On the Role of Spectrum Selection to Improve Coverage Extension through Opportunistic Networks

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Abstract—**This paper discusses the role played by Opportunistic Networks (ONs) as a means to bring Future Internet services to users in different situations. After the identification of technical challenges associated to the operation of ONs the paper focuses on their applicability in the coverage extension of a wireless network. In particular, the flexibility offered by the availability of multiple spectrum bands to select for the set-up of the ON link is analysed. Results in a scenario with 2D correlated shadowing are obtained to illustrate how a proper spectrum selection influences on improving the coverage extension capabilities.**

Keywords - Opportunistic Network; Coverage Extension; Spectrum Selection

I. INTRODUCTION

Given that the key elements for the success of Internet have been its flexibility, its accessibility via different physical mediums, and the simple support of many different types of applications and data types, it is expected that wireless access will prevail in the context of the Future Internet (FI). At the same time, a growing interest for more application areas beyond classical file-transfer, e-mail, media streaming and client-server based web services is envisaged. In contrast to today's model, it can be safely assumed that the "best effort" delivery model will not hold. Instead, applications, services and content will have to be delivered meeting certain Quality of Service (QoS) levels. Such hard requirements will set the networks under an enormous stress for resources (e.g. bandwidth, storage processing required) in both core and access networks. These continuously increasing requirements motivate the quest for further efficiency in resource provisioning, targeting higher utilization of resources, reduction of transmission powers and energy consumption and reduction of the total cost.

In order to satisfy the demand for applications/services and respective resources through increased efficiency in resource provisioning and utilization, innovative solutions are required. In this respect, Opportunistic Networks (ONs) are considered in this paper as a candidate [1][2]. ONs are temporary, localized network segments that are created under certain circumstances. In this vision, ONs are governed by the radio access network (RAN) operator (which provides the resources, the policies, the knowledge, etc.) so they can be considered as coordinated extensions of the infrastructure network. ONs comprise both nodes of the infrastructure and infrastructure-less devices. The aim for a RAN operator to use ONs is to improve the performance of the infrastructure network, but also (and perhaps via a third party) to provide a new span of localized or closed-group services. Further on, the introduction of cognitive techniques for the management of the ONs and for coordinating the infrastructure will lead to robustness and to capitalize the learning capabilities that must be intrinsic to cognitive systems. This cognitive management system will implement capabilities for context acquisition and reasoning, profile management and policy-awareness; cooperation with other cognitive management systems; building and sharing knowledge, and decision-making based on the acquired knowledge and experience as well as the operation context.

Some illustrative scenarios for ONs are identified in [3]. Among them, the "Opportunistic coverage extension" describes a situation in which a device cannot connect to the network operator's infrastructure, due to lack of coverage or a mismatch in the radio access technologies, and an ON is created with other devices that have coverage and provide the connectivity. A second scenario is the "Opportunistic capacity extension" in which a device cannot access the operator infrastructure due to the congestion of the available resources at the serving access node. In this case, the access route is performed through an ON that avoids the congested network segment. Another scenario is the so-called "Infrastructure supported opportunistic ad-hoc networking" in which a localized, infrastructureless ON among several devices is created for a specific purpose (peer-to-peer communications, home networking, location-based service providing, etc.).

In the above framework, this paper focuses on the analysis of the opportunistic coverage extension scenario by identifying the technical challenges involved in terms of spectrum selection and its relationship with node selection. Then it discusses, based on a numerical analysis in a scenario with 2D spatially correlated shadowing, how the flexibility offered by the availability of multiple spectrum bands with different characteristics can be used to improve the coverage extension capabilities through ONs.

The rest of the paper is organized as follows. In Section II the life cycle of an ON and its associated technical challenges are presented from a general perspective, common to the identified scenarios. Section III addresses the opportunistic coverage extension by further developing the technical elements that play a role and discussing related work. Section IV presents some results to evaluate the possibilities offered by this scenario when different spectrum bands are available and finally conclusions are summarized in Section V.

