Cognitive Spectrum Portfolio Optimisation, Approaches and Exploitation

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Abstract— **A major challenge for cooperative cognitive radio networks is the creation and optimisation of a suitable spectrum portfolio, utilised by the radio nodes in the process of dynamic spectrum management. This paper presents several optimisation approaches for spectrum portfolios. Their characteristics are discussed regarding a variety of different scenarios, and it is shown how different approaches can complement each other to optimise the overall spectrum management, in particular considering spectrum portfolio optimisation under mobility and QoS constraints. Special consideration of upcoming TV whitespace communication use cases is shown in this discussion.**

Index Terms — **Spectrum portfolio, dynamic spectrum management, TV white space, self-organising networks, quality of service, mobility**.

I. INTRODUCTION

During the past years, the evolutionary path of wireless communication systems considered enablers such as self-organising networks (SON) [1], reconfigurable radio systems (RRS) [2], cognitive radio (CR) [3], dynamic spectrum management (DSM) [4], and dynamic spectrum access (DSA) [5]. Significant progress in this area has been achieved through large-scale European research projects (e.g. [6]), worldwide standardisation efforts and by an evolving spectrum regulation framework that will allow for spectrum sharing, spectrum trading and other advanced coexistence scenarios [7]-[9].

Recently, the Digital Dividend [10] as well as the notion of authorised and licensed shared access (ASA and LSA) and spectrum white space have emerged as new opportunities for additional spectrum resources consequently luring market entrepreneurs and driving a demand for advanced spectrum management solutions.

The European research project QoSMOS [11] included among its goals the provision of DSM solutions addressing the technological challenges that come along with the shared dynamic use of spectrum resources and satisfying the demands for market relevance. The latter results from the need for competiveness of wireless communication systems that utilise shared spectrum in contrast to wireless communication systems operating in exclusive use licensed spectrum [12]. In addition, QoSMOS also considered the need to adopt business-driven requirements by major stakeholders, the applicability to all major application scenarios incorporating shared and dynamic spectrum utilisation, and the openness with respect to an evolving regulatory framework (e.g. [13]) as major key performance indicators of a versatile spectrum management solution.

This paper presents the QoSMOS cognitive spectrum management approach focusing on the functional architecture and the methods utilised for spectrum portfolio optimisation.

The rest of this paper is organised as follows. First, Section II describes the concept of spectrum portfolio, the central entities of the spectrum manager architecture, and recalls the main tasks of the spectrum manager in optimising spectrum portfolios. Section III details some of the optimisation algorithms realised as a toolkit that the spectrum manager utilises for spectrum portfolio optimisation. It describes approach, results and potential application areas of the algorithms considered. Section IV elaborates on the utilisation of spectrum optimisation approaches described in this paper in the scope of the QoSMOS spectrum manager. Section IV concludes this paper and provides an outlook on further work.

II. QOSMOS COGNITIVE SPECTRUM MANAGEMENT

The QoSMOS spectrum management solution relies on the notion of a spectrum portfolio as the descriptor of a portion of frequency spectrum, its usage constraints, and its performance for a certain scenario as experienced by the user of this spectrum (e.g. by performing measurements and reporting). For spectrum trading scenarios, a spectrum portfolio provides information about the spectrum ownership identifies current spectrum users and describes temporary usage rights and policies, as well as the current economical value of this portion of spectrum (e.g. the price of spectrum).

As a resource description, a spectrum portfolio can be optimised regarding several targets such as interference minimisation, incumbent protection, increased spectrum effectiveness (cf. [9] for a discussion of efficiency in contrast to effectiveness), enhanced user experience or maximisation of economical yield. In particular, spectrum portfolio optimisation is a multi-purpose optimisation (see also Section III.D) for individual use (i.e. by a single node), for shared use (e.g. for a dedicated radio access network, RAN, or technology, RAT), for corporate use (e.g. across all RANs of one operator) or for use in a coexistence scenario (e.g. across technology domains, operator domains or regulatory domains).

