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A Spectrum Selection Framework for Opportunistic Networks

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Abstract: This paper presents a framework for including cognitive management functionalities in the spectrum selection process for Opportunistic Networks (ONs).The framework is based on a decision making functionality interacting with a knowledge management block that stores and processes information about the spectrum use. Different approaches for spectrum selection are discussed covering specific cases including the capability to aggregate different bands and the possibility to jointly select the spectrum and the network interface. Illustrative results of the proposed framework are presented.

Keywords: Spectrum selection, Opportunistic Network, Cognitive Management.

1. Introduction

Future wireless networks will have to cope with the requirements posed by the different services while at the same time ensuring an efficient use of network resources to allow a reduction of operational expenditures. In addition, the complexity in the network operation will be increased due to the diversity of requirements in the envisaged applications, as well as the availability of multiple coexisting network topologies (e.g. macrocells, femtocells, ad-hoc networks, etc.) and technologies. The additional consideration of flexibility in the spectrum use envisaged by the Dynamic Spectrum Access (DSA), enabling the assignment of spectrum portions in different bands with different regulatory constraints, makes the situation even more complex as there will be multiple options for satisfying the diverse application requirements. This claims for the inclusion of cognitive principles in the way how networks will be managed to be able to reach the most suitable configuration decisions for each situation based on a smart analysis of their operation context.

Different works have considered recently the inclusion of cognitive management functionalities to provide Future Internet services. In [1] the challenges to be addressed by the management functionality or the capabilities of the infrastructure are discussed. In the context of the OneFIT project [2] the cognitive management of the so-called operator-governed Opportunistic Networks (ONs) is addressed. ONs act as local and temporary, capacity- or coverage-oriented, extensions of the infrastructure. Cognitive systems decide on the suitability, creation, modification and release of an ON. ONs have applicability in different scenarios, such as coverage or capacity extension, home networking, etc. Also, applicability to machine-to-machine (M2M) communications could be envisaged.

In this context, this paper focuses on the inclusion of cognitive management functionalities for the spectrum selection problem for ONs, and presents a general framework with the different functional elements to deal with the problem. The paper is organised as follows. Section 2 presents the problem definition and related work. Section 3 presents the proposed general framework whose functions are detailed along Section 4 and illustrated with some results in Section 5. Finally, conclusions are summarised in Section 6.

2. Spectrum selection: problem definition

Spectrum Selection refers to the functionality intended to choose the most adequate spectrum portion(s) to carry out the transmissions in the links of an ON using DSA. Selection should consider the characteristics of the channel, the user requirements and also the maximum interference tolerated by other receivers, including in this case primary users (PUs) whenever the secondary use of licensed bands is considered. Spectrum selection has to be executed either when a transmission starts 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) due to e.g. the current channel becoming unavailable.

Spectrum selection takes as input the frequency bands that are available for establishing the communication. This will be the outcome of an "observation" stage in which the system achieves the necessary awareness on its environment to make the appropriate decisions. Spectrum awareness can be achieved by spectrum sensing mechanisms and/or through information stored in databases [3].

Spectrum selection can make use of spectrum aggregation techniques that enable use of multiple bands to satisfy user demands for larger bandwidths and achieve better spectrum utilization. Spectrum aggregation can be classified into three types: (i) Intra-band contiguous spectrum aggregation when multiple sub-channels are adjacent to each other within the same band, (ii) Intra-band non-contiguous aggregation when multiple sub-channels within the same band are used in a non-contiguous manner, and (iii) Inter-band non-contiguous aggregation when multiple sub-channels belong to different bands (e.g. one sub-channel in 800MHz and another in 2GHz).

Spectrum aggregation can lead to system overheads and complexity. If the level of fragmentation of spectrum is excessive, transmitters are required to aggregate a lot of small sub-channels, thus requiring excessive filtering and/or guard bands to protect adjacent users, and increased channel search times [4]. Similarly, allocation of contiguous spectrum is beneficial in terms of spectrum utilization when nodes have a limited range of spectrum aggregation capability. Communication using spectrum aggregation for different bands implies a substantial complexity [5].

