability information

Policies:

•Allowed frequency bands

•Allowed transmission power

•Requirenments set by the regulator for protecting legacy user (e.g. probability of detection)

3.4.6 Algorithm 2 description

3.4.6.1 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 [56][57].

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 [55] 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 [57]. For instance, the new LTE-Advanced system is meant to support a new non-continuous channel aggregation feature [82], 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 [83] as:

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

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 19, 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.

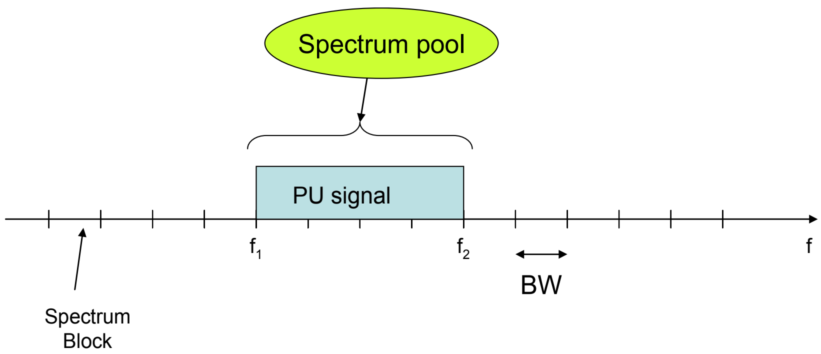


Figure 19: Example: spectrum pool formation to detect unknown bandwidth signals

As a second example to illustrate the pool formation, let consider Figure 20, 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.

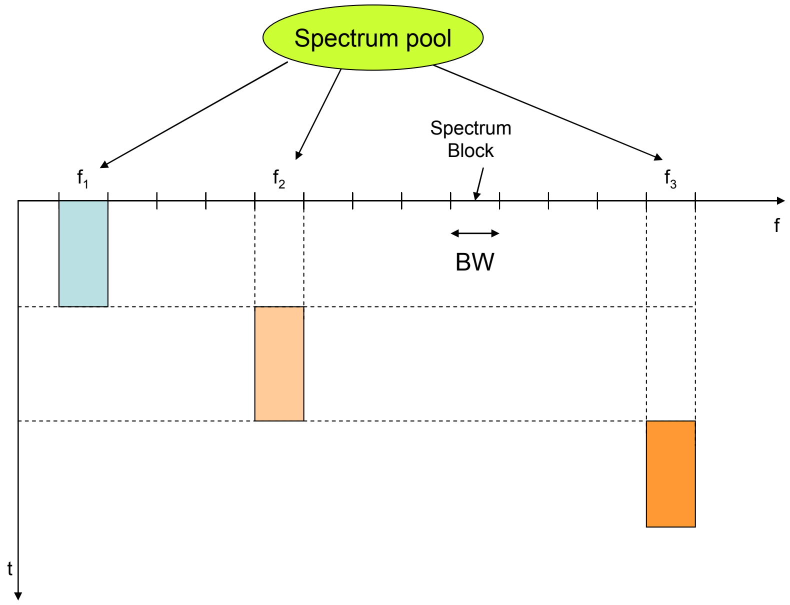


Figure 20: Example: spectrum pool formation with highly correlated signals

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.

3.4.6.2 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 [84]:

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

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:

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

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:

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

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:

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

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:

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

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 $R_{req,l}$.

3.4.6.3 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:

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

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

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

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

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

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

3.4.6.4 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)
    - 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 (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 behavior 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.

3.4.7 Algorithm 2 evaluation

3.4.7.1 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 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 21. 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}=70·10^{-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 3.4.6.4 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 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 ΔT *=0.01s.* All updates/estimations are made using ξ=5, β=0.2, γ=0.2 and *K*=1.

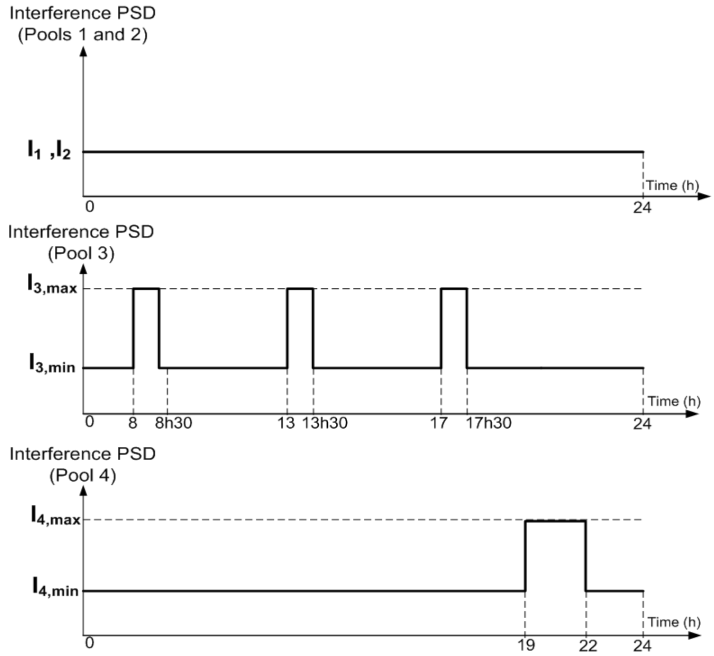


Figure 21: Daily pool interference patterns

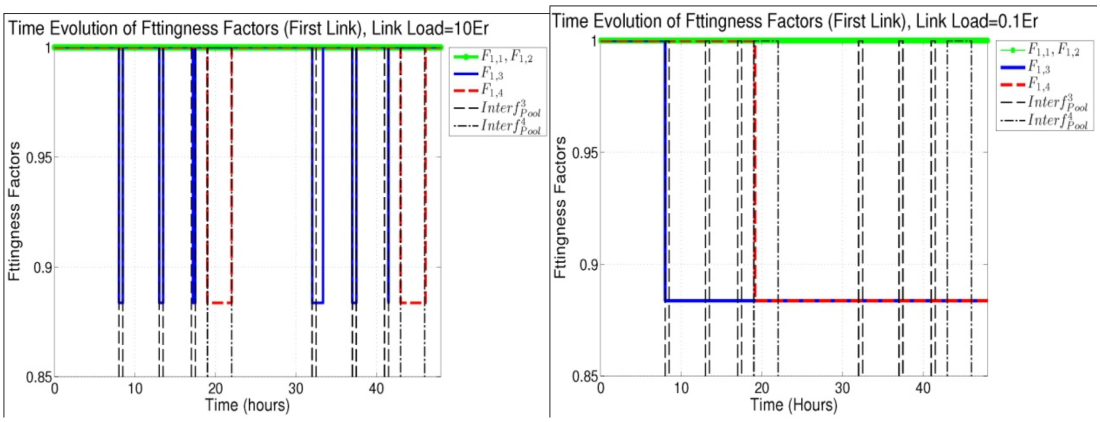
3.4.7.2 First performance evaluation

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 22 and Figure 23 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 22 (a) and Figure 23 (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 23 (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.

