Opportunistic spectrum sharing scheme for secondary WiFi-like devices in TV white spaces

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***Abstract*— Secondary spectrum access is a promising approach to improve spectrum utilization by enabling new wireless systems to opportunistically use and efficiently share the licensed bands. This paper targets a WiFi-like reuse of available spectrum in the TV bands and proposes a novel cooperative centralized spectrum sharing scheme that enables protection for the primary users and provides efficient usage of the available spectrum for multiple coexisting secondary users. The proposed scheme relies on a Non-Linear Integer Programming (NLIP) optimization method to maximize the average SIR per secondary user. Furthermore, the sharing scheme introduces interference protection zones for primary users' protection from excessive interference. The simulation results show performance enhancements in terms of average throughput increase for the secondary users. Finally, the paper investigates the relations between secondary channels widths and the number of secondary users under strict interference constraints for primary users' protection. In this respect, the smaller step sizes for the channel widths lead to higher SIR increase regardless of the number of users.**

Keywords – Opportunistic spectrum access, TV white spaces, Spectrum sharing, Interference protection zone, Flexible channel widths, Central frequencies adjusment.

I. INTRODUCTION

The need for anytime-anywhere wireless service access leads to a number of user wireless devices requiring dedicated spectrum resources. Therefore, efficient spectrum utilization is of great interest today. It fosters discovering of spectrum opportunities that enable new emerging technologies and services and also yields utilization of the licensed frequency bands with increased spectrum efficiency.

The Cognitive Radio (CR) represents a key enabling technology for secondary spectrum usage [1]. It facilitates the unlicensed Secondary Users (SUs) to opportunistically access available spectrum that is currently not used by the legacy Primary Users (PUs) owning a license to operate in the particular spectrum band. Two main functionalities characterizing the CR concept are spectrum sensing and spectrum sharing. *Spectrum sensing* is a method used to determine whether a certain portion of the spectrum is available for a possible set of secondary transmissions. *Spectrum sharing* refers to techniques enabling multiple SUs to access and to coexist in the available vacant spectrum.

The spectrum sharing schemes can be classified according to different criteria (e.g., based on the network architecture, based on the possible mutual cooperation among the SUs, based on the access technology, based on the method used for spectrum availability retrieval etc). The classification according to the spectrum availability retrieval criterion results in *sensing based*, *database based* and *mixed approaches*. In the sensing based approach, the SUs use only the CR functionality of spectrum sensing in order to determine whether there is an available spectrum for possible secondary transmissions. Database based spectrum availability retrieval is more suitable for static and predictable in time and space primary systems (e.g., TV networks). This approach is preferred in practical implementations yielding a centralized topology where the central entity hosts the database providing information on spectrum availability (e.g., FCC ruling on database based sensing [2], other sharing approaches [3] etc.). Therefore, the newly proposed scheme in this paper relies on the database based approach to spectrum sharing.

One of the most promising scenarios for secondary spectrum access is the usage of TV white spaces for WiFi-like secondary transmissions. The term *white spaces* is used by the FCC [4] to denote available spectrum at Very High Frequency (VHF) and Ultra High Frequency (UHF) TV bands. These bands provide better propagation possibilities in terms of transmitting range, shadowing etc., but pose additional technical challenges and limitations such as risks of generating excessive interference due to multiple secondary transmissions, establishment of control channel for SUs signaling etc. [5]. The use of these bands for WiFi-like systems enables higher coverage and higher transmission rates. Excessive knowledge on TV bands spectrum availability will be also available in terms of Radio Environmental Maps (REMs) and databases [6]. However, the lack of awareness and cooperation between the secondary systems in future WiFi-like scenarios can cause significant degradation of the primary and coexisting secondary systems due to interference. Hence, intelligent sharing schemes among secondary systems can provide

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protection for the primaries while at the same time guarantee an efficient usage of the available spectrum.