II. Life Cycle of an ON and Technical Challenges

Being operator-governed, the life cycle of an ON comprises the following phases: (i) Suitability determination, where the operator assesses the convenience of setting up a new ON according to the triggering situation, previous knowledge, policies, profiles, etc. The suitability assessment is the result of a rough feasibility analysis in order to keep complexity moderate. This functionality will require to acquire pertinent inputs from context awareness and involves the identification of potential nodes (through discovery procedures), potential radio paths (i.e. to derive the proper routes across the nodes forming the ON and to identify the spectrum opportunities for the communication) and the assessment of potential gains achievable by the ON; (ii) Creation, which includes the selection of the optimal, feasible configuration for the ON (selection of the participant nodes, the spectrum and the routing pattern). The possible candidate ON configurations are analyzed in further detail in this stage, thus probably requiring additional context awareness and/or more accurate estimations related to diverse aspects of the radio environment; (iii) 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. Capabilities for the ON reconfiguration will provide the necessary adaptability to changing conditions. Relevant changes include changes in nodes, spectrum, finalization of an application, changes in the gains achieved with the ON, etc.; (iv) Termination, when the motivations for the creation of the ON disappear (e.g. finalization of end-nodes' applications, assessment that the gains achieved with the ON are inadequate) or the ON can no longer provide the required QoS. After the termination decision the corresponding signaling will be triggered in order to release the resources used by the ON. In case of forced terminations with on-going services expected to survive ON termination, handover to the infrastructure decisions are needed to properly transfer these services via the network infrastructure (e.g., selection of infrastructure nodes, selection of the services to be handled, modification of QoS settings, etc.).

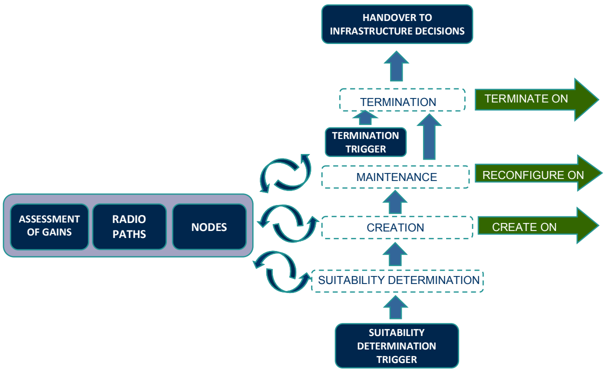


Figure 1. ON management and decision making process

The sequential view of the ON management and decision making process is summarized in Figure 1. The core functionalities to be undertaken along the ON life cycle are related to: (i) Nodes (i.e. who is around the ON); (ii) Radio paths (i.e. what communications means can be considered and how to establish communications around the ON); (iii) Assessment of gains (i.e. where and when the observed conditions advice to establish 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.

III. Opportunistic Coverage Extension

A. *Introduction and related work*

This section focuses on the formation of an ON to provide coverage extension [3]. The scenario assumes a wireless infrastructure (e.g. base station of a cellular system) providing coverage in a certain area, where a mobile node having direct coverage from this infrastructure can be configured to form an ON with another node outside the direct coverage area, so that the former acts as a relay enabling the later to gain access to the infrastructure. Another situation in which this coverage extension is applicable would be the case where, even though the node is within the coverage range of the infrastructure, the device´s air interfaces are not compatible with those provided by the infrastructure. In this case, another node with the adequate capabilities can offer the connectivity. The ON for coverage extension can be formed by one or multiple hops and it can include different technologies in each link.

