A radio resource management framework for TVWS exploitation under the RTSSM policy

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Abstract—**This paper elaborates on the design implementation and performance evaluation of a prototype Radio Resource Management (RRM) framework for TV white spaces (TVWS) exploitation, under the Real Time Secondary Spectrum Market (RTSSM) policy. The proposed RRM is applied in centralised CR network architectures, where exploitation of the available TVWS is orchestrated by a Spectrum Broker. Efficient RRM performance as a matter of maximum-possible spectrum utilisation and minimum fragmentation is performed by decision-making optimisation methods based on the Backtracking and the Simulated Annealing algorithms. Experimental tests that were carried-out under controlled conditions environment, verified the validity of the proposed framework, besides identifying fields for further research.**

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

I. INTRODUCTION

Cognitive Radio (CR) concept [1] is researched and developed in response to the current wireless networks' needs for increased spectrum availability and better exploitation of the available radio resources [2]. Deployment of CR networks can satisfy/fulfil the increasing users' demand for bandwidth-hungry QoS-sensitive mobile services, by enabling dynamic access to the available spectrum pool, along with on-demand utilisation of the radio resources. Major obstacle, however, towards the wide-spread deployment and massive exploitation of CR networks is the current spectrum management framework, i.e. the Command-and-

Control regime, allowing only licensed/Primary systems to operate in specific frequency bands, while prohibiting any other secondary transmission within these frequencies. Such a case constitutes the so-called TV white spaces (TVWS) [3]), i.e. television frequencies that comprising VHF/UHF frequencies 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]. More specifically, currently TVWS can be only utilised by Primary Systems (e.g. DVB-T, DVB-H, PMSE, etc.), unless a new spectrum policy and management framework is applied.

Among the envisaged frameworks are the "Spectrum of Commons" (or unlicensed policy), and the "Real-time Secondary Spectrum Market - RTSSM" (or licensed policy) [5], [6]. The former, 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. However, despite the fact that unlicensed spectrum promotes efficiency through sharing, QoS cannot be guaranteed, which is a serious problem especially for QoS-sensitive applications. Defining spectrum policies and etiquette rules to promote fairness and

avoid the "tragedy of the commons" [4] are also key challenges.

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 policy 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. The license holder runs 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 occur through intermediaries such as a Spectrum Broker, exploiting radio resource management algorithms (RRM) [6], [7] for determining through optimisation techniques 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 spectrum is needed, and they 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.

This paper elaborates on the implementation of a prototype RRM algorithm adopted in a centralised/Broker-based CR network architecture for TVWS exploitation under the RTSSM regime. Section 2 discusses optimisation techniques based on decision-making algorithms for realising CR radio resource management schemes, Section 3 elaborates on the design and implementation of a prototype RRM that may utilise either integer/combinatorial programming or mathematical optimisation techniques for dynamic TVWS allocation and spectrum trading among Secondary Systems, while Section 4 elaborates on the performance evaluation of the proposed RRM. Finally, Section 5 concludes the paper by identifying fields for future research.

II.   SPECTRUM OPTIMISATION BASED ON DECISION-MAKING APPROACH

A vital part of most centralised CR network architectures is the radio resource management entity (RRM), which is responsible for the radio resource allocation process, besides satisfying the Secondary System's QoS requirements and maintaining interference-free operation among Primary and Secondary Systems. To achieve these, the RRM exploits optimization methods [8], [9], among which are the decision-making ones, which are trying to reach an optimal solution through classical mathematical rationalization, i.e. by formulating an objective function so that equality and inequality constraints are not crossed [9]. 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). 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 [10].

It should be noted, however, that the choice of the most appropriate decision-making RRM implementation technique constitutes an application-driven approach, based on specific use-case scenarios, and by taking into account the corresponding implementation intricacies. Thereupon, metrics such as the complexity of the RRM algorithm, the range of the possible solutions to be checked, the processing time and computational power required for obtaining the optimum solution have to be considered prior to choosing the most applicable technique.

