A centralised broker-based CR network architecture for TVWS exploitation under the RTSSM policy

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Abstract – The paper discusses the TV white spaces exploitation by a prototype centralised cognitive radio network architecture, under the real time secondary spectrum management scheme. Vital part of this architecture is a spectrum broker that coordinates the radio resources allocation process among secondary systems, as well as the transactions of spectrum trading following a fixed-price policy. Efficient broker operation as a matter of maximum-possible spectrum utilisation and minimum fragmentation is obtained by decision-making methods based on Backtracking, Simulated Annealing and Genetic algorithm. The validity of the proposed approach is verified via a number of experiments under controlled conditions, while its performance is evaluated against a number of secondary systems competing for TVWS exploitation, each one featuring different transmission characteristics.

Keywords – Cognitive Radio; Spectrum Broker; Radio Resource Management; TVWS; Spectrum Trading.

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. Although conceptually quite simple, the introduction of CR networks is not a straightforward process especially in licensed bands, where the existing spectrum management framework (i.e. the Command-and-Control regime) allows only licensed/Primary systems to operate (e.g. DVB-T, DVB-H, PMSE, etc.), while prohibiting any other secondary/unlicensed transmission. Such a case of

licensed spectrum are the TV white spaces (TVWS) [4]), i.e. television frequencies that comprising VHF/UHF frequencies, which 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") [5]. Therefore, introduction of CR networks in TVWS currently represents a disruption to the "command-and-control" paradigm of TV/UHF spectrum management, and thus the exploitation of the CR technology is highly intertwined with the regulation models that would eventually be adopted.

Amongst the envisaged schemes [6], [7] is the "Real-time Secondary Spectrum Market - RTSSM" policy, enabling Primary users (i.e. license holders) to trade spectrum usage rights to Secondary players (i.e. license vendees), thereby establishing a secondary market for spectrum leasing and trading. RTSSM policy may be realized in centralised CR architectures, where spectrum trading is carried out by intermediaries, such as a Spectrum Broker, which orchestrates the frequency allocation process through a radio resource management entity (RRM) [6], [8], besides federating the economics of such transactions. Secondary users, dynamically request access to TVWS and they are charged based on spectrum utilization basis, as a matter of type of services, access characteristics, and QoS level requests.

Radio resource management is an important functionality in CR networks, which involves dynamic spectrum access and aims at satisfying the requirements of both primary and secondary systems. A number of research approaches for RRM in CR networks have been proposed in the literature. In [9], an optimization problem was formulated for managing spectrum access, the solution of which gives the highest satisfaction to the cognitive radio systems, considering interference constraints. Moreover, in [10], Quality of Service (QoS) performance in a CR system, involving primary and secondary users, was analyzed by using Markov chain. In this context,

this paper elaborates on trading of TVWS under the RTSSM regime, by proposing a centralised CR network architecture, where a prototype Spectrum Broker entity orchestrates in real-time the operation of the RRM and the economics of the transaction. The proposed RRM research approach aims to exploit unused radio spectrum parts, such as TVWS, by respecting different QoS level requirements of secondary systems that request access to the available resources. Following this introductory section, Section 2 discusses the design of the Spectrum Broker by elaborating on optimisation techniques and decision-making algorithms 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 TVWS TRADING UNDER THE RTSSM POLICY

This section elaborates on the design of a Broker-based CR network that enables the efficient exploitation/trading of TVWS under the RTSSM policy. The overall architecture of this network is depicted in Figure 1, where a Spectrum Broker coordinates the TVWS allocation among all competing secondary systems, besides administrating the economics of such spectrum transactions. For this reason, the broker utilizes:

a) a radio resource management module (RRM) responsible for optimally allocating the available TVWS as a matter of maximum possible utilisation and minimum frequency fragmentation. The RRM exploits optimisation methods [11], [12], among which are the decision-making ones that are trying to reach an optimal solution through classical mathematical rationalization [12]. 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 [13].

b) a trading module that performs the economics of the TVWS transactions, taking into account a "spectrum-unit price" (e.g. cost per MHz), either on a fixed-value or an auction-based trading policy [14].