This paper proposes *a novel centralized spectrum sharing scheme* using a NLIP-based optimization in order to enable efficient spectrum resources utilization for WiFi-like devices accesssing TV white spaces. Moreover, the scheme introduces *strict interference constraints for PUs' protection* and allows for maximization of the SUs' achievable throughput. The sharing scheme envisiones granular channel widths and dynamic central frequencies for the SUs.

The paper is organized as follows. Section II provides an overview of the related work in the field. Section III describes the targeted scenario and gives insight into the proposed spectrum sharing scheme. Sections IV and V give the analytical background and the performance evaluation of the spectrum sharing scheme, respectively. Finally, Section VI concludes the paper and pinpoints future research directions.

II. RELATED WORK

A number of organizations and research groups work today on developing protocols or applications that would enable efficient reuse of TV white spaces by secondary WiFi-like devices. From a spectrum sharing perspective, the work mostly refers to more efficient resource management that improves spectrum utilization, ensuring interference protection.

The 802.11 task group is developing 802.11af standard also called White-Fi, which will be used in the unlicensed TV white spaces [7].

The authors in [8] propose a framework for decentralized control and management solutions in dense Wireless Local Area Network (WLAN) environments using multi agent systems. The impact of both inter-WLAN and co-channel Wireless Personal Area Network (WPAN) interference is considered. The method emphasizes the predictability of the time-varying network states using predictive models while incorporating the impact of interference into the sharing scheme. The decentralized scheme is compared with a centralized approach that uses a similar concept as the one being a subject of interest in this paper. Reference [9] elaborates similar approach for managing channels in WLAN scenarios. The developed solution uses a distributed algorithm for assigning non-overlapping channels and managing fixed and roaming users in the network. A NLIP optimization method is used for interference minimization. The proposed algorithm is used to maximize the channel efficiency and network throughput in indoor dense WLAN scenarios. Ref. [10] proposes Radio Resource Broker (RRB) architecture for fair resources allocation among providers. The algorithm limits the number of available channels and implements load balancing. The simulation results show the effectiveness of the method for dynamic radio resources redistribution. While all these papers refer to resource management in pure dense WLAN scenarios, reference [11] concentrates on PU protection in networks with opportunistic secondary access. It proposes a planning tool and channel assignment mechanism for cellular OFDMA networks that takes into account the primary system requirements. The concept introduces cell division into interference zones that will limit the secondary transmissions.

Unlike previous work, this paper proposes a spectrum sharing scheme that uses a NLIP optimization for efficient resources management among SUs. The sharing scheme is envisioned for centralized database based secondary WiFi-like in TV white spaces system. It introduces strict constrains for the SUs in order to enable PUs interference protection for the specified scenario. Moreover, the sharing scheme proposes flexible channels widths and adaptable central frequencies for SUs transmissions.

III. NOVEL SPECTRUM SHARING SCHEME

This section elaborates the targeted scenario (i.e. WiFi-like usage of TV white spaces) and proposes a novel spectrum sharing scheme. It tries to closely resemble a future realistic scenario.

A. Envisioned scenario

The scenario envisions WiFi-like secondary systems opportunistically accessing TV white spaces. Its essential components are (Figure 1):

- *TV broadcast network* as a *primary system* and
- *WiFi-like system* as a *secondary* network.

The secondary WiFi-like system components comprise:

- *WiFi-like Access Points* referred as Secondary APs (SAPs);
- *End WiFi-like users* (each connected to only one SAP) referred as Secondary Users (SUs);
- *Central Network Controller (CNC)* that controls all SAPs and conducts the resources optimization and
- *Database* (possible REMs [6]), collocated with the CNC, that stores information on spectrum opportunities (TV white spaces).

The scenario envisions that multiple SAPs coexist in a small geographic area, e.g., as office buildings, a city downtown area or a university campus (Figure 1). The SAPs can be placed randomly as in traditional WiFi systems. The present observed scenario does not concern users' mobility.

