Real-Time TVWS Trading Based on a Centralized CR Network Architecture

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Abstract—**This paper discusses the design and prototyping of a cognitive radio system architecture that enables for TVWS exploitation under the real time secondary spectrum market policy. It describes a centralized infrastructure-based network, where TVWS allocation among unlicensed systems is administrated by a spectrum broker, carrying out radio-resource management and spectrum trading in real time. For optimum system performance as a matter of maximum-possible radio resource exploitation and trading revenue, the paper studies and implements 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 verified the validity of the proposed architecture, besides establishing its capacity for maximum spectrum utilisation and minimum fragmentation under a fixed-price trading policy.**

Keywords- Spectrum trading; TVWS; cognitive radio; radio resource management; spectrum broker.

I. INTRODUCTION

Advanced mobile applications and telecommunication services, rich in user-generated content with stressed end-to-end QoS requirements, call for more network resources thus raising the needs for frequency availability and creating new challenges in spectrum administration. Whereas the use of advanced signal processing techniques allows for a very efficient spectrum-usage even the framework of the traditional "command-and-control" regime, there is a global recognition that such methods of spectrum administration have reached their limit and are no longer applicable. Spectrum utilisation studies have shown that most of the licensed frequencies are under-utilised [1], and significant part of the radio spectrum is available when both dimensions of space and time are considered. Such an example of under-utilised spectrum is the "television white spaces" (TVWS), which consist of VHF/UHF frequencies that are either released by the digital switchover process ("Spectrum Dividend"), or are completely unexploited (especially at local level) due to frequency planning issues and/or network design principles ("Interleaved Spectrum") [2].

TVWS usually comprise some tenths of MHz mainly at local/regional level [3], allow for low cost and low power system design, provide superior propagation conditions and building penetration, and at the same time their sufficient short wavelength allows the development of resonant antennas, at a smaller size and shape, which is appropriately acceptable for many handheld-mobile devices. Therefore, TVWS are well-suited for wireless applications and mobile telecommunication systems. However, the traditional command-and-control spectrum-administration policy permits only licensed systems/users (Primary), such as DVB-T, DVB-H, iTV, PMSE, etc., to exploit TVWS, while it prohibits any other unlicensed transmission [4]. Therefore, the problem of spectrum shortage as perceived today, is one of inefficient frequency-management policy rather than of spectrum scarcity. The envisioned policies include those where unlicensed (Secondary) systems are allowed to opportunistically utilise the unexploited VHF/UHF channels [5].

Such a liberalised and opportunistic TVWS exploitation can be based on Cognitive Radio technologies [6], [7], [8], which aim to provide dynamic spectrum access to unlicensed users by avoiding interference to licensed ones. Most existing CR network architectures are classified (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], [10]. Nevertheless, in all cases vital part of CR networks is the radio resource management (RRM) framework [11], [12], [13], which tries to achieve the desired network objective (or wireless applications/services requirement) under the constraint on available radio resources (e.g. the radio spectrum in terms of frequency band or time slot, or transmission power). Existing RRM implementations, as are proposed in [9], [14], fall within two main categories of optimisation algorithms: a) the decision making algorithms, which are trying to reach an optimal solution through classical mathematical rationalization, and b) game theory algorithms [15], [16] that view the radio-resource optimisation as a "game" and try to find the optimal way to "play" it.

Although conceptually quite simple, the introduction of CR networks in TVWS represents a disruption to the current "command-and-control" paradigm of TV/UHF spectrum management, and therefore the exploitation of the pre-mentioned architectural/technological CR solutions 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" (RTSSM) may be the most appropriate solution, especially for applications that require sporadic access to spectrum and for which QoS guarantees are important. RTSSM 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.

This paper elaborates on TVWS exploitation under the RTSSM regime, by proposing a centralized infrastructure-based CR network architecture, where operation of secondary systems is orchestrated through a spectrum broker. Following this introductory section, Section 2 elaborates on the overall configuration of the proposed CR network architecture under the RTSSM regime and analyses the TVWS allocation and trading processes carried by a prototype RRM in the Spectrum Broker. Section 3 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 maximising persistence of TVWS channel allocations as well as the interference-free coexistence with primary systems (i.e. DVB-T systems). Finally, Section 4 concludes the paper by elaborating on fields for future research.

II. SYSTEM ARCHITECTURE

This section elaborates on the system design of a centralized infrastructure-based CR network, operating under the RTSSM regime (as this 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), 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.

