QoS provisioning and policy management in a broker-based CR network architecture

Athina Bourdena
Department of Information and Communication Systems Engineering
University of the Aegean
Samos, Greece
abourdena@icsd.aegean.gr.

Evangelos Pallis
Department of Applied Informatics and Multimedia
Technological Educational Institute of Crete
Heraklion, Crete, Greece
pallis@epp.teicrete.gr

Georgios Kormentzas, Charalabos Skianis
Department of Information and Communication Systems Engineering
University of the Aegean
Samos, Greece
gkorm@aegean.gr, cskianis@aegean.gr

George Mastorakis
Department of Commerce and Marketing
Technological Educational Institute of Crete
Ierapetra, Crete, Greece
gmastorakis@staff.teicrete.gr

Abstract—**The paper presents an infrastructure-based cognitive radio network architecture that enables for TV white spaces exploitation, QoS provisioning and policy management, under the real time secondary spectrum market policy. It describes the configuration of a spectrum broker that coordinates the radio resource management process (RRM) among LTE secondary systems as a matter of maximum possible TVWS utilisation and minimum frequency fragmentation, and also administrates the economics of such transactions towards maximum revenue following a fixed-price trading. The validity of the proposed architecture is verified via a number of tests carried under controlled experimental conditions (i.e. simulations) exploiting a decision-making algorithm.**

Keywords - Cognitive Radio, QoS, Radio Resource Management, Spectrum Broker, Spectrum Policy, TVWS.

I. INTRODUCTION

Cognitive Radio (CR) technology [1], [2], [3] was introduced in response to wireless networks' needs for increased spectrum availability and improved radio-resource utilisation. To achieve these, CR devices 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. Towards addressing the challenge for increased spectrum demand, a number of sophisticated technologies may be additionally 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, when both dimensions of space and time are considered [5], as well as coexist with other telecommunication systems. Such a case of unused spectrum bands are the TV white spaces (TVWS) [6] that usually sum up-to tenths of MHz at local/regional level [7], provide superior propagation conditions and building penetration capabilities, facilitate low cost and low power system design, while at the same time their sufficiently short wavelength enables for the construction of resonant antennas, at a shape and size, which is acceptable for many mobile devices.

TVWS are well-suited for wireless network applications and cellular systems, such as LTE ones that can take advantages from low frequency propagation characteristics, enabling mobile operators to cover large geographical areas with less number of base stations. This will decrease the investment cost of mobile operators, allowing them to provide cheaper cellular broadband services, especially to end users located in rural areas. On the other hand, TVWS could be used for peaking support in dense urban areas, while schemes for obtaining and sharing channels on a temporary basis (short or medium term) need to be investigated, in order to provide relief for crowded networks experiencing peak loads. The exploitation of TVWS will allow more carriers to be available at lower frequencies (in UHF band) and despite the fact that part of the band will be occupied, (e.g., by Digital Terrestrial Television and wireless microphones), a great part of it will be still available for other usages.

Although conceptually quite simple, the deployment of LTE secondary systems within TVWS is currently hampered by the traditional "command and control" spectrum policy, thus a new spectrum management policy is vital towards overcoming this issue. Among the envisaged schemes [8], [9] is the "Real-time Secondary Spectrum Market - RTSSM" policy, which is the most appropriate solution, especially for deployments of LTE systems that require sporadic access to spectrum and for which QoS guarantees are important. RTSSM policy, adopts spectrum trading by permitting the spectrum license holder to run an admission control algorithm that allows secondary users to access spectrum only when QoS of both primary and secondary systems are adequate. Trading of secondary spectrum usage may occur through intermediaries such as a spectrum broker, exploiting radio resource management algorithms (RRM) [8], [10], 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 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 requirements. 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.

A number of resource allocation algorithms have been proposed by Wong et al. [11], to take advantage of both the frequency selective nature of the channel and the multi-user diversity. Most of the works in literature follow either the margin adaptive approach, formulating dynamic resource allocation with the goal of minimising the transmitted power with a rate constraint for each user [12], [13], [14], or the rate adaptive approach aiming at maximising the overall rate with a power constraint [15], [16]. Furthermore, the main purpose for using game theory [17], [18] in flexible radio spectrum access and RRM is to model some strategic interactions among secondary users with a need and a potential to access the limited spectrum resources and optimally exploit network resources. It derives well-defined equilibrium criteria to study the optimality of game outcomes for various game scenarios. The application of the economic concepts, such as competition, cooperation or the mixture thereof, allows one to analyse the problem of flexible usage of limited radio resources in a competitive environment. Game theory can be a powerful tool for finding its solution in overlapping, QoS supporting, standardised or proprietary wireless networks.