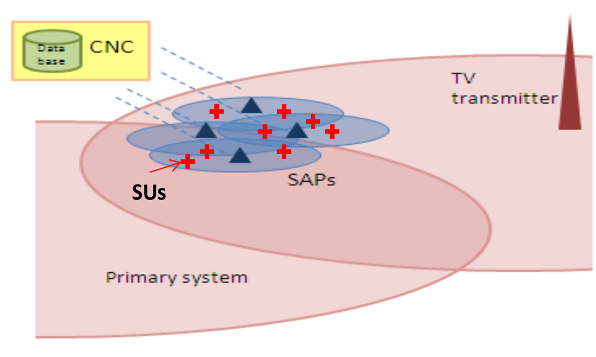

Figure 1. Scenario with overlapping secondary WiFi-like systems in TV white space

B. *Novel spectrum sharing scheme*

This subsection proposes a novel, database based, spectrum sharing scheme for WiFi-like devices opportunistically accessing the TV white spaces. The main objective is to *maximize* the SIR at an SU level and allocate an appropriate portion of the vacant spectrum to different SAPs. This would result in SUs throughput increase.

The scheme's operation is depicted on Figure 2. All SAPs communicate periodically with the CNC transferring parameters such as SAP Identification Number (ID), number of SUs associated to the specific SAP and location. Each SAP is envisioned to be equipped with a geo-location device in order to report its location to the CNC. After the SAP is associated with the CNC, it retrieves information from the database about spectrum opportunities in terms of available UHF channels (white spaces) in its vicinity. The SAPs receive information on Signal to Interference (SIR) at every user, communicating with the SUs. The SIR per SU data is resent to the CNC in order to be taken in the optimization calculations. The CNC calculates the optimal resources allocation and applies control decisions to the SAPs based on the received information, environmental parameters and predefined limitations. All SAPs retransmit this information to the connected SUs in order to adjust their communication parameters to the redistributed resources.

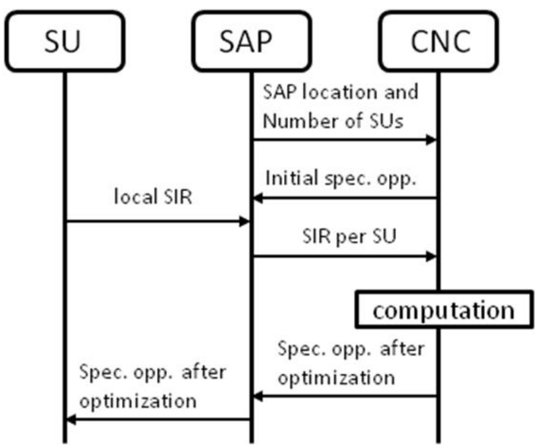

Figure 2. Message sequence chart for the proposed scenario

The newly proposed spectrum sharing scheme in this paper introduces a PU protection zone in terms of multiple SAPs' transmitting range overlapping limit. The overlapping limit represents a newly introduced mechanism ensuring interference protection for a possible primary receiver located in this PU protection zone. Namely, the uncontrolled random deployment of different SAPs would inevitably lead to overlap of multiple SAPs transmitting ranges. This often results in excessive interference for the PUs in the overlapping areas. Regarding this limitation, the best case scenario would be when every two SAPs have *non-overlapping PU protection zones*, thus the channel assignment can be any set of *overlapping channels*.

The following section provides the necessary analytical background of the algorithm used for resources optimization in the proposed spectrum sharing scheme.

IV. ANALYTICAL BACKGROUND

The objective of the proposed sharing scheme is to maximize the SIR at the SU level, which reflects in maximization of the throughput per user. The actual optimization is carried out in the CNC. The CNC uses the available information on SIR per SU for calculating the optimal channel allocation pattern.

The targeted scenario considers a set of M SUs and a set of N SAPs to be served by the SAPs. The SAPs and the SUs are randomly distributed in a certain area. Each user is assigned to a single SAP. The power received by every user is evaluated using the free space path loss model (used in WiFi-like secondary systems models [12]), i.e.

$$PL_{ij} = \left(\frac{4\pi d_{ij}}{\lambda} \right)^2 \tag{1}$$

where d_{ij} is the distance between SU_i and SAP_j and λ is the signal wavelength.