The use of relaying to enhance the coverage of wireless networks has been a topic of interest during the last years. In particular, the use of fixed nodes acting as relays is seen as an attractive solution to improve the signal to noise ratio at the cell edge in future systems such as LTE-Advanced thus enabling larger data rates [4][5]. Also in the context of wireless LANs, relays have been used [6]. The possibility to provide the coverage extension of cellular networks through multi-hop networks, enabling the transmission using different hops through mobile stations towards the access point or base station has also been investigated since the initial works in [7][8]. As a difference from previous works, the purpose of the present study is to analyze how the utilization of a relay through an ON can benefit from the availability of different spectrum bands, and how the selection of one or another band will influence on the performance that can be obtained by the node whose coverage is to be enhanced.

Among the technical challenges discussed in Section II, the formation of the ON in this case needs to address two different problems. First, the node selection should identify appropriate subset of nodes, among those that happen to be in the particular area to form the ON, based on profile and policy information of the operator. Second, selection of the spectrum that will be designated by the operator has to be carried out, to enable the communication of the nodes of the ON.

Focusing on the spectrum selection to decide the appropriate frequency band for setting up the ON, the process should be divided in two differentiated steps. First, the spectrum opportunity identification will be in charge of finding out the set of possible frequency bands that are available in a given position. Second, and based on the results of the previous step, the spectrum decision will perform the selection of the most adequate band for the communication.

The spectrum opportunity identification can make use of CR (Cognitive Radio) techniques to discover the available spectrum bands allowing an opportunistic access when they are detected to be unused by primary license holders. This can be carried out through spectrum sensing executed at one or several nodes that cooperate to have a more accurate view of spectrum utilization. Additionally, the process can be assisted by means of databases that store, among other environment characteristics, the frequency occupation in a given geographical area. Radio Environment Maps (REMs), envisioned as an integrated space-time-frequency database consisting of multi-domain information, constitutes an example of this type of databases [9]. Even from a more general perspective, the possibility that the network provides knowledge about the current spectrum bands available through some control channel can also be considered.

As for the spectrum decision, this refers to the selection of the most adequate spectrum band to carry out the transmission based on the communication requirements set by the ON. Selection should be made based on the characteristics of the channel in terms of e.g. the maximum capacity or maximum interference. Decision making process can benefit from the application of learning strategies that, based on experience acquired from prior decisions, can orient the decisions towards the selection of some channels in front of others.

B. *Problem formulation*

To characterize the opportunistic coverage extension problem, let consider a wireless infrastructure operating at frequency f, using bandwidth BW and transmitted power P_T, as illustrated in Figure 2. When providing a service with a certain bit rate requirement R_{min}, the associated coverage area will be given by all points fulfilling the following condition:

$$R = BW \log_2\left(1+\frac{P_T}{L(f,d)I_o BW}\right) \geq R_{\min} \qquad (1)$$

where L is the propagation loss that will depend on the frequency f and the distance d, and I_o is the noise and interference power spectral density (that in general can be position dependent). Note that the above condition is formulated in terms of the Shannon bound in order to perform a technology-agnostic analysis.

For those nodes that are outside the coverage area, the possibility to form an ON with another node having direct coverage is considered, as depicted in Figure 2. It is assumed that the node with direct coverage can use its full capacity for relaying the ON link. The spectrum selection will be able to choose among a set of frequencies f_i and associated characteristics in terms of bandwidth BW_i and transmit power $P_{T,i}$ to set up the ON. In this case, the following two elements need to be considered:

1.- Link performance: Depending on the propagation and interference characterization of the different bands, the capacity achievable in the ON link will differ. Specifically, to establish the ON, the following condition needs to be fulfilled for the bit rate R_i in the ON link using the i-th band:

$$R_i = BW_i \log_2\left(1+\frac{P_{T,i}}{L_i(f_i,d)I_{o,i} BW_i}\right) \geq R_{\min} \qquad (2)$$

where L_i is the propagation loss depending on frequency f_i and distance d to the node with direct coverage, and $I_{o,i}$ is the total noise and interference power spectral density.

