Spectrum sharing: A coordination framework enabled by fuzzy logic

Konstantinos Chatzikokolakis, George Beinas, Nancy Alonistioti
Department of Informatics and Telecommunications
National and Kapodistrian University of Athens
Athens, Greece
{kchatzi,gbeinas,nancy}@di.uoa.gr

Panagiotis Spapis, Alexandros Kaloxylos
European Research Center
Huawei Technologies, Duesseldorf GmbH
Munich, Germany
{panagiotis.spapis, alexandros.kaloxylos}@huawei.com

***Abstract*— The exploding growth of the number of mobile devices and their traffic demands indicate that Mobile Network Operators (MNOs) will face significant barriers serving their users with their dedicated spectrum resources. Spectrum reallocation for exclusive usage from MNOs is a time-consuming regulatory process making thus, imperative the need to improve spectral efficiency through new spectrum sharing mechanisms. This implies that towards 5G, the MNOs will need to use their spectrum resources in a cooperative fashion either with other communication systems (i.e. LSA sharing, unlicensed sharing, etc.) for covering the increased traffic requirements. In this paper we present a novel spectrum sharing mechanism based on fuzzy logic to facilitate MNOs to select the most suitable spectrum sharing option so as to cover their needs. The proposed solution is based on a novel coordination framework that enables MNOs and other spectrum license holders to exchange information about spectrum resources and realizes multi-option spectrum sharing.**

Keywords— Mobile Network Operators, 5G systems, Licensed Shared Access, Co-primary Spectrum Sharing, Fuzzy Logic

I. Introduction

The mobile communications have experienced an exploding growth of the connected devices over the past few years. Quantitative results reported by Cisco in Visual Network Index (VNI) reports indicate that this phenomenon is not expected to change in the near future and many efforts will be spent in research, standardization and regulation for facilitating the service requirements of 5G networks. The latest VNI report [1] shows that more than 11.5 billion mobile devices will be connected by 2019.

Meanwhile, radio spectrum has loomed out to be a scarce resource that needs to be carefully considered when designing 5G communication systems. Thus, MNOs will need to revisit business models that were not of their prior interest (e.g. Cognitive Radio) or consider adopting new business models that emerge (e.g. Licensed Shared Access) so as to cover the extended capacity needs. Up to now, operators were reluctant investing money for extra network technologies that would offer spectrum flexibility, and they preferred following the traditional exclusive access scheme for their resources, which led to reduced spectrum utilization (variations in utilization may range from 15% to 85% [2]). Thus, new mechanisms for handling spectrum efficiently are required.

Schemes for spectrum sharing may be divided into two categories, namely unlicensed and licensed schemes [3] based on the license-holder. In the first category, the users share the same medium and cognitive radio mechanisms have been proposed for handling interference issues. In the second category, various sharing schemes have been proposed depending on the involved stakeholders. More specifically, the co-primary sharing, the Licensed Shared Access (LSA), and the light-licensing sharing schemes have been proposed up to now. In the co-primary sharing scheme, the primary license holder agrees on a joint use of (or parts of) his licensed spectrum (horizontal access). In the LSA case, the incumbent user grants his spectrum access rights to one or more other users based on service conditions dictated by the National Regulatory Authority (NRA). In the light-licensing scheme, the spectrum access licensing procedures are similar to the ones in the LSA case, though there are not strict requirements to the spectrum licensees about causing interference to the primary license holder.

Even though cooperation and sharing schemes have been proposed, the way for an operator to proceed in decisions regarding the most suitable spectrum chunks for it has not been studied adequately, mainly lacking considerations for the special characteristics of the traffic or its source (e.g., the mobility of the users that cause the need for additional spectrum). This implies that an MNO may proceed in acquiring spectrum not suitable for the traffic characteristics and the mobile users it wants to support.

In this paper we present a reasoning scheme, based on fuzzy logic, for identifying the most suitable spectrum for covering an MNO’s needs in a specific location and time. The fuzzy logic controllers are developed for incorporating the operator’s renting strategy aims to maximize his revenues while covering the users’ needs. This joint combination may lead to contradictive objectives, thus making fuzzy logic an ideal tool for handling the respective problem. The MNOs will have the flexibility to select either acquiring LSA spectrum resources, or proceed to renting spectrum resources from another operator. The scheme could be easily extended to other spectrum sharing options as well (e.g., unlicensed access). In order to enable such spectrum sharing scheme we apply the functional architecture for LSA and Co-primary sharing we developed and presented in [3]. Based on this, we introduce the additional functionalities for enabling the operators to proceed in flexible decisions.