The sharing scheme represents a channel assignment problem formulated as a NLIP [13] optimization. The complexity of solving the problem increases with the increase of number of entities in the simulation. Each SAP and SU is enabled to use different central frequencies and flexible channel widths (channels granularity). The available spectrum opportunity can be divided into chunks of up to 2 MHz subchannels. The SUs are envisioned to be able to adapt their central frequency and channel width to a multiple of 2 MHz subchannels located in the UHF band.

The sharing scheme permits a channel bandwidth overlap for non-overlapping PU protection areas, while it dedicates non-overlapping channels to overlapping SAPs' PU protection zones (see Figure 3). This limitation protects the PUs from interference produced from multiple SUs transmissions. In order to quantify this rule, a parameter s_{jk} is defined as:

$$s_{jk} = \max(0, overlapping\_area_{jk}) \tag{2}$$

where $overlapping\_area_{jk}$ can have a binary value depending on whether the primary protection zones of the two SAPs j and k overlap. The variable s_{jk} has also a binary value (i.e. 0 or 1).

The interference level factor, α_{jk}, is defined as:

$$a_{jk} = \max(0, 1 - | fc_j - fc_k | m) \tag{3}$$

where fc_j is the central frequency of the channel assigned to SAP_j, fc_k is the central frequency of the channel assigned to SAP_k and m is the narrower channel width for the two channels, expressed in MHz. One example is the case when two SAPs, SAP_j and SAP_k use overlapping channels, where

SAP_j utilizes three UHF channels from 694 Mhz to 718 MHz and SAP_k utilizes the three UHF channels from 702 MHz to 726 MHz. In this case, α_{jk} = max(0, 1-|706-714|x1/24) = 2/3. It should be noted that if the channels overlap, then $fc_j - fc_k$ =0, whereas if the channels do not overlap, then $\alpha_{jk} = 0$. The scheme enables SAPs to be assigned with minimum overlapping channels.

The optimization problem in the sharing scheme targets maximization of the SIR per SU, i.e. minimization of the interference from other SAPs (downlink transmissions) at a user level. The induced constraints due to interference in overlapping areas to the primary system are applied as:

$$\sum_{j=1}^{N} G_{ij} P_{ij} \leq I_{th} \tag{4}$$

where G_{ij} is the channel gain and P_{ij} is the power transmitted by SAP_j to location i. The overall power transmitted in the area should not exceed the interference threshold of the primary system denoted as I_{th}.

The NLIP formulation of the channel assignment performs:

$$\max \sum_{i=1}^{M} \sum_{j=1}^{N} SIR_{ij}(k) \qquad j \neq k \tag{5}$$

subject to:

$$a_{jk} = \max(0, 1 - |\, fc_j - fc_k \,|\, m) \tag{6}$$

$$s_{jk} = \max(0, overlapping\_area_{jk}) \tag{7}$$

$$I_{ij} = \sum_{i=1}^{M} \sum_{j=1}^{N} (P_{ij} a_{jk} s_{jk}) \qquad j \neq k \tag{8}$$

$$SIR_{ij}(k) = \frac{P_{ik}}{I_{ij}} \qquad \forall i, j, j \neq k \tag{9}$$

where $i \in \{1,...M\}$, $j,k \in \{1,...N\}$, $fc_j, fc_k \in \{1,...K\}$, K is the number of possible channels in the entire system, P_{ik} is the power received by SU_i associated with SAP_k, P_{ij} is the power received by SU_i from the interfering SAPs and I_{ij} is the interference experienced by user i due to all SAPs j where $j \neq k$.

The following section provides performance evaluations of the newly proposed spectrum sharing scheme.

V. Performance Evaluation

The performance evaluation of the proposed sharing scheme for WiFi-like opportunistic usage of TV white space is conducted in MATLAB [14].

