A Radio Resource Management Framework for Opportunistic TVWS Access

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ABSTRACT
This paper elaborates on the design, implementation and performance evaluation of a prototype Radio Resource Management (RRM) framework for opportunistic TV white spaces (TVWS) exploitation, under an auction-based approach. The proposed RRM framework is applied in a centralised Cognitive Radio (CR) network architecture, where exploitation of the available TVWS by Secondary Systems is orchestrated via a Spectrum Broker. Efficient RRM framework performance, as a matter of maximum-possible resources utilization and benefit of Spectrum Broker, is achieved by proposing, implementing and evaluating an auction-based algorithm. This auction-based algorithm considers both frequency and time domain during TVWS allocation process which is defined as an optimization problem, where maximum payoff of Spectrum Broker is the optimization goal. Experimental tests that were carried-out under controlled conditions environment, verified the validity of the proposed framework, besides identifying fields for further research.

Keywords
Opportunistic cognitive radio systems, TVWS access, radio resource management algorithms, spectrum broker, centralized network architectures

1. INTRODUCTION
Cognitive Radio (CR) technology [1] was introduced in response to wireless networks needs for increased spectrum availability and improved radio-resource utilisation. Towards this direction, CR systems sense the surrounding spectral environment, identify any possible unused/unoccupied frequencies and adapt their transmission/reception parameters (operating spectrum, modulation, transmission power, etc.) for opportunistically accessing them, besides maintaining interference-free operation. Although conceptually quite simple, the introduction of opportunistic CR systems is not a straightforward process especially in licensed bands, where the existing spectrum management framework (i.e. the Command-and-Control regime) allows only Licensed/Primary systems to operate (e.g. DVB-T, DVB-H, PMSE, etc.), while prohibiting any other secondary/unlicensed transmission. Even though the utilization of advanced signal processing techniques may enable a very efficient spectrum-usage, under the existing spectrum management framework of “command-and-control”, there is a worldwide recognition that these methods of spectrum management have reached their limit and are no longer optimal. Furthermore, studies [2] have shown that there is a large number of under-utilised licensed spectrum, such as the TV white spaces (TVWS) [3], while in order to break away from the inflexibility and inefficiencies of command and control regime, a new spectrum policy is vital to be adopted that will permit the introduction of opportunistic CR systems in such spectrum bands.

Amongst the envisaged schemes are the “Spectrum of Commons” (or unlicensed policy) and the “Real-time Secondary Spectrum Market-RTSSM” (or licensed policy) [4], [5], [6]. The former, i.e. “Spectrum of Commons”, represents the case where coexistence with incumbent primary transmissions (e.g. DVB-T) is assured via the control of interference levels rather than by fixed spectrum assignment. In a “spectrum of commons” usage model there is no spectrum manager to preside over the resource allocation, similarly to the wireless ISM bands where users have to fulfil the technical rules ensuring good coexistence, but do not need to negotiate with existing players. However, despite the fact that unlicensed spectrum promotes efficiency through sharing, QoS cannot be guaranteed, which is a serious problem especially for QoS-sensitive applications. Sensing techniques for reliable detection of TVWS and coexistence mechanisms for interference avoidance are the main technical challenge. Defining spectrum policies and etiquette rules to promote fairness and avoid the “tragedy of the commons” are also key challenges.

On the orher hand, RTSSM policy enables Primary users (license holders) to trade spectrum usage rights to Secondary players (license vendees), thereby establishing a secondary market for opportunistic spectrum leasing and trading. The license holder runs an admission control algorithm, which allows secondary users to access spectrum only when QoS is adequate. RTSSM policy may be the most appropriate solution, especially for applications that require sporadic access to spectrum and for which QoS guarantees are important. Trading of secondary use may also occur through intermediaries such as a spectrum broker, exploiting spectrum resource management algorithms (RRM) for determining the frequency, at which a secondary user should operate along with the economics of such transactions. Secondary users, on the other hand, dynamically request access when-and-only-when spectrum is needed, and are charged based on spectrum utilization basis, as a matter of types of services, access characteristics and QoS level requests. The access types could consist of a long-term lease, a scheduled lease, and a short-term lease or spot markets. Each type requires different discovery mechanisms and applies with different levels of service agreements. Extensive research work has been contacted based on economic aspects, such as game theory [7], contract theory [8], auctions [9] and commodity pricing [10]. Among the proposed research approaches, auction-based algorithms have been exploited, towards elaborating on spectrum allocation issues [11], because of their fairness, efficiency and valuation independence [12]. A critical factor for auction-based approaches is to guarantee an economic property namely truthfulness [12], which denotes that bids submitted by the secondary systems requesting access to the available spectrum, reflect their true valuation.