According to Figure 1, Secondary Systems' requests for TVWS access are communicated to the Spectrum Broker, where the 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 the Trading Module. 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.
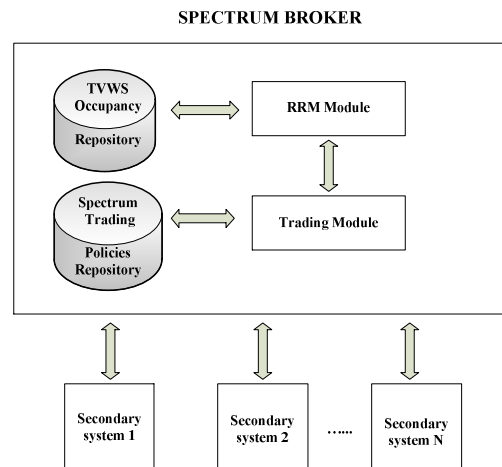

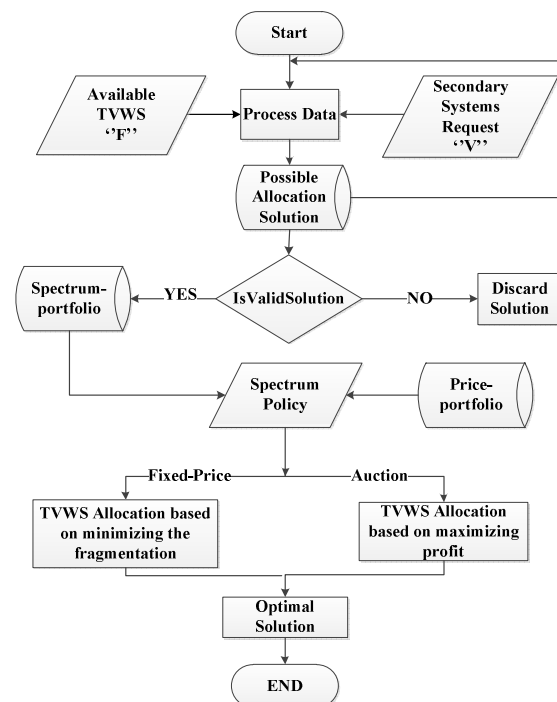Fig. 1. Broker-based network architecture operating under the RTSSM regime.

Fig. 2. Logical diagram of RRM and trading modules towards establishing the optimal allocation solution

Figure 2 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 2, which examines if a Possible Allocation Solution fulfills 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.

III. PERFORMANCE EVALUATION

A. Test-bed description

Towards verifying the validity of the proposed CR architecture and evaluating its capacity for efficient TVWS exploitation within the RTSSM policy, the authors implemented three versions of the proposed decision-making process: the first one by exploiting the Backtracking algorithm, the second one by utilising the Simulated Annealing and the third one by developing the Genetic Algorithm [13]. The simplest approach in order to solve an integer-programming problem, such as spectrum allocation in CR networks, is to generate all possible spectrum allocations, by performing systematic/exact search. Backtracking is capable to generate each one 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. The backtracking algorithm may be improved by some filtering techniques, which aim at pruning the search space in order to decrease the overall duration of the search.

On the other hand, Simulated Annealing is a heuristic algorithm for the global optimisation problem, which can be applied in resource allocation. Simulated Annealing algorithm replaces, at each step, the current allocation solution by a random "nearby" solution. This allocation solution is chosen with a probability that depends on the difference between the corresponding function values and on a global parameter T (called the temperature). The probability is large when the temperature is high so that the algorithm will not be stuck in a certain local optimum. On the other hand, the probability is low since the probability of local optima is low. When the temperature is zero, the algorithm reduces to the greedy algorithm. Typically this step is repeated until the system reaches a state that is good enough for the application, or until a given computation budget has been exhausted.