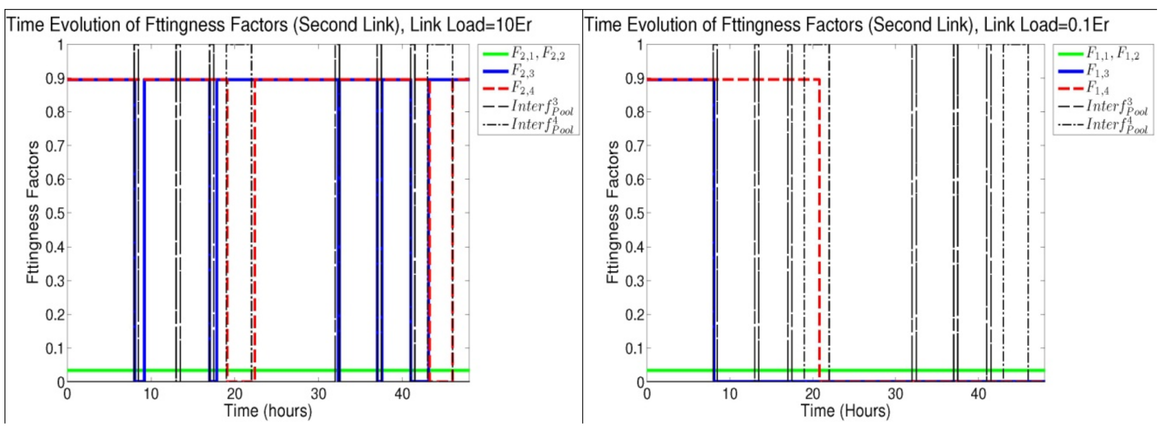
In turn, Figure 22 (b) and Figure 23 (b) illustrate the case of low traffic loads. The main observation is that, once interference level increases for the first time for a given pool, the fittingness factor associated to both links (both CR applications) is reduced and then kept unchanged during the 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 22 (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 22: Time evolution of fittingness factors of the first link (a) High Traffic load ($\lambda_1 T_{req1}$=10Er) (b) Low Traffic load ($\lambda_1 T_{req,1}$=0.1Er)



(a) (b)

Figure 23: Time evolution of fittingness factors for the second link (a) High Traffic load ($\lambda_2 T_{req,2}$=10Er) (b) Low Traffic load ($\lambda_2 T_{req,2}$=0.1Er)

Figure 24 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 (1Er) to 15% for high traffic load (5Er). 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 5 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 $R_{meas}(2,3)>R_{req,2}$.

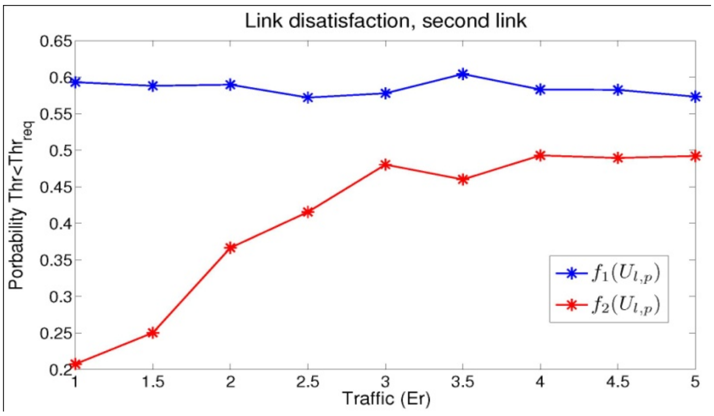


Figure 24: Link dissatisfaction of the second link

Table 5. Pool usage distribution for traffic=1Er

	$f_1(U_{l,p})$				$f_2(U_{l,p})$			
	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

3.4.7.3 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.

3.4.8 Requirements for Global Consistency

3.4.8.1 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 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.
- From Infrastructure to Terminal (through relay Node in case)

- For each spectrum block *k-th* forming the selected spectrum pool
    - Central frequency f_k
    - Bandwidth BW_K
    - 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.

3.5 Route pattern selection in ad hoc network

3.5.1 Technical challenge addressed

The algorithm focuses mainly on the Suitability Determination and Maintenance the technical challenges as they have been analyzed during WP2. The OneFIT network supports ad hoc configuration is operator governed.

3.5.2 Rationale

The plurality of user applications imply 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 [6] and [7]. In an opportunistic network composed of heterogeneous equipments having different characteristics, it is necessary to take into account the specifities 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 speficic metrics.

3.5.3 Use cases mapping

The general objective of scenarios is to rely 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 these scenario is to take in account that the different nodes are heterogeneous, to take in account that nodes are mobiles but not all, some nodes are not mobile.

<u>Scenario 1 Opportunistic coverage extension</u>

The main challenge of this scenario, from routing pattern selection point of is mainly described in the Use Case 4, when several hops are necessary to rely the infrastructure. It 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.

<u>Scenario 2 Opportunistic capacity extension</u>

In this scenario the uses case 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.

3.5.4 State Of The Art

3.5.4.1 Reactive routing protocols:

AODV (Ad hoc On-Demand Distance Vector) [31] 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.

DYMO (Dynamic Manet On Demand Routing) [36] exploits the multiplexing MANET data format defined by the IETF in [37] to be shared by the different reactive or proactive routing protocols.

3.5.4.1.1 Proactive routing protocols:

OLSR (Optimized Link State Routing) [43] 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. An enhanced version of OLSR [44] has been specified, with a more efficient signalling and with simplifications. It uses neighbourhood discovery protocol (NHDP) [42] to exchange Hello messages, and Packet and Message Format composed of type-length-value structure

3.5.4.1.2 QOS adapted routing protocols

Due to new traffic requirements (in particular IP voice communications, streaming, huge files loading) the self organized networks are not *a priori* well fit to manage and assess the underlying quality of service required for these traffic, and still more the multi flow prioritization management.

One of the issues of the MANET QoS management, is the combination of the new route path computation and the QoS metrics reservation & analysis, issue becoming particularly critical in the field of dynamic self adaptation of the network topology.

FQMM (A Flexible Quality of Service Model for Mobile Ad-Hoc Networks) [FQMM, 2000] is one of the pioneer work on the QoS routing of Mobine Ad-hoc NETworks (MANETs). FQMM proposes a flexible QoS model for MANETs. FQMM attempts to combine the QoS of IntServ and DiffServ according to specific MANET features: dynamic topology, hybrid provisioning and adaptive conditioning. This QoS model for MANET proposes to combine the IntServ per-flow granularity and per-class granularity in DiffServ for the allocation provisioning. FQMM addresses small to medium size (50 nodes given as upper bound) flat networks.

SWAN (Stateless Wireless Ad Hoc Networks) [SWAN, 2002], proposes a stateless network model using distributed feedback based control algorithm, in particular explicit congestion notification (ECN) from the additive increase multiplicative decrease (AIMD) [AIMD] rate control mechanism to dynamically regulate admitted real time traffic.

QOLSR [QOLSR, 2004], is a proposal of QoS extension of the OLSR routing protocol to support multiple-metric routing criteria. The QOLSR adapt the multipoint relay selection algorithm according to these new metrics (for example maximum bandwidth and minimum delay).

CEQMM (a complete and efficient quality of service Model for MANETs) [CEQMM, 2006] combines per-flow and per-class provisioning for quality of service. CEQMM applies QOLSR to support multiple –metric routing criteria. The basic idea of CEQMM is that it uses both per-flow state property of IntServ for highest priority flows, and service differentiation of DiffServ for lowest priority flows.

3.5.4.1.3 Stability based routing

The stability based routing protocols are protocol dedicated to Mobile Ad hoc Networks (MANET), they are mainly derived from the family of the "on demand protocols". They are adaptative according to the topology changes. Here are presented the most significative 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 determine the selected route. The principle is to consider that the less stable links are the bottleneck of transmission.

MABR [[41]] **(Multipath Associativity-Based Routing Protocol)**

The MABR protocol 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. And 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 [SSA, 1997] **(Signal Stability-based Adaptive Routing)**

The purpose of the SSA 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 [32] **(Ad-hoc On-demand Stability Vector routing protocol)**

The purpose of the AOSV 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.

3.5.5 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 algorithm also 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 [7], the algorithm considers the 4 following service classes:

- Conversationalclass
- Streaming class
- Interactive class
- Background class

Each one having specific constraints and characteristics.. The end user applications require also a minimum throughput to be satisfied. These information are 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 : the information related to the neighbouhing nodes are provided by the C4MS, and the information dedicated to the local node are mainly provided by the lower layers (e.g.: available RATs).