Although conceptually quite simple, such a liberalised and opportunistic TVWS exploitation and the introduction of new spectrum models in CR networks require the appropriate network architectures. In this respect, CR networks are exploiting architectures that can be characterized (amongst the others) a) either as infrastructure-based or ad-hoc depending on the frequency that the network topology changes, b) or as single-hop or multi-hop depending on the communication between a transmitter and a receiver, and c) either as centralized if the decision of spectrum access is made by a central controller/module or distributed in case that the decision is made locally by each individual frequency-agile device. Nevertheless, in all cases vital part of CR networks is the radio resource management (RRM) [4], [13] which is responsible for providing optimized network performance and maintaining system-level control of the co-channel interference. Existing RRM implementations, as are proposed in [14], fall within two main categories of optimization algorithms: a) the decision making algorithms, which are trying to reach an optimal solution through classical mathematical rationalization, and b) game theory algorithms that view the radio-resource optimization as a “game” and try to find the optimal way to “play” it. The former is based on formulating an objective function (i.e. the goal of the optimization), as well as on setting equality and inequality constraints that the optimal solution must not cross, and comprises three groups of solutions, i.e. closed form solution, integer/combinatorial programming and mathematical programming. On the other hand, the game theory approach is based on the formulation of a “game” for the resource allocation problem, comprising two fundamental concepts, i.e. the Nash equilibrium and the Pareto optimality.

Also, integer/combinatorial programming encompasses the optimization problems that involve parameters with integer values or parameters that are of combinatorial nature (i.e. the word combinatorial refers to the fact that only a finite number of alternative feasible solutions exist). These are multi-objective problems that can be solved only as a search for the optimal answer through the entire set of possible answers. The goal of the integer/combinatorial programming is shortening the search to a smaller subset of possibilities. In CR networks, integer/combinatorial optimization problem formulations can be used to obtain efficient resource allocation methods, which meet the desired objectives when the values of some or all of the decision variables are restricted to be integers. Constraints on basic resources, such as modulation, channel allocation, and coding rate, restrict the possible alternatives that are considered. For example, channel allocation, modulation level, channel coding rate, and even power are discrete in a practical system.

However, a vital issue in such spectrum allocation processes is to achieve the most optimal solution, in terms of increasing Spectrum Broker benefit and provide an efficient spectrum utilisation. In a Broker-based CR architecture, the most optimal allocation can be performed, through collaboration among a radio resource management entity (RRM) as well as a spectrum trading entity. The former is responsible for optimally allocating the available TVWS, as a matter of maximum possible spectrum utilisation and minimum frequency fragmentation by exploiting optimisation methods [14]. On the other hand, spectrum trading entity undertakes/performs the economics of the TVWS transactions, taking into account a “spectrum-unit price” (e.g. cost per MHz).

More specifically, the objective of Spectrum Broker, during spectrum allocation process, is to maximize its revenue/profit, while the buyer desires to maximize the utility of spectrum usage, as well as its satisfaction in terms of QoS performance. However, these objectives generally conflict with each other. Therefore, an optimal and stable solution for spectrum allocation in terms of pricing would be required so that both the seller and the buyer are satisfied as close as to their willing. For this purpose, pricing can be considered as a major issue, closely related to spectrum allocation process that can keep fairness among the secondary systems and offer revenue to the Spectrum Broker. For instance, an integrated pricing, allocating and billing system is proposed in [15] for cognitive radio networks and a joint power/channel allocation scheme used in order to improve the performance of the network, is proposed in [16].