The QoSMOS approach [14] resolves these challenges by introducing a separation of spectrum management and resource management across two architectural entities, namely the cognitive manager for resource management (CM-RM) [15] and the cognitive manager for spectrum management (CM-SM), see Figure 1. While the former operates on a short timescale (based for example on knowledge about individual node's spectrum utilisation, node positions, traffic loads and radio channel characteristics), the latter operates on a mid to long timescale (relying on knowledge about wider area spatiotemporal spectrum utilisation, including interference and coexistence situations, incumbent activities and regulatory constraints). Different levels of interaction between the two managers have been defined based on the exchange of an interface data structure representing a spectrum portfolio. In most scenarios, the dataflow is bi-directional, assuming that the CM-SM plays the role of a 'spectrum provider' (deploying or revoking spectrum portfolios) and the CM-RM plays the role of a 'spectrum user' (also providing spectrum utilisation context and representing multiple nodes or RANs/RATs consuming spectrum resources).

The CM-SM itself operates on spectrum portfolios obtained from an authority (e.g. by licensing shared spectrum) or from a different CM-SM (e.g. operated by a spectrum trader). It can also exploit the information from a geolocation database (e.g. operated by a regional white space coordinator) or from a spectrum-sensing infrastructure (e.g. operated by a 'smart city' municipality). In other words, the main task of the CM-SM is the optimisation and management of spectrum portfolios.

The above operations involve elements at coexistence, coordination and networking domains [14], from top down, respectively, in Figure 1: Internet, core network and base station (in a cellular example). Operations originate at dot-headed lines, proceed through open arrowheads and end at filled arrowheads. An outer path proceeds through dash-dotted lines marked with italic font labels, whereas three inner paths go along solid lines marked with upright font labels. For example, sensing measurements made available by the spectrum sensing (SS) block are exploited at the CM-SM, and propagated up to a common portfolio repository.

Aiming at a versatile solution that allows a deployment within a reasonable timeframe to existing and upcoming network infrastructures as well as to self-organising ad hoc network configurations that opportunistically utilise licensed or shared spectrum, the QoSMOS project decided to approach spectrum management by:

- Providing a number of spectrum portfolio optimisation algorithms and methods that allow to create spectrum portfolios suitable for the various scenarios addressed by the project [16], focusing on the support of quality of service (QoS) and mobility in DSM;
- Realising a number of selection strategies that enable providing optimised spectrum portfolios to spectrum users according to their current demands;
- Defining architectural entities, interfaces and protocols needed to efficiently manage spectrum portfolios and to provide these to a variety of potential spectrum users.

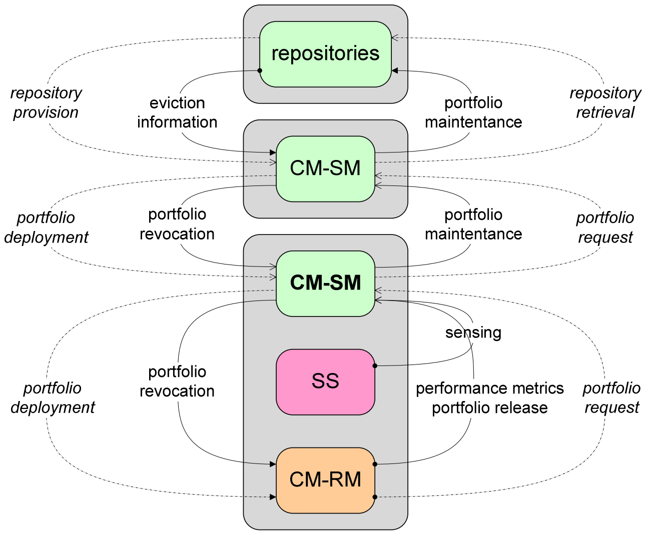

Fig. 1: Spectrum management flows through the QoSMOS system.