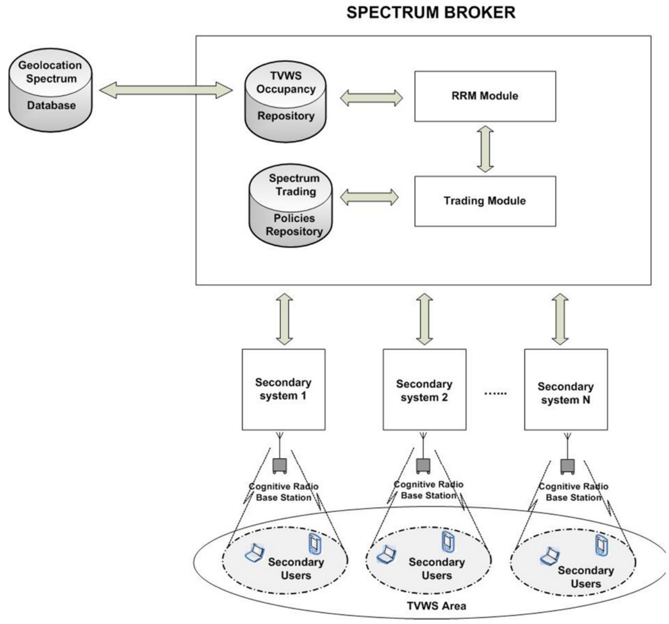

Fig. 1. Architecture of the proposed CR network operating under the RTSSM regime

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 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, which in our case can be accommodated by Backtracking algorithm [17].

The choice of the most appropriate algorithm, which will be suitable to solve a problem, is usually a captious question. Naturally, each optimisation algorithm has strong and weak points. A general comparison for every situation is impractical, and an application-driven choice is recommended. Thus, an interesting challenge consists of pondering all important conveniences and drawbacks in the sense to answer a single question; which algorithm is the most suitable under specific scenario, purpose, and implementation limitations? Thereupon, applicability, processing time and computational complexity queries must be considered.

Based on the above, the simplest approach in order to solve an integer-programming problem, such as spectrum allocation in CR networks, is to enumerate all possibilities. The most common algorithm for performing systematic/exact search is backtracking, which generates each possible solution exactly once avoiding both repetitions and missing solutions. This approach eliminates processing time and reduces the algorithm complexity, which is given by O(F!/(F-V)!), where "F" is the total available TVWS channels and "V" the number of all competing secondary systems.

Backtracking incrementally attempts to extend a partial solution (i.e. A = (a_1, a_2, ..., a_k)) that specifies consistent values for some of the variables, toward a complete solution, by repeatedly choosing a value for another variable consistent with the values in the current partial solution. In the backtracking method, variables are instantiated sequentially and as soon as all the variables relevant to a constraint are instantiated, the validity of the constraint is checked. If a partial solution violates any of the constraints, backtracking is performed to the most recently instantiated variable that still has alternatives available, as a result to eliminate a subspace (i.e S_k) of all variable domains. Backtracking constructs a tree of partial solutions, where each vertex represents a partial solution. Below the related pseudo-code is presented that performs the backtracking:

```
Backtracking(A, k)
    if A = ($a_1$, $a_2$, ..., $a_k$) is a solution, report it.
    else
        k=k+1                  // k is a counter
        compute $S_k$          // $S_k$ is the subset of variables
        while $S_k \neq$ □ do
            $a_k$ = an element in $S_k$
            $S_k = S_k - a_k$    // Remove $a_k$ from $S_k$ subset
Backtracking(A, k)
```

During the first step of the algorithm, the RRM establishes all possible solutions for allocating the available TVWS to the competing 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 (utilising Backtracking Algorithm [17]) is applied over all possible solutions. For example, assuming that "F" is the total available TVWS channels and "V" the number of all competing secondary systems, it comes that the number of all possible combinations/solutions (NPS) will be:

$$NPS = \frac{F!}{(F-V)!} + \sum_{x=1}^{V-1} (F * V * x). \quad (1)$$

each one denoting a specific allocation scheme/pattern for assigning a certain TVWS frequency to a single SS. 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 BW(i,f), thus constituting a subset of NPS solutions when a an optimisation approach is applied over them (i.e. over all NPS solutions) following the objective function C(A'_n):

$$C(A'_n) = \sum_{i \in V} \sum_{f \in F} x_{if} P(i,f) BW(i,f) \quad (2)$$

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,

$$P(i,f) = \sum_{f \in F} p(f) x_{if} \quad (3)$$

denotes the allocation x_{if} where the maximum allowed power of the "f" TVWS can satisfy the SS technical requirements.

