A prototype cognitive radio architecture for TVWS exploitation under the real time secondary spectrum market policy

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\textbf{Abstract}

This paper elaborates on the design and implementation of a prototype system architecture enabling for TVWS exploitation by LTE Advanced systems, under the real time secondary spectrum market policy. It describes a centralised infrastructure-based cognitive radio network, where dynamic TVWS allocation among unlicensed systems is administrated by a spectrum broker, carrying out radio-resource management and spectrum trading in real time. For efficient system performance as a matter of both maximum-possible radio resource exploitation and trading revenue, the paper discusses the design and implementation of a prototype mechanism at the spectrum broker side, which exploits backtracking algorithm for obtaining the best-matching solution. Performance evaluation experiments carried-out under controlled conditions (i.e. simulation) verified the validity of the proposed architecture, besides establishing its capacity for maximum spectrum utilisation and minimum fragmentation under a fixed-price trading policy.

\textbf{Keywords:} TVWS, CR, Spectrum Broker, RRM, Spectrum Trading

\section{INTRODUCTION}

Emerging types of wireless applications and telecommunication services, rich in user-created content with high demands for network resources and stressed end-to-end QoS requirements, put more and more pressure on the available radio-spectrum (i.e. the fundamental resource in wireless systems), thus raising the needs for frequency availability and creating new challenges in radio-spectrum management and administration. While the utilization of advanced signal processing techniques may enable a very efficient spectrum-usage even in the traditional framework of “command-and-control” regime, there is a worldwide recognition that these methods of spectrum management have reached their limit and are no longer optimal. In fact spectrum utilization studies have shown that most of the assigned (licensed) spectrum is under-utilized [1], and considerable radio-frequencies are available when both dimensions of space and time are considered. The advent, however, of a number of state-of-the-art technologies, such as the LTE-Advanced [2], [3], which can adapt their operation for exploiting any unused spectrum according to the transmission environment characteristics and the users’/services’ needs, in terms of transmission/reception bandwidth, modulation and coding schemes etc, may provide a solution. Such an example of under-utilized spectrum is the so-called “television white spaces” (TVWS), comprising VHF/UHF
channels that are either released/freed by the digital switchover process (“Spectrum/Digital Dividend”), or being totally unexploited (mainly at local level) due to frequency planning issues and/or network design principles (“Interleaved Spectrum”) [4]. TVWS usually sum-up to tenths of MHz at local/regional level [5], facilitate low cost and low power system design, provide superior propagation conditions and building penetration, while at the same time their sufficiently short wavelength allows the construction of resonant antennas, at a size and shape that is acceptable for many mobile devices.

LTE-A can take advantage of TVWS propagation characteristics and cover large geographical areas with less number of base stations (and, therefore, with lower cost), besides enabling operators to offer cheaper mobile broadband services to more consumers, especially in rural areas. In dense urban areas, TVWS could be used for peaking support, 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 enable 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 Terrestrial Digital Video Broadcasting and wireless microphones), a great part of it will be still available for other usages. Although conceptually quite simple, the introduction of LTE-A networks in TVWS represents a disruption to the current “command-and-control” paradigm of TV/UHF spectrum management, and therefore the exploitation of LTE-A is highly intertwined with the regulation models that would eventually be adopted. Among the envisaged regulation models are the “Spectrum of Commons” (or unlicensed policy) and the “Real-time Secondary Spectrum Market” (or licensed policy). “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, and QoS cannot be guaranteed. On the other hand, “Real-time Secondary Spectrum Markets” (RTSSSM) may be the most appropriate solution, especially for deployments of LTE-A systems that require sporadic access to spectrum and for which QoS guarantees are important. RTSSSM regime adopts spectrum trading, which allows primary users (license holders) to sell/lease spectrum usage rights and secondary players to buy them (license vendees), thereby establishing a secondary market for spectrum leasing and spectrum auction through intermediaries such as a spectrum broker. A key enabler for both licensed and unlicensed regulators models, is the Cognitive Radio (CR) technology [6], [7], [8], which aims to provide dynamic spectrum access to unlicensed users by avoiding interference to licensed ones. To do so, CR exploits either infrastructure based architecture, 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. LTE-A systems may enable for the provision of guaranteed QoS, exploiting the RTSSSM policy, which can be deployed by a centralised architecture, where a Spectrum Broker orchestrate the available network resources.