The purpose of the algorithm is to The both information are provided to the algorithm to allow the determinta, so the importance of each metric differs according to the requested service. The algorithm following the servicesradio link nad the node charar the metrics to consider sh The different metrics used to compute the best route are received from the other nodes through the C4MS protocol and they are provided by the lower layers (e.g.:RATs).

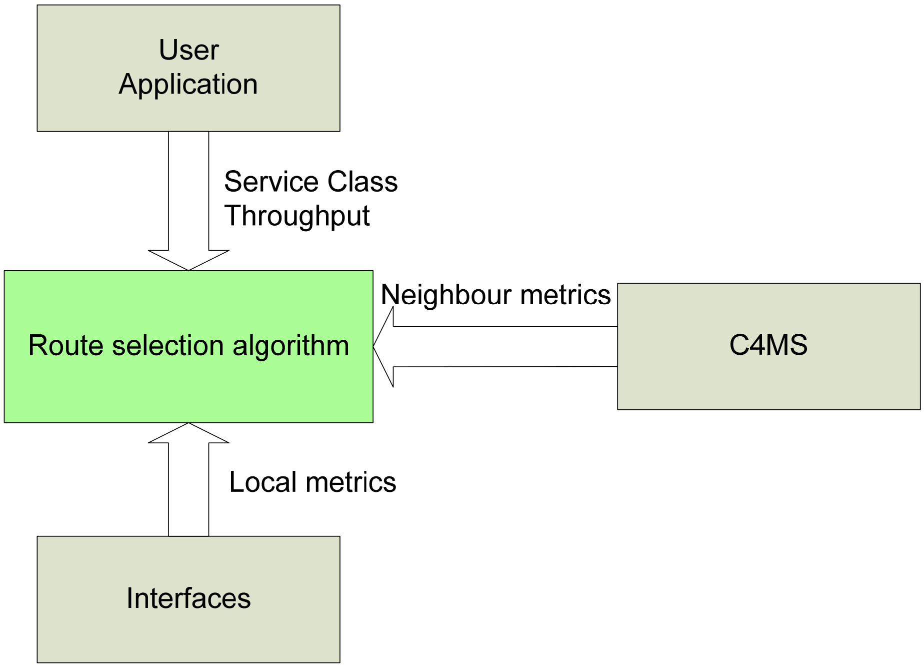


Figure 25 – Inputs for Route selection algorihtm

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 set of metrics is selected according to the requested end user application. The calculation to qualify the each available routes apply also a weight for each considered metric depending of its importance related to the sevice class.

It has to be noticed that some information have to be correlated between them, for example, the mobility constraint is different following the used RAT because the reach ability of RATs are different.

3.5.6 Algorithm evaluation

3.5.6.1 Simulation Environment description

The simulation is performed under OMNET++ environment, using the framework [124]. 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 strcutre of the simulated protocol stack is depicted on the figure below (*Figure 26*)

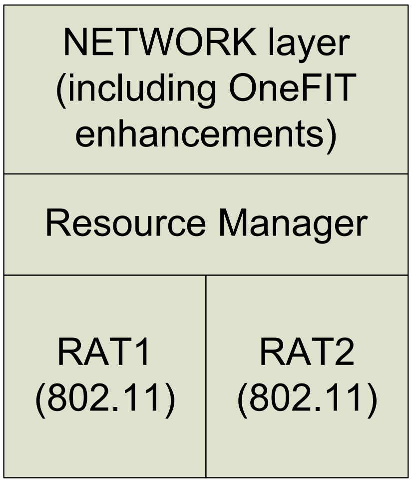


Figure 26 – Simulation Protocol stack overview

The NETWORK layer contains the routing protocol (DYMO) modified to include the OneFIT enhancements, it also emulate the C4MS message echanges. 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.

3.6 QoS and Spectrum – aware Routing Techniques

3.6.1 State Of The Art

3.6.1.1 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 1 is extracted from the work of [68]. We have given a general idea about the most popular and efficient QoS based routing protocols in this section which are QOLSR, CEQMM and AODV.

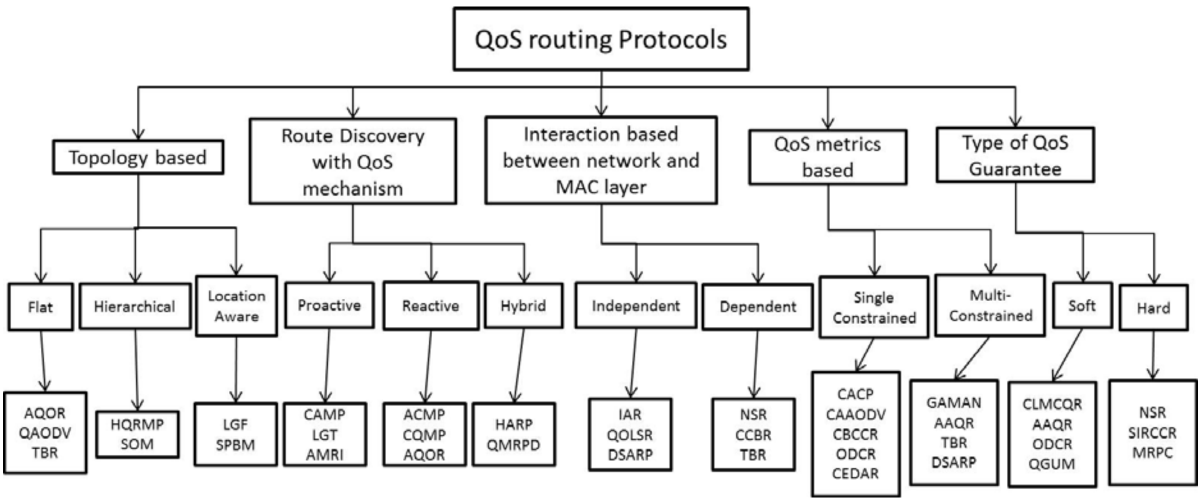


Figure 1: Taxonomy of the QoS routing protocols

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 [69]. 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 [70]. 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 [71]. 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 [72]. 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 [73]. 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) [74] 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.

3.6.1.2 Spectrum-aware routing Protocol

Cognitive radio networks are differentiated from the normal types of multi-channel networks in the sense that the multiple channels are provided to the network equipment opportunistically, meaning that the channels used by them 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 (CCC) for the Secondary Users (SU) to provide a guaranteed signalling channel for management of the SUs. There are many challenges in the routing of such networks consisting of, how to vacate the current spectrum band and move to another available spectrum band in case of interference of SUs with the PUs, periodic route maintenance and repair, unpredictable route failure, sudden appearance of a PU in an area occupied by and SU, etc. All these problems and many others that are not mentioned should be addressed by the spectrum aware routing that will be designed for this type of Opportunistic Cognitive Mobile Adhoc Networks (MANETs).

The tree shown in the Figure 2 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.