In this architecture, spectrum portfolios in general 'flow' between spectrum-providing entities, portfolio repositories and spectrum-consuming entities, as it can be seen in Figure 1.

A spectrum manager (i.e. a CM-SM entity) in this concept is both consuming spectrum and providing spectrum simultaneously. That is, it obtains spectrum from a different spectrum manager or a repository (e.g. maintained by an operator or by a regulatory authority), and provides optimised portfolios to a spectrum user such as a localised resource manager (e.g. a CM-RM associated with a base station subsystem). The spectrum manager in particular is dedicated to the optimisation of spectrum portfolios considering regulatory and operator's policies considering associated context. It is assisted in that by context-providing entities such as spectrum sensors or spectrum consumers (CM-RMs) that can perform measurements and can provide details on outcome or impact of utilising a certain spectrum portfolio in its particular operating environment.

The subsequent section focuses on various complementary solutions for optimising spectrum portfolios studied by the QoSMOS project, and on their respective applicability to the scenarios pointed out in the beginning.

In particular, Section III.A puts the focus on cellular scenarios and details the exploitation of a self-learning scheme to improve a spectrum portfolio with regards to improving a performance-energy metric. Section III.B considers mobile whitespace spectrum users exploiting context information obtained from geolocation databases to build signal-to-interference-plus-noise ratio (SINR) maps that assist the spectrum manager in identifying and optimising spectrum portfolios to be used along their path of motion. Section III.C focuses on the optimisation of spectrum portfolios in small cell scenarios while considering incumbent protection distance and shared spectrum utilisation load generated by opportunistic spectrum users as performance metrics. Section III.D looks at optimising spectrum portfolios according to a price-based metric, which enables spectrum-trading scenarios that consider the cost of spectrum prior to deploying spectrum portfolios upon request of a prospective spectrum user. Section III.E turns onto considering an optimisation of context acquisition strategies based on the spectrum portfolio's utilisation, channel occupation monitoring and probability of channel availability.

The above elaboration consequently formulates the basic building blocks, or toolkit functions, for portfolio optimisation available to the spectrum manager. The spectrum manager is capable of composing suitable spectrum optimisation strategies from these by applying cognitive strategies while considering policies applicable to the scenario addressed and the type of spectrum request received.

III. APPROACHES FOR PORTFOLIO OPTIMISATION

This section briefly presents different approaches and techniques enabling the CM-SM to determine and optimise the best suited spectrum portfolio for different investigated scenarios as studied within the QoSMOS project.

A. Distributed Self-learning SON Spectrum Management

This spectrum portfolio optimisation approach provides for cellular wireless networks a distributed SON concept for each distributed CM-SM. Based on collected information from a local area cluster including some surrounding CM-SM, and from external constraints such as from spectrum databases, the SON entity is then offline evaluating a large set of possible candidate spectrum portfolio configurations, spectrum parts and their transmission power within this local area. Their performance is calculated via a prediction model which assesses the resulting impact of these portfolio variations and especially considers and resolves the occurring interactions and coupling. This SON prediction model is self-learning and adapts itself to the current CM-SM specific situation.

For characterising and validating this concept, it has been implemented into a simplified LTE system simulator with an intentionally simple scenario consisting of five heterogeneous cells and with diverse input traffic created via snapshot user placements [17]. Figure 2 illustrates as an example simulation results for simultaneous spectrum portfolio and transition power configuration and optimisation, which shows that this SON and self-learning approach manages to quickly improve the chosen performance-energy metric at each iteration step for various different starting parameter configurations and for various different traffic load situations [18].