Spectrum selection optimization has received a lot of attention in the last years when considering the interference avoidance to legacy services. Some works are [6]-[8] that considered different channel selection schemes to enable the access of secondary users to licensed bands without interfering primary users. In [7][8], channel selection has been improved through learning techniques to learn optimal policies based on the interactions with the environment. While most of the previous works have addressed the spectrum selection problem in the operation between primary and secondary users, this does not necessarily has to be the case in many systems where Cognitive Radio (CR) techniques are envisaged. In that respect, the spectrum selection problem can be generalised to cope with the availability of bands having different regulatory constraints. As an example, a mobile operator may decide on the convenience of selecting among a set of different bands (e.g. an operator-owned band, a TVWS band or an ISM license-exempt band) to establish the communication between two devices under its control in an ON. Based on this, the main contribution of this paper is to present a general framework for spectrum selection in this type of scenarios based on cognitive management principles, identifying the main functional ingredients of this framework and then proposing specific solutions for each one.

3. Spectrum selection: solution approach

The general cognitive management framework for spectrum selection considered in this paper is shown in Figure 1. It is based on the interaction between a decision making entity and a knowledge management functional block. Both elements are residing in the infrastructure of the operator that is governing the ONs. The knowledge management functional block includes on the one hand the current knowledge on spectrum use indicating the status (e.g. idle/busy) of the available spectrum portions as well as different features of each portion (e.g. measured noise and interference, etc.). This information can be processed and stored in a database in the form of different statistics reflecting the experience of past situations. Such database can be used by learning methods to support the decision making processes. The decision making entity contains two main elements. The first one is the spectrum selection, that decides which spectrum portion is to be assigned to each communication link in the network. In turn, the decision on the method to obtain knowledge on spectrum use will select the most adequate strategy and configuration for acquiring knowledge about the status of the different spectrum portions (e.g. sensing method, control channel, etc.). Both decision making and knowledge management blocks use the information captured from the radio environment where the network operates in terms of context awareness, operator policies and user/application profiles. The components of the cognitive management framework will be further detailed in next section.

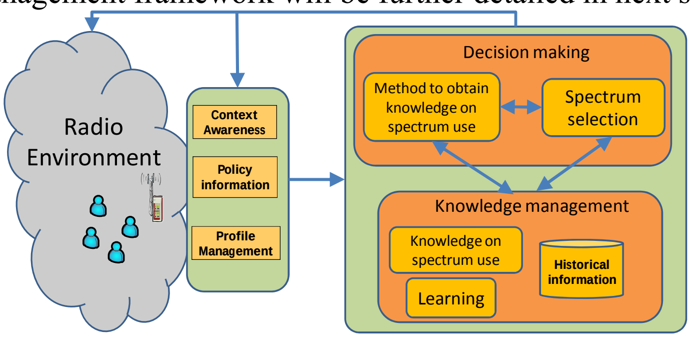


Figure 1: General framework for spectrum selection

4. Spectrum Selection solution: components description

4.1 – Input parameters

Parameters for spectrum selection can be divided in the following categories (see Figure 1):

- Policy related information: It can be retrieved from a database or it is known by the operator. This information contains knowledge about frequency bands that are permitted to be used for ON purposes, transmission power constraints in each band, and allowed bandwidths. This is defined by the regulatory framework applicable to each band (e.g. FCC Orders on the use of TVWS in the US [9]). Policies may indicate also the method to obtain knowledge on spectrum use in specific bands and, in case of sensing, they can define probability of detection, sensing threshold, and minimum time required for spectrum sensing.
- Profile related parameters: Each mobile device involved with ON creation needs to exchange information about its own parameters and capabilities. This includes e.g. user equipment velocity, location/coordinates, spectrum sensing capabilities, device spectrum aggregation capability, etc. Information about the application requirements such as minimum bit rate, latency, application duration, etc. needs to be provided to the decision making entity, as well as information regarding network interface capabilities (e.g. supported bit rates and bandwidths of each network interface). This information is used to guarantee Quality of Service (QoS) for different applications.