Furthermore, in a spectrum auction process, the bidders submit their bids (e.g. in terms of bidding price and quantity per spectrum unit) to the auctioneer, in order the latter to determine the winning bidder. Then, the spectrum is leased at a price, which will be defined during the auction process. Thereby, secondary systems can express their urgency to obtain access into the radio resources by submitting their bids. Thus the auction process allows secondary systems to actively influence the radio resources, in contrast to the Fixed Price Market, in which systems can only passively access the spectrum according to the first-come-first-served principle [17]. However, the above mentioned and related research approaches have not yet addressed the auction process for TVWS allocation, considering both frequency and time domains.

In this context, this paper proposes a RRM framework that exploits a combinatorial auction process, enabling to opportunistically lease the unused television spectrum (i.e. TVWS) to mobile operators and wireless network providers (i.e. secondary systems), by respecting a number of technical constrains that guarantee specific QoS requirements (i.e. transmission power limitations, bandwidth usage, interference limitations). To achieve this, a spectrum trading mechanism is proposed, operating in a centralized entity, (i.e. Spectrum Broker), which is in charge to optimally allocate the available TVWS of a specific location, based on the results of a combinatorial auction process. Spectrum Broker increases revenue, either by minimizing the spectrum fragmentation, under a fixed-price policy derived from market-driven rules [18], or by maximizing its profit, as well as the spectrum usage efficiency, under an auction-based policy. The auction-based algorithm that is proposed in this paper, considers both frequency and time domains, exploiting the second revenue model (i.e. spectrum auctions), while research work regarding fixed-price model is presented in [4], [5].

Following this introductory section, section 2 discusses the proposed radio resource management scheme based on a centralized CR network architecture, operating under the RTSSM regime. Section 3 elaborates on the auction process problem formulation and the performance evaluation of the proposed algorithm, in terms of spectrum broker utility/benefit, while section 4 concludes the paper by identifying fields for future research.

2. RADIO RESOURCE MANAGEMENT IN OPPORTUNISTIC CR SYSTEMS

This section firstly presents a broker-based CR network architecture for the efficient exploitation of TVWS under the RTSSM regime. The overall architecture of this network is depicted in Figure 1, and comprises two core subsystems: a) a Spectrum Broker responsible for coordinating TVWS access and administrating the economics of radio-spectrum exploitation, and b) a number of Secondary Systems (i.e. mobile network operators and wireless network providers), competing/requesting for TVWS utilisation.

According to this architecture, Spectrum Broker consists of four sub-entities, a TVWS occupancy repository, a RRM module for TVWS allocation, a spectrum trading repository and a spectrum trading module. The TVWS occupancy repository obtains information from the national database, namely as Geo-location database, which includes data regarding the available TVWS in specific locations and the maximum allowable transmission power of secondary systems per channel, in order to avoid causing interference to primary systems. The TVWS occupancy repository creates a spectrum-portfolio, including all the above mentioned information that is advertised to bidders. Moreover, the RRM module matches the secondary systems requirements with available resources and thus allocates the TVWS based on QoS requirements. The TVWS allocation mechanism implements an algorithm that uses information from the Geo-location database to determine the TVWS bands and power at which a secondary system should be allowed to operate, in order to avoid spectrum fragmentation, optimise QoS and guarantee fairness in TVWS access. Moreover, trading module is responsible to determine the revenue of Spectrum Broker, which aims to trade/lease spectrum with temporary exclusive rights to the most valuable bidder. Finally, spectrum trading repository hosts information about the TVWS selling/leasing procedure, as well as the spectrum-unit price to be exploited during the trading phase, creating a price-portfolio.

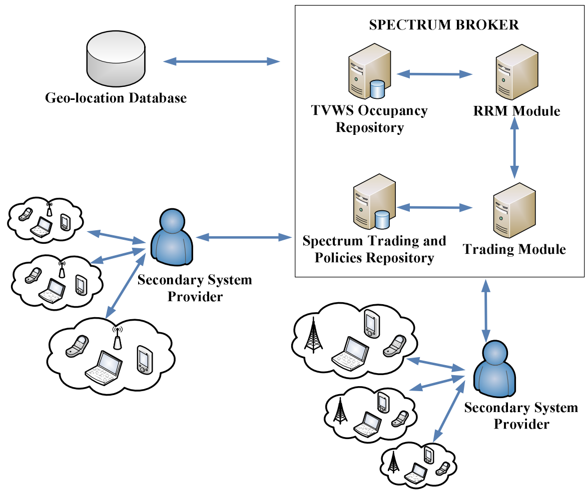

Figure. 1. Architecture of the proposed CR network operating under the RTSSM regime

The system operation is based on three layers/entities, as depicted in Figure 2, each one denoting a significant process for the resource allocation. The layers of the system comprised of the Local Recourse Manager (LRM), the Spectrum Manager (SM) and the Spectrum Broker (SB).