These proof-of-concept simulation results validate this SON and self-learning approach, the distributed CM-SMs adapt themselves quickly to the currently given specific local situation and to the external constraints and manage to find quickly and in a stable way a pretty good spectrum portfolio [17][18]. It shall be noted, that this is achieved very quickly only via virtual CM-SM internal predictive calculations and without any further measurement on the running system. It is recognised that a prediction from this highly complex and coupled system cannot be as accurate as real measurements on a live system; thus, this approach does typically only give a pretty good solution and not necessarily the optimum one. Furthermore, it has been found that there is a certain operating range where the SON and self-learning system works fine for a wide range of reasonable parameters for which the system has been designed and tested. But for extreme situations and for extreme parameter ranges, further special case handling and maybe model extensions are needed. It could be proposed to let first this approach find pretty good solutions, and thereafter, fine tuning could be considered with another SON mechanism, maybe a single parameter technique and which may need direct system feedback.

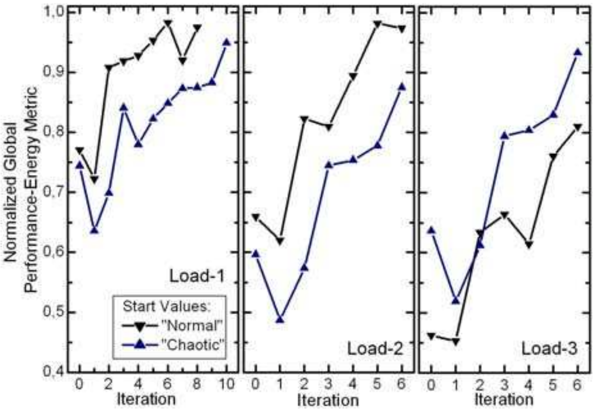

Fig. 2: Performance gains with spectrum and power optimisations.

B. Portfolio for Mobile TVWS Users

This section introduces an optimisation technique for mobile cognitive users operating in TV white space (TVWS) frequencies. The investigated scenario is a geographical area with fixed TV broadcasting service supplying the fixed users (incumbents), and mobile (opportunistic) users, utilising the common UHF frequency band in a cognitive manner. A central management entity in this system is the cognitive spectrum management system (CM-SM).

In order to improve the spectral efficiency a special optimisation technique is proposed. The physical structure of the radio network determines the non-variable part of the radio environment that can be characterised by the SINR, which determines the sufficient radio transmission power levels to service the incumbents. Where the system allows the opportunistic usage of the same frequency without disturbing the incumbents are the 'white spaces'. As an opportunistic user moves in this area, the actual state of the whole system has to be determined and managed by the central control entity. The CM-SM ensures the required level of the system service quality (QoS). Applying a geographical database, an SINR map can be created, which is applicable to determine the locations where the opportunistic usage of white spaces is possible. The movement of the cognitive user is reported through the service channel. However the exact location is unknown between two consecutive reports. In the present approach the CM-SM interpolates the opportunistic user positions with linear translation using the previous measured positions and performs a prediction. In Figure 3, the estimation method with linear translation is depicted, marking the real and the estimated route and the success of decisions.

This method is applicable to handle mobile opportunistic users in TVWS, and the route estimation algorithm can be built into the CM_SM system. The output of the algorithm is the ranking of the next estimated position in point of view of the

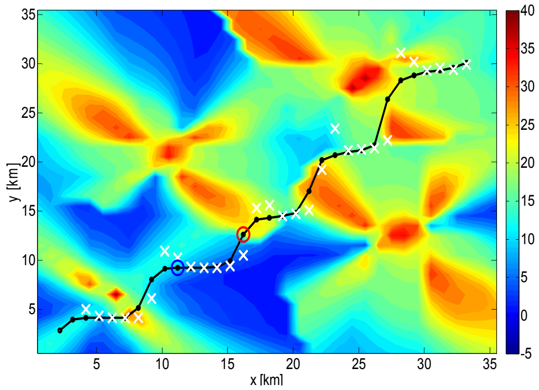

Fig. 3: SINR map with four fixed transmitters. The opportunistic user is moving on the black line marked path, while the estimated route is marked with white crosses. False predictions are shown with red and blue circles.

opportunity of cognitive operation. This may support the spectrum portfolio optimisation technique, and comparing it with a random prediction movement a better route calculation and therefore a better resource management can be foreseen.