2.- Node density: The possibility of forming an ON with a node that has direct coverage will be related with the density of mobile nodes η in the scenario, together with the propagation constraints. For the sake of simplicity, let assume a homogeneous density η nodes/km^2 in a scenario with area S_{TOT}. When considering a node A outside the direct coverage area of the infrastructure, the probability of finding a node able to form an ON is given by:

$$P_{COV,ON} = 1-\left(1-\frac{S_i}{S_{TOT}}\right)^{\eta S_{TOT}} \qquad (3)$$

where S_i is the portion of area with direct coverage that is reachable by node A when setting up the ON using the i-th spectrum band. Based on the above expression, the probability of having coverage at any point in the scenario is given by:

$$P_{COV} = P_{COV,ON}\left(1-P_{COV,D}\right)+P_{COV,D} \qquad (4)$$

where $P_{COV,D}$ is the probability of having direct coverage.

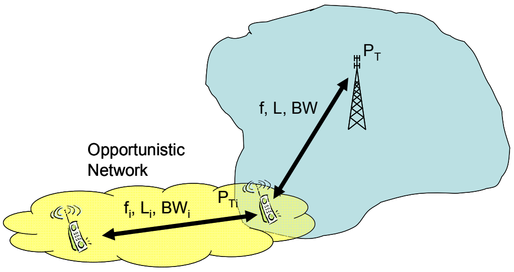


Figure 2. Opportunistic coverage extension

IV. RESULTS

To evaluate the impact of the different possibilities of spectrum selection, let assume a scenario with dimensions 10 km x 10 km, and the transmitter of the infrastructure located in the central point. Scenario parameters are presented in Table I. Three possibilities are considered to set-up the frequency for the ON composed by a single link. The first option makes use of 20 MHz in the license-exempt ISM band at 2.4 GHz. The second option uses the TV White Space (TVWS) band at 600 MHz operated opportunistically so that transmission is allowed whenever no interference is generated to TV receivers. Finally the third option uses some MNO (Mobile Network Operator) licensed band owned by the operator at 1800 MHz.

Given the different characteristics of the propagation for the direct link (i.e. from a mobile node to a base station) and for the ON link (i.e. from a mobile node to another mobile node), the following general propagation model is assumed, whose parameters are particularized for each case [10]:

$$L_p(dB) = K + \beta \log f(GHz) + \alpha \log d(km) + S \qquad (5)$$

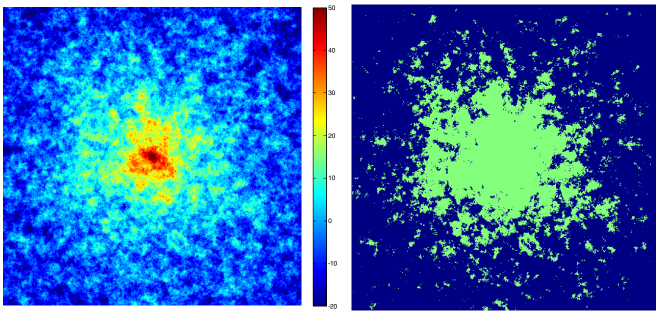
S(dB) corresponds to the shadowing, following a Gaussian distribution with mean 0 and standard deviation σ dB. Shadowing is spatially correlated with exponential autocorrelation and decorrelation distance d_{corr}. The generation of 2D spatially correlated shadowing follows the methodology of [11] based on filtering a set of independent shadowing samples using a 2D filter defined from the Fourier transform of the exponential autocorrelation function. The shadowing of the direct and the ON links are independent.

A minimum bit rate of R_{min}=5 Mb/s (measured at physical layer from the Shannon bound) is needed by the application. This requirement poses the limits for the coverage of both the direct and the ON links. More specifically, in Figure 3(a) the SNR (Signal to Noise Ratio) is plotted in the different points of the scenario. Based on this SNR and (2), Figure 3(b) plots the area where the direct communication at R_{min} is possible.