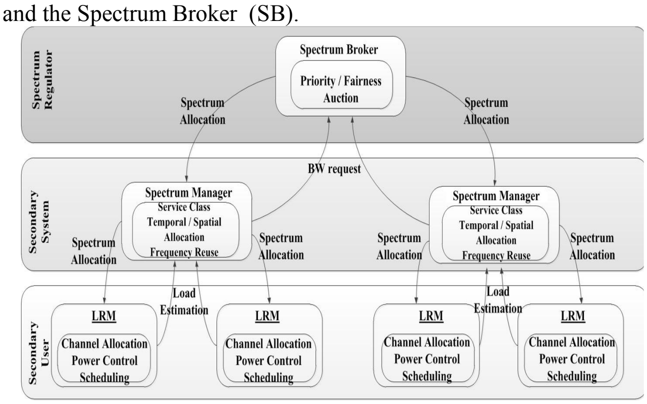

Figure. 2. Layers of system operation

The LRM is responsible for the disposal/assignment of spectral resources within the area of each secondary system. More specifically, LRM calculates the required bandwidth needed for each class, taking into account the radio link operation and the traffic load. Depending on the requests sent by the secondary users through the LRMs, the spectrum manager of each secondary system assigns to them the TVWS resources. Moreover, each spectrum manager sends information to the Spectrum Broker based on the requested bandwidth of each secondary system, the load handled, and the priority of classes. It also sends a negotiation request, in case that a secondary system requests for more bandwidth than the initial needs for bandwidth. The Spectrum Broker is responsible for conducting the spectrum allocation process, either utilising a fixed-price or an auction approach, based on negotiations and requests for required bandwidth.

Figure 3 illustrates the logical diagram of the proposed RRM framework and the trading processes/modules based on a decision-making approach, where a "Process Data" function is initially taking place for producing all possible combinations, and therefore a set of "Possible Allocation Solutions". As soon as all these Possible Allocation Solutions are established, the RRM calculates the optimum ones, and creates the Spectrum Portfolio that will be used by the Broker during the trading process. This Spectrum Portfolio is the result of the iterative process namely as "IsValidSolution" in Figure 3, which examines if a Possible Allocation Solution fulfils the SS's technical requirements. In such a case the Possible Allocation Solution is registered in the Spectrum Portfolio, otherwise it is discarded. To this extent, the selection of the best-matching solution (Optimal Solution), is the result of an optimisation process targeting either to minimise spectrum fragmentation (fixed-price policy) or to maximise the profit (auction-based trading), whichever is appropriate.