III.   DESIGN OF A PROTOTYPE RRM FOR TVWS EXPLOITATION BY CR NETWORKS UNDER THE RTSSM POLICY

This section elaborates on the design of a prototype RRM in a Broker-based CR network for the efficient exploitation of TVWS under the RTSSM regime. The overall architecture of this network is depicted in Figure 1, and comprises two core subsystems: a) a Spectrum Broker responsible for coordinating TVWS access and administrating the economics of radio-spectrum exploitation, and b) a number of Secondary Systems, competing/requesting for TVWS utilisation.

According to this architecture, Secondary Systems' requests for TVWS access are communicated to the Spectrum Broker, where a Radio Resource Management module (RRM) analyses and processes them as a matter of the Secondary Systems' 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 by a Trading Module, taking into account a spectrum-unit price (e.g. cost per MHz) that may be based either on fixed-price or spectrum-auction policies [11]. 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 RTSSM regime/policy. In other words, the Broker is responsible for obtaining the best-matching solution through an optimisation-based process, taking into account parameters with integer values or combinatorial nature (e.g. number of the available TVWS channels), the number of Secondary Systems, the required bandwidth, the maximum allowable transmission power, the spectrum-unit price, etc. Eventually, the anticipated best-matching solution (spectrum allocation scheme) will be the result of a decision-making approach that can be based on integer/combinatorial programming or mathematical technique.
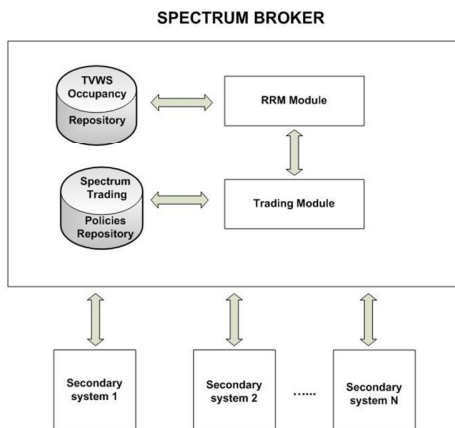

Figure 1.   Architecture of the proposed CR network operating under the RTSSM regime.

Figure 2 illustrates the logical diagram of this 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 2, 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.
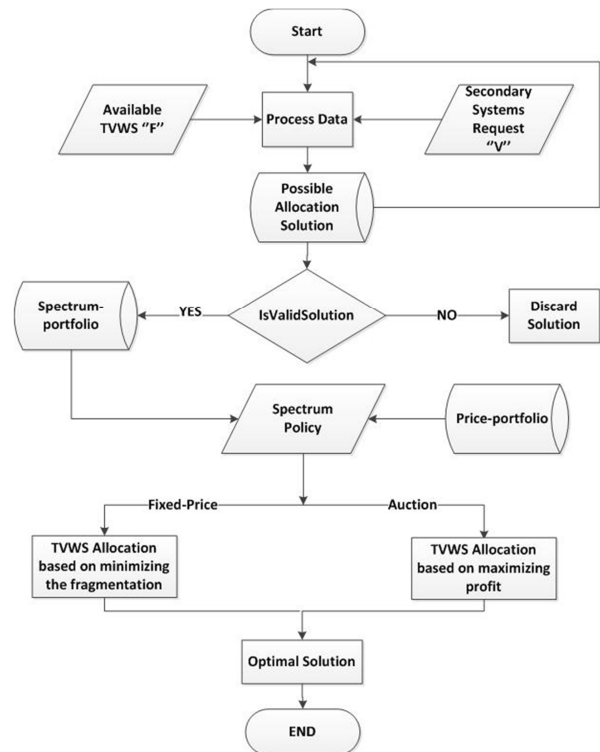

Figure 2.   Logical diagram of the proposed decision-making approach towards establishing the optimal allocation solution

IV.   PERFORMANCE EVALUATION

Towards verifying the validity of the proposed RRM and validating its capacity for efficient TVWS exploitation within the RTSSM policy, the authors implemented two versions of the proposed decision-making process, one by exploiting the Backtracking algorithm (with and without pruning technique) and another by utilising the Simulated Annealing one.