The rest of this paper is structured as follows. In section II we describe other solutions proposed for spectrum sharing and we argue the benefits of our solution. In section III we introduce the fundamentals of the concept of Fuzzy Logic, which is the basis of the decision making entity for spectrum sharing in the proposed approach. In section IV we describe in details the spectrum sharing mechanism and the way the controllers address the trade-off between maximizing the MNO revenues and covering users' needs in terms of capacity, latency and reliability. In section V we provide the evaluation of the proposed mechanism and finally, section VI concludes our work by summarizing our contribution and sketching the way forward.

II. Related Work

Spectrum sharing techniques may be divided into two categories, vertical and horizontal spectrum sharing depending on the predefined priority that each communication system has. In vertical sharing concept there is a license-holder, also known as primary user or incumbent, that could grant usage rights to licensees (as in [5]) or the other players (i.e. besides the license-holder) could use the spectrum in opportunistic way [6]. In [9], a rule-regulated distributed and collaborative spectrum sharing approach is proposed. The solution aims at improved system fairness and spectrum utilization and reduced signaling overhead but lacks flexibility. However, solutions that enable spectrum sharing on unlicensed basis fail to give QoS guarantees to the users.

In horizontal sharing the communication systems that use the same spectrum have equal rights of usage. Inter-operator spectrum sharing is a typical paradigm of horizontal sharing that has emerged over the past years [4][7][8]. A partially distributed implementation method using game theory and learning algorithms proposed in [4], focusing on sharing in multiple licensed bands and aiming to reduce network latency and call dropping rate. In [7], a game theoretical framework that enables Dynamic Spectrum Access through a utility function that takes into account network measurements is proposed. In [8], authors proposed a coordination protocol to enhance utilization between mobile operators using auctions. The spectrum sharing protocol is based on one-shot games between operators without using operator-specific information exchange. Game-theoretic approaches though, induce significant computational complexity to the network, rely on predictive behavior from MNOs and occasionally assume the knowledge of information that is not possible to be obtained.

All the solutions described in this section focus on a single sharing scheme limiting thus the potentials for spectrum sharing. In addition, the game-theoretic approaches either assume cooperation between MNOs or rely on the good-willingness of an MNO, which though is impractical for real systems. On the other hand our proposed mechanism is a flexible solution for optimizing the spectrum acquisition process by taking into account multiple sharing schemes (i.e. co-primary and LSA schemes).

III. Fuzzy Logic Decision Making

Fuzzy logic is a multivalued logic that allows intermediate values to be defined between conventional evaluations like true/false, yes/no, high/low, etc. Compared to other reasoning methods tries to link fuzzy values and enable the decision maker to proceed in decisions. The key benefits of fuzzy logic are linked to its simplicity and flexibility as well as its ability to handle imprecise and incomplete data. The complex nature of the spectrum sharing problem, where multiple optimization opportunities may arise, make the fuzzy logic an ideal tool for handling it. Additionally, the fact that fuzzy logic resembles human logic enables the introduction of the operators' strategies in the spectrum trading process.

Fuzzy logic schemes are implemented as Fuzzy Inference Systems (FIS), that consist of three parts, namely the fuzzyfier, the inference engine, and the defuzzifier. The fuzzyfier transforms the crisp values to fuzzy ones by mapping the degree to which they belong to a state [10]. The input is a numerical value limited to the universe of discourse of the input variable (it could be a real value, integer, natural, etc.) and the output is a fuzzy degree of membership (always between the interval [0, 1]). The inference system links the inputs to the outputs using specific rules compiled by experts. Then, in the inference system, all single outputs of every rule are being aggregated to a one fuzzy set. Several aggregation schemes have been proposed and applied, namely the maximum, the probabilistic or, the sum, etc. with the latter being the most common one. Finally, the defuzzifier undertakes the defuzzification process, which is the aggregation of the outcomes of all the rules and the production of a single number; the single number is a crisp value.