Finally, Genetic Algorithms are search algorithms that operate via the process of natural selection. They begin with a sample set of potential solutions, which then evolves toward a set of more optimal solutions. Within the sample set, solutions that are poor tend to die out while better solutions mate and propagate their advantageous traits, thus introducing more

solutions into the set that boast greater potential. A little random mutation helps guarantee that a set will not reach to local optima and simply fill up with numerous copies of the same solution.

It should be noted that the choice of the most appropriate decision-making 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 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. In this context, a number of experiments were designed and conducted under controlled-conditions (i.e. simulations) concerning the performance of the above algorithms, as a matter of the number of secondary systems that each algorithm can accommodate, the resulted spectrum utilization and frequency fragmentation [15], the time needed to provide the best-matching solution, as well as for obtaining qualitative comparison results among the three RRM implementations. The experimental test-bed comprised:

- 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 [16], concerning the TVWS availability between 626MHz (Ch.40) and 752MHz (Ch.60) in Munich area [17]. 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.
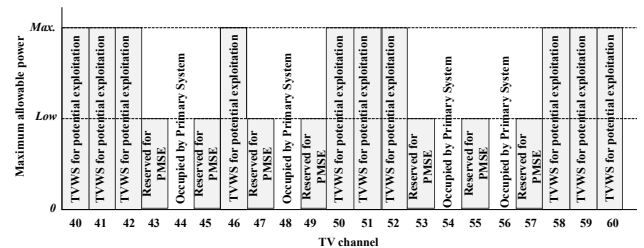
Fig. 3. Maximum allowable transmission power by secondary systems in TV spectrum for Munich area

- 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.

- A number of Secondary Systems with different radio characteristics/requirements that were simultaneously competing for the available TVWS. These systems were based on LTE [18] operating with Time-Division-Duplexing (TDD), WiFi [19] and Public Safety [20] technologies. More specifically, CR networks operating in

the TVWS can facilitate multi-organisational (e.g. fire-brigade and police) interventions at operational level, which would not be based on the need for dedicated and harmonised spectrum assignment to Public Safety systems at the European level. Instead, systems could collectively use possible TVWS spectrum that is available in an open access manner. For each one of the above mentioned secondary systems, a different QoS-level requirement was selected, thus the optimisation algorithm was also taking into account this parameter during the spectrum allocation process under a real-time procedure. More specifically, requests of secondary systems are received and processed in real-time by Spectrum Broker, which identifies their technical characteristics and provides an immediate response respecting the QoS constraints. Additionally, for every new time period of the simulation, the secondary systems were entering the test-bed, under a fixed schedule, requesting access to the available (at the given Time Period) TVWS frequencies. The technical specifications of the secondary systems are presented in Table 1.

TABLE I
TECHNICAL SPECIFICATIONS OF EACH SECONDARY SYSTEM

Service Type	Power (Watt)	Bandwidth (MHz)	Priority/QoS Requirement
LTE 1	4	20	Medium
LTE 2	4	10	Medium
LTE 3	4	20	Medium
LTE 4	4	5	Medium
WiFi 1	0.25	22	Low
WiFi 2	0.25	22	Low
WiFi 3	0.25	22	Low
Public Safety 1	0.1	1	High
Public Safety 2	0.1	1	High

B. Results and qualititve comparison

Based on this test-bed, five time periods were designed and conducted as follows:

- Time Period 1: "LTE 1" system is requesting access to TVWS up to time period 2.

- Time Period 2: "LTE 1" maintains access to the spectrum, while two new secondary systems "Public Safety 1" and "WiFi 1" are requesting access to the spectrum up to time periods 5 and 4, respectively.

- Time Period 3: "LTE 1" releases the occupied spectrum as well as the "Public Safety 1" and "WiFi 1" maintain their access to TVWS. Also, two new secondary systems ("LTE 2" and "Public Safety 2") are accessing the available spectrum up to time period 5.

- Time Period 4: "Public Safety 1", "WiFi 1", "LTE 2" and "Public Safety 2" are still operating, while two new secondary systems, "LTE 3" and "WiFi 2", are accessing the available spectrum, up to time period 5.

