A Dynamic Spectrum Management Framework for Efficient TVWS Exploitation

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Abstract-**This paper elaborates on a prototype spectrum management framework, for dynamic exploitation of underused radio spectrum, such as TV White Spaces (TVWS), QoS provisioning and policy management, under the real time secondary spectrum market policy. The proposed framework is applied in a centralised Cognitive Radio (CR) network architecture, where the exploitation of the available TVWS, as well as the administration of the economic transactions is orchestrated via a Spectrum Broker. Towards efficiently exploiting TVWS, a fixed-price algorithm is proposed that coordinates the available resources among Secondary Systems, in terms of maximum possible TVWS utilisation and minimum frequency fragmentation. Furthermore, an auction-based algorithm is proposed that considers both frequency and time domain during TVWS allocation process, where maximum payoff of Spectrum Broker is the optimization target. Experimental tests that were carried-out under controlled conditions environment, verified the validity of the proposed framework, besides identifying fields for further research.**

Keywords: Optimization Algorithms, Spectrum Broker, Spectrum Management Framework, TVWS

I. 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 devices sense the surrounding spectral environment [2], [3] 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 CR networks 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 [4] have shown that there is a large number of under-utilised licensed spectrum, such as the TV white spaces (TVWS) [5], 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 CR networks in such spectrum bands.

Amongst the envisaged schemes [6], [7], is the "Real-time Secondary Spectrum Market - RTSSM" policy, enabling Primary users (license holders) to trade spectrum usage rights to Secondary players (license vendees), thereby establishing a secondary market for spectrum leasing and trading. RTSSM policy may be realized in centralised CR architectures, where intermediaries, such as a Spectrum Broker, carry out spectrum trading, which can be based on technical and financial aspects. Spectrum Broker is in charge of allocating spectrum dynamically among competing secondary systems, in terms of type of services, access characteristics and QoS level requests, besides federating the economics of such transactions. Extensive research work has been contacted based on economic aspects, such as game theory [8], contract theory [9], auctions [10] and commodity pricing [11]. Among the proposed research approaches, auction-based algorithms have been exploited, towards elaborating on spectrum allocation issues, 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.

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) [6], [13] as well as a spectrum trading entity. The former is responsible for optimally allocating the available TVWS, in terms of maximum possible spectrum utilisation and minimum frequency fragmentation by exploiting optimisation methods. 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, in [14] authors proposed an integrated pricing, allocating and billing system for cognitive radio networks, as well as in [15] a joint power/channel allocation scheme is exploited in order to improve the performance of the network.

Furthermore, in a spectrum auction process, 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 [16]. However, the above mentioned methods, as well as 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 Dynamic Spectrum Allocation framework that exploits either fixed-price or combinatorial auctions, enabling to 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 the dynamic spectrum allocation process. Spectrum Broker increases revenue, either by minimizing the spectrum fragmentation, under a fixed-price policy derived from market-driven rules, or by maximizing its profit, as well as the spectrum usage efficiency, under an auction-based policy, considering both frequency and time domains.

Following this introductory section, section 2 discusses the design of a cognitive radio network architecture, operating under the RTSSM regime under fixed-price and auction-based mode. Section 3 elaborates on problem formulation for both fixed-price and auction-based approaches as well as on the performance evaluation of the proposed algorithms, in terms of Spectrum Broker utility/benefit and spectrum fragmentation. Finally, section 4 concludes the paper by identifying fields for future research.

II. Cognitive Radio Network Architecture for QoS Provision

This section 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. In particular, this network architecture consists of secondary systems, that provide different services classes depending on the type of service, voice data, etc.

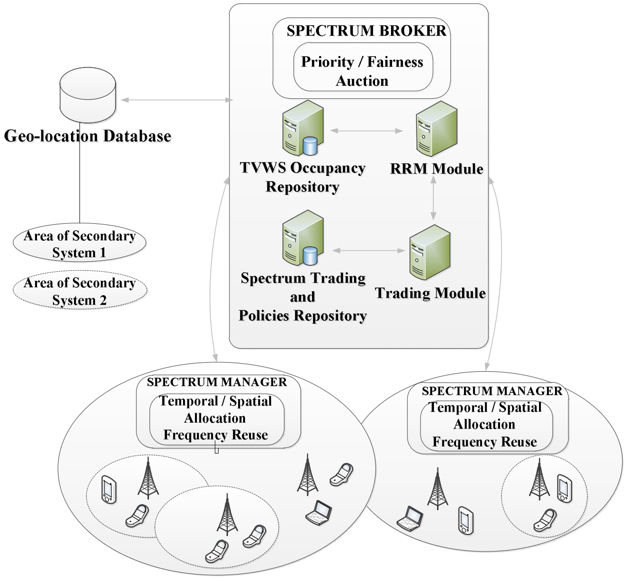

Fig. 1. Architecture of the proposed CR network operating under the RTSSM regime

According to this architecture, Spectrum Broker comprised 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.