A. Simulation setup

The simulation assumes a centralized architecture and WiFi-like devices capable of dynamic central frequency and channel bandwidth adaptation. The simulation parameters are summarized in Table I.

TABLE I. SIMULATION PARAMETERS

No. of SAPs	No. of SUs	Transmit power	Receiver sensitivity threshold	Spectrum availability pool	Service area
5	30 – 210 (with step of 30)	17 dB (50 mW [15])	-85 dBm [9]	(686 – 726 MHz) 8 MHz UHF ch.	1200x1200 m

Figure 3 depicts one possible scenario configuration. The solid, the dashed and the dotted circles on Figure 3 represent the range limits in means of, respectively: receiver sensitivity threshold -85 dBm, primary user interference threshold -90 dBm and primary receiver protection zone, i.e. the distance in which the transmitted power decreases to -93 dBm and assumed to be an overlapping limit (the 3 dBm decrease from the interference threshold provides sufficient PU protection, even if two SAPs' protection zones overlap).

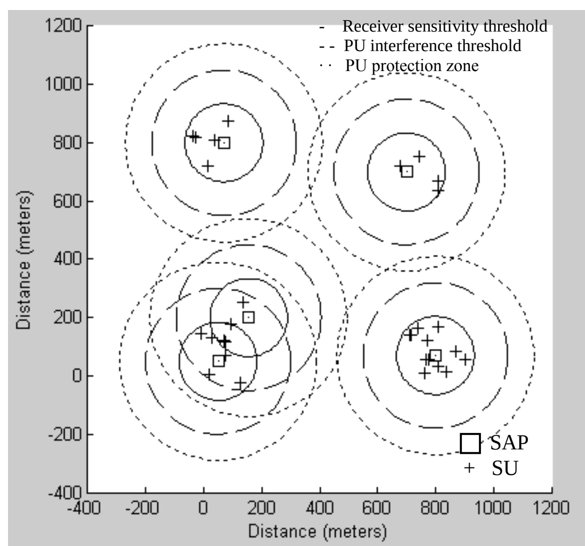

Figure 3. Scenario configuration snapshot

B. Simulation results

This subsection will first focus on the simulation results regarding SIR maximization in the case with constant number of SUs and granular channel widths. Second it will show the throughput per SU analysis with changing number of SUs.

1) SIR maximization analysis: Table II shows the parameters' behavior from the analyzed simulation scenario at the initial phase (no sharing scheme implemented) and after the implementation of the sharing scheme. The parameters of interest comprise an initial random number of users connected to a specific SAP. The channel width dedicated to every SAP suits the number of SUs that it serves at that specific moment. The table clearly depicts the central transmitting frequencies for every SAP in the initial and in the end phase after implementing the sharing scheme and completing the simulation. It is evident that SAPs 2 and 4 changed their central frequencies in order to achieve maximum average SIR per SU in the whole system.

TABLE II. COMPARISON BETWEEN INITIAL CHANNEL ALLOCATION AND CHANNEL ALLOCATION AFTER OPTIMIZATION

No. of SAPs	No. of SUs per SAP	Relative load per SAP (%)	Dedicated channel width (MHz)	Initial central frequencies (MHz)	Optimal central frequencies (MHz)
1	6	20	12	692	692
2	7	23.33	12	704	720
3	5	16.66	8	702	702
4	10	33.33	16	714	718
5	2	6.66	8	710	710

The purpose is to compare the effect of channel assignment at the initial design stage, and later stage when the optimization algorithm is applied.

Figure 4 depicts the average SIR in the initial channel allocation phase and the increase in average SIR per user after implementing the sharing scheme. It is evident that the implementation of the sharing scheme improves the average SIR by 29.7% in this specific configuration as shown on Figure 4.