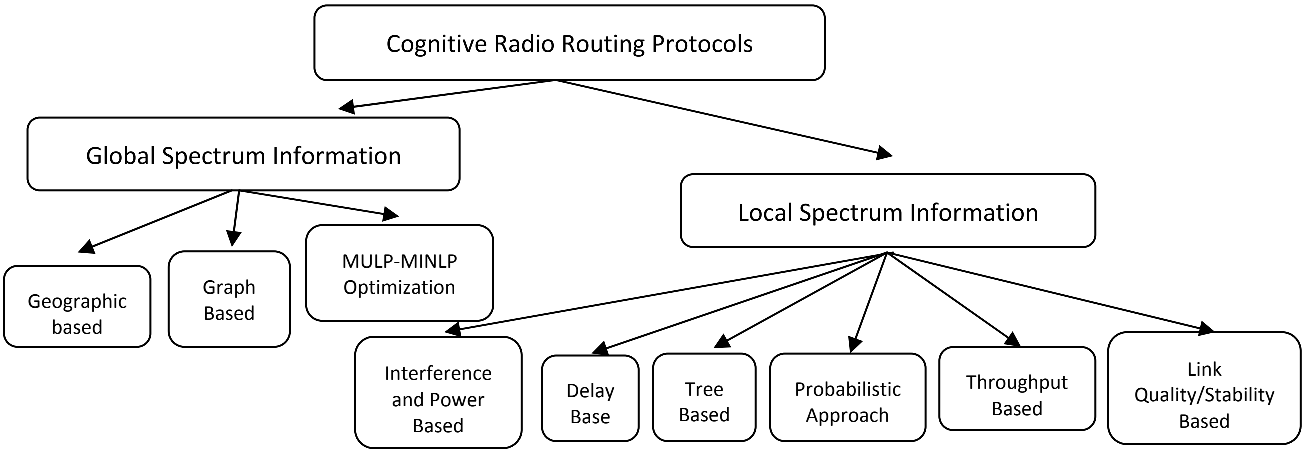


Figure 2: Different methods to address spectrum aware routing

3.6.1.2.1 Global Spectrum Information

Geographic based routing

These types of routing protocols require the geographic location of the SUs to be able of predicting their future movement. By having the geographic location of a user, the routing decisions can be much more accurate and efficient.

Greedy Perimeter Stateless Routing (GPSR) [75], 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) 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 [76]. SEARCH 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 in Spectrum Awareness is a method proposed by [77] 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 [78] (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 [79], [80], the focus is on designing an 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 [81], 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.

3.6.1.2.2 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 such category of routing protocols.

Minimum Power Routing

The work of the [82] 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 [83] 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 [84] to [85], which consider different delay components including:

a) The *Switching Delay* that occurs when a node in a path switches from one frequency band to another;
b) The *Medium Access Delay* based on the MAC access schemes used in a given frequency band;
c) 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, the author in [86] propose an efficient and practical protocol, 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 in [87] 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 [88]. 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 $W1, \ldots, WM$ (in Hz).

Throughput-based Routing Protocols

Throughput maximization is the main objective of the routing protocols described here.

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) [89], 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 [90]. 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.

3.6.2 Requirements for Global Consistency

3.6.2.1 Requirements on the C^4MS protocol definition & Technical challenges

To provide a global consistency to the routing protocol that will be implemented according to our algorithm, there are parameters that the signalling protocol (C4MS) from the network should be capable of providing them. The number of parameter depends on the exact 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 sensing related parameters.
- And many more other parameters that the need for them will be figured during the algorithm defining phase.

3.7 Machine Learning based Knowledge Acquisition on Spectrum Usage

3.7.1 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.

3.7.2 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 [93][GA, 2008], 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 [94][island, 2008].

Reinforcement Learning

In [95][DCS_RL, 2009], 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 [96][CRAHs, 2010]. In [97][E3_RL, 2009], 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.

3.7.3 Algorithm description

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 (e.g. 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 dist. (not idd)). In order to meet the required QoS for ON nodes, the algorithm will consider the each channel condition such as channel PER, noise level and bit-rate and the interference effect on primary users. In addition to generate opportunities, the algorithm will use the spectrum reallocation scheme. It is to release portions that could then be temporarily assigned for the formation of the opportunistic network or improve on QoS of ongoing services. Whilst the spectrum is being vacated, spectrum mobility/vertical HO procedures will ensure minimal impact to QoS by keeping the interference & signaling overheads as a minimum. 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.

3.7.4 Requirements for Global Consistency

3.7.4.1 Requirements on the C^{4}MS protocol definition & Technical challenges

When the message of Spectrum_Assignment.Request (SAR) is sent via C^{4}MS, 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.

3.8 Techniques for Aggregation of Available Spectrum Bands/Fragments

3.8.1 Rationale

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

3.8.2 Use cases mapping

3.8.3 State Of The Art

3.8.3.1 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. [98][LTE-A, 2010]

IEEE 802.16m

In 802.16m standard version, “multicarrier 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. [99] [16m, 2010]

IEEE 802.22

In 802.22, two types of aggregation of adjacent channels, channel aggation and channel bonding was considered and It is concluded that channel bonding was perceived as a better solution at least in the contiguous case [100][Bonding, 2006]

3.8.3.2 PHY/MAC independent solution

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. [101] [MSALCS, 2010]

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. [101][MSALCS, 2010]

3.8.4 Algorithm description

The algorithm has the admission/allocation strategies and aggregation techniques, resulting in increased spectrum utilization based on MSA. In order to satisfy QoS of user request, the channel quality is considered whilst the levels of potential interference that may result from the opportunistic network is evaluated. In addition, the predictive-based aggregation scheme based on LCS will be adopted (admission strategies) to decrease overhead associated with re-allocation.

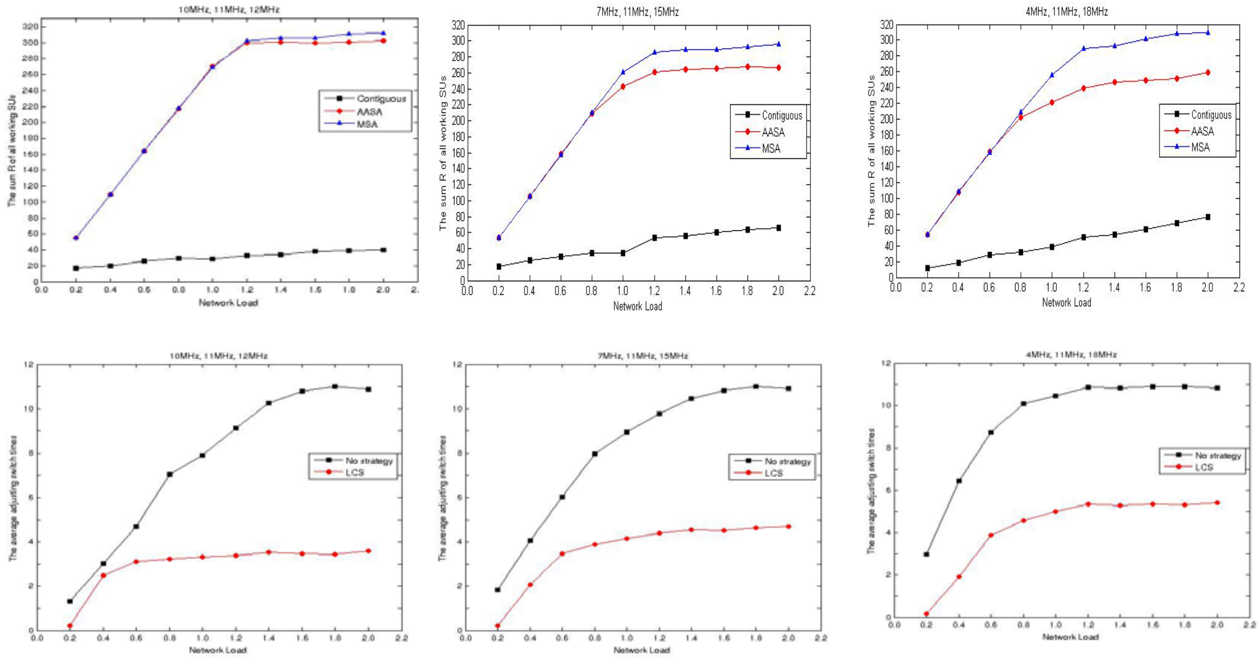
3.8.5 Algorithm evaluation

3.8.5.1 Simulation Environment description

The Initial simulation of the model developed is carried out using Matlab without reference to any specific system. In addition, the user mobility is not considered.