C. Pre-calculation of Suitable Candidate Bands

When building up the spectrum portfolios, the CM-SM needs to account for the potential consequences of selecting every particular band, not only for the incumbent system in terms of experienced interference levels, but also for the opportunistic system in terms of expected performance and overall efficiency of spectrum use. Thus, the feasibility of the coexistence between the incumbent and opportunistic systems in the same spectrum needs to be analysed carefully to identify the most convenient bands to produce optimum portfolios.

Considering an opportunistic Long-Term Evolution (LTE) system operating in Digital Television (DTV) bands, and based on simulations (see [19][20]), this concept is illustrated in Table I (protection distance for DTV receivers), Table II (LTE throughput performance) and Table III (efficiency of spectrum use). The minimum required distance (Table I) is determined by the total interference, which increases with the load of supported LTE users (note that larger bandwidths imply a potentially larger load of users). For instance, for a separation of 25 km between the LTE and DTV systems, bandwidths of 1.4 or 5 MHz could be reused from the DTV band. However, reusing blocks of 20 MHz would be feasible only under low LTE loads. While the use of larger bandwidths would result in higher cell throughput rates for the LTE system (Table II), the higher number of LTE users supported at higher bandwidths also leads to increased levels of LTE internal interference, which results in lower spectrum efficiencies (Table III) and thus lower user throughput rates (Table II).

These results illustrate how the suitability of individual candidate bands can be analysed based on operation distances, supported load and performance requirements. This kind of pre-calculations enables the QoSMOS SM to decide on the suitability of various candidate bands to produce optimum spectrum portfolios capable to meet particular needs, and how much spectrum can be reused for opportunistic exploitation based on relevant scenario and operation conditions.

TABLE I: REQUIRED PROTECTION DISTANCES FROM THE BORDER OF THE DTV COVERAGE AREA [19][20].

		Load		
		Low	***Medium***	***High***
Bandwidth	***1.4 MHz***	9.82 km	14.82 km	19.83 km
	5 MHz	19.83 km	22.41 km	24.82 km
	20 MHz	24.81 km	29.81 km	34.79 km

TABLE II: AVERAGE LTE USER/CELL UPLINK THROUGHPUT (MBPS) [19][20]

		Load		
		Low	***Medium***	***High***
Bandwidth	***1.4 MHz***	0.94 / 0.97	0.32 / 0.94	0.13 / 0.79
	5 MHz	0.78 / 3.91	0.31 / 3.82	0.12 / 3.04
	20 MHz	0.77 / 15.5	0.30 / 14.9	0.11 / 11.6

TABLE III: EFFICIENCY OF SPECTRUM UTILISATION (BITS/SEC/HZ) [19][20]

		Load		
		Low	***Medium***	***High***
Bandwidth	***1.4 MHz***	0.78	0.76	0.61
	5 MHz	0.77	0.75	0.58
	20 MHz	0.69	0.67	0.57

D. Multi-objective Optimisation for Cognitive Radio Networks

CR will enable terminals with access to licensed and unlicensed portions of the spectrum. However, different parts of the spectrum experience not only different network conditions, but also different licensing/billing agreements. Therefore, in order for operators to obtain the major profit and the most efficient network usage, resource allocation must now target technical and economical performance metrics. This problem can be conveniently formulated as a multi-objective portfolio optimisation problem, which has been studied in detail in the field of Economics.

A spectrum selection and radio resource allocation scheme has been proposed based on a multi-objective portfolio optimisation where each frequency band and radio resource are regarded as financial assets with different values of return and risk (variance of the return). The algorithm provides with the optimum set of resources and the optimum amount of spectrum to be allocated to primary/secondary transmissions that maximise the return and reduce the risk. In a scenario with two WiMAX networks, it is observed in Figure 4 that an optimum value of the parameter that measures the trade-off between return and risk also leads to maximum throughput in the Pareto solution, particularly if the primary band has higher return and lower risk than secondary bands (case 1). Figure 4 shows the total throughput versus the parameter that measures the trade-off between return and risk for two cases of economical parameters: case 1 where primary band has higher return and lower risk, and case 2 where primary band has lower return and lower risk. Finally, risk was found to be closely related to the interference created by secondary user transmissions.

