# Radio Resource Management Algorithms for Efficient QoS Provisioning over Cognitive Radio Networks

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*Abstract*—**This paper proposes two radio resource management (RRM) algorithms for efficient QoS provisioning over an infrastructure-based cognitive radio network architecture that enables for TV White Spaces exploitation. QoS provisioning and policy management is achieved via a spectrum broker that coordinates the RRM process among LTE secondary systems, under the real time secondary spectrum market policy. The proposed RRM algorithms administrate the economics of the transactions between the spectrum broker and secondary systems, following a fixed-price and an auction-based trading process. The validity of the proposed algorithms is verified via a number of tests, carried under controlled experimental conditions (i.e. simulations), evaluating spectrum broker benefit and secondary systems service rate.**

***Keywords – TVWS Management, QoS Provisioning, Cognitive Radio Networks, RRM Algorithms.***

## I. INTRODUCTION

Cellular networks services, rich in multimedia content, raise the needs for increased radio spectrum availability and create new challenges in wireless networks resources management and guaranteed QoS provisioning. Radio spectrum utilization studies have resulted that most of the licensed spectrum is under-utilized [1] and considerable parts of it, would be available when both space and time dimensions are taken into account. “TV White Spaces” (TVWS) is an example of under-utilized spectrum that comprise of VHF/UHF channels, released after the process of digital switchover, as well as of interleaved spectrum, which is available due to frequency planning issues [2]. TVWS include large parts of radio spectrum especially at local/regional level, enabling for low cost and low power systems design due to superior propagation conditions [3]. Therefore, TVWS are well suited for wireless networks services, provided by sophisticated cellular systems. However, the current “command-and-control” radio spectrum management policy allows only for primary (i.e. licensed) systems to exploit TVWS for the provision of primary services, such as terrestrial digital video broadcasting (DVB-T), handheld digital video broadcasting (DVB-H), interactive (iTV), Programme Making and Special Events (PMSE), while prohibiting any other secondary transmission. Hence, the problem of spectrum scarcity is due to inefficient radio spectrum management, rather than the wireless resources shortage.

Towards addressing the need for increased radio spectrum demand, a number of sophisticated technologies may be exploited, such as the LTE standard [4] that provides flexible deployment, in terms of high spectral efficiency, bandwidth and different modulation/coding schemes. In addition, LTE systems can be designed to operate in alternative unused spectrum bands (e.g. TVWS), when both dimensions of space and time are considered [5], and they can coexist with other telecommunication systems. LTE deployment over TVWS may enable cellular networks operators to cover large geographical areas with less number of base stations, decreasing investment costs and providing cheaper cellular broadband services, especially to end users located in rural areas. Furthermore, this specific part of spectrum could be exploited to support peak data traffic in urban areas with increased bandwidth demands, while several schemes to share channels on a temporary basis of short or medium duration may be investigated, towards providing relief of crowded cellular networks that experience peak loads. The exploitation of TVWS will allow for more network carriers to be available at lower frequencies and despite the fact that a part of VHF/UHF radio spectrum will be dedicated for digital terrestrial television and wireless microphones services, another part of it will remain under-utilized for future secondary usage.

The deployment of LTE systems requires a new radio spectrum management policy. Among the envisaged schemes

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[6], [7] the “Real-time Secondary Spectrum Market - RTSSM” policy is the most appropriate solution, especially for deployments that require sporadic access to radio spectrum and for which QoS guarantees are important. RTSSM policy, adopts spectrum trading by permitting the spectrum license holder to run admission control algorithms that allow secondary systems to access radio spectrum only when QoS is adequate. Trading of secondary spectrum usage may occur through network management entities (e.g. spectrum broker), exploiting radio resource management (RRM) algorithms [6], [8], in order to efficiently allocate the available resources to secondary systems [9], [10]. Secondary systems, in this case, dynamically request access only when radio spectrum is needed, and are charged based on channel utilization basis, as a matter of types of services, access characteristics and priority level requirements. The access types may comprise a long-term lease, a scheduled lease and a short-term lease or spot markets, while the discovery mechanisms and levels of service agreement vary from one access type to another.