In this context, this paper elaborates on TVWS exploitation under the RTSSSM regime, by proposing a centralised infrastructure-based network architecture, where operation of LTE-A secondary systems is orchestrated through a spectrum broker. Following this introductory section, Section 2 discusses the applicability of LTE-A systems over the TVWS and deployment issues based on CR architectures, while it briefly analyses current optimization techniques for RRM realization, Section 3 elaborates on the overall configuration of the proposed CR network architecture under the RTSSSM regime and analyses the TVWS allocation and trading processes carried by a prototype RRM in the Spectrum Broker. Section 4 presents performance evaluation results carried over a simulation test-bed, verifying the validity of the adopted architecture for efficient TVWS exploitation, and the capacity of the proposed RRM algorithm in maximizing persistence of TVWS channel allocations as well as the interference-free coexistence of LTE-A with primary systems (i.e. DVB-T systems). Finally, Section 5 concludes the paper by elaborating on fields for future research.
2. DEPLOYMENT OF LTE-A OVER TVWS BASED ON CR NETWORK ARCHITECTURES AND RRM APPROACHES

As already mentioned in the previous section, LTE-A over TVWS can be applicable in dense urban areas for peaking support in order to provide relief to crowded networks experiencing peak loads. For instance, the demand for additional network traffic is higher in areas that host events such as Olympic games. This event is characterized by different parallel sessions of Olympic sports, scattered around the city stadiums, where a large number of end users is concentrated. In such a case, there is a high probability that the serving cell will be fully occupied and the services could not be normally provided for specific time periods. LTE-A systems could be used in such areas to relieve other crowded networks as well as to provide multimedia services regarding the Olympic games. In this context, the deployment of LTE-A over the available TVWS of a specific area (information confirmed by operator with the GPS coordinates sent by terminal), could be useful in high traffic hours. When services requests are increased and a network congestion situation is detected, network operator could request to gain access to TVWS by the Spectrum Broker, which is in charge of assigning the available channels by protecting primary systems. Once the primary systems are protected, the LTE-A systems are providing services to the end users located in congested areas by exploiting TVWS.

Although the scenario described above is quite simple, a number of issues are arisen regarding the feasibility of LTE-A as a secondary system within TVWS. The deployment of LTE-A is currently hampered by the traditional “command and control” spectrum policy, thus RTSSM regime can be exploited in order to overtake this issue. More specifically, RTSSM policy, adopts spectrum trading that permit the license holder to run an admission control algorithm, which allows secondary users to access spectrum only when QoS of both primary and secondary are adequate. The 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 spectrums 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.

However, deployment of RTSSM regime for the exploitation of TVWS over the LTE-A can be enabled by an infrastructure that support dynamic spectrum access, such as CR networks. CR 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 [9]. For LTE-A deployment based on RTSSM regime, a centralized architecture is more appropriate due to the need for QoS that can be guarantee through a central controller (i.e. Spectrum Broker), which undertake to take the decision on spectrum access by collecting information about the spectrum usage of the licensed users as well as information about the transmission requirements of the unlicensed ones. Based on this information, an optimal solution (e.g. one which maximizes spectrum utilisation) on dynamic spectrum access can be obtained. The decisions of the central controller are communicated/broadcasted to all unlicensed users in the network. However, information collection and exchange to/from the central controller can incur a considerable overhead.

Nevertheless, in all cases, and no matter which architecture or spectrum policy is utilized, the deployment of LTE-A networks over TVWS leads to another challenge regarding the coexistences with heterogeneous telecommunication systems. Hence, channel interference is one of the most challenging prospects that have to be addressed. Unlike current cellular
networks that are all planned according to specific network topologies under fixed frequency allocation schemes, future deployment scenarios (i.e. LTE-A) will operate opportunistically, causing adjacent channel interference to another operator’s system. Therefore, such a deployment results the necessity/need to accommodate dynamic adjacent channel interference control, as well as more sophisticated radio resource management (RRM) techniques [11], [12], [13]. RRM is considered as an optimized solution for allocating network resources in order to increase the network performance. While this optimization can be generally focused on optimizing either a single objective or a set of objectives, the nature of the wireless communications almost exclusively requires the multi-objective one. In other words, the optimization point of view to the cognitive radio paradigm is on how to formulate CR networking problems as optimization problems from the perspective of resource allocation. Usually, multi-objective optimization can be executed following either the decision making theory concept or the game theory concept [9], [10]. Whereas the former attempts to reach an optimal solution through classical mathematical rationalization, the latter views the optimization problem as a “game” and tries to find the optimal way to “play” it. For the scope of this paper, we focus on the decision making theory concept, while more information about the game theory approach can be found in [14], [15].