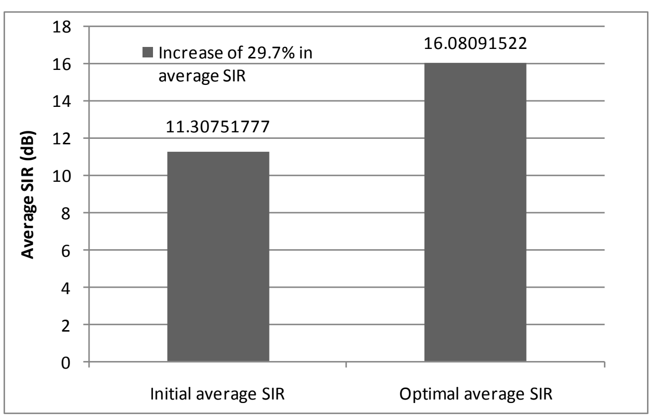

Figure 4. Comparison between total average SIR in initial channel allocation and after maximization

As previously explained, the channel bandwidths per SAP are allocated in accordance with the relative number of users per SAP. Figure 5 depicts the achieved average SIRs in the initial phase and after implementing the sharing scheme, depending on flexibility of the channels bandwidth. Although the maximum average SIR is achieved with step of 4 MHz for the channels granularity, the highest percentage improvement in maximizing the average SIR is reached with a granularity of 2 MHz (i.e. 9 possible channel bandwidths). As a result, the flexible channel bandwidth can also improve the maximal throughput per SAP, where the flexibility is customized according to the number of SUs per SAP. However, the channel width step size can be limited by the devices' hardware characteristics in practical implementations.

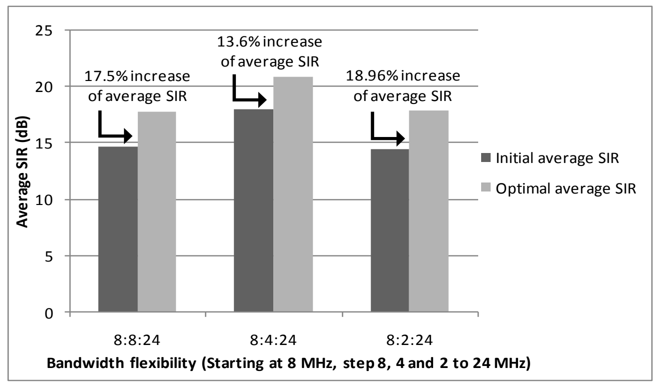

Figure 5. Total average SIR in initial phase and after optimization for different granulations in dynamic channel bandwidths

2) Throughput analysis: The average throughput per SU is calculated as:

$$THR_{ij} = B_{ij} \cdot \log_2\left(1 + SINR_{ij}\right) \tag{10}$$

where B_{ij} is the channel bandwidth dedicated between SU_i and SAP_j and $SINR_{ij}$ is the Signal to Interference and Noise Ratio obtained through simulation at SU_i.

Figure 6 shows the variations in the average throughput per SU, (calculated as depicted in (10)) increase obtained through 100 simulations performed for 100 different SAP configurations and number of users ranging from 30 to 210. The figure clearly shows that the throughput increase is around 25% regardless of the number of users.

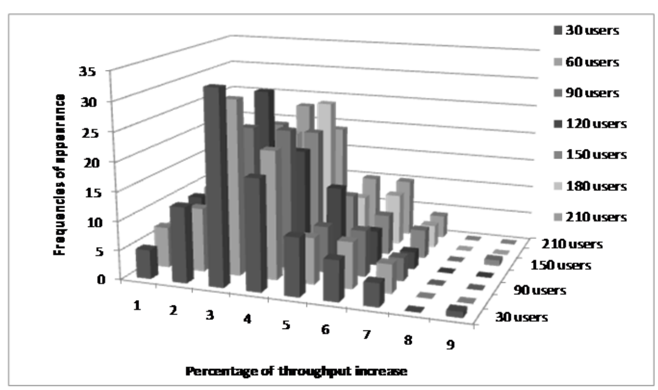

Figure 6. Variance of the throughput increase for different number of users

The average throughput per SU can be calculated using the IEEE 802.11a standard [16] specifications. The throughput per user is calculated based on the received power from the corresponding SAP. The roughly calculated physical level mapping between the SINR and throughput is presented in Table 3.