IV. Proposed Spectrum Sharing Mechanism

A. *Coordination Framework*

As argued in the introduction, it is clear that an MNO who wishes to discover spectrum opportunities to cover its increased capacity requirements will have to select between more than one spectrum sharing schemes. Thus, the respective entities shall be available so as to coordinate the sharing of the spectrum chunks. In this paper, using as reference the regulation and standardization activities in [11][12], where the requirements and the basic functionalities for spectrum sharing have been described, we propose a functional architecture for enabling LSA and Co-primary sharing (Fig. 1). The entities of the proposed architecture presented in Fig. 1 are the following:

- NRA/Regulator: regulates the overall procedure, guarantees and provides use of rights to the actor requesting spectrum resources
- Incumbent user: is only related to the LSA sharing scheme and its roles are to advertise and negotiate the unused spectrum to one or several LSA licensees.
- Coordination Entity: is responsible to handle requests for spectrum from MNOs and to provide to them spectrum resources.

- MNO: is granted authorization access from the NRA and exploits the unused spectrum offered by one or more other actors. In each MNO, resides a Spectrum Controller, which is responsible for making decisions related to forecasted spectrum needs and for the reporting regarding the available spectrum chunks to the Coordination Entity.

Note that although in the proposed architecture the presence of a central logical entity for coordinating the MNOs is assumed, such entity could be actually distributed to more than one physical entities, or directly controller by the NRA.

In terms of this paper, we focus on the Spectrum Controller of the MNO and more specifically on the decision-making functionality. The following subsection presents the Fuzzy Logic enabled Spectrum Controller, which based on the current network view and the demand trend proceeds in decisions for the more preferable spectrum sharing option.

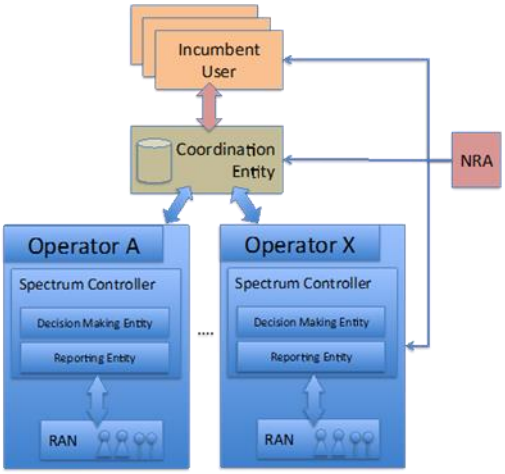


Fig. 1. Spectrum Sharing Functional Architecture

B. *Fuzzy Logic enabled Spectrum Controller*

In the proposed spectrum sharing scheme (Fig. 2), a Decision Making algorithm consisting of two FRs, which resides in the Spectrum Controller is introduced. The one FR handles co-primary whereas the other handles for LSA spectrum sharing authorization options. Other FRs may be introduced for incorporating additional sharing schemes. Each FR captures the corresponding suitability of each sharing scheme for fulfilling future network demands. The FRs take into consideration four inputs. Three of them are related to network conditions, namely load trend, (experienced) interference and average user mobility. The fourth one, namely spectrum efficiency captures the exploitation of the acquired spectrum for each of the sharing schemes. More specifically, the

- Load Trend is the input that captures the (overall) user bandwidth demands over a time window, which shows the increasing need for spectrum.
- (Experienced) Interference expresses the users' satisfaction and is being captured by the channel state information (i.e. packet error rate)
- Average user mobility captures the dynamic nature of the way the users affect the traffic load in a specific location due to their mobility behavior.
- (LSA or Co primary) Spectrum Efficiency relates the past transactions (i.e. spectrum acquisitions) with future spectrum requests so as to obstruct operators from buying spectrum resources if acquired spectrum is not properly exploited.

Then each FR produces a suitability factor indicating whether LSA or Co-primary spectrum resources should be obtained. This is performed due to the fact that spectrum provided under LSA sharing scheme is time/location/frequency specific, while in case of co-primary such limitations lie on the mutual agreements among the MNOs. It should be mentioned that it is foreseen that the cost of the LSA spectrum (acquired through auctioning) will be significantly less of that of the co primary (acquired through trading) [13]. Additionally, each FR captures the strategy of the operator, which is developed based on the time and geographic area characteristics of each sharing scheme. Furthermore, given the fact that the LSA licensees are not necessarily coordinated, interference may occur among them which will increase the packet error rate and thus it is less preferable compared to the interference free co-primary spectrum sharing in highly interfered areas. Finally, it is assumed that the operator wishes to consume the already acquired spectrum before proceeding in spectrum requests.