The decision making approach is based on formulate an objective function, as well as on setting equality and inequality constraints that the optimal solution must not cross [9]. Three groups of solutions arise for this type of optimization approach, i.e. closed form solution, mathematical programming and integer/combinatorial programming. The former is the general decision-making optimization understanding, where an optimization goal is reached by using approximations and solving Lagrangian equations in closed form. The mathematical programming is used for most real-world optimization problems, and can be divided into 5 major subfields, i.e. linear, convex, non-linear, dynamic and stochastic programming. Linear programming is the problem of maximizing/minimizing a linear function over a convex polyhedron, can be solved via the simplex method [16], where the fixed values can then rotated until an optimum is found. The convex programming is based on convergence of the considered values towards the highest local value, by exploiting the equality of the local and global optimum. The optimization process involving non-linear objective functions and constraints is called non-linear programming, where the key difference with the linear one is the inequality between the local optimum and the global optimum i.e. there can be more global optimums and a simple “climbing uphill” algorithm cannot solve the optimization problem. Popular solutions for solving a non-linear programming problem are genetic algorithms, simulated annealing and the Monte Carlo method. Dynamic programming is based on the optimality principle that states: “In an optimal sequence of decisions or choices, each subsequence must also be optimal”. Two approaches can be considered, i.e. a top-down approach, where the general problem is broken into subproblems being optimized in order to reach an optimum for the general problem, and a bottom – up approach, where all subproblems are envisioned in advance and larger problems are built up from their optimal solutions. The last subfield of mathematical programming is the stochastic programming, which is an optimization process that incorporates probabilistic elements in the problem formulation. Possible solutions include a sampling method based on the Monte Carlo method, genetic algorithms and simulated annealing.

Last, but not least, group of the decision making approach is the integer/combinatorial programming, which encompasses the optimization problems that involve parameters with integer values or parameters that are of combinatorial nature (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.

3. SYSTEM ARCHITECTURE

This section elaborates on the system design of a centralised infrastructure-based CR network, operating under the RTSSM regime (as described in the introductory section), where radio resource administration and spectrum leasing/auction is carried over a prototype RMM exploiting integer/combinatorial programming. Figure 1 depicts the overall architecture that 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 (SS), based on LTE-A, each one accommodating users geographically adjacent to it, competing/requesting for TVWS utilisation. According to this architecture, SSs’ requests for TVWS access are communicated (e.g. via dedicated links) to the Spectrum Broker, where a Radio Resource Management module (RRM) analyses and processes them as a matter of the Secondary System’s technical requirements (e.g. requested BW, transmission power, etc.) and the locally available TVWS channel characteristics (hosted within the TVWS Occupancy Repository – see Figure 1). Prior to any spectrum allocation, the economics of TVWS transactions are also analysed/elaborated (Trading Module in Figure 1), taking into account the spectrum-unit price (e.g. cost per MHz) either based on fixed-price or spectrum-auction policies (Spectrum Trading Policies Repository in Figure 1). Finally, an optimised solution combining the RRM results and the Trading Module output is obtained, enabling the Broker to sell/assign TVWS frequencies to the corresponding Secondary Systems under the Real Time Secondary Spectrum Market regime/policy.

In other words, all activities within the envisaged Real Time Secondary Spectrum Market are coordinated by the Broker, which is responsible for obtaining the best-matching solution through an optimisation-based process, taking into account parameters with integer values or combinatorial nature, such as the number of the available TVWS channels, the number of LTE-A secondary systems, the required bandwidth, the maximum allowable transmitted power, the spectrum-unit price, etc. Eventually, the anticipated best-matching solution (spectrum allocation scheme) will be the result of a decision-making approach based on integer/combinatorial programming (see Section 2), which in our case can be accommodated by Backtracking algorithm [16], in a three-phase procedure: Preparation and Analysis phase, a Trading phase and a Maintenance one.