- Context awareness information: This refers to information about how the spectrum is used in the different bands, including spectrum occupancy for the specific time/place where the ON operates (see section 4.2 for more details). It also includes the measurements to monitor the degree of QoS of the applications in the ON.

4.2 – Knowledge on spectrum use

Future mobile communications systems with ONs will have a variety of spectrum bands to operate on, including e.g. operator governed mobile service bands, license-free ISM bands, and bands where the network operates as a secondary user and protects the higher priority systems from harmful interference (e.g. TV white spaces in the UHF band). This calls for different approaches to obtain knowledge on the spectrum use, categorized to cognitive control channels, databases, and spectrum sensing, see e.g. [10]. On operator governed bands, a possible method is to use control channels to obtain knowledge on spectrum use. On license-free bands there are typically no high priority systems and one potential way to obtain knowledge on spectrum use is to use spectrum sensing. On bands where the opportunistic network is created as a secondary system to coexist with higher priority systems, the spectrum regulators will set policies to decide the techniques to obtain knowledge on spectrum use. It is possible that the operations on a given band will require a combination of several different methods. Moreover, there is a need to select a specific technique from the general class. As an example, the selection of a specific spectrum sensing method (e.g. among energy based, correlation based, or/and waveform based techniques) can be done by using a simple rule-based decision making system based on fuzzy logic, see [11][12]. This would be executed in the decision making on the method to obtain knowledge of spectrum use (see Figure 1).

Using the spectrum sensing information gathered by the nodes and stored in the database, the system can obtain a set of different statistics (e.g. average idle periods, correlations, etc.) to be used to estimate idle times based on traffic prediction.

4.3 – Spectrum selection decision-making process

Spectrum selection is responsible for choosing the adequate frequency and bandwidth to be used by the different links of an ON. Each link is used to support a certain application with specific requirements. A baseline spectrum selection solution based on the fittingness factor concept is presented first. Then, the extension of the problem to consider spectrum aggregation is addressed. Finally, the inclusion of the network interface selection is also embedded into the spectrum selection problem.

- **Spectrum Selection based on the Fittingness factor framework**

This approach assumes that spectrum is organised into spectrum blocks each one characterized by a certain bandwidth, operating band, as well as different constraints in terms of maximum transmit power or total noise and interference. In order to cope with the spectrum selection problem of associating a block to each link of the ON, the considered framework introduces the so-called “Fittingness Factor” $F_{l,p}$ as a metric between 0 and 1 to capture how suitable a specific block p is for the radio link l. It is given by the following relationships dependent on the ratio between the required bit rate $R_{req,l}$ and the actually achievable bit rate with block p, $R(l,p)$, obtained through measurements [13]:

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

where ξ is a shaping parameter to capture different degrees of elasticity of the application with respect to the required bit rate and λ is a normalization factor to ensure that the maximum of the fittingness factor is equal to 1.

The knowledge database contains different statistics about the measurements of $F_{l,p}$. They are the probabilities that it is above or below a certain threshold $\delta_{l,p}$ (i.e. $P_H^{l,p}(\delta_{l,p}) = \Pr\left[F_{l,p} \geq \delta_{l,p}\right]$ and $P_L^{l,p}(\delta_{l,p}) = \Pr\left[F_{l,p} < \delta_{l,p}\right]$) and the average values when it is above/below $\delta_{l,p}$ (i.e. $\overline{F_H^{l,p}} = E(F_{l,p} | F_{l,p} \geq \delta_{l,p})$ and $\overline{F_L^{l,p}} = E(F_{l,p} | F_{l,p} < \delta_{l,p})$). Statistics include also the probability $p(\Delta t)$ that the state or $F_{l,p}$ (i.e. either above or below $\delta_{l,p}$) at a given point of time will not have changed with respect to the last measurement taken Δt time units before. Based on these statistics, at a new link l establishment, an estimation of $F_{l,p}$ in each block is performed and used as a decision variable. This estimation is the last measured value if $p(\Delta t)>Th$. On the contrary, the estimation is set to $\overline{F_L^{l,p}}$ with probability $P_L^{l,p}(\delta_{l,p})$ or to $\overline{F_H^{l,p}}$ with probability $P_H^{l,p}(\delta_{l,p})$. Then, the decision making criterion will select the block p with the largest estimated fittingness factor among the available ones.