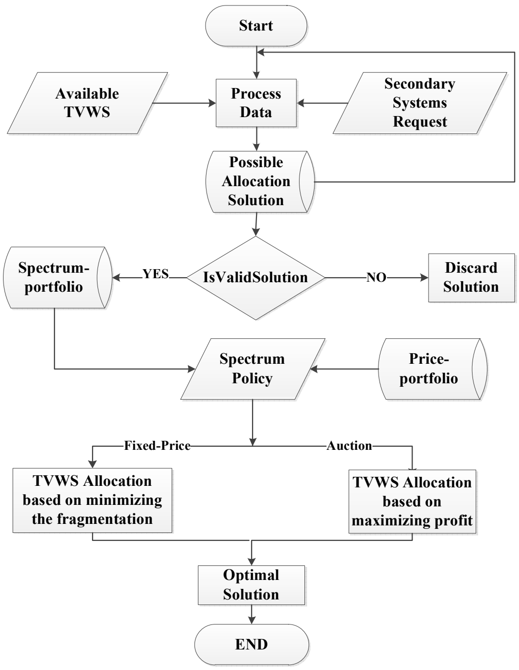

Figure 3. Logical diagram of the proposed RRM framework and trading modules

In case of spectrum auctions, the Spectrum Broker of the proposed network architecture is in charge of trading the available spectrum to a number of competitive secondary systems or bidders (denoted as I) that participate in the auction process. The total available spectrum, which can be leased by the Spectrum Broker is denoted as BW, comprising 10 TV channels (each one of 8MHz), scattered in the UHF spectrum, according to the spectrum pool depicted in Figure 4. In this case, the commodity of the auction is the spectrum, which consists of four fragments denoted as F, each one having different power requirements and sizes in MHz, denoted as Fi. Based on this spectrum pool, fragments sizes are F1 = 24MHz, F2 = 8MHz, F3=24MHz and F4 = 24MHz, while the aggregated available spectrum is 80 MHz. The total spectrum can be leased to I auction participants, such as LTE, WiMax, UMTS, WiFi and Public Safety secondary systems with different bandwidth and transmission power requirements. The final allocation of the fragments depends on the bids of all secondary systems and the profit maximization function of the Spectrum Broker.

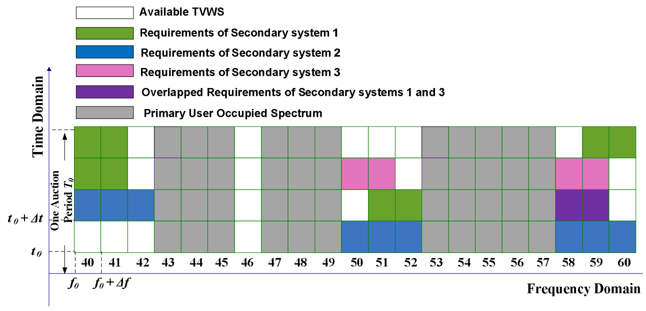

Figure 4. Time and Frequency domains for TVWS allocation

The Spectrum Broker of the proposed CR network architecture initially advertises data regarding spectrum portions that are available to be leased to secondary systems, as well as relevant maximum allowable transmission power thresholds. This information originated from the Geo-location database, is hosted within the TVWS Occupancy Repository. The Spectrum Broker firstly advertises the spectrum-portfolio and the price-portfolio to the secondary systems, in order to be informed for the transmission characteristics and the call price of the TVWS spectrum. After this stage, bidders (i.e. secondary systems) send/define their bids for the spectrum of interest, as well as the offered price. Spectrum Broker collects all bids and sends them to Radio Resource Management (RRM) module. RRM module analyses and processes bids as a matter of secondary systems technical requirements and the locally available TVWS channel characteristics. For each spectrum portion/fragment, Spectrum Broker creates and maintains a list with bids per time period, namely as auction-portfolio, in order to choose the most valuable bidder for each specific time slot. It has to be noted here that if two secondary systems send bids with the same requirements, factor of time defines the priority of the bid in order to be on higher position in the auction-portfolio. The auction portfolio is also analysed/elaborated by a Trading Module, taking into account a spectrum-unit price or call price (e.g. cost per MHz) that is based on spectrum-auction policies.

Finally, an optimised solution combining the RRM results and the Trading Module output is obtained, enabling Spectrum Broker to sell/assign TVWS frequencies to the corresponding secondary systems under the RTSSM regime/policy. In other words, Spectrum Broker is responsible for obtaining the best-matching solution, through an optimisation-based process, which constitutes a NP-hard problem, thus an approximation algorithm is required in order to solve the auction process.

3. AUCTION-BASED PROCESS PROBLEM FORMULATION AND PERFORMANCE EVALUATION

TVWS channels can be considered for opportunistic leasing by Spectrum Broker, taking into account both time and frequency domains, as shown in Figure 4. More specifically, Figure 4 depicts the occupied and the available TVWS, as well as requirements of secondary systems for accessing spectrum at specific time durations. S denotes all available TVWS, while Δt and Δf denote time and frequency interval respectively. For each (Δt,Δf) an unused part of spectrum is available for specific time (i.e. slot). According to the proposed auction process (see Table 1) and when CR network architecture operates under the auction-based mode, Spectrum Broker collects bids to lease spectrum to secondary systems and subsequently determines the allocation solution along with the price for each spectrum portion from the price portfolio, in order to maximize its profit. The auction process is then repeated, when spectrum portions are still available.