- Time Period 5: "WiFi 1", "WiFi 2" and "LTE 3" release the occupied TVWS, while "Public Safety 1", "Public Safety 2" and "LTE 2" are still operating. During this time period "LTE 4" and "WiFi 3" systems are requesting access to the spectrum.

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. Spectrum fragmentation 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 [15]. 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. Finally, Figure 6 represents a qualitative comparison among Backtracking (with and without Pruning technique), Simulated Annealing and Genetic algorithms, as a matter of the duration of the simulation before obtaining the optimum solution. From Figure 6 it can be observed that that Simulated Annealing and Genetic Algorithm perform better than Backtracking one regarding the simulation time, while the Pruning technique alleviates their differences.
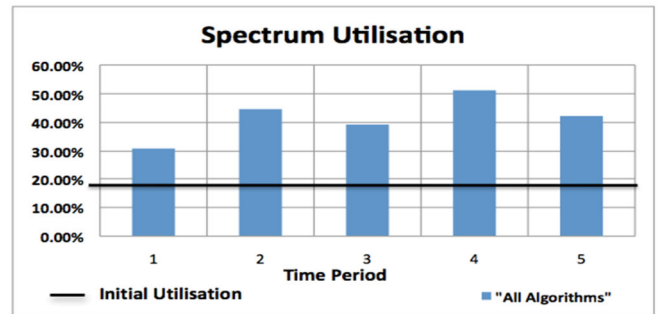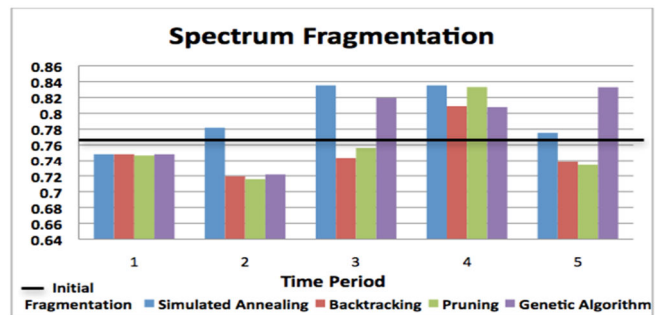
Fig. 4. Spectrum Utilization
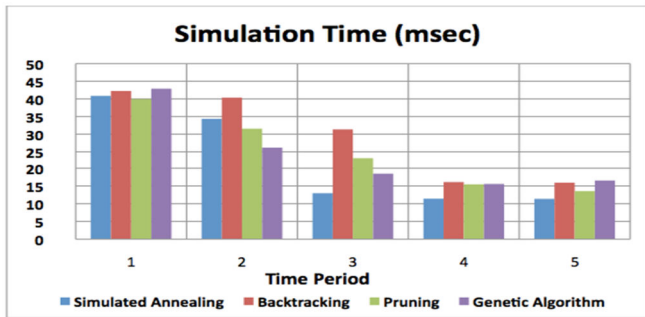
Fig. 5. Spectrum Fragmentation

Fig. 6. Simulation Time

Additionally to the above results, a very interesting outcome is related to the broker's capability in accommodating secondary systems when the available TVWS spectrum is shorter than the total requested bandwidth, and therefore only part of the competing systems can be served. In such a case, the broker takes into account the priority level of each secondary system, and grants access only to those of the highest level. For example, during Time Period 4, there are already four secondary systems active (i.e. "Public Safety 1", "WiFi 1", "LTE 2" and "Public Safety 2"), and the total available spectrum sums about 32MHz, scattered within TV channel 46, 58, 59 and 60 (see Figure 7). For this spectrum two more secondary systems are competing, i.e. "LTE 3" of medium priority level requesting 20MHz, and "WiFi 2" of low priority level requesting for 22MHz. Evidently, while both "LTE 3" and "WiFi 2" are competing for the spectrum within channel 58 to channel 60, only one of them is served, i.e. that of the higher priority ("LTE 3").
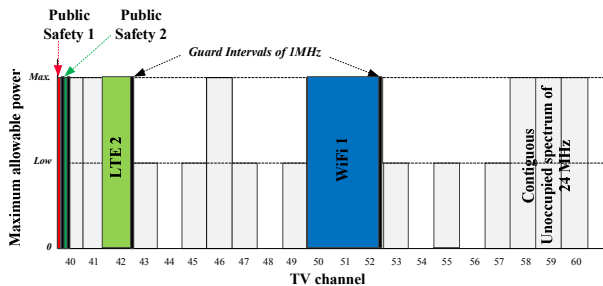