A vital enabler towards the deployment of LTE systems over TVWS, considering the RTSSM policy is Cognitive Radio (CR) technology/networks [11], [12]. CR networks enable for the dynamic access of radio spectrum from secondary systems, by avoiding the interference to primary ones. For this purpose, a centralized network architecture [13] is appropriate for LTE deployment based on RTSSM policy, rather than a distributed one, due to QoS provisioning requirements. Furthermore, the exploitation of a spectrum broker will enable for orchestrating the available network resources, by collecting information about radio spectrum access usage stemming from primary systems, as well as information about the transmission requirements/demands from secondary ones. Based on this information, an optimal solution (e.g. solution that maximises spectrum utilisation) on dynamic spectrum access can be obtained. Nevertheless, in all cases, and no matter which network architecture or radio spectrum management policy is adopted, the deployment of LTE networks over TVWS leads to another challenge, regarding the proper coexistence of primary with secondary systems, avoiding possible channel interference. Unlike current cellular networks, operating, under fixed radio spectrum allocation schemes, future LTE deployment scenarios will take into account adjacent channel interference issues with other telecommunication systems. Therefore, such a deployment results the necessity to accommodate dynamic adjacent channel interference control, as well as more sophisticated radio resources management techniques, by considering optimized solutions to allocate network resources, in order to increase network performance and provide guaranteed QoS.

Although excellent efforts [14], [15] have been made, towards addressing RRM challenges in CR networks, all research approaches mainly focus on resource management among primary and secondary systems, assuming an ideal spectrum sensing by secondary ones. However, an ideal spectrum sensing is impractical due to hardware limitation, short sensing period and network connectivity issues [16]. Moreover, the ongoing developments of the wireless applications require to support heterogeneous services with diverse QoS. Most existing research works focus on only one type of service carried by secondary systems.

In this context, this paper is making progress beyond the current state-of-the-art, by proposing two RRM algorithms for efficient QoS provisioning and TVWS management over a CR network architecture. The operation of such CR network architecture and the economic transactions of TVWS management, are orchestrated via a radio spectrum broker, which receives TVWS information from a geo-location database and is in charge to guarantee QoS provisioning over LTE secondary systems. Following this introductory section, Section 2 discusses the design of the spectrum broker by elaborating on optimisation techniques for the implementation of the RRM and trading modules and presents the proposed TVWS allocation algorithms. Section 3 elaborates on the performance evaluation of the proposed RRM algorithms and provides simulation results, while section 4 concludes the paper by identifying fields for future research.

## II. QoS Provisioning over a Broker-Based Cognitive Radio Network

This section firstly presents a broker-based CR network architecture for the efficient exploitation of TVWS, under the RTSSM regime. The overall network architecture is depicted in Figure 1, comprising of a spectrum broker that coordinates TVWS access and administrates the economics of radio spectrum exploitation, a number of LTE secondary systems, competing/requesting for TVWS utilization, as well as of a Geo-location database. According to this architecture, the 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 geographical locations and the maximum allowable transmission power levels 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 LTE secondary systems.

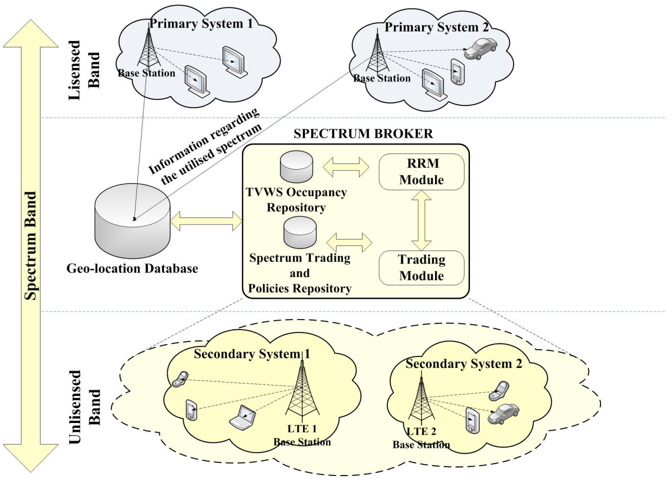


Fig. 1. Broker-based network architecture enabling TVWS management

Moreover, the RRM module matches the LTE systems requirements with available resources and thus allocates the TVWS based on specific QoS requirements. The proposed TVWS allocation mechanism adopts/implements RRM algorithms, which exploit information stemming from the Geo-location database, in order to determine the available channels and maximum transmission power levels, at which a secondary system is allowed to operate, towards avoiding spectrum fragmentation, optimising RRM process and supporting QoS provision or guaranteed fairness of TVWS access. Also, the trading module is responsible to determine the revenue of the spectrum broker, which aims to trade/lease radio spectrum with temporary exclusive rights to the most valuable secondary systems. Finally, the module of spectrum trading repository possesses data, regarding the TVWS leasing process and the price per spectrum-unit that is vital during the phase of resources trading, towards creating a price-portfolio.