The detailed pseudo-codes are shown in Table 1 and 2 respectively.

TABLE I. BACKTRACKING ALGORITHM PSEUDO-CODE

Backtracking()
  Create initial solution S
  for i = 1 to subset of variable length **do**
      Generate a new solution S_i
      if (Objective_function(S) ≤ Objective_function(S_i))
            then save the new solution S_i to best found S
            else reject the S_i solution
  Return S

TABLE II. SIMULATED ANNEALING ALGORITHM PSEUDO-CODE

Simulated-Annealing()
  Create initial solution S
  Initialize temperature t
  repeat
    for i = 1 to iteration-length **do**
      Generate a random transition from S to Si
      if (Objective_function(S) ≤ Objective_function(S_i))
            then save the new best solution S_i to previous one S
            else
                Change state/solution with a random probability
            Reduce temperature t
    until (t=1)
  Return S

These RRM implementations were used for carrying-out a number of experiments under controlled-conditions test-bed (simulations) comprising:

- A TVWS Occupancy Repository, hosting information about UHF/TV frequencies that can be exploited by Secondary Systems'. The information in this repository was built around actual/real spectrum data (gathered within the framework of the ICT-FP7

"CogEU" project [12]), concerning the TVWS availability between 626MHz (Ch.40) and 752MHz (Ch.60) in Munich area. Following this data (see Figure 3), only 10 TV channels are available in Munich area for exploitation by Secondary Systems, each providing a spectrum of 8MHz and altogether a total/aggregate bandwidth of 80MHz, providing an initial spectrum utilisation of 19.05% and featuring a fragmentation of about 0.76817.

- A number of Secondary Systems' (based on the LTE standard [13]) competing for TVWS exploitation and operating with Time-Division-Duplexing (TDD), utilising 5MHz bandwidth, and transmission power of 4Watts. During these tests the LTE systems were accessing the available TVWS in a sequential mode one-by-one at the start of the simulation and remain active through the duration of the simulation, i.e. for every new experiment (Time Period) an additional LTE system was entering the test-bed, requesting access to the available (at the given Time Period) TVWS frequencies.

- 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. 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.
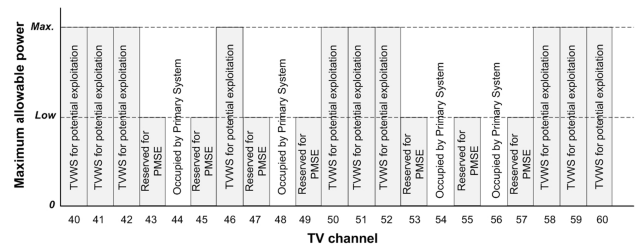

Figure 3. Maximum allowable transmission power by secondary systems in TV spectrum for Munich area

It should be noted that this test-bed was not only used for evaluating the performance of the proposed RMM when Backtracking (with and without Pruning technique) and Simulated Annealing algorithms are

utilised, but also – and most predominant –for obtaining qualitative comparison results among the two RRM implementations. More specifically, 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 RRM performance in respect to a) the processing time of the simulation in order to reach the best-matching solution in every time period b) the spectrum utilisation and c) the resulting spectrum fragmentation [14] when the best-matching solution is applied.

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). Figure 4 depicts the results obtained in every Time Period for each RRM implementation, where the black line in represents the initial value of the spectrum utilization, i.e. when only primary systems operate in the TVWS channels. From this figure it can be verified that all-three algorithms result in the same spectrum utilisation (for each Time Period), given that the same number of secondary systems was accommodated. Additionally, spectrum fragmentation (or Fragmentation Score) was calculated by taking into account the number of fragments (unused spectrum-portions) as well as the size/bandwidth of each individual fragment, as it is proposed in [14]. Figure 5 depicts the results obtained in every Time Period for each RRM implementation, where the black line again denotes the initial condition when no secondary system is accommodated. From this figure it can be verified that all algorithms provide 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. The experimental results also indicated that up-to 13 LTEs can be efficiently served by the proposed RRM, no matter if Backtracking (with or without Pruning technique) or Simulated Annealing is utilised, providing an overall spectrum utilization of 57.74% (see Figure 4) and similar spectrum fragmentation of about 0.9 (see Figure 5).