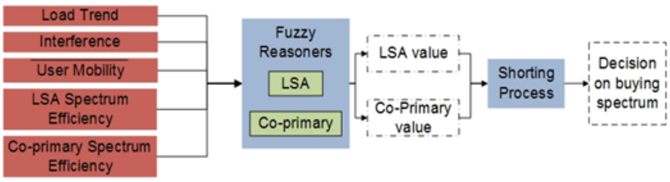


Fig. 2. Fuzzy Logic based Spectrum Controller

Based on the nature of each input, several types of membership functions could be used for capturing its special characteristics. More specifically, for the average user mobility and the load trend triangular membership functions have been used, because at certain values we are certain about the state that they are capturing (e.g., low/high mobile user, low/high load trend). On the other hand, for the interference and the spectrum efficiency Gaussian membership functions have been used for exploiting the non-zero nature of this membership function at the definition domain.

Regarding the output, Gaussian membership functions are being used for their smoothness in the decision making process. Since the LSA sharing scheme imposes constraints over time/frequency/location domains and enables the spectrum usage from multiple licensees it is assumed in the model that acquiring LSA spectrum resources will be less expensive compared to co-primary sharing. Finally, after a shorting process of the outputs the mechanism determines whether LSA or Co-primary spectrum resources should be obtained.

V. Evaluation Results

In order to quantify the benefits of the Fuzzy Logic-based spectrum sharing solution we have performed a series of experiments so as to compare its performance against three other schemes namely, no sharing, Co-primary sharing, and LSA sharing based on the available sharing options for the MNO. All those schemes and our proposed mechanism have been evaluated using the discrete event network simulator NS-3. Our simulation scenario is based on the shopping mall case proposed in METIS project [14]. The considered topology is a 100x50x10 m floor with 10 rooms (that form a 5x2 grid). Three base stations have been deployed in the area; one macro cell located 200 meters away from the building and two femtocells deployed in the considered area. Table I below summarizes our simulation setup.

In the evaluated scenario, UEs that follow a random mobility have been placed in the simulation area and the average delay and throughput both in downlink and uplink communication over a time window of 100 seconds have been measured. Fig. 3 presents a comparison between the Fuzzy Logic-based spectrum sharing solution and the other approaches (i.e., no sharing, only co-primary, and only LSA sharing). In all four simulated cases the UEs initiate consuming services. In the three cases where we assume sharing, when the UEs consume a certain portion of the available bandwidth (i.e., 90% - so as to have some resource blocks still available to serve new incoming service requests till the newly acquired spectrum is available, as well as for capturing the nature of the load trend) the spectrum controller is triggered and proceeds in renting spectrum. In the co-primary and LSA cases the controller rents what he is preconfigured to (i.e., co-primary and LSA spectrum respectively), whereas in the FL-based spectrum sharing it rents what the algorithm dictates. When the operator rents spectrum from LSA users, there is the probability that the incumbent user will reclaim his spectrum. In such case the UEs that are being served using LSA spectrum will have to be served by MNO’s dedicated resource blocks, thus decreasing the throughput and increasing the delay.

At this point it should be mentioned that the available economical capacities are the same in all three cases, so the spectrum controller has the same amount of money to consume. Additionally, we assume that the co-primary spectrum has twice the price of the LSA. This implies that in the cases of the LSA as well as in the FL-based spectrum sharing the controller may rent more spectrum, which however, is not guaranteed for the overall time of the sharing. More specifically, in the case of LSA spectrum sharing the operator may acquire twice the co-primary spectrum chunks. Similarly, in the case of the FL-based spectrum sharing if the operator decides to rent only LSA spectrum he may acquire twice the spectrum of the co-primary cases, whereas if he decides to rent only co-primary he may rent exactly as many resource blocks as in the co-primary case. In all the other occasions of the FL-based spectrum sharing scheme the economical capacities are split in the two sharing options.