TABLE I. SCENARIO PARAMETERS

Direct link		
Frequency (f)		900 MHz
Bandwidth (BW)		3 MHz
Noise and interference spectral density (Io)		-164 dBm/Hz
Transmit power (P_{Tmax})		40 dBm
Propagation model	α	37.6
	β	21
	K	122.1 dB
	σ	6 dB
	d_{corr}	100m
ON link		
Option 1: ISM band	f_1	2.4 GHz
	BW_1	20 MHz
	$I_{o,1}$	-164 dBm/Hz
	$P_{T,1}$	17 dBm
Option 2: TVWS band	f_2	600 MHz
	BW_2	8 MHz
	$I_{o,2}$	-164 dBm/Hz
	$P_{T,2}$	20 dBm
Option 3: MNO band	f_3	1800 MHz
	BW_3	5 MHz
	$I_{o,3}$	-164 dBm/Hz
	$P_{T,3}$	21 dBm
Propagation model	α	40
	β	30
	K	141.7 dB
	σ	6 dB
	d_{corr}	40 m

Based on the coverage map depicted in Figure 3 for the direct link, the probability of having coverage either direct or through the ON is analyzed at different distances *D* from the infrastructure transmitter. For each distance, the results are averaged for a total of 359 positions with a separation of 1°. Figure 4 plots the probability of having direct coverage as a function of distance *D*. For comparison purposes, the reference case without shadowing is plotted. In this case, note that there is a distance limit around 2.4 km beyond which it is not possible to achieve the required 5 Mb/s with the direct link. In turn, when shadowing is considered, there is a gradual reduction in the probability as the distance *D* increases, and for 2.4km the probability of having direct coverage is 50%.



(a) (b)

Figure 3. (a) SNR (dB) with the direct link, (b) area (in green) where the direct communication can be established

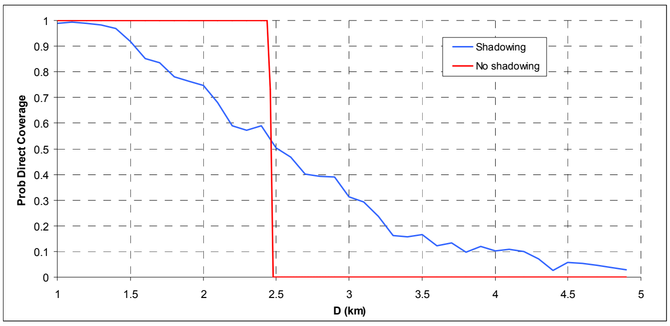


Figure 4. Probability of having direct coverage as a function of the distance *D* to the infrastructure transmitter with and without shadowing

Figure 5 plots the resulting total coverage probability for the three considered options for the ON link to provide service to those nodes outside the direct coverage area. Computations assume in this case a node density η=50 nodes/km^2. Firstly, it can be noted how the selection of one or another spectrum band has a high influence over the coverage probability. Clearly, the use of TVWS, operating at a lower frequency, allows having higher coverage probabilities than the use of the MNO or the ISM bands. Secondly, it is observed how the effect of shadowing is overall beneficial from the perspective of coverage probability. For instance, with TVWS for the ON link it is possible to have a significant coverage probability above 80% even at large distances such as 4 km. On the contrary, in the case without shadowing, the ON is only able to extend the coverage in roughly 400m beyond the limit of 2.4km when TVWS are used. To complement this result, Figure 6 plots the corresponding value of the surface S_i defined in (3) consisting in the points of the direct coverage area that can be reached by a node without coverage located at distance *D*. It can be seen that the area is larger with TVWS than with the rest of bands, and also that its value is larger when there is shadowing than when there is not. In the latter case, this area tends quickly to zero, while with the presence of shadowing the area is kept at non-zero values even at large distances. This fact, combined with the node density of η=50 nodes/km^2, allows having a significant probability of finding a node to form the ON even at large distances. Note that for distances below 2.4 km, S_i is not defined in the case without shadowing because all points have direct coverage.