Finally, Figure 6 represents a qualitative comparison among Backtracking (with and without Pruning technique), and Simulated Annealing, as a matter of the duration of the simulation before obtaining the optimum solution. From Figure 6 it can be observed that Simulated Annealing performs better than Backtracking one, regarding the simulation time, while the Pruning technique alleviates their differences. More specifically, we can observe in Figure 6 that when the range of possible solutions is high (e.g. in Time Period 0) Simulated Annealing is faster, thus obtaining the best-matching solution in a shorter Simulation Time than Backtracking, while providing comparable results when the range of possible solutions is small (e.g. Time Period 13).
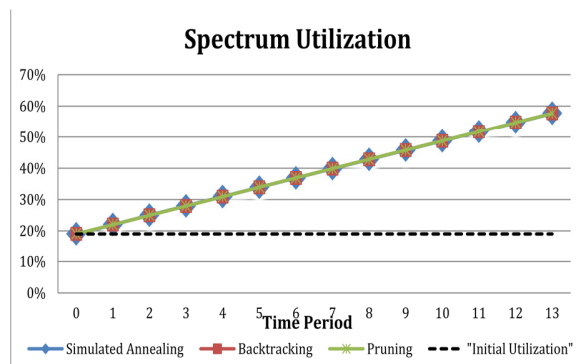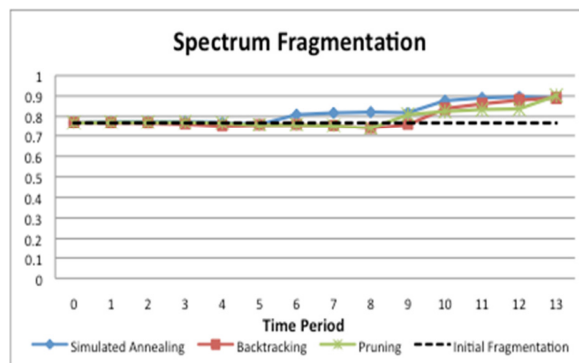

Figure 4. Spectrum utilization
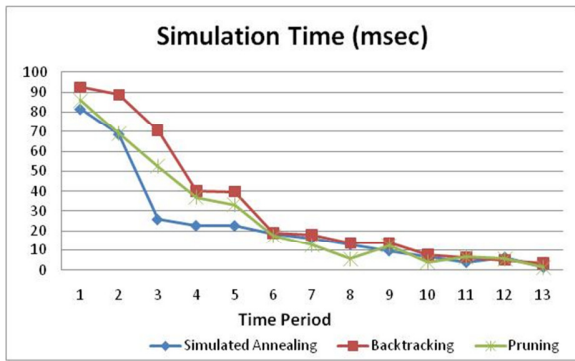

Figure 5. Spectrum fragmentation

Figure 6.   Simulation time

V. CONCLUSIONS

This paper discussed the design of an RRM framework, which can be utilised in a centralized/Broker-based Cognitive Radio architecture for TVWS exploitation under the RTSSM policy. Following, the paper elaborated on the implementation of a prototype RRM, according to the design specifications, by utilising a decision-making process based on Backtracking and Simulated Annealing algorithms. Towards evaluating the RRM performance, a set of experiments was designed and conducted under controlled conditions test-bed, where LTE systems of fixed bandwidth were sequentially accessing a given TVWS spectrum. The obtained experimental results verified that the same number of LTE systems can be efficiently served by the proposed RRM, no matter which algorithm is utilised, resulting in maximum TVWS exploitation and minimum spectrum fragmentation. Fields for future research include secondary systems that concurrently compete for TVWS utilization, with different technical specifications and diverse QoS requirements, as well as real time TVWS exploitation under the auction-based trading policy.

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