E. Optimisation of Spectrum Sensing Strategies Based on Portfolio Statistics

The CM-SM collects arrival and departure times of incumbent users based on sensing results from the network

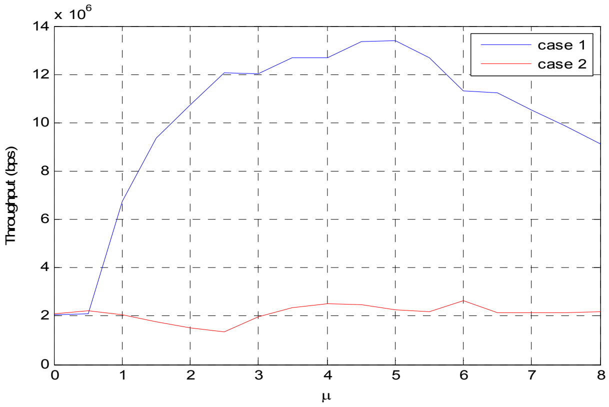

Fig. 4: Throughput vs. μ (trade-off between return and risk).

terminals and builds statistics about the ON/OFF pattern for each channel [19][21]. The ON/OFF pattern is then used to select the channel with highest probability of being available. Furthermore, the ON/OFF pattern can also be used to optimise the configuration of the sensing mechanism in network terminals to increase throughput while protecting the incumbent users. As a simple example, if the ON/OFF statistics indicate low probability of incumbent user appearance, a less robust sensing strategy with longer interval between sensing periods can be used. An example application of this could be for systems operating in TVWS where unregistered wireless microphones (WMs) appear dynamically with predictable patterns in venues such as churches and schools.

Figure 5 presents simulation results for the ON/OFF spectrum selector (SSE-OnOff) when implemented and used by the IEEE 802.22 standard implemented in the NS-2 simulator. The IEEE 802.22 opportunistic users (height 1.5 m, EIRP 20 dBm, 16-QAM ½) are mobile with random speeds between 1 and 20 m/s. A single cell with one BS (height 15, EIRP 36 dBm) is considered where four channels of bandwidth 6 MHz are available after accessing the geo-location database. Unregistered WMs (height 1.5m, EIRP 50mW, bandwidth 200 kHz) appear on each of the channels according to a negative exponential distribution for inter-arrival and burst departure time with mean 15 and 5 seconds respectively. The IEEE 802.22 system reports sensing detection of these WMs to the SM which then calculates the ON/OFF statistics over time and select the channel with highest probability of being idle. It can be seen from the results that SSE-OnOff achieves higher throughput than the more basic spectrum selection function where the channel with lowest detected signal is selected (SSE-Power). Please refer to [19][21] for more details on the SSE-OnOff function and performance evaluation with the simulator.

IV. UTILISING SPECTRUM PORTFOLIO OPTIMISATION IN SPECTRUM MANAGEMENT

The purpose of spectrum management in the scope considered here is to optimise the exploitation of underutilised frequency spectrum. A suitable solution thus must be applicable to upcoming as well as existing communication systems and, ideally, must provide a reasonable migration path. Furthermore, it should be possible to consider cellular as well as ad hoc network use cases, licensed as well as licence-exempt and opportunistic spectrum users, and coexistence scenarios among these including terrestrial and satellite systems as well. Thus no single straight solution may exist and modularity, configurability and extensibility are of uttermost importance.