Despite the benefits that obviously arise from adopting LTE systems to operate over TVWS, in terms of coverage and capacity, QoS per service must also be taken into account, according to specific service level agreements (SLAs). TVWS allocation has to guarantee the exclusivity of radio spectrum usage, while interference levels have to be kept low, in order to guarantee QoS among LTE base stations and user terminals. In this context, a second level RRM process between LTE operator and user terminals (access network) may be adopted, in order to take advantage of this new available portion of radio spectrum. Such second level RRM procedures are implemented at operator's network and aim to optimise the available radio resources provided by spectrum broker, increasing coverage and capacity, without compromising QoS. Basically, the second level RRM process should at each moment guarantee QoS (e.g. bit rate, delay, jitter), the network Key Performance Indicators (KPIs) and at the same time targeting the highest system capacity. During traffic peaks, the use of extra channels over TVWS is welcome, in order to provide extra capacity and keep the QoS above the minimum value. The LTE operator has a SLA that should be taken into consideration and defines the minimum quality that operator should provide to its user terminals. The second level RRM exploits several QoS parameters that describe the properties of the transmission channel, including bit rates, packet delay, packet loss, bit error rate, and scheduling policy in the LTE access network.

The radio spectrum broker entity adopted in the proposed CR network architecture (see Figure 1) is in charge to manage/trade the available channels among a number of secondary systems (LTE), which participate to this network resources allocation process. It initially informs secondary systems, regarding spectrum portions that are available to be leased, 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 advertises both a spectrum-portfolio and a price-portfolio to the secondary systems, in order to be informed for the transmission characteristics and the call price of the available TVWS. After this stage, LTE systems provide their demand for the available spectrum portions, which is defined by the offered price. Spectrum broker firstly collects all radio spectrum requests/demands in the RRM module, which is in charge to analyse and process them, as a matter of all technical requirements of LTE systems and the available TVWS characteristics. For each spectrum portion/fragment, spectrum broker creates and maintains a list with the requests, namely as request-portfolio, in order to allocate each spectrum fragment to the most valuable LTE system that showed interest, respecting QoS requirements/constraints (i.e. priority level). It has to be noted here that if two LTE systems request for a spectrum fragment with the same price and QoS requirements, then a first-come-first-served scheme is adopted, in order to sort requests on the appropriate position in the request-portfolio. The request-portfolio is also analysed/elaborated by a Trading Module, taking into account a spectrum-unit price or call price (e.g. cost per MHz).

Finally, an optimised solution, by combining radio resource management results and Trading Module output is feasible to be achieved, enabling spectrum broker to assign TVWS channels to the appropriate secondary systems, under the RTSSM policy. In this spectrum management policy, the choice of the optimal solution can be obtained based on an optimisation procedure, aiming either to minimise spectrum fragmentation (fixed-price mode) or to maximise the profit (auction-based mode). 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 this network resources allocation process. For this purpose, the proposed radio spectrum broker adopts/exploits optimisation methods [17], including decision-making ones, which are able to reach to an optimal problem solution by exploiting classical mathematical rationalization. In this optimization category, a number of techniques can be exploited, in order to provide the optimal solution, such as the integer/combinatorial programming (e.g. Backtracking) and the mathematical programming (e.g. Simulated Annealing, Genetic Algorithm). While the former obtains a "global" optimum solution through all the set of solutions, the latter selects it from a smaller set of solutions that respect the objective function.

Towards solving the fixed-price allocation process, algorithm 1 below is proposed that obtains the optimal solution by minimising an objective function (equation 1) *"C(A')"*, as a matter 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). The goal in fixed-price mode is to minimize spectrum fragmentation as possible, in order to avoid having small ineffective "chunks" of spectrum that minimize spectrum utilization. Keeping spectrum fragmentation in low levels results to an optimum spectrum utilization. Also, the probability a secondary system to operate in fragmented, un-continuous radio spectrum is low and thus valuable wireless networks resources remain unexploited.