A key enabler for LTE deployment over TVWS based on the RTSSM regulator model is the CR technology that enables for dynamic spectrum access to secondary users by avoiding interference to primary ones. LTE deployment based on RTSSM regime can be based on a centralised architecture rather than a distributed one, due to the requirements for QoS provision, exploiting a central resources controller (i.e Spectrum Broker). Spectrum Broker is in charge of taking the decisions on spectrum access by collecting information about its usage by primary users, as well as information about the transmission requirements/demands of the secondary ones. Based on this information, an optimal solution (e.g. solution that maximises spectrum utilisation) on dynamic spectrum access can be obtained. The decisions of the Spectrum Broker are communicated/broadcasted to all secondary users in the network.

Nevertheless, in all cases, and no matter which architecture or spectrum policy is utilised, the deployment of LTE networks over TVWS leads to another challenge regarding the coexistence with heterogeneous telecommunication systems. Hence, channel interference is one of the most challenging issues that have to be addressed. Unlike current cellular networks that are planned considering fixed frequency allocation schemes, future deployment scenarios (i.e. LTE) will operate opportunistically, causing adjacent channel interference to other operators' systems. Therefore, such a deployment results the necessity to accommodate dynamic adjacent channel interference control, as well as more sophisticated RRM techniques by considering optimized solutions for allocating network resources in order to increase the performance of the network.

Furthermore, LTE based secondary systems will exploit limited wireless network resources over the TVWS, while bandwidth-hungry applications, such as peer-to-peer (P2P) services and video, will eventually require increased network capacity. Providing high service quality by over-provisioning network capacity will eventually leave a LTE secondary system at a competitive disadvantage to providers that offer the same or better QoS, at a lower cost. Therefore, a solid policy management strategy is required especially during peak traffic times and spikes in users' demands, for providing QoS at acceptable levels.

In this context, this paper elaborates on TVWS trading under the RTSSM regime, by proposing a centralised CR network architecture, where the operation of the RRM and the economics of the transactions are orchestrated through a Spectrum Broker entity, towards providing QoS guarantees for LTE secondary systems. Moreover, this paper is making a progress beyond the state-of-the-art, by proposing a RRM framework, which provides QoS through both margin and rate adaptive approaches. 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 briefly describes the TVWS allocation and trading processes carried out when secondary systems compete for TVWS exploitation. Section 3 elaborates on the performance evaluation of the proposed architecture, while section 4 concludes the paper by identifying fields for future research.

II. Design of a prototype Broker-based network architecture for QoS provision under the RTSSM policy

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 LTE Secondary Systems, competing/requesting for TVWS utilisation. 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 locations, the maximum allowable transmission power of secondary systems per channel in order to avoid causing interference to primary systems. The TVWS occupancy repository then creates a spectrum-portfolio including all the above mentioned information that is advertised to LTE secondary systems.

Moreover, the RRM module matches the LTE systems requirements with available resources and thus allocates the TVWS based on specific 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 LTE secondary system should be allowed to operate in order to avoid spectrum fragmentation, optimise QoS and guarantee fairness in TVWS access. Also, the trading module is responsible to determine the revenue of the Spectrum Broker, which aims to trade/lease the spectrum with temporary exclusive rights to the most valuable secondary system. Finally, the 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.

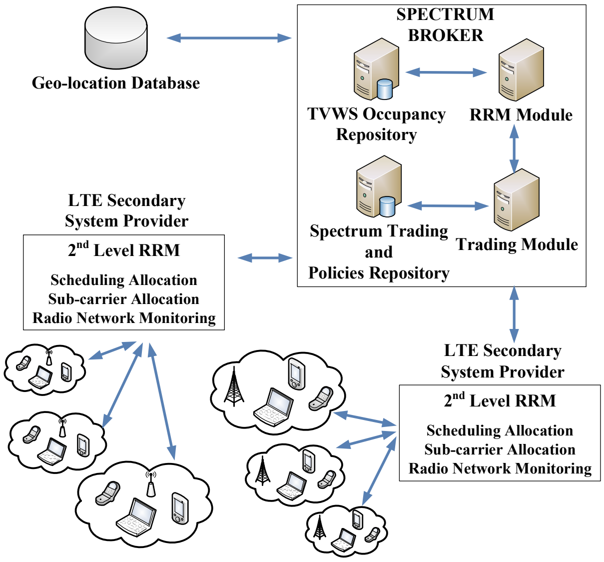

Fig. 1. Broker-based network architecture operating under the RTSSM regime.