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

3.1 PREPARATION AND ANALYSIS PHASE
During the Preparation and Analysis phase the RRM establishes all possible solutions for allocating the available TVWS to the competing LTA-SS, and creates a spectrum portfolio comprising only valid solutions, i.e. those allocation schemes that match the SS technical requirements/specifications with the TVWS characteristics (valid solutions). In other words, this spectrum portfolio is the set (“$A'_n$”) of valid allocation schemes, when an optimisation-based approach (utilizing Backtracking Algorithm [16]) is applied over all possible solutions. For example, assuming that “$F$” is the total available TVWS channels (i.e. one TVWS channel is equal to 1MHz) and “$V$” is the spectrum demand (i.e. number of TVWS channels requested) of all competing secondary systems, it comes that the number of all possible combinations/solutions (NPS) will be:

$$N_{PS} = \frac{F!}{(F-V)!} + \sum_{x=1}^{F-V} (F \times V \times x), \forall F \geq V$$

(1)

each one denoting a specific allocation scheme/pattern for assigning a certain TVWS channel to a single LTE-A SS. It has to be noted here that this function is valid only in the case when the total number of available TVWS channels (F) is greater or equal than spectrum demand (V). In case that F is less than V, then an auction-based approach is followed, considering the number of bids, which are submitted by SS in order to calculate NPS. From all these solutions, the spectrum portfolio will include only those matching the SS technical specifications, such as the maximum allowable power $P(i,f)$ and the transmission bandwidth, thus constituting a subset of NPS solutions when an optimisation approach is applied over them (i.e. over all NPS solutions) following the objective function $A'_n$:

$$C(A'_n) = \sum_{i \in V} \sum_{f \in F} x_{if} \left[ P(i,f) + BW(i,f) \right]$$

(2)

where $n = \{1…NPS\}$, and $x_{if}$ is equal to one, when the TVWS “$f$” is allocated to the SS “$i$”, while $x_{if}$ is equal to zero in other situation. Also, $P(i,f)$, denoting the allocation $x_{if}$ where the maximum allowed power of the “$f$” TVWS, can satisfy the SS technical requirements. Moreover, $BW(i,f)$, representing the bandwidth of the allocation $x_{if}$ where the “$i$” Secondary System, can be satisfied from the “$f$” TVWS.

The logical diagram for implementing this Backtracking algorithmic process in the RRM is depicted in Figure 2, where the first step is the process/calculation of all possible TVWS allocation schemes, as a matter of the number requested spectrum channels of competing secondary systems (“$V$”) and the number of the available TVWS channels (“$F$”) hosted by the TVWS Occupancy Repository. Following Figure 2, this “Process Data” function is an iterative process with “NPS” stages (see equation 1), and therefore “NPS” combinations, which constitute the “Possible Allocation Solutions”. As soon as all these Possible Allocation Solutions/combinations are established ($A_n$), the Backtracking algorithm calculates/finds the optimum ones, which match specific technical requirements of the competing secondary systems (e.g. power level constraint, BW, etc.) with the available TVWS characteristics. These optimised Allocation Solutions ($A'_n$), i.e. a subset of ($A_n$), comprise the Spectrum Portfolio that will be used by the Broker during the Trading phase. More specifically, and according to Figure 2, this Spectrum Portfolio is the result of the iterative process “IsValidSolution”, which examines if a Possible Allocation Solution/Scheme fulfils the technical requirements. In such a case, the Possible Allocation Solution is registered in the spectrum portfolio, otherwise it is discarded.
3.2 TRADING PHASE

During this phase, the Trading Module within the Broker elaborates on the economics of TVWS transactions and decides upon the best-matching solution following specific trading policies under the RTSSM regime. More specifically, the Trading Module estimates the cost of every TVWS Allocation Scheme (present within the spectrum portfolio), taking into account a “spectrum-unit price” (e.g. cost per MHz) either under a fixed-value or an auction-based trading policy. For this reason, a Price-Portfolio is created/maintained within the Broker (see Spectrum Trading and Policy Repository in Figure 1), based on various price estimation methods [17], [18], among which are the Market Valuation ones (e.g. Spectrum Market Transaction, Value of Spectrum Owning Companies, Capacity Sales of Spectrum-Utilising services, etc. – [17], [18]) and the Direct Calculation methods, including the Standard Net Present Value (NPV) and Least Cost Alternative (LCA) [17], [18]. In turn, and according to the logical diagram in Figure 3, the selection of the best-matching solution (Optimal Solution) is the result of an optimisation process (utilising Backtracking algorithm) targeting either to minimise spectrum fragmentation (fixed-price policy) or to maximise the profit (auction-based trading).
More specifically, if a fixed-price policy is selected the Backtracking algorithm obtains the best-matching solution (Optimal Solution) by minimising an objective function “C(A)’”, as a matter of spectrum fragmentation (Frag(i,f)) and/or Secondary Systems’ prioritisation (Pr(i)) (e.g. in case that some secondary technologies must be served before others):