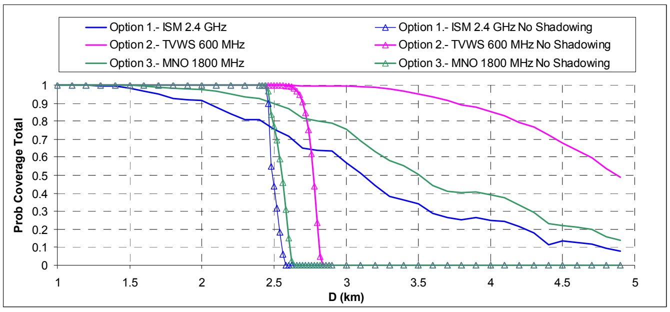


Figure 5. Coverage probability as a function of distance *D* for the different spectrum band alternatives, with and without shadowing.

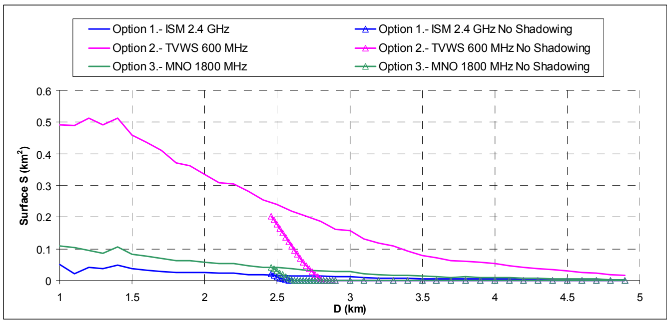


Figure 6. Average value of the surface S_i with direct coverage that can be reached through an ON link for the different options.

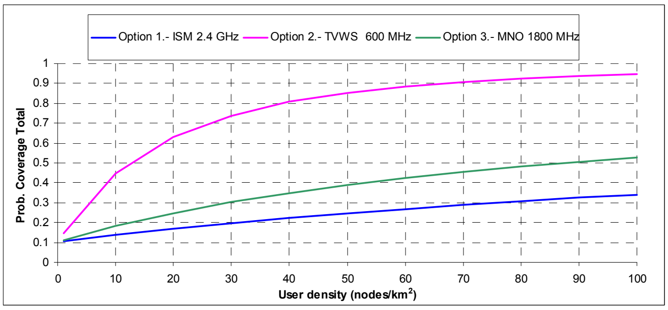


Figure 7. Coverage probability as a function of the node density η at distance *D*=4km when shadowing is considered

Figure 7 plots the variation of the coverage probability thanks to the ON formation as a function of node density η when terminals are at *D*=4 km in case of shadowing. The same trend with respect to the best behavior of the TVWS band is observed like in previous results. It can also be noticed how the coverage probability is very sensitive to the node density. Focusing for instance on the TVWS, the coverage probability can range from around 15% for the case with the lowest node density considered here up to around 95% for the largest density. Note that for *D*=4 km, the case without shadowing (not plotted in the figure) would yield a coverage probability of 0% regardless the node density, because at this distance the surface S_i with direct coverage reachable with the ON link is 0 for all the considered options as seen in Figure 6.

V. CONCLUSIONS AND FUTURE WORK

Among the scenarios in which the formation of ONs can be of interest as a means of bringing Future Internet services to users, this paper has focused on the opportunistic coverage extension, in which a ON is formed to provide coverage to nodes outside the coverage area of a wireless network. Spectrum and node selection have been identified as two key technical challenges to be resolved in order to materialize this scenario. Considering 2D correlated shadowing effects, it has been analyzed how the flexibility offered by the availability of multiple spectrum bands in the spectrum selection impacts over the coverage extension improvements in accordance with the node density existing in the scenario. It has been obtained that the probability of coverage can be significantly increased by a proper spectrum selection when setting up the ON links. Building on these first results, future work expects to develop the algorithmic component to perform the spectrum and node selection tasks in the different stages of the ON lifecycle.

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