3.8.5.2 First performance evaluation

Initial results indicate superiority of MSA over other techniques in terms of satisfaction of user requested bandwidth and of LCS in terms of minimization of channel switching as compared to no strategy.



For performance evaluation of initial algorithm, the assumptions are following. The considering total width of spectrum is set to 600MHz and the spectrum aggregation range is 40MHz. The bandwidth requirements of users are randomly chosen from the predefined sets. 100 simulation scenarios with fixed random spectrum availability are used for achieving average performance.

3.8.6 Requirements for Global Consistency

3.8.6.1 Requirements on the C^{4}MS protocol definition & Technical challenges

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

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

3.9.1 Technical challenge addressed

Algorithm that is described in this section will address 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 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.

3.9.2 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. 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).

3.9.3 Use cases mapping

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

3.9.4 State Of The Art

For purpose of quality and efficient media delivery various approaches are used. The best known are content delivery networks (CDN) 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 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.

Cognitive proactive and reactive caching techniques are proposed in many research works and publications

Caching of content in networking equipment (routers, proxy servers, access points…) will provide better network resource utilization (most of all power consumption) 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 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 the multimedia content on them it 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.

3.9.5 Algorithm description

Algorithm that will be developed and evaluated during the WP4 course will provide framework for ON suitability determination, creation and maintenance 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 that all APs be able to cache certain amount of media data.

Proactive caching will provide initial placement of video files over access points. 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);
- 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…);
- Spatial and time distribution of user requests;
- Status of backhaul nodes (available storage in APs, popularity of currently cached data, available bandwidth for streaming…);
- Backhaul traffic patterns.

By processing above mentioned data, proactive caching mechanism will place certain number of copies of video file (video file's chunks) into the storage space of WMN APs.

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).

For every user request ON will be created among WMN APs which will provide aggregation of storage resources in order to locally stream as much chunks of video file as possible. ON will provide support for reactive caching mechanism.

3.9.5.1 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).

3.9.5.2 Creation

When candidate nodes are derived, creation phase has to choose among candidate nodes those that are most appropriate for addressing user request for the particular video file. 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.

3.9.5.3 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 are bigger than 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 origin server.

For all these phases appropriate algorithms, proposed by other partners, could be used and therefore tested in more pervasive environment with other ON compatible algorithms.

3.9.6 Algorithm evaluation

3.9.6.1 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 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 18. 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 neighboring 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 18Wats and additional 5Wats (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.

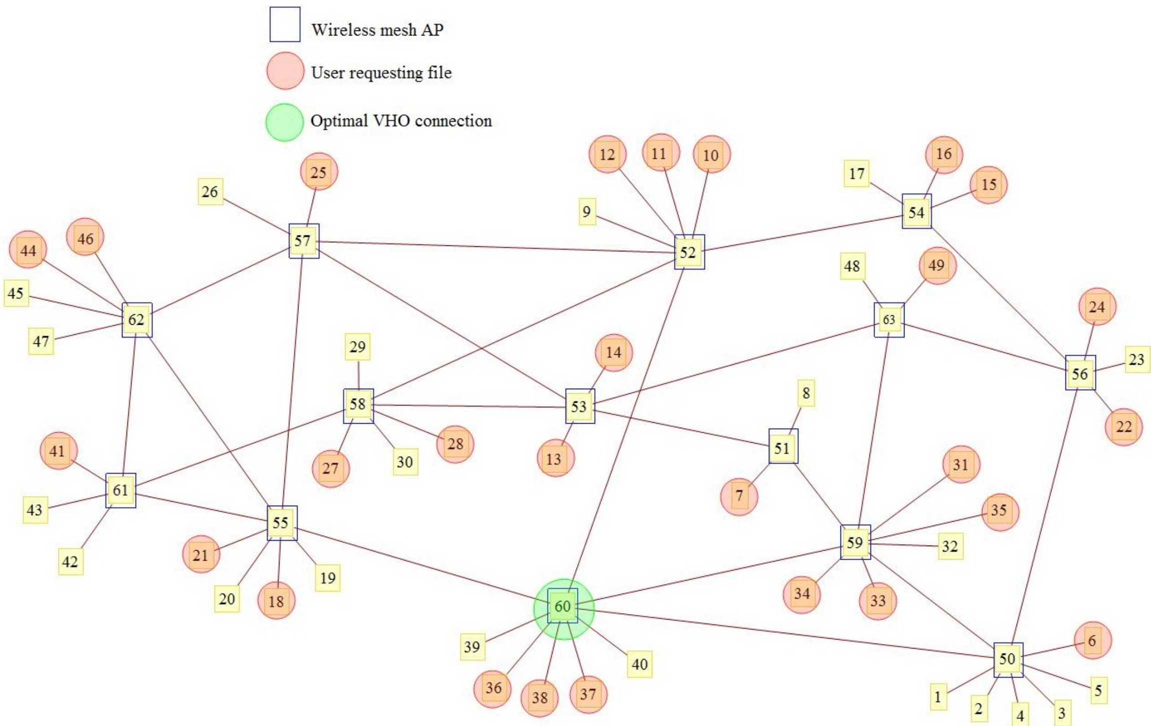


Figure 27 - Topology of wireless mesh network used for the experiment

3.9.6.2 First performance evaluation

Experimental results, for example network graph depicted in figure 18, show that 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 tradeoff is shown in figure 19. 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.

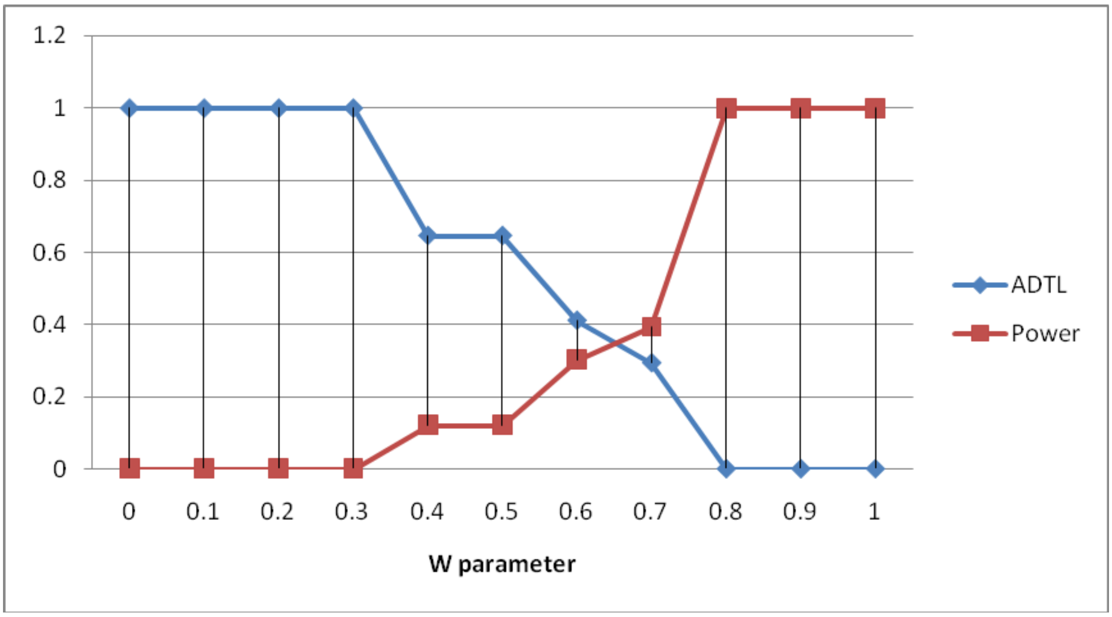


Figure 28 – Average delivery tree length and power consumption are two opposed optimisation criteria