TABLE I. Simulation Parameters

Simulation Setup	
Number of Operators	1
Number of Access Nodes	3
Number of UEs	{20,30,40,50}
UEs distribution	Random distribution on each room
Radio Propagation Model	NS-3 Hybrid Propagation Loss Model
Carrier Frequency	2.1 GHz(for dedicated and Co-primary spectrum), 2.3 GHz for LSA spectrum
Dedicated Bandwidth	20 MHz
Shared bandwidth	3 MHz
Maximum Tx Power per AN	eNB 23 dBm, femto 13 dBm
Maximum Tx Power per UE	10dBm

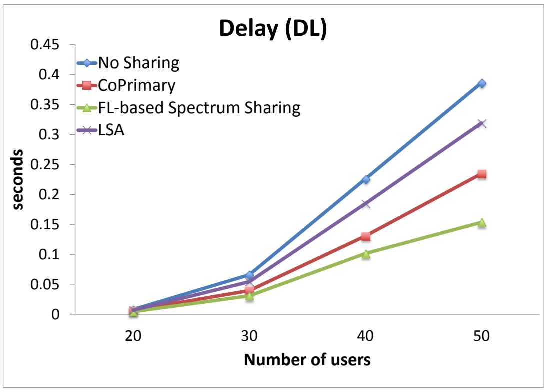
The results show significant improvement regarding the average delay and throughput when sharing is applied, compared to the no sharing case. Additionally, when comparing the FL-based spectrum sharing to the rest of the sharing schemes we observe that in general the FL-based spectrum sharing and the co-primary sharing perform significantly better than the LSA scheme. This is due to the fact that in the LSA case there is a probability that the incumbent may re-claim his spectrum, thus causing significant delays and throughput reductions. Additionally, for small numbers of UEs the gains from renting spectrum are relative small, since the already available spectrum may cover the user needs, but when the number of UEs increases the no sharing scheme does not manage to capture the user needs. What it worth mentioning is that when the number of UEs increases, the rate of increase in the throughput is reduced since even though that the operator rents spectrum, system’s capacity also reaches its limitations.

Additionally, it should be highlighted that the developed mechanism outperforms the co primary spectrum sharing since it may rent more spectrum when it suits to the users in the vicinity, due to the fact that the controller may split its economical resources to both LSA and co primary spectrum.

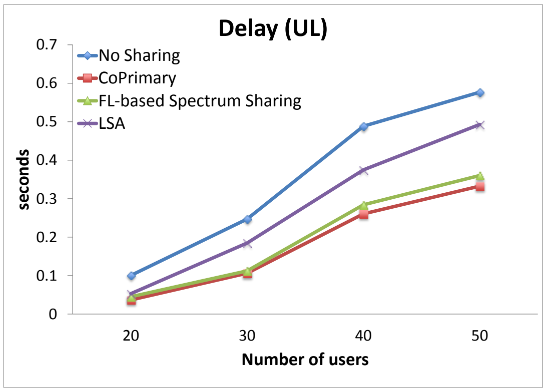
VI. Concusion

As presented in this paper, it is foreseen that spectrum sharing will be required in the future for enabling the operators to cover the 5G requirements. Thus, mechanisms for enabling the operators to decide the most suitable spectrum for their needs are required. In this paper we have presented a novel mechanism based on Fuzzy Logic, which is located in the Spectrum Controller of each operator and proceeds in decisions for spectrum acquisition by considering the users in the area and their traffic and mobility characteristics.

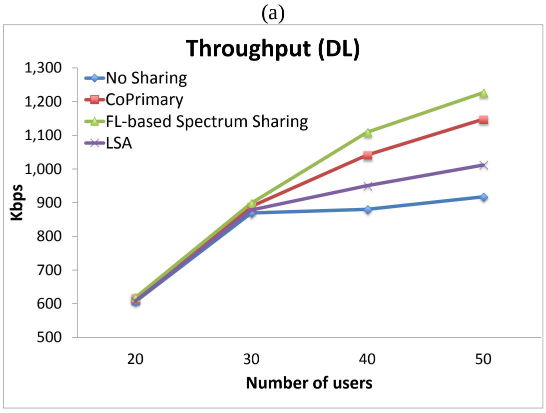
The simulation analysis highlights that the proposed scheme performs significantly better in terms of throughput and delay, when no sharing is applied, or when other sharing mechanisms that proceed in predefined decisions (i.e., only co primary or only LSA) are applied. This is even more impressive if we consider that the economical restrictions are the same in all three cases. Next steps include evaluation in further 5G scenarios that are more dynamic (e.g., stadium, open air festival, etc.) and the incorporation of light sharing and unlicensed spectrum access.