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

(3)

where Frag(i,f) denotes the spectrum fragmentation level (as a percentage) when a secondary system “i” is assigned to a specific frequency “f”.

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).

### 3.3 MAINTENANCE PHASE

Phase III, Maintenance, involves the Update of the TVWS occupancy repository for recently allocated spectrum with the coverage area of the secondary systems. The algorithm can be run again, when there is still an unused spectrum and a demand from new incoming secondary users or in a periodic basis (the market opens every day or every week).

### 4. PERFORMANCE EVALUATION

#### 4.1 TEST-BED DESCRIPTION

Towards verifying the validity of the proposed architecture and validating its capacity for efficient TVWS exploitation within the Real Time Secondary Spectrum policy (RTSSM), a set of experiments was designed and contacted under controlled-conditions environment. In this context, a simulation test-bed conforming to the overall design specifications (see Figure 1) was set-up, comprising:

- A TVWS Occupancy Repository, hosting information about UHF/TV frequencies that can be exploited by Secondary Systems. The information in repository was built around actual/real spectrum data concerning the TVWS availability in Munich area, which have been acquired within the framework of the ICT-FP7 “CogEU” [19]. Following these actual/real data, Figure 4 depicts the Maximum Allowable Power (MAP) at which a Secondary System may transmit within the range of TV channel 40 (626-632 MHz) to TV channel 60 (746-752 MHz). It should be noted that the actual MAP for adjacent and no-adjacent channels is still under investigation, and therefore a symbolic notation for y-axis is considered in Figure 4 for illustrative proposes. In this context, channels with “0” MAP (e.g. channel 44) represent frequencies occupied by Primary Systems (DVB-T), while those of “Low” MAP represent spectrum reserved for PMSE transmission (e.g. channel 45). Therefore, both these cases were not considered as TVWS. On the other hand, in channels where “Max.” MAP is permitted, Secondary Systems can be accommodated (e.g. channel 40, 50, 60, etc.). Thus the initial data within the TVWS Occupancy Repository comprised 10 UHF/TV (each one of 8MHz and total/aggregate bandwidth of 80MHz), scattered in the UHF spectrum according to Figure 4.

- A number of Secondary Systems competing for TVWS exploitation, based on the LTE-A standard. For these LTE-A systems Frequency Division Duplexing (FDD) was chosen utilising 5MHz bandwidth for the uplink channel (UL) and 5MHz for downlink one (DL), with an UL/DL-spacing of at least 1MHz. Furthermore, the transmission power of each LTE was selected to be 4W.
- A Spectrum Trading and Policy Repository, hosting information about the TVWS selling/leasing procedure, as well as the spectrum-unit price to be exploited during the trading phase. It should be noted that in our tests, the fixed-price policy was selected, based on a single spectrum-unit price that was applied for every TVWS frequency trading process.

Figure 4 Maximum allowable transmission power by LTE-A secondary systems in TV spectrum for Munich area

4.2 PERFORMANCE EVALUATION

Based on the described test-bed, a set of experiments was conducted towards estimating the maximum number of LTE-A systems that can be efficiently accommodated under the RTSSM policy, as well as for evaluating the overall performance in respect to: a) the number of possible allocation solutions explored before reaching the best-matching one and b) the spectrum utilization and the resulting spectrum fragmentation [20] when the best-matching solution is applied. Spectrum utilisation was estimated as the percentage of how much of the total bandwidth within TV channel 40 and TV channel 60 (i.e. 168MHz) is exploited/used by both Primary and Secondary Systems:

\[
\text{Spectrum Utilization (\%)} = \frac{\text{BW exploited by all systems (in MHz)}}{168\text{MHz}} \quad (4)
\]