Moreover,

$$BW(i,f) = \sum_{i \in V} b(i) x_{if} \quad (4)$$

represents 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 of competing secondary systems ("V") and the number of the available TVWS channels ("F") hosted by the TVWS Occupancy Repository. Following in 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 process. 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.

Next, 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 [18], [19], among which are the Market Valuation ones (e.g. Spectrum Market Transaction, Value of Spectrum Owning Companies, Capacity Sales of Spectrum-Utilising services, etc. – [18], [19]) and the Direct Calculation methods, including the Standard Net Present Value (NPV) and Least Cost Alternative (LCA) [18], [19]. In turn, and according to the logical diagram in Figure 2, 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).

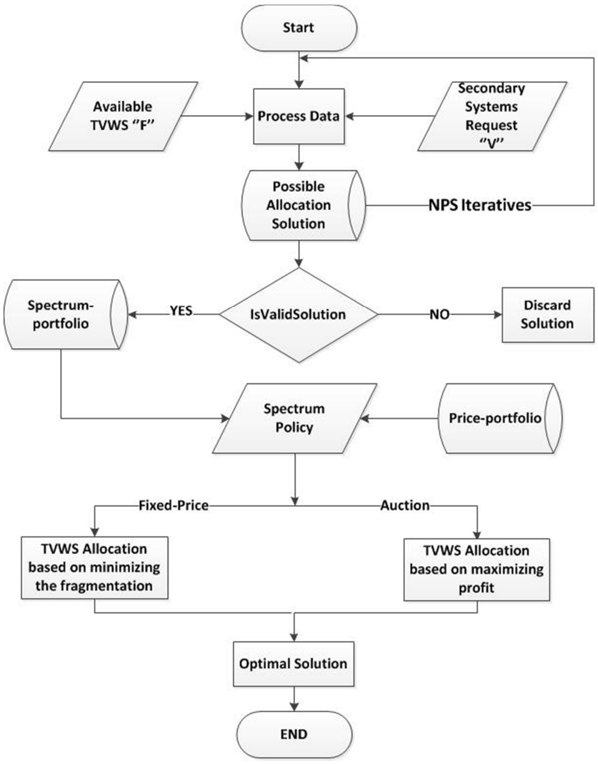

Fig. 2. Logical Diagram of Backtracking Process in order to reach to the optimal allocation solution

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):

$$\text{minimise } C(A') = C(A'_n)\sum_{i\in V}\sum_{f\in F} Frag(i,f)\Pr(i) \qquad (5)$$

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

$$Frag(i,f) = \sum_{f\in F} frg(f)\, x_{if} \qquad (6)$$

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 maximise the spectrum broker profit. The auction would then be repeated as spectrum portions become available (i.e. as they are released by supplying players).

Finally, the RRM module has the responsibility to inform/update the TVWS occupancy repository (see Figure 1) for the allocation scheme that the Backtracking produced. Thus, the information regarding the optimum allocation solution is vital for the TVWS occupancy repository, especially when there is still an unused spectrum as well as a demand from new incoming secondary users. With this updated information the algorithm can be run again.

III. PERFORMANCE EVALUATION

A. *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" [20]. Following these actual/real data, Figure 3 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 3 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 3.

- A number of Secondary Systems competing for TVWS exploitation, based on the LTE standard [21], [22]. For these LTE systems Time Division Duplexing (TDD) was chosen utilising 5MHz bandwidth, while 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 process in Figure 2. 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.

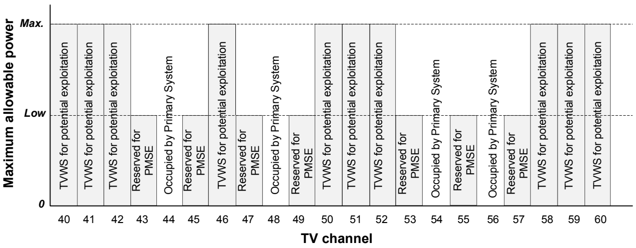

Fig. 3. Maximum allowable transmission power by secondary systems in TV spectrum for Munich area

B. *Performance evaluation*

Based on the described test-bed, a set of experiments was conducted towards estimating the maximum number of LTE 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, b) the processing time of the simulation in every time period and c) the spectrum utilisation and the resulting spectrum fragmentation [23] when the best-matching solution is applied. Spectrum utilisation was estimated as the percentage the exploited bandwidth (by both Primary and Secondary Systems) over the totally available spectrum within TV channel 40 and TV channel 60, (i.e. 168MHz).