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).

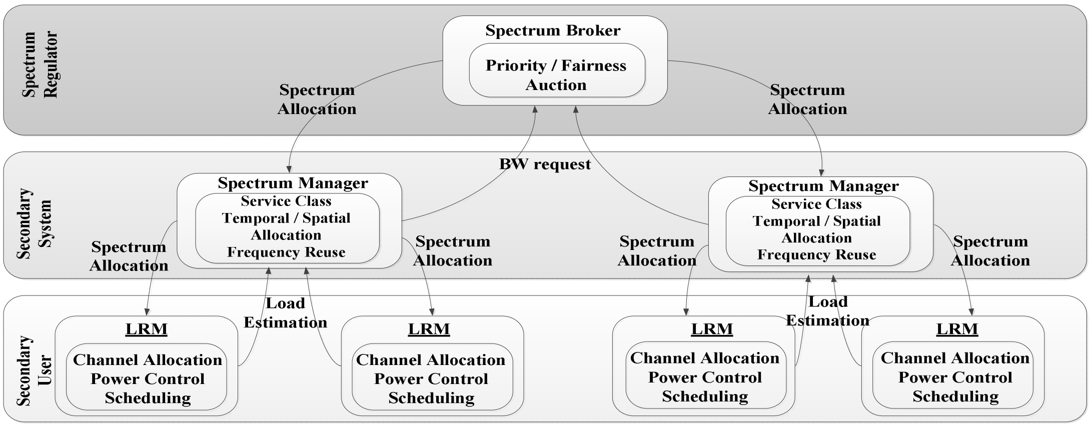

Fig. 2. Layers of system operation

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.

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 allocation/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 3. In this case, the commodity of the allocation/auction is the spectrum, which consists of four fragments denoted as F, each one having different power requirements and sizes in MHz, denoted as F_i. Based on this spectrum pool, fragments sizes are F_1 = 24MHz, F_2 = 8MHz, F_3 = 24MHz and F_4 = 24MHz, while the aggregated available spectrum is 80 MHz. The total spectrum can be leased to I allocation/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 interest/bids of all secondary systems and the profit maximization function of the Spectrum Broker.

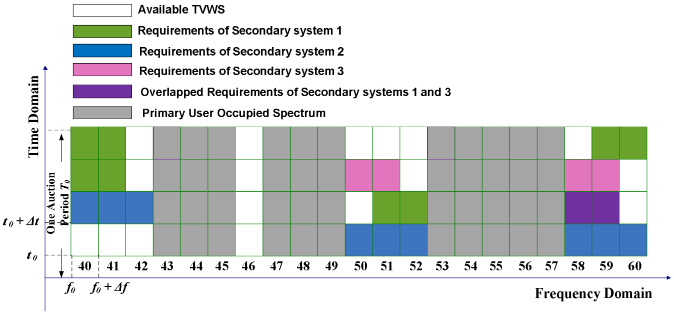

Fig. 3. Time and Frequency domains for TVWS allocation

The Spectrum Broker of this 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. It has to be noted here that the following description of the RRM is taking into account both market-driven policy (i.e. fixed-price), as well as auction-based policy. Thus, 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 needs/bids for the spectrum of interest, as well as the offered price, in case of auctions. Spectrum Broker collects all interests/bids and sends them to Radio Resource Management (RRM) module. RRM module analyses and processes them in terms 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 interest/bids per time period, namely as auction-portfolio, in order to choose the most valuable bidder for each specific time slot, in case of auction process, or to assign TVWS to secondary systems that causing the least spectrum fragmentation, in case of fixed-price. 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 either the fixed-price or the auction process.

III. PROBLEM FORMULATION AND PERFORMANCE EVALUATION

TVWS channels can be considered for leasing by Spectrum Broker, taking into account both time and frequency domains, as shown in Figure 3. More specifically, Figure 3 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 fixed-price allocation process (see Algorithm 1), the Spectrum Broker obtains the optimal solution by minimising an objective function *"C(A')"*, in terms of allowable transmission power (*P(i,f)*), requested bandwidth (*BW(i,f)*), spectrum fragmentation (*Frag(i,f)*) when a secondary system *"i"* is assigned to a specific frequency *"f"* and/or secondary systems' prioritisation (*Pr(i)*) (e.g. in case that a number of secondary systems must be served before other ones, due to higher QoS level priority).

$$minimise: C(A') = \sum_{i\in V}\sum_{f\in F} x_{if[P(i,f)+BW(i,f)+Frag(i,f)+\Pr(i)]} \qquad (1)$$

On the other hand, in auction process (see Algorithm 2), the, 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.