- **Utility-based approach for Spectrum Aggregation**

This approach addresses the case where spectrum selection includes the capability to aggregate different channels. A utility-based algorithm is considered to find a channel consisting of multiple sub-channels in different bands for each link.

To ensure an interference-free allocation between links of the ON, the problem is addressed as a graph multi-coloring approach [14]. The spectrum assignment problem is formulated as an optimization function that considers channel availability and interference constraints, to allocate M sub channels to the set of L links. When the capacity of a single sub-channel cannot satisfy the bit rate requirement of a link, multiple sub-channels will be aggregated based on the aggregation capabilities of the terminals. The utility function in the optimization includes three components associated to three different objectives:

1. To maximize the spectrum utilization: To allocate the channel with highest SNR to a link, the utility value with the modified hyperbolic tangent function [15] is considered.
2. To perform spectrum aggregation with the least complexity: The preference of aggregation from the complexity perspective can be ordered as following: contiguous intra-band aggregation, non-contiguous intra-band aggregation and inter-band aggregation.
3. To reduce channel switchings: The ON needs to monitor the allocated channels to vacate them when they are no longer available (e.g. because of a returning PU). To reduce the overhead, this objective targets the allocation of the spectrum with the least-likelihood for the appearance of a PU. This is done by estimating the remaining availability times of the different channels as in [16].

The three objectives above are weighted by parameters $\{w_1,w_2,w_3\}$ in the utility function. Based on this, the algorithm assigns sequentially the sub-channel that will experience the highest utility to the link taking into consideration users' requested throughput. Consequently, it is aimed at maximizing the global utility values achievable with the available resources. Since this algorithm considers a sequential resource allocation process, it does not provide the highest achievable global utility value as this would require computation and comparison of all assignment combinations (of all sub-channels). However, the proposed solution does provide a sub-optimal solution with a reduced computational cost that allows for its potential real implementation.

- **Modular-decision flow for joint selection of spectrum and network interface**

This approach is used whenever both the spectrum and the network interface (i.e. to decide among the radio access technologies such as WLAN, LTE or LTE-A) need to be selected for forming an ON. It uses a modular decision flow presented in Figure 2. The approach was initially introduced in [17] and here an evolution is presented that reduces the computational complexity and the amount of different combinations. The procedure is executed at the operator infrastructure and the first eight blocks represent the ON suitability determination phase to select a small group of candidate centre frequency, bandwidth and network interface combinations. In the first step, spectrum policy information is used to indicate which bands are allowed for ON purposes. Application bit rate and spectral efficiency of each interface are used to calculate the minimum required bandwidth below which bandwidths are discarded. The next step is to form four parameter combinations from supported network interfaces, remaining bandwidths, allowed bands and their subbands. In the next two steps the combinations not fulfilling the upper bound for carrier frequency and transmit power are discarded. More detailed descriptions of these stages can be found in [17]. For the candidate combinations fulfilling the previous requirements, the bands are replaced with corresponding centre frequencies. Combinations with already occupied centre frequencies in different bands are discarded. After this, the ON creation phase sorts the remaining combinations in ascending priority order depending on operator preferences, application duration and estimated channel idle time. The combination with the highest priority is selected for further examination. If the selected combination is on an IMT band governed by the operator of the ON, it can be used directly for ON transmission. Otherwise the channel availability is checked using database, control channel or spectrum sensing technique [12]. If channel is vacant, it is used for ON purposes otherwise the second combination in the list is checked. This continues until finding an available combination.