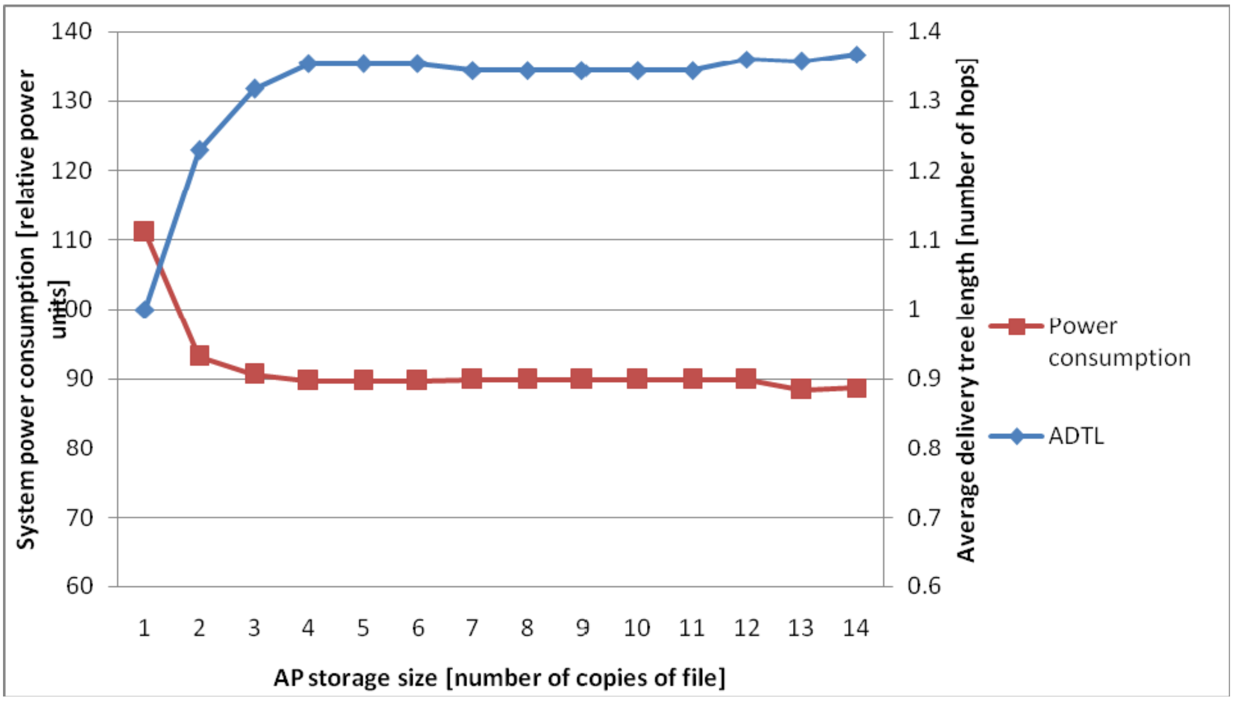


Figure 29 - Impact of the increasing storage capacity of the APs in terms of ADTL and consumed power metrics

In figure 20 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 5 sec for example graph showed in figure 18. 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…).

3.9.7 Requirements for Global Consistency

3.9.7.1 Requirements on the C^{4}MS 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 users 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 behavior 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.

3.9.7.2 Requirements for inter Technical challenges consistency

3.10 Application cognitive multipath routing in wireless mesh networks

3.10.1 Technical challenge addressed

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

3.10.2 Rationale

OneFIT scenario 5 proposes backhaul bandwidth aggregation as one of its use cases. To achieve bandwidth aggregation proper multipath routing algorithms 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 multipath 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 application that is used and QoS that this application requires.

3.10.3 Use cases mapping

Proposed multipath routing algorithm is being developed for the purpose of backhaul bandwidth aggregation use case 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 that require multipath routing.

3.10.4 State Of The Art

Specific nature of 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 [104].

Selection of routing protocol is also very important. Different routing protocols have different signaling 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 [104]. Reactive routing protocols discover paths on demand (when needed) and therefore impose less signaling 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 signaling 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) [104].

Multipath routing algorithms for WMNs are heavily studied in [105]. Appropriate routing metrics for WMNs are proposed as well as multiple paths selection algorithm. Previous work concentrated on selection of previously determined number of routing paths for multipath routing which could lead to aggregated throughput degradation as described in [105]. Reactive route management procedure that heavily uses DSR (Dynamic Source Routing) is used in [105]. Routing metric AAC (Average Available Capacity) is proposed in [105]. This value is obtained from a set of paths by combining their long term availability with their achievable capacity. Further improvement of the multipath routing over wireless mesh network is achieved with network coding and algorithm for gateway selection [105].

3.10.5 Algorithm description

Multipath algorithm that will be developed for the purpose of the OneFIT scenario 5 use cases will include 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 destination will be sorted and appropriate set will be selected for packet forwarding. When some links in wireless mesh backhaul become unavailable or experience high congestion ON creation is triggered in order to solve presented problem by means of load sharing between other paths in wireless mesh network. Alternate paths will be discovered and established by multipath routing algorithm incorporating special metrics. Packet forwarding mechanism will be directed to send all packets from one group of application (i.e. delay and/or jitter sensitive application) over one alternative path and other packets over other paths. This classification of traffic based on applications from which it originated, allows cognitive multipath routing to be used.

In figure 21 are depicted building blocks of application cognitive multipath 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 multipath routing algorithm will use different routing protocols for these purposes depending on 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 best performances and resource utilization. Selected paths will be used by the packet distribution mechanism which selects appropriate paths for different packets based on path cost and profile of the application that generated 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 minimize jitter in packet transmissions.

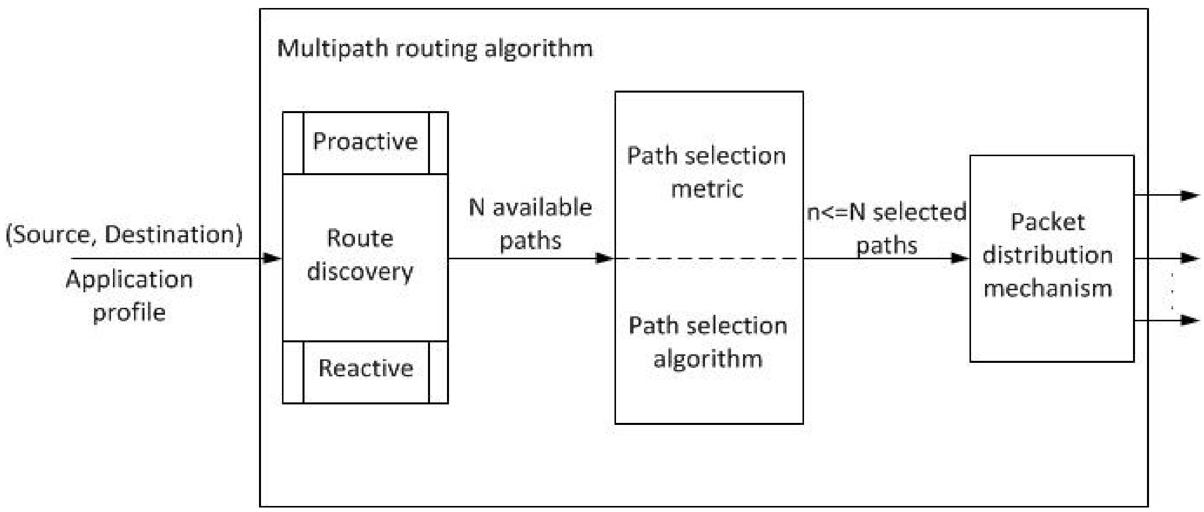


Figure 30 – Multipath routing engine

3.10.6 Algorithm evaluation

3.10.6.1 Simulation Environment description

Application cognitive multipath 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.