Furthermore, in case of auctions, 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 x_i portions of spectrum for a specific time t_i by reporting a price $P_i^{(b)} = \{x_i, t_i\}$ (i.e. Bid Price), while Spectrum Broker leases y_n portions of spectrum for a specific time t_i by reporting a price $P_n^{(s)} = \{y_n, t_i\}$ (i.e. Asking Price). Finally, $x_{i,n}$ 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:

$$maximise: \sum_{i=1}^{i}\sum_{n=1}^{n} x_{i,n} t_i (P_i^{(b)} - P_n^{(s)}) \qquad (2)$$

ALGORITHM 1: FIXED-PRICE PSEUDO-CODE

```
Inputs: $TVWS_{pool}$, Location(x,y), $Power_{max}$, $Demand_{SS}$
Update TVWS repository from Geo-location database
Estimate the spectrum-unit price
Create and advertise price-portfolio
Receive secondary systems request R= {$R_1$,…, $R_I$},
  where $R_i$ = {$x_i$, $t_i$}
for all Requests do
    Sort $R_i$ in descending order based on priority and
    update the price-portfolio
end for
Calculate the minimum fragmentation (Frag(i,f)) for all
secondary system requests
Create initial solution S
for i = 1 to subset of variable length do
    Generate a new solution $S_i$
    if (Objective_function(S) ≤ Objective_function($S_i$))
        then save the new allocation solution $S_i$ to best found S
    end if
end for
return Best Allocation Solution
```

ALGORITHM 2: AUCTION-BASED PSEUDO-CODE

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

According to the simulation scenario for both fixed-price and auction-based mode, the allocation/auctions periods are divided into 15-minutes long (i.e. four time-periods 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 quantitative and qualitative comparison of both policies in terms of the Spectrum Broker utility and spectrum fragmentation for different number of secondary systems. Figure 4 depicts Spectrum Broker utility for both algorithms, which is increased when the number of secondary systems that are competing together to access TVWS, is increasing, according to the above mentioned simulation scenario.

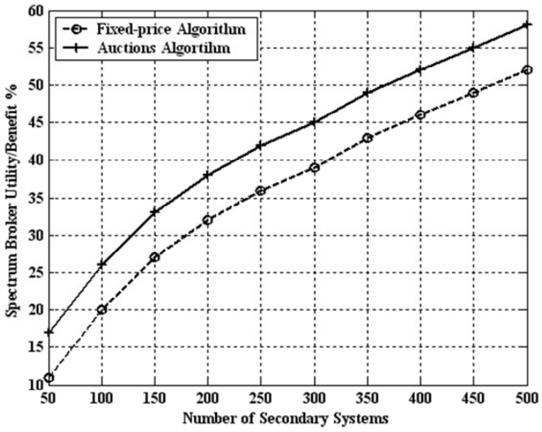

Fig. 4. Spectrum Broker Utility/Benefit

Moreover, Figure 5 represents Spectrum Fragmentation obtained after the spectrum allocation process for both algorithms. Fixed-price algorithm offers optimum values with a lower Spectrum Fragmentation in comparison to the auction-based approach.

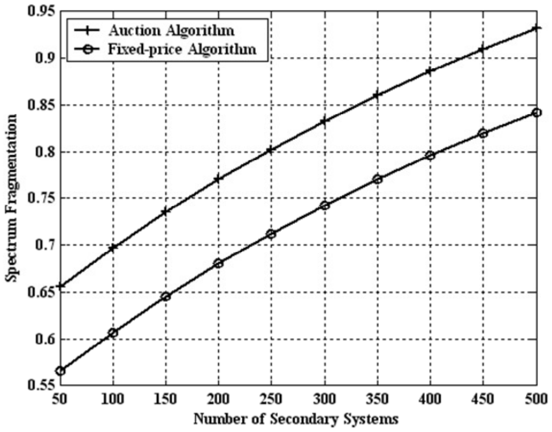

Fig. 5. Spectrum Fragmentation

IV. CONCLUSIONS

This paper discussed a centralised CR network architecture that exploits TVWS under the RTSSM regime and elaborated on the design, implementation and performance evaluation of a prototype 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 in terms 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.

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