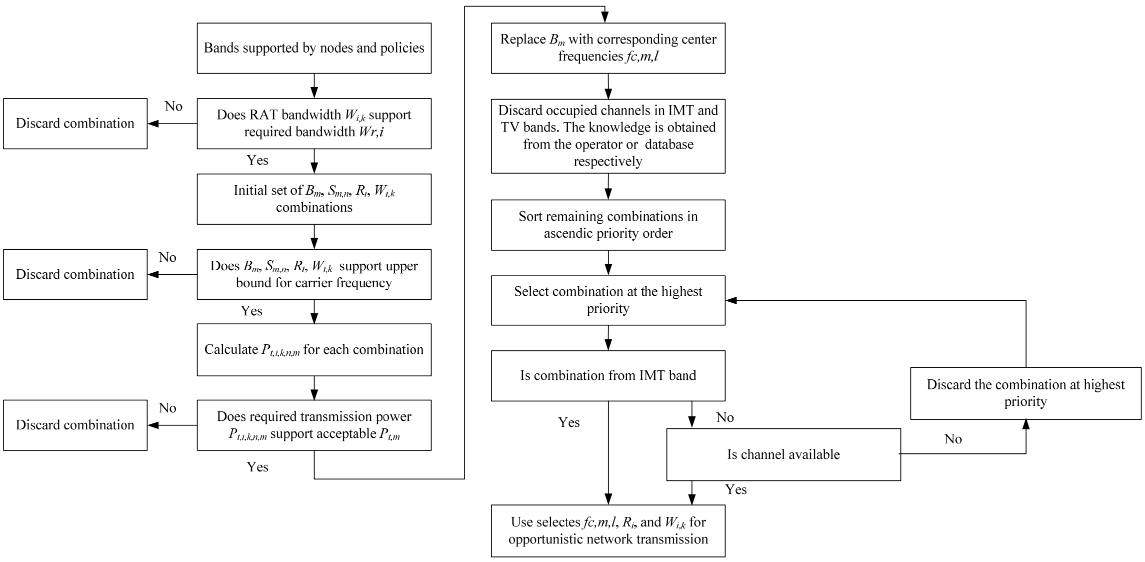


Figure 2: Modular decision flow

5. Performance evaluation

This section provides some illustrative simulation results about the performance of some of the approaches discussed in the previous framework.

5.1 – Spectrum selection based on the Fittingness Factor

To illustrate the benefits of the spectrum selection strategy based on the fittingness factor concept, a scenario with 2 different links having requirements of 64 kb/s and 1 Mb/s is considered. There are 4 different spectrum blocks, two of them with bandwidth 0.4 MHz (and achievable bit rate 512 kb/s) and the other two with 1.2 MHz. The latter two suffer from intermittent and random interference, which reduces the available capacity (from 1536 kb/s down to 96 kb/s). ξ=5, $\delta_{l,p}$=0.9, *Th*=0.9 are considered. Figure 3 presents the results in terms of the dissatisfaction probability (i.e. the percentage of time that the application is not able to achieve the desired bit rate requirements) for different load levels. Performance of the fittingness-factor based approach is compared against a reference scheme that makes a random allocation among the available channels. Results correspond to the link with the requirement of 1 Mb/s, since the other one is always satisfied. Clearly, the fittingness factor approach is able to significantly reduce the dissatisfaction probability by performing a smart assignment of those channels that fit better the requirements.