Consequently, the initial condition in our tests comprised a spectrum utilisation of 19.04%. Additionally, spectrum fragmentation (or Fragmentation Score) was estimated by taking into account the number of unused spectrum-portions as well as the size of each individual fragment, according to formula (5) [21],

\[
Z = 1 - \frac{\sum f_i^r}{\left(\sum f_i\right)^p} \quad (5)
\]

where “\(n\)” is the number of the scattered fragments (i.e. number of unused spectrum portions), “\(f_i\)” is the bandwidth of the \(i\)-th fragment (e.g. in MHz), while “\(p\)” is a constant, which in our experiments was equal to “2” as proposed in [21]. In such a case, it is evident that when Fragmentation Score (Z) is equal to “0” there is only fragment and therefore the spectrum is considered as un-fragmented, while as Z increases towards “1”, the number of fragments also increases and the spectrum becomes more-and-more fragmented (many blocks of unexploited frequencies). Therefore, applying equation (5) over the Munich frequency allocation pattern (see figure 5), an initial Fragmentation Score of 0.76817 was considered as the starting point for simulation tests.

During these performance evaluation experiments the LTE-A systems were accessing the available TVWS in a sequential mode and not concurrently, i.e. for every new simulation-test (Time Period) an additional LTE-A system was entering the test-bed, requesting access to the
available (at the given Time Period) TVWS frequencies. That means that every time a new LTE-A system is assigned the requested spectrum (i.e. frequencies for UL and DL traffic), the TVWS Occupancy Repository updates its data with the new spectrum allocation scheme, which in turn will be used during the next simulation test. Furthermore, and towards avoiding any interference between LTE-A systems that are placed at consecutive frequencies, “frequency guard intervals” of 1MHz are utilised, one placed at upper-bound of an LTE-A system DL spectrum and another at its upper bound of the UL spectrum.

For example, while in the Time Period 1 the first LTE-A requests frequencies from the initially available TVWS spectrum (i.e. from 80MHz), in Time Period 2 the new LTE-A requests access to the remaining frequencies, that is 68MHz available (i.e. 80MHz minus the 10MHz allocated to the 1st LTE-A along with the 2MHz of the “guard intervals” assigned to it).

Figure 5 below depicts the spectrum allocation scheme after the 1st Time period, i.e. when the first LTE-A system is accommodated within the available TVWS, including the “guard intervals” placed at the upper bounds of the UL and DL portions. From this first simulation test (Time Period 1), the experimental results indicated a Fragmentation Score of 0.769148 and a Spectrum utilisation of 26.19%, while the Backtracking algorithm explored 3230 possible allocation solutions (in 27.34 seconds) before finding and applying the best-matching one.

Table 1 below presents the experimental results for each of these simulation tests (Time Periods), where Time Period “0” represents the initial conditions, while Time Period 6 the case where the last LTE-A was accommodated.

Figure 6 illustrates the final placement of these 6 LTE-A systems within the Munich TVWS spectrum.
5. CONCLUSIONS

This paper discussed the design and implementation of a prototype system architecture enabling for TVWS exploitation, by LTE-A systems, under the real time secondary spectrum market policy. It described a centralised infrastructure-based cognitive radio network, where dynamic TVWS allocation among secondary systems is coordinated by a spectrum broker, which also administrates the economics of such transactions utilising either fixed-price or auction-based policies. For efficient system performance as a matter of maximum-possible radio resource exploitation and trading revenue, the paper elaborated on the study and development of a prototype mechanism at the spectrum broker side, which is based on the backtracking algorithm for obtaining the best-matching solution. Towards evaluating the system performance, a set of experiments was designed and conducted in a controlled conditions environment (i.e. simulation), where LTE-A systems of fixed UL/DL bandwidth were sequentially accessing the available TVWS. The experimental results verified the validity of the proposed architecture, besides establishing the capacity of the described Spectrum Broker mechanisms for maximum spectrum utilisation and minimum fragmentation under a fixed-price trading policy, fields for future research. Fields for future research include more complicated scenarios, where heterogeneous secondary systems of different radio characteristics/requirements are concurrently competing for the available TVWS. Additionally, real time TVWS exploitation under the auction-based trading policy, also constitutes another area for further study.

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References
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