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.

3.10.7 Requirements for Global Consistency

3.10.7.1 Requirements on the C^{4}MS protocol definition & Technical challenges

For enabling and supporting application cognitive multipath 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 multipath 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…).

3.10.7.2 Requirements for inter Technical challenges consistency

3.11 Multi-flow routes co-determination

3.11.1 Technical challenge addressed

In the general case of opportunistic networks, and more particularly on the scenario description described in [1], these scenarios integrate (even if most of the networks description are operator governed) self-organizing network 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 have been proposed in to optimize routing protocols for the specific mobile networks, proactive OLSR, OLSRv2 [2], [3], reactive AODV, DYMO [4], [5]. FEQMM [6], SWAN [7], QOLSR [8] and CEQMM [9] 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 [8], combining both per-flow state property of IntServ for highest priority flows, and service differentiation of DiffServ for lowest priority flows [6], [9], or applying an explicit congestion notification from a rate control mechanism to dynamically regulate admitted real time traffic[7].

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 these 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 path, benefiting by the information transmitted on other paths for these flows.

3.11.2 Rationale

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

3.11.3 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 and
- Scenario 3 : Infrastructure supported opportunistic ad-hoc networking.

3.11.4 State Of The Art

The concept of *network coding* was first introduced for satellite communication networks in Yeung and Zhang [11] and then fully developed in Ahlswede et al. [12].

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 ingress 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 *31* 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) .

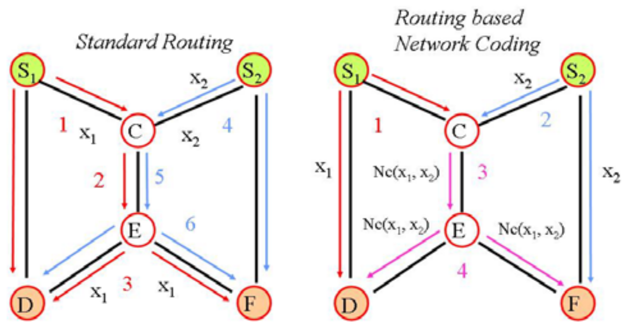


Figure 31: Network coding principle from the butterfly topology

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 [coperef], with n as number of relay nodes. The examples provided present network 2 inter-flows coding optimizations. The principles presented in this paper may be extended to n-flows optimization, with *Nc()* defined as a linear combination of n flows.

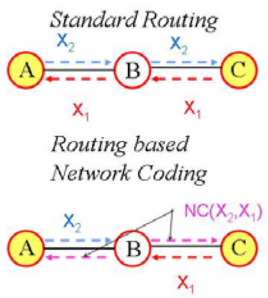


Figure 32: Network coding principle from the 2 sides flows relay topology

3.11.5 Algorithm description

3.11.5.1 Rationale on a concrete example

The following figure 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 egress S1 to the ingress 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 egress S2 to the same ingress nodes D and F.

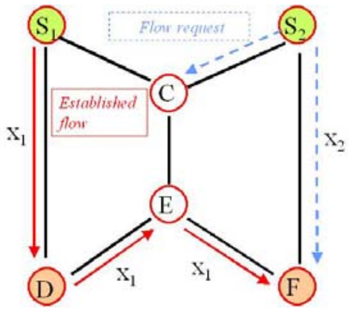


Figure 33: Routing path application example

The figure 5 describes a potential routing path definition using a "classical" routing algorithm (called Routing X) which allows to optimize 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 6, 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 ingress nodes D and F. These modifications are illustrated on figure 6.

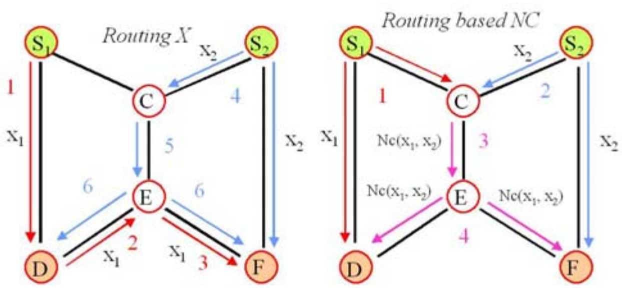


Figure 34: Comparison between a classical routing and a routing based NC

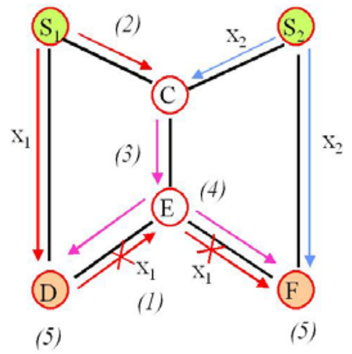


Figure 35: Modifications to be applied to go from Routing X to Routing based NC

The issue to solve remains to collect at a node the information needed to define a decision of network coding. These information are in one hand a 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 6 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.

3.11.5.2 Protocol steps description

In order to illustrate the protocol steps, we will take the classical routing flows situation described in figure 5 as starting situation the algorithm will be applied.

Flooding of traffic route information over the network

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

This first step can be done on a bounded distance Dijkstra algorithm [13]. The selection of short paths to the egress 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 36*, on a 3 hop bounded flooding exploration.

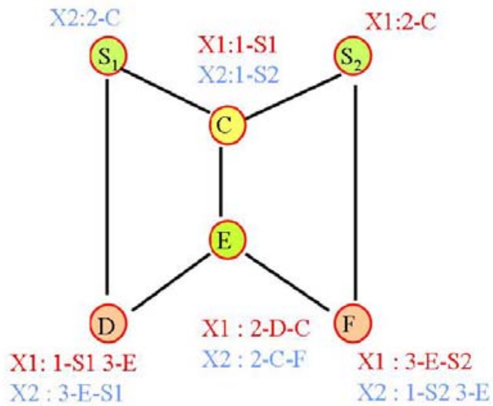


Figure 36: Step One

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

This step consists, periodically from candidate ingress 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 ingress 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 egress node of the flow.

In the next figures  represents Mtopo messages.

As illustrated in *Figure 37*, a node (in the example the node E) receiving such message from different ingress node has the sufficient information to determine if it can be such a potential “pivot” node. The ingress nodes that can send such messages are nodes ingress 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.

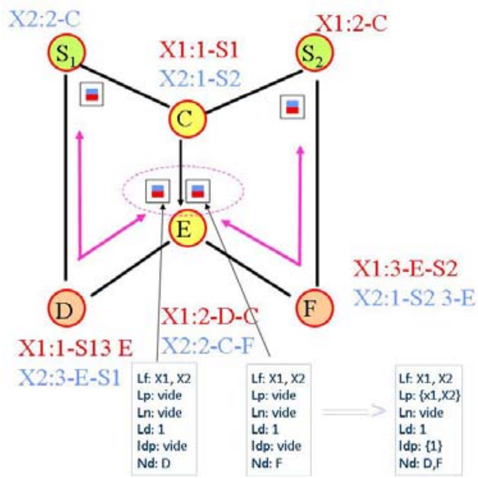


Figure 37: Step 2

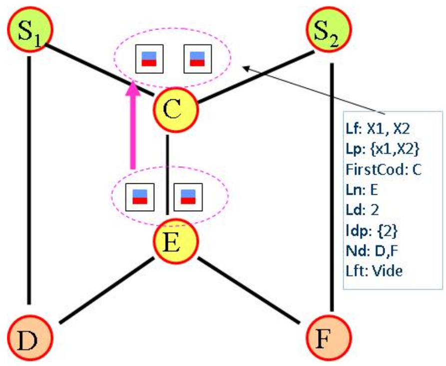


Figure 38: Step 3

Decision function on egress nodes

The messages are finally sent to the egress nodes. From the information received from the different paths of these information, network coding is applicable only if one path is common with an other 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 receive information from the two originator nodes. Protocol between the egress nodes and the pivot node may be defined to know if the egress nodes decide or not to apply network coding.