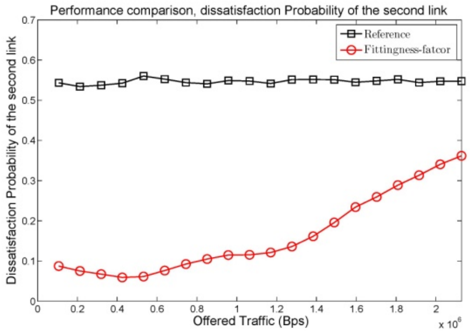


Figure 3: Dissatisfaction probability

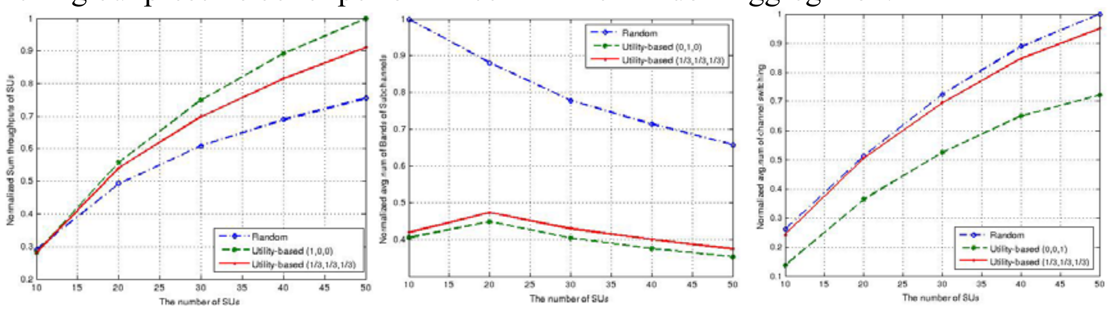
5.2 – Utility-based approach for Spectrum Aggregation

This section evaluates the considered approach for spectrum selection with aggregation capabilities. The scenario assumes that 5 MHz is available for 5 different bands. The bandwidth of a sub-channel is set to 200 kHz, and PU activity in these channels is modelled through an ON/OFF process. Each link in the ON requires 10 Mb/s during the service time that follows a uniform distribution with the mean 5 s. In the simulations, we start off by assigning the same priority to three different objectives i.e. the weight-vector of multi-objective utility $\{w_1,w_2,w_3\}$ is set as {1/3,1/3,1/3} for experimentation purposes. However, the weight of each objective can be set differently depending on metric to be optimized. Performance evaluations in the following sections compare performance of the random aggregation method (labelled as "Random") with different settings of the weight vector.

Figure 4(a) presents the total throughput experienced by the SUs in the different links. It compares the case with equal-weight setting {1/3,1/3,1/3} against the optimal setting for {1,0,0} that allocates the channel with the highest SNR and thus is optimal from the perspective of throughput. It is observed that the proposed equal-weight setting outperforms Random algorithm and can reach 90% performance of the optimal setting.

Figure 4(b) evaluates the complexity of spectrum aggregation. It shows the average number of bands of sub-channels for a channel. The lower this value, the lower the complexity is. The algorithm which only considers the complexity of spectrum aggregation through the setting {0,1,0} is the optimal from the perspective of this criterion. However, the equal-weight setting achieves a performance close to this optimum.

Lastly, channel switching performance is evaluated in Figure 4(c). The algorithm which only considers the remaining idle time through the setting {0,0,1} becomes the optimal algorithm for channel switching. The equal-weight setting results in more channel switching but presents better performance than the Random aggregation.



(a) (b) (c)

Figure 4: (a) Normalized system Throughput, (b) Normalized number of Bands used for aggregation, (c) Normalized number of channel switchings

6. Conclusions

This paper has presented a framework for spectrum selection in Opportunistic Networks based on cognitive management functions. It consists in a knowledge management entity that stores and processes information about spectrum use obtained from the interaction with the environment. Acquired knowledge is used by the decision making entity to choose the different spectrum bands to be assigned to each link in the ON and to choose the appropriate method to acquire the knowledge on spectrum use. The paper has presented different solutions addressing the spectrum selection based on the fittingness factor concept, the extension of the problem to include spectrum aggregation and the inclusion of the network interface selection. Some simulation results have been presented to illustrate the performance of the proposed framework.

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