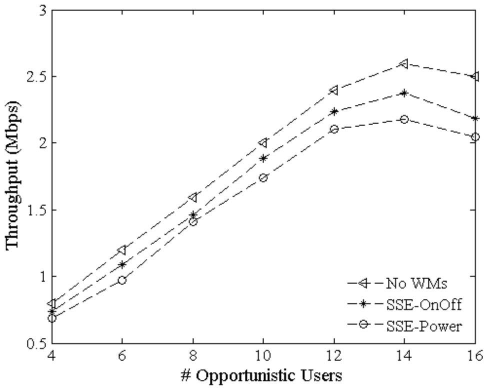

Fig. 5: Throughput for the ON/OFF spectrum selection function (SSE-OnOff) compared with the more basic (SSE-Power) and with the near optimal throughput when WMs are located at 3km from cell edge (No WMs).

The QoSMOS architecture is designed to flexibly adapt to diverse scenarios as outlined in Section II. Throughout different scenarios, the spectrum manager takes responsibility for optimising and deploying spectrum portfolios as requested by a resource manager, for example. The cognitive decision-making capacity of the spectrum manager utilises or composes the optimisation methods described in Section III according to the desired optimisation goal that is defined by the scope of operation of the spectrum manager, and by policies applicable to that scope. Since the spectrum manager in general is physically realised as a number of hierarchically distributed and collaborating instantiations, different optimisation schemes may apply in parallel in a local or global scope.

For example, in a cellular operator's realm (i.e. in the global scope) the spectrum manager may optimise for interference mitigation across neighbouring cells under price of spectrum and energy constraints (see Sections III.A and III.D), while in the scope of network nodes within cell areas (i.e. in the local scope) the spectrum manager may optimise the SINR for mobile users (Section III.B). This joint optimisation is feasible since spectrum portfolios can be optimised, split into sub-sets (e.g. into distinct sets of frequency bands) and then deployed to spatiotemporally distinct areas. Subsequent optimisations on the local scope including optimisation of related context acquisition (see Section III.E, e.g. regarding spectrum sensing through mobile nodes) then takes place in the scope of a portfolio sub-set considering only policies of local relevance. If significant timing constraints apply in the local scope, in particular regarding deadlines for decision-making of the spectrum manager, this is more easily resolved close to the context sources (i.e. at mobile nodes or cell controller entities). Such scenarios are considered in the QoSMOS approach through its hierarchical architecture and by enabling to optimise a selection of deployable spectrum portfolios (i.e. providing alternatives), which then form the basis for a quick one-out-of-many selection in the local scope based on very few locally relevant context parameters and policies communicated along with a selection of spectrum portfolios.

V. CONCLUSIONS AND OUTLOOK

This paper has presented and analysed five different spectrum portfolio optimisation approaches within the flexible QoSMOS spectrum management framework. Section III.A showed the exploitation of learning methods to improve a performance-energy metric. Section III.B moved to the spatial domain and exploited geographical databases to build SINR maps used to identify opportunities for mobile opportunistic users. Section III.C targeted at optimising the spectrum utilisation looking at incumbent protection distance and opportunistic network load. Section III.D introduced an additional axis to the problem and investigated the resulting spectrum selection optimisation problem when distinct pricing is attached to spectrum portions. Finally, Section III.E put the focus on the incumbent to exploit knowledge of its activity in time domain to select the spectrum portions with a longer availability and to optimise sensing overhead.

As the different scenarios and different applications mentioned above are based on a different information basis, and as different aspects and parameters are in the optimisation focus, there are different algorithmic approaches applied in the five investigated use cases. This set of approaches constitutes a tool-box and a building block available to create and design particular CR functionality according to the QoSMOS applications and use-cases.

Currently, the QoSMOS spectrum management approach has been applied to a number of appealing scenarios, and proof-of-concept implementations have been provided. In particular, the TV whitespace use case has been considered in depth. Further studies are so far focused on investigations on constrained use-cases restricting the analysis on well-defined particular aspects. Whether further (more detailed) studies may be performed depends on the arrival of new concrete application scenarios. One of these seemingly of some relevance is in the upcoming white space utilisation through machine-to-machine (M2M) communications and, in particular, through vehicular communications in that area.

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