Consequently, the initial condition in our tests comprised a spectrum utilisation of 19.05%. 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 (7) [24],

$$Z = 1 - \frac{\sum_{i=1}^{n} f_i^{p}}{(\sum_{i=1}^{n} f_i)^{p}} \quad (7)$$

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 [24]. 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 (7) over the Munich frequency allocation pattern (see Figure 3), an initial Fragmentation Score of 0.76817 was considered as the starting point for simulation tests.

During these performance evaluation experiments the LTE 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 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 is assigned the requested spectrum, 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 LTEs that are placed at consecutive frequencies, “frequency guard intervals” of 1MHz are utilised, each one placed at upper-bound of every LTE’s spectrum.

TABLE I
EXPERIMENTAL RESULTS WHEN MAXIMUM NUMBER OF LTES ARE ACCOMMODATED IN THE MUNICH TVWS

Time Period	Spectrum Utilisation (%)	Fragmentation Score	Number of solutions Explored	Processing Time (msec)
0	19.05%	0.76817	–	–
1	22.02%	0.77292	62	17.811418
2	25.00%	0.77312	55	11.857024
3	27.98%	0.77358	50	11.231002
4	30.95%	0.76962	44	10.164928
5	33.93%	0.76000	38	10.042048
6	36.90%	0.80865	36	9.893824
7	39.88%	0.81737	29	8.567040
8	42.86%	0.82118	24	7.989056
9	45.83%	0.81826	20	6.526976
10	48.81%	0.87750	13	5.983168
11	51.79%	0.89102	6	4.550400
12	54.76%	0.89681	4	2.748480
13	57.74%	0.89109	2	1.608000
Total	–	–	383	108.9733632

For example, while in the Time Period 1 the first LTE requests frequencies from the initially available TVWS spectrum (i.e. from 80MHz), in Time Period 2 the new LTE requests access to the remaining frequencies, that is 74MHz available (i.e. 80MHz minus the 5MHz allocated to the 1st LTE along with the 1MHz of the “guard intervals” assigned to it).

Similar simulation tests that carried-out towards exploiting the entire TVWS in the Munich spectrum-data (see Figure 3), indicated that up-to 13 LTEs can be efficiently accommodated as secondary systems under the described RTSSM policy, resulting in an overall spectrum utilisation of 57.74% and a Fragmentation Score of 0.89109. Table 1 above presents the experimental results for each of these simulation tests (Time Periods), where Time Period “0” represents the initial conditions, while Time Period 13 the case where the last LTE was accommodated. Figure 4 illustrates the final placement of these 13 LTEs within the Munich TVWS spectrum (as those presented in Figure 3).

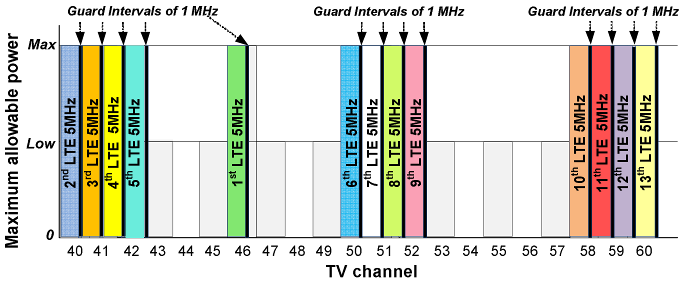

Fig. 4. Allocation of all LTEs within the Munich TVWS

IV. CONCLUSION

This paper discussed the design and implementation of a prototype system architecture enabling for TVWS exploitation under the real time secondary spectrum market policy. It described a centralized infrastructure-based cognitive radio network, where a Spectrum Broker coordinates the dynamic TVWS allocation process among secondary systems, as well as 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 through simulations, where LTEs of fixed bandwidth were sequentially accessing the available TVWS.

Performance evaluation results verified the validity of the proposed architecture, besides demonstrating its capacity for maximum spectrum utilisation and minimum fragmentation under a fixed-price trading policy. Also, preliminary experimental results show that backtracking algorithm can obtain the best matching allocation in a lower processing time, rather than other related exact optimisation methods (e.g. Generate and Test algorithm - GT) [25]. On the other hand, in order to further minimise the processing time heuristic algorithms can be utilised (e.g. Simulated Annealing) providing allocation solutions similar to those found by the Backtracking. In this respect, fields for future research include qualitative and quantitative comparison between the backtracking and simulated annealing, where heterogeneous secondary systems of different radio characteristics/requirements are simultaneously competing for the available TVWS. Additionally, real time TVWS exploitation under the auction-based trading policy also constitutes another area for further research.

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