Table 1. Auction-Based Algorithm Pseudo-Code

1: **Inputs:** $TVWS_{pool}$, Location(x,y), $Power_{max}$, $Demand_{SS}$
2: Update TVWS repository from Geo-location database
3: Estimate the spectrum-unit price
4: Create and advertise price-portfolio
5: Receive secondary systems bids $P^{(b)} = \{P_1^{(b)},\ldots, P_I^{(b)}\}$,
   where $P_i^{(b)} = \{x_i, t_i\}$
6: **for** all Bids **do**
7:     Sort $P_i^{(b)}$ in descending order based on price and
       create the auction-portfolio
8: **end for**
9: Calculate the highest valuation S[i,j] for all TVWS slots
   (i,j) ϶ {1, 2,…, m}
10: set $S_{optimal} = S[i,j]$
11: **for** slot =1 to m **do**
12:     **if** (S[i,j]) ≤ (S[i+1, j+1])
13:         **then** save the new allocation solution (S[i+1,
            j+1]) to the best found
14:     **end if**
15: **end for**
16: **return** Best Solution

Furthermore, Spectrum sellers are denoted as N = {1,2,…,n}, while in the proposed CR network architecture N=1 (i.e. Spectrum Broker, leasing the available TVWS S = {1,2,…,s} to I = {1,2,…,i} secondary systems). Each buyer "i" is able to purchase xi portions of spectrum for a specific time ti by reporting a price $P_i^{(b)} = \{x_i, t_i\}$ (i.e. Bid Price), while Spectrum Broker leases yn portions of spectrum for a specific time ti by reporting a price $P_n^{(s)} = \{y_n, t_i\}$ (i.e. Asking Price). Finally, xi,n is the quantity that "i" secondary system purchases from Spectrum Broker.

Towards maximizing benefit of both Spectrum Broker and secondary systems, an optimization problem can be formulated as a linear programming problem as follows:

$$\max\ : \sum_{i=1}^{i} \sum_{n=1}^{n} x_{i,n} t_i (P_i^{(b)} - P_n^{(s)})$$

According to the simulation scenario, the auction period is divided into 15-minutes long (i.e. four time-auctions per hour) during the experimental test, as well as the available TVWS channels are 10. Therefore, the number of frequency-time slots for the competitive secondary systems are m=40. The experimental results that were obtained after the simulation tests referred to the evaluation of the Spectrum Broker utility for different number of secondary systems. Figure 5 depicts Spectrum Broker utility that is increased when more secondary systems are competing together to opportunistically access TVWS, according to the above mentioned auction process.

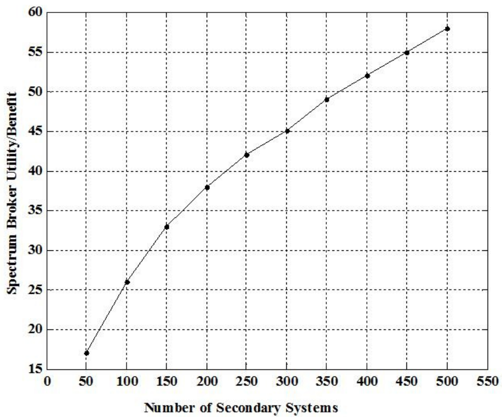

Figure 5. Spectrum Broker Utility/Benefit

4. CONCLUSIONS

This paper discussed a centralised CR network architecture that opportunistically exploits TVWS under the RTSSM regime and elaborated on the design, implementation and performance evaluation of a prototype auction-based RRM framework. Towards evaluating the performance of the proposed framework, a set of experiments was designed and conducted under controlled conditions, where various secondary systems were requesting access to the available TVWS by sending auction bids. The obtained experimental results verified the validity of the proposed framework as a matter of maximum-possible benefit of the Spectrum Broker. In this respect, fields for future research include qualitative and quantitative comparison between alternative auction-based algorithms, where the TVWS exploitation can be obtained in real time.

5. ACKNOWLEDGMENTS

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