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

ALGORITHM 1: FIXED-PRICE ALGORITHM 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= $\{R_1,\ldots, R_I\}$,
  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

Alternatively, for the auction-based mode (see Algorithm 2) spectrum broker collects bids to buy from secondary systems, bids to sell from Spectrum Trading and Policies Repository, and subsequently determines the allocation solution along with the price for each spectrum portion from the price portfolio, in order to maximize the spectrum broker profit. The auction process is then repeated based on the available radio spectrum remaining. Towards maximising the benefit of both Spectrum Broker and LTE secondary systems, an optimization problem can be formulated as a linear programming problem as follows:

$$max\colon \sum_{k=1}^{k}\sum_{k=1}^{k_n}(P_i^{(b)} - P_n^{(s)})x_{i,n} \qquad (2)$$

where, each buyer *"i"* (i.e. LTE secondary systems) wishes to purchase $x_i$ portions of spectrum by reporting a price $P_i^{(b)}$ (Bid Price) and each seller *"n"* (in our case n=1, the spectrum broker) wishes to sell $y_n$ portions of spectrum by reporting a price $P_n^{(s)}$ (Asking Price). $k$ is the total number channels (i.e TVWS that a secondary system wishes to buy). Finally, $x_{i,n}$ is the quantity that the *"i"* secondary system purchase from the spectrum broker (i.e n=1).

ALGORITHM 2: AUCTION-BASED ALGORITHM 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 $P^{(b)} = \{P_1^{(b)},\ldots, P_I^{(b)}\}$,
  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,s] for all TVWS slots
  (i,s) ∍ {1, 2,…, m}
set $S_{optimal}$ = S[i,s] //Random solution for algorithm initiation
**for** slot =1 to m **do** //Iteration process in order to find the best solution
  **if** (S[i,s]) ≤ (S[i+1, s+1]) // Check if the current solution is better or not to the neighbor solution
    **then** save the new allocation solution (S[i+1, s+1]) to the best found
  **end if**
**end for**
**return** Best Solution

## III. PERFORMANCE EVALUATION

### *A. Test-bed description and technical specifications*

Towards verifying the validity of the proposed RRM algorithms and the capacity of the CR network architecture for efficient TVWS exploitation and QoS provisioning within the RTSSM policy, a decision making process was implemented by exploiting Simulated Annealing algorithm [17]. In this context, several sets of experiments were designed and conducted under controlled-conditions (i.e. simulations) evaluating the performance of the above algorithms, as a matter of LTE secondary systems service rate and the percentage of spectrum broker benefit. The experimental test-bed consists of a TVWS Occupancy Repository, which keeps records about UHF/TV frequencies that can be utilised by LTE secondary systems. Information in this repository was built around actual/real spectrum data gathered within the framework of the ICT-FP7 "CogEU" project [18], concerning TVWS availability between 626MHz (Ch.40) and 752MHz (Ch.60) in Munich area, Germany [19]. It should be noted that in the simulation tests that were conducted, both fixed-price and auction-based modes were selected, based on a single spectrum-unit price that was applied for every TVWS trading process.

In this context, simulation scenario includes seven LTE secondary systems with different radio characteristics that were simultaneously competing for the available TVWS during 4 different time periods. More specifically, Figure 2 presents the time periods of operation for seven LTE secondary systems demanding access to the available radio spectrum (i.e. TVWS). LTE secondary systems operate under Time-Division-Duplexing (TDD) mode, while a different QoS level was adopted for each system, based on specific services requirements. This QoS level was respected by the optimisation algorithms for both fixed-price and auction-based mode, during spectrum allocation process. Additionally, for each new simulation period (namely as Time Period in the experimental tests) secondary systems with different QoS expectation were entering the test-bed, under a fixed schedule, requesting access to the available (at the given Time Period) TVWS. The technical specifications of such LTE secondary systems are presented in Table 1.

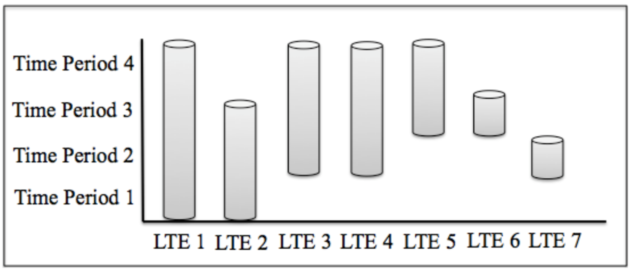


Fig. 2. Time Periods of simulation scenario

From Table 1 it comes that there are two major types of services defined with guaranteed bit rate (GBR) and non-guaranteed bit rate (Non-GBR). GBR services are real-time applications, such as conversational voice and video, while Non-GBR services include P2P and Web applications. For a GBR service, a minimum amount of bandwidth is reserved by the proposed system and the network resources provision is guaranteed, by taking into account specific QoS requirements.