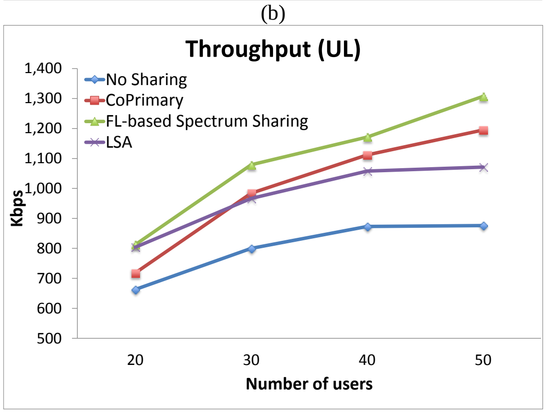
(a)



(b)



(c)



(d)

Fig. 3. Simulation results for 20, 30, 40 and 50 users. (a) Downlink Delay, (b) Uplink Delay, (c) DL Throughput, (d) UL Throughput

ACKNOWLEDGMENT

This work has been performed in the framework of the FP7 project ICT-317669 METIS. The authors would like to acknowledge the contributions of their colleagues. This information reflects the consortium's view, but the consortium is not liable for any use that may be made of any of the information contained there.

REFERENCES

[1] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2014–2019, March 2015

[2] M. Bennis, J. Lilleberg, "Inter-Network Resource Sharing and Improving the Efficiency of Beyond 3G Systems," 41st Annual Conference on Information Sciences and Systems, 2007. CISS '07., pp.357,362, 14-16 March 2007

[3] K. Chatzikokolakis, P. Spapis, A. Kaloxylos, N. Alonistioti, "Towards spectrum sharing: opportunities and technical enablers". IEEE Communication Magazine (to appear)

[4] Y.-T. Lin, H. Tembine, and K.-C. Chen, "Inter-operator spectrum sharing in future cellular systems," in Proc. IEEE GLOBECOM, Dec. 2012, pp. 2597–2602

[5] J. Khun-Jush, P. Bender, B. Deschamps, and M. Gundlach, "Licensed shared access as complementary approach to meet spectrum demands: Benefits for next generation cellular systems," in ETSI Workshop Reconfig. Radio Syst., Cannes, France, Dec. 2012.

[6] W.-Y. Lee and I. Akyldiz, "A Spectrum Decision Framework for Cognitive Radio Networks," IEEE Trans. Mobile Computing, vol. 10, no. 2, pp. 161-174, Feb. 2011.

[7] H. Kamal, M. Coupechoux, P. Godlewski, "Inter-operator spectrum sharing for cellular networks using game theory," IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), 2009 , pp.425,429, 13-16 Sept. 2009

[8] B. Singh, K. Koufos, O. Tirkkonen, "Co-primary inter-operator spectrum sharing using repeated games," IEEE International Conference on Communication Systems (ICCS), 2014, pp. 67-71, 19-21 Nov. 2014.

[9] Cao, L., Zheng. H., "Distributed Rule-Regulated Spectrum Sharing," Selected Areas in Communications, IEEE Journal on, vol. 26, no. 1, pp. 130-145, 2008.

[10] L. A. Zadeh, "Making computers think like people", IEEE. Spectrum, vol. 8, pp. 26-32, 1984

[11] ECC report 205 Licensed Shared Access (LSA), CEPT, 9.10.2013

[12] ETSI TS 103 154 Reconfigurable Radio Systems (RRS); System Reference Document; Mobile broadband services in the 2300 MHz – 2400 MHz frequency band under Licensed Shared Access regime

[13] Ofcom's final report, "International benchmarking of 900MHz and 1800MHz spectrum value", September 2013

[14] M. Fallgren and B. Timus (editors), "Future radio access scenarios, requirements and KPIs," METIS deliverable D1.1, March 2013. Available: https://www.metis2020.com/documents/deliverables/