Despite the benefits that clearly arise from extending the LTE use over TVWS, in terms of coverage and capacity, the QoS per service must be taken into account according to specific service level agreement (SLA). The allocation of the TVWS has to ensure the exclusivity of the spectrum usage and low interference levels in order to guarantee the QoS among LTE base stations and user terminals. Regarding this, a second level RRM between the LTE operator and the user terminal (access network) may be adopted in order to take advantage of the new portion of the spectrum. These second level RRM procedures are implemented at operator's network and aim to optimise the available radio resources provided by the Spectrum Broker, increasing coverage and capacity, without compromising QoS. Basically this second level RRM should at each moment guarantee the 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 Service Level Agreement (SLA) that should be taken into consideration and defines the minimum quality that operator should provide to its user terminals. This 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 Spectrum Broker of the proposed network architecture (see Figure 1) is in charge of trading the available spectrum to a number of competitive secondary systems (denoted by S) that participate in the spectrum allocation process. The total available spectrum, which can be leased by the Spectrum Broker is denoted as BW and comprised 10 UHF/TV (each one of 8MHz and total/aggregate bandwidth of 80MHz), scattered in the UHF spectrum according to the spectrum pool depicted in Figure 2 [19]. In this case, the commodity of the allocation 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 the spectrum pool, the 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 S participants, such as LTE systems with different bandwidth requirements. The final allocation of the fragments depends on the demand of all secondary systems and the profit maximization function of the Spectrum Broker.

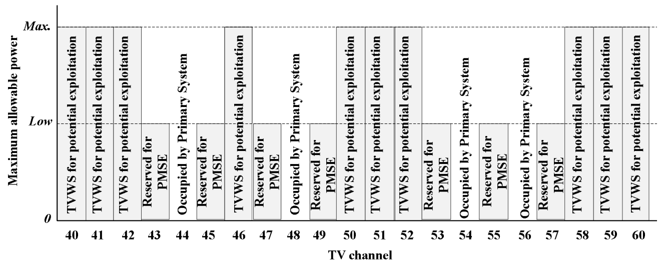

Fig. 2. Maximum allowable transmission power by secondary systems in TV spectrum for Munich area

The Spectrum Broker initially informs the secondary systems regarding the spectrum portions that are available to be leased, as well as the 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 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 the LTE systems provide their demand for the available spectrum portions, which is defined by the offered price. The Spectrum Broker collects and sends all requests to the RRM module, which analyses and processes them as a matter of the Secondary Systems' technical requirements and the locally available TVWS channel characteristics. For each spectrum portion/fragment, the Spectrum Broker creates and maintains a list with the request, namely as request-portfolio, in order to allocate each fragment to the most valuable LTE system that showed interest, respecting the QoS requirements/constraints (i.e. Priority Level). It has to be noted here that if two LTE systems request for a fragment with the same price and QoS requirements, then a first-come-fist-served scheme is adopted in order to sort the 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 combining the RRM results and the Trading Module output is obtained, enabling the Spectrum Broker to sell/assign TVWS frequencies to the corresponding Secondary Systems under the RTSSM regime/policy. In other words, the 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 allocation process. For this purpose, the Spectrum Broker exploits optimisation methods [20], [21], in terms of the RRM, among which are the decision-making ones that are trying to reach an optimal solution through classical mathematical rationalization [21]. Such decision-making RRMs may be implemented through a number of optimisation techniques, such as the integer/combinatorial programming (e.g. Backtracking) and the mathematical programming (e.g. Simulated Annealing, Genetic Algorithm). While the former provides a "global" optimum solution among all possible ones, the latter picks it from a smaller set of solutions that satisfy the objective function [22].

Figure 3 illustrates the logical diagram of the RRM 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.

More specifically, if a fixed-price policy is selected the RRM algorithm obtains the optimal solution by minimising an objective function *"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).