GBR services should not experience packet losses or high latency in case of network congestion.

TABLE I
TECHNICAL SPECIFICATIONS OF EACH SECONDARY SYSTEM

| **Secondary System** | **Services Provided** | **Bandwidth (MHz)** | **Priority/QoS Level** |
|---|---|---|---|
| **LTE 1** | TCP-based services (GBR) | 20 | Medium |
| **LTE 2** | P2P (Non-GBR) | 5 | Low – Best Effort |
| **LTE 3** | Internet (Non-GBR) | 20 | Low – Best Effort |
| **LTE 4** | Video (GBR) | 20 | High |
| **LTE 5** | Video (GBR) | 10 | High |
| **LTE 6** | P2P (Non-GBR) | 5 | Low – Best Effort |
| **LTE 7** | Video (GBR) | 5 | Medium |

On the other hand, Non-GBR services are provided under a best effort scheme and a maximum bit rate is not guaranteed on a per-service basis. Based on the above mentioned request for specific time period of operation, by LTE secondary systems (see Figure 2), as well as the QoS requirements (see Table 1) that represent priority level of each system, both the proposed algorithms of this paper are evaluated and compared.

### *B. Simulation Results*

Performance evaluation results that were obtained after multiple simulation/experimental tests provide a quantitative and qualitative comparison of both proposed RRM algorithms, in terms of spectrum broker benefit and secondary systems service rate. More specifically, the upper diagram of Figure 3 depicts spectrum broker benefit for both RRM algorithms (i.e. auction-based and fixed mode). It can be observed that spectrum broker benefit is increasing when the number of LTE secondary systems concurrently accessing TVWS channels, is increasing during all time periods of the above mentioned simulation scenario. Furthermore, auction-based mode provides an optimized performance, in terms of spectrum broker benefit (i.e. increased percentage), in comparison to fixed-price mode. The lower diagram of Figure 3 represents the service rate of all secondary systems for both allocation processes (i.e. algorithms). It can be observed that the proposed spectrum broker and RRM algorithms respect QoS requirements of secondary systems, according to the simulation scenario defined above.

## IV. CONCLUSION

This paper proposes two radio resource management algorithms, operating in a centralised CR network architecture, towards providing TVWS exploitation, QoS provisioning and network management, under the RTSSM policy. It elaborated on the design of the radio resource management and the trading modules of a spectrum broker, by utilising decision-making processes based on Simulated Annealing. Towards evaluating the performance of the proposed RRM algorithms, a number of experimental tests, was designed/conducted under controlled simulation conditions, where LTE secondary systems were concurrently accessing the available TVWS channels during different time periods. The obtained experimental simulation results verified the efficiency of the proposed spectrum broker, in terms of QoS provisioning, respecting a number of constraints that were defined for the LTE secondary systems. In this respect, fields for future research include qualitative and quantitative comparison between other optimisation algorithms, where the TVWS exploitation and QoS provisioning can be obtained by adopting alternative optimisation methods/techniques.

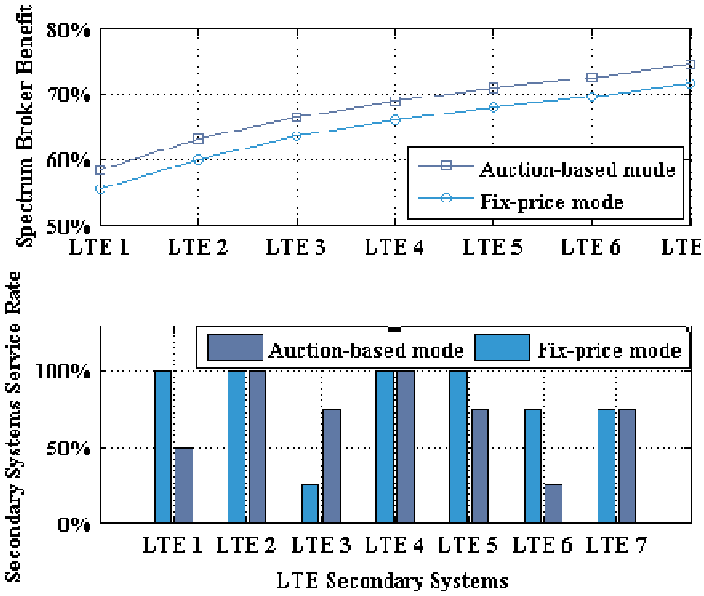


Fig. 3. Performance Evaluation Results


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