Fig. 7. TVWS allocation during the Time Period 4

IV. CONCLUSION

This paper discussed a centralised CR network architecture, which can be utilised for TVWS exploitation under the RTSSM policy. 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, Simulated Annealing and Genetic algorithms. 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 that the same number of secondary systems can be efficiently served by the proposed CR network architecture, no matter which algorithm is utilised, providing for maximum-possible TVWS utilisation and minimum spectrum fragmentation under a fixed-price trading policy. In this respect, fields for future research include qualitative and quantitative comparison between these optimisation algorithms, where the TVWS exploitation can be obtained in real time under the auction-based trading policy.

REFERENCES

[1] J. Mitola III and G. Q. Maguire, "Cognitive Radio: Making Software Defined Radio More Personal", IEEE Pers. Commun., vol. 6, no. 4, Aug. 1999.

[2] A. Wyglynski, M. Nekovee, and T. Hou, Eds., Cognitive Radio Communications and Networks: Principles and Practice, Academic Press, 2009.

[3] R. W. Thomas, L. A. DaSilva, A. B. MacKenzie, "Cognitive Networks", IEEE DySPAN, First Symposium on Dynamic Access Networks, Baltimore USA, 8-11 November 2005.

[4] Unlicensed Operation in the TV Broadcast Bands, Final Rules, Available: http://edocket.access.gpo.gov/2009/pdf/E9-3279.pdf.

[5] The Economics of Spectrum management: A Review, Australian Communication and Media Authority (ACMA), 2007.

[6] 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, 05-09 December, 2011, pp. 994-999.

[7] I. F. Akyildiz, W.- Y. Lee, M. C. Vuran, and S. Mohanty, "A Survey on Spectrum Management in Cognitive Radio Networks", IEEE Communications Magazine, April 2008

[8] F. Cavalcanti, S. Andersson (eds), "Optimizing Wireless Communications Systems", Springer, 2009.

[9] Y. Xing, C. N. Mathurm, M. A. Haleem, R. Chandramouli, and K. P. Subbalakshmi, "Dynamic spectrum access with QoS and interference temperature constraints", IEEE Trans. Mobile Computing, vol. 6, no. 4, pp. 423-433, Apr. 2007.

[10] P. K. Tang, Y. H. Chew, L. C. Ong, and M. K. Haldar, "Performance of secondary radios in spectrum sharing with prioritized primary access", in Proc. IEEE MILCOM'06, Oct. 2006

[11] E. Hossain, D. Niyato, Z. Han, "Dynamic spectrum access and management in cognitive radio networks", first ed. Cambridge University Press, 2009.

[12] Newcom++ project, DR9.1 "Identification of relevant scenarios, use cases and initial studies on JRRM and ASM strategies"

[13] Steven S. Skiena, "The Algorithm Design Manual", Second Edition, Springer, ISBN: 978-1-84800-069-8

[14] T. K. Forde, L. E. Doyle, "Combinatorial clock auction for OFDMA-based cognitive wireless networks", Proceedings of 3rd ISWPC, 7-9 May 2008

[15] Measuring Fragmentation of Two-Dimensional Resources Applied to Advance Reservation Grid Scheduling, Julius Gehr, Jorge Schneider, 9th IEEE/ACM International Symposium on Cluster Computing and the Grid

[16] http://www.ict-cogeu.eu/

[17] http://www.ict-cogeu.eu/pdf/COGEU_D4%201(ICT_248460).pdf

[18] 3GGPP LTE: http://www.3gpp.org/LTE

[19] http://standards.ieee.org/about/get/802/802.11.html

[20] W. Lehr and N. Jesuale, "Public Safety Radios Need to Pool Spectrum", IEEE Communications Magazine, March 2009.