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

Alternatively, in the auction-based mode the Spectrum Broker collects bids to buy from the secondary systems, bids to sell from the 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 would then be repeated as spectrum portions become available (i.e. as they are released by supplying players). To maximize the benefit of both Spectrum Broker and LTE secondary systems an optimization problem can be formulated as a linear programming problem as follows:

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

where, each buyer *"i"* (i.e. LTE secondary systems) wants 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) wants to sell y_n portions of spectrum by reporting a price $P_n^{(s)}$ (Asking Price). k is the total number channels (i.e The TVWS that a secondary system wants to buy). Finally, $x_{i,n}$ is the quantity that the *"i"* secondary system purchase from the Spectrum Broker.

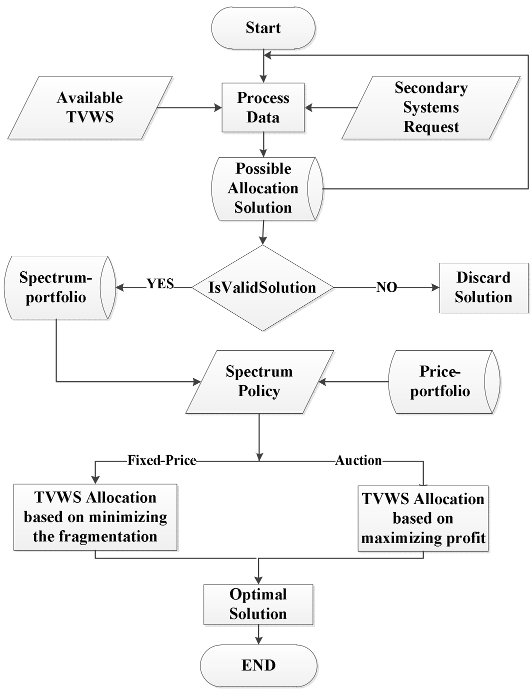

Fig. 3. Logical diagram of RRM and trading modules towards establishing the optimal allocation solution

III. PERFORMANCE EVALUATION

A. Test-bed description

Towards verifying the validity of the proposed CR network architecture and evaluating its capacity for efficient TVWS exploitation and QoS provisioning within the RTSSM policy, a decision making process was implemented by exploiting the Backtracking algorithm [22]. Backtracking performs systematic/exact search in order to generate each possible spectrum allocation solution exactly once avoiding both repetitions and missing solutions. In the backtracking method, as soon as an allocation solution is generated, the validity of the constraint is checked. If an allocation solution violates any of the constraints, backtracking rejects this one, thus is able to eliminate a subspace of all variable domains.

In this context, a set of experiments were designed and conducted under controlled-conditions (i.e. simulations) evaluating the performance of the above algorithm, as a matter of the number of secondary systems that can be accommodated, the resulted spectrum utilization and frequency fragmentation [23]. The experimental test-bed comprised of a TVWS Occupancy Repository, hosting information about UHF/TV frequencies that can be exploited by Secondary Systems. Information in this repository was built around actual/real spectrum data gathered within the framework of the ICT-FP7 "CogEU" project [24], concerning the TVWS availability between 626MHz (Ch.40) and 752MHz (Ch.60) in Munich area [11]. As already mentioned above (see Figure 2), only 10 TV channels are available in Munich area for exploitation by Secondary Systems, providing an initial spectrum utilisation of 19.05% and featuring a fragmentation of about 0.76817, only when primary systems are considered. It should be noted that in the simulation tests that were conducted, the fixed-price policy was selected, based on a single spectrum-unit price that was applied for every TVWS frequency trading process.

The simulation scenario includes five LTE Secondary Systems with different radio characteristics that were simultaneously competing for the available TVWS. These systems were based on LTE, operating 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 algorithm, during the spectrum allocation process. Additionally, for every 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.