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

In the example, the egress 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 egress node to the ingress node F (resp.D).

The S1 and S2 nodes have the sufficient information to (re)establish the optimal traffic routes as depicted in figure 5 and labeled "Routing based NC".

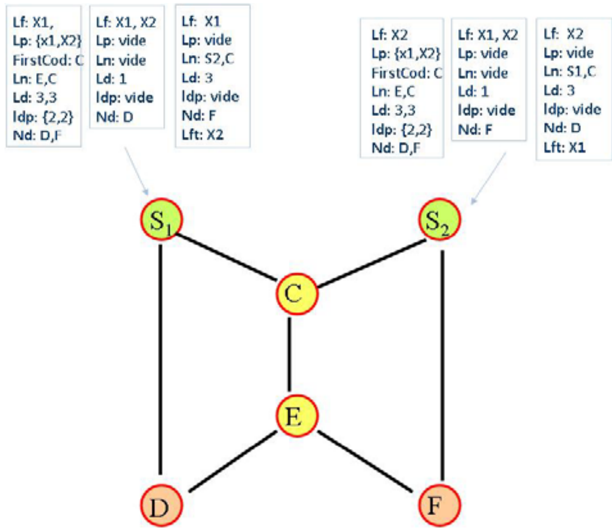


Figure 39: Step 4

Traffic paths re-establishment

The fifth step is the network coding application on common path and decoding on the ingress nodes. The egress 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 ingress nodes.

Each node receiving the MEstab message:

allocate the resources needed to kinitiate the traffic,

suppress its id in the nodes tree

transfer the message to the neigbour nodes of the tree

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

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

The algorithm presented in section 5, is restricted to the egress nodes from originator of independent paths. The egress nodes are also restricted to egress nodes of several traffics. The following figure introduce the notion of :

delegated egress nodes, on with the capability to stamp the **Lft** field of the MTopo messages is delegated.

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

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

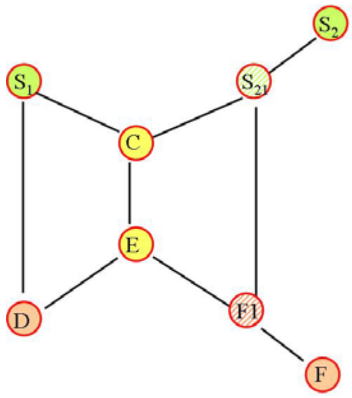


Figure 40: egress and ingress delegated nodes

The Decision function on egress nodes may define the paths the network coding is applicable. One solution is to deterministically select one of the path (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.

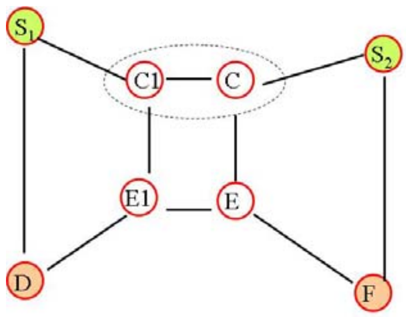


Figure 41*: multi paths optimization determination*

3.11.5.4 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 re the following:

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

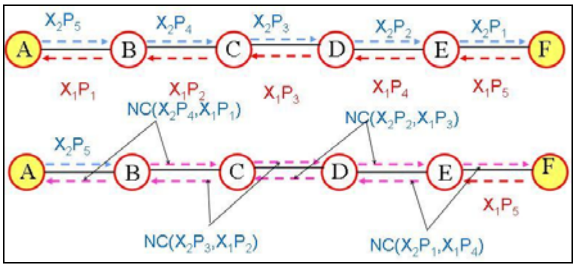


Figure 42:2 bi-directional flows with 4 relay nodes with standard routing and network based routing

The algorithm based on MTopo message transmission from ingress node to egress nodes is applied, with a specific field indicating the flows are bi-directional, as illustrated in figure 14.

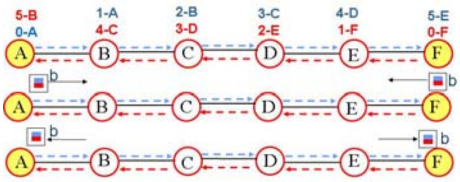


Figure 43: MTopo messages go through within the network

When receiving MTopo messages from the two ingress nodes, the relay nodes allocate resources to memorize 2 packets of the two flows (as shown in figure 15).

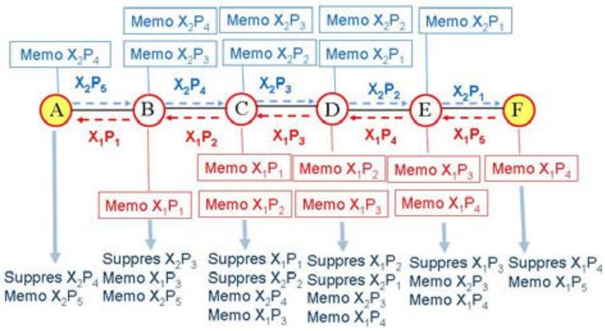


Figure 44: First step of memorization after reciept of the mTopos messages from both sides for each node

The egress 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 encoding steps from the first encoding nodes to the others is illustrated in the figures 16 and 17.

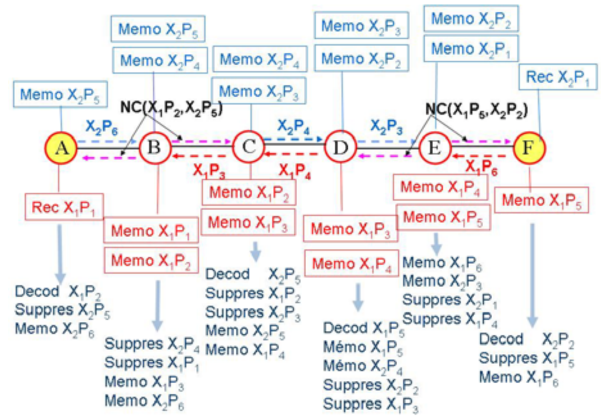


Figure 45: The relay nodes close to the in/egress nodes are the last to receive the MTopo messages, all the other are ready to decode the data they encode, from MEstab message from e/ingress nodes

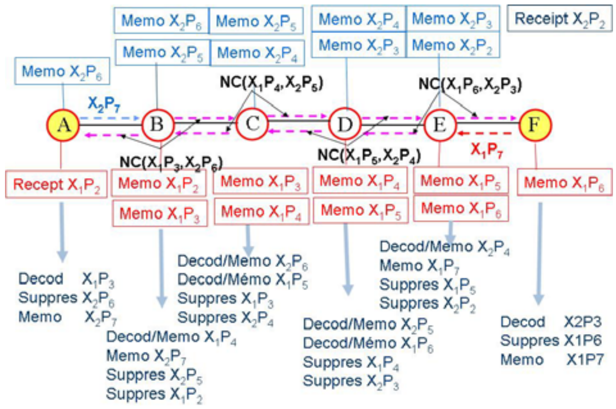


Figure 46: nominal situation, all nodes coding and decoding packets received.

3.11.6 Requirements for Global Consistency

3.11.6.1 Requirements on the C^{4}MS protocol definition & Technical challenges

As related in the algorithm description, the C^{4}MS 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.

3.11.6.2 Requirements for inter Technical challenges consistency

As described in the State of the art section, the use of network coding may optimize the routes in term of radio resource optimization. As egress nodes of traffic flows share their knowledge of the close topology and multi-flows route allocation, these nodes, commonly with the `Mestab` messages on flows establishment, may transmit information on the resource allocation required with respect to the optimization determined with the proposed algorithm.

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