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)	5 -10	High

From Table 1 it comes that there are two major types of services provided 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 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. 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 simulation scenario, four time periods (see Table 2) were defined as follows:

TABLE 2
SIMULATION SCENARIO TIME PERIODS

	Time Period 1	Time Period 2	Time Period 3	Time Period 4
LTE 1	√	√	√	√
LTE 2	√	√	√	–
LTE 3	–	√	√	√
LTE 4	–	√	√	√
LTE 5	–	–	√	√

- Time Period 1: "LTE 1" and "LTE 2" systems are requesting access to TVWS up to time period 4 and 3, respectively.
- Time Period 2: "LTE 1" and "LTE 2" maintain access to the spectrum, while two new secondary systems "LTE 3" and "LTE 4" are both requesting access to the spectrum up to time period 4.
- Time Period 3: "LTE 1", "LTE 2", "LTE 3" and "LTE 4" maintain their access to TVWS, while an additional secondary system "LTE 5" is accessing the available spectrum up to time period 4.
- Time Period 4: Four LTE systems are operating and a higher services provision demand stemming from "LTE 5" terminals, creates the need for more traffic resources for this specific LTE secondary system.

B. *Results and qualitative comparison*

Spectrum utilisation was estimated as the percentage of the exploited bandwidth (by both Primary and Secondary Systems) over the totally available spectrum within TV channel 40-60, (i.e. 168MHz). Table 3 summarizes the results obtained in every Time Period by exploiting the RRM algorithm. Table 3 also presents the initial value of the spectrum utilization, i.e. when only primary systems operate in the TVWS channels. Spectrum fragmentation was calculated by taking into account the number of fragments (i.e. unused spectrum-portions) as well as the size/bandwidth of each individual fragment, as it is proposed in [24]. Table 3 summarizes the results obtained in every Time Period, where the initial condition is also shown, when no secondary system is accommodated. From these results, it can be verified that the proposed algorithm provides an acceptable fragmentation score, taking into account that: a) the value "0" represents an "un-fragmented" spectrum, while when moving towards "1" the spectrum becomes more-and-more fragmented, i.e. there exist many blocks of unexploited frequencies.

Table 3 presents the results obtained for each Time Period according to the simulation tests:

- Time Period 1: Two secondary systems are requesting for 20MHz and 5MHz respectively. A spectrum fragmentation of 14.88% and a fragmentation score of 0.75513 was obtained.

- Time Period 2: Four secondary systems are requesting for 20MHz, 5MHz, 20MHz and 20MHz respectively. In this case, spectrum utilisation is 38.69%, while fragmentation score is 0.85658.
- Time Period 3: Five secondary systems are requesting access to TVWS increasing spectrum demand. In such a case, Spectrum Broker allocates the available TVWS, respecting QoS requirements. More specifically, "LTE 5" is served with a higher priority, than "LTE 2", which operates under a best-effort mode. Spectrum utilisation is 38.69% and fragmentation score is 0.85658 at this time period.
  Time Period 4: In this time period, "LTE 5" is requesting for more traffic resources and exploits 10MHz instead of 5MHz. For this scope, Spectrum Broker assigns the extra available spectrum, respecting QoS priority. In this case, "LTE 3" that operates, exploiting 20MHz under a best-effort mode, releases the spectrum, which is then assigned to "LTE 5". This allocation process results a spectrum utilisation of 29.76%%, and a fragmentation score of 0.80341.

TABLE 3
EXPERIMENTAL RESULTS

Time Period	Spectrum Utilisation (%)	Fragmentation Score	Number of LTE SS Accommodated
0	19.05%	0.76817	-
1	14.88%	0.75513	2
2	38.69%	0.85658	4
3	38.69%	0.85658	4
4	29.76%	0.80341	3

IV. CONCLUSION

This paper discussed a centralised CR network architecture, which can be utilised for TVWS exploitation, QoS provisioning and policy management, under the RTSSM regime. It elaborated on the design of the radio resource management and the trading modules in the broker side, and presented their implementation, by utilising decision-making processes based on Backtracking, algorithm. Towards evaluating the broker performance, a set of experiments was designed and conducted under controlled conditions, where various secondary systems were concurrently/simultaneously accessing the available TVWS. The obtained experimental results verified the efficiency of the broker, in terms of QoS provision, respecting a number of constraints of different LTE secondary systems. In this respect, fields for future research include qualitative and quantitative comparison between alternative optimisation algorithms, where the TVWS exploitation and QoS provisioning can be obtained in real time under the auction-based trading policy.

ACKNOWLEDGMENT

The work presented in this paper is supported by the European Commission, Seventh Framework Programme (FP7), under the project 248560, ICT-COGEU.

REFERENCES

[1] J. Mitola III, G. Q. Maguire, "Cognitive Radio: Making Software Defined Radio More Personal", IEEE Pers. Com. 6, 1999.
[2] A. Wyglynski, M. Nekovee, T. Hou, "Cognitive Radio Communications and Networks: Principles and Practice", Academic Press, 2009.
[3] R. W. Thomas, L. A. DaSilva, A. B. MacKenzie, "Cognitive Networks", in proc. IEEE DySPAN, First Symposium on Dynamic Access Networks. Baltimore, USA, 2005.
[4] 3GGPP LTE: http://www.3gpp.org/LTE
[5] Shared Spectrum Company. New York City Spectrum Occupancy Measurements September 2004.
[6] Unlicensed Operation in the TV Broadcast Bands, Final Rules, Available: http://edocket.access.gpo.gov/2009/pdf/E9-3279.pdf.
[7] OFCOM, "Digital Dividend Review: geographic interleaved awards 470 - 550 MHz and 630 - 790 MHz -- Consultation on detailed award design", June 2008.
[8] A. Bourdena, E. Pallis, G. Kormentzas, C. Skianis, G. Mastorakis, "Real-Time TVWS Trading Based on a Centralised CR Network Architecture", in proc. IEEE Globecom2011, IEEE International Workshop on Recent Advances in Cognitive Communications and Networking, Texas, Houston, USA, 2011, pp. 964-969.
[9] I. F. Akyildiz, W.Y. Lee, M.C. Vuran, S. Mohanty, "A Survey on Spectrum Management in Cognitive Radio Networks", IEEE Coms. Mag. 46, 40-48, 2008.
[10] F. Cavalcanti, S. Andersson, "Optimizing Wireless Communications Systems", Springer, 2009.
[11] C. Wong, R. Cheng, K. Letaief and R. Murch, "Multiuser OFDM with adaptive subcarrier, bit and power allocation", IEEE Journal on Selected Areas in Communications, Vol. 17, No. 10, pp. 1747–1758, Oct. 1999.
[12] D. Kivanc, G. Li and H. Liu, "Computationally efficient bandwidth allocation and power control for OFDMA", IEEE Transactions on Wireless Communications, Vol. 2, No. 6, pp. 1150–1158, Nov. 2003.
[13] M. Moretti and M. Morelli, "A novel dynamic subcarrier assignment scheme for multiuser OFDMA systems", in Proc. of VTC'06 Spring – 63rd IEEE Vehicular Technology Conference, Melbourne, Australia, May 2006.
[14] I. Kim, I. Park and Y. Lee, "Use of linear programming for dynamic subcarrier and bit allocation in multiuser OFDM", IEEE Transactions on Vehicular Technology, Vol. 55, No. 4, pp. 1195–1207, July 2006.
[15] W. Rhee and J. Cioffi, "Increase in capacity of multiuser OFDM system using dynamic subchannel allocation", in Proc. VTC'00 Spring – 51st IEEE Vehicular Technology Conference, Tokyo, Japan, May 2000.
[16] J. Jang and K. B. Lee, "Transmit power adaptation for multiuser OFDM systems", IEEE Journal on Selected Areas in Communications, Vol. 21, No. 2, pp. 171–178, Feb. 2003.
[17] G. Owen, Game Theory, Academic Press, London, UK, 1995.
[18] P. D. Straffin, Game Theory and Strategy, The Mathematical Association of America, Washington, DC, USA, 2002.
[19] COGEU-ICT-FP7-248560, COGnitive radio systems for efficient sharing of TV white spaces in EU context, Deliverable 6.1, Dynamic radio resource management algorithms for an efficient use of TVWS, http://www.ict-cogeu.eu/pdf/COGEU_D6.1%20%20(ICT_248560).pdf.
[20] E. Hossain, D. Niyato, Z. Han, "Dynamic spectrum access and management in cognitive radio networks", Cambridge University Press, 2009.
[21] Newcom++ project, DR9.1: Identification of relevant scenarios, use cases and initial studies on JRRM and ASM strategies.
[22] S. S. Skiena: The Algorithm Design Manual, Springer.
[23] J. Gehr, J. Schneider, "Measuring Fragmentation of Two-Dimensional Resources Applied to Advance Reservation Grid Scheduling", in proc. 9th IEEE/ACM International Symposium on Cluster Computing and the Grid, Shanghai, China, 2009, pp. 276-283.
[24] COGEU-ICT-FP7-248560, COGnitive radio systems for efficient sharing of TV white spaces in EU context, http://www.ict-cogeu.eu/.