TABLE III. THROUGHPUT PER USER CALCULATION BASED ON IEEE 802.11 STANDARD

Received power in dB	10	14	21	31	32	>38
Throughput in Mbps	6	12	24	36	48	54

Figure 7 shows the variance of the average throughput increase for different number of SUs (similarly as in Figure 5). Results show average throughput increase above 30% regardless of the number of users. The average throughput increase is greater due to granular throughput dedication mechanisms used in IEEE 802.11 standard.

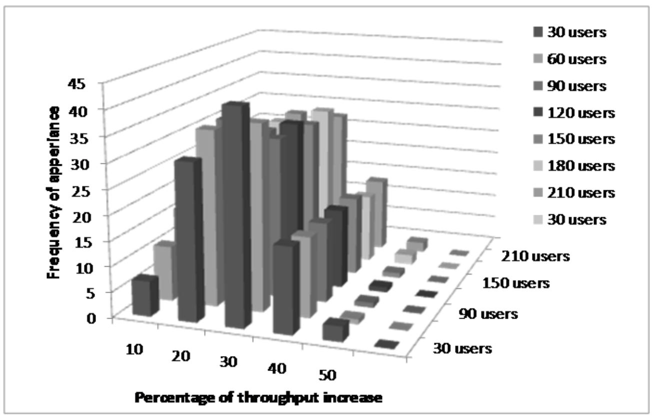

Figure 7. Variance of the throughput increase based on the IEEE 802.11a standard

Figure 8 shows how the simulation time needed for NLIP optimization depends upon the number of SAPs and SUs in the system. Though it is hardware dependent, the figure clearly shows how greater number of secondary entities increases problem complexity and would result in longer processing time in the CNC.

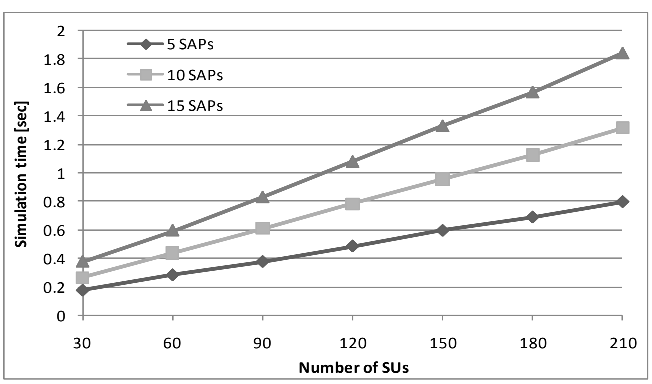

Figure 8. Average estimated simulation time for one scenario configuration for different number of SAPs and SUs

The proposed and analyzed sharing scheme establishes an efficient way for secondary WiFi-like use of the TV white spaces that leads to evident system performance increase and efficient PU protection. Moreover, the elaborated idea for the sharing scheme sets the basis and opens further possibilities for additional investigation and analyses.

VI. CONCLUSIONS

The use of TV white spaces is expected to become one of the key drivers in the development of the secondary systems fostering new wireless applications and driving novel technical solutions. Different scenarios and possible implementation examples are scrutinized in the academia and industry. The WiFi-like secondary systems deployment in TV white spaces is currently the most interesting scenario because of the TV digital switchover.

The spectrum sharing scheme proposed in this paper targets the WiFi-like usage of TV white space scenario and provides the improvement of the average SIR leading to a higher throughput per SU. The optimization method combines the channel widths and central frequencies at the SUs while enabling interference protection for the PUs from multiple transmitting SAPs through usage of interference protection zones. The sharing scheme proposes granular adjusting channel widths and central frequencies increasing SUs' performance (i.e. achieve a higher SIR per SU). Higher performances are experienced with smaller steps of the channel widths. The scheme's performance is independent of the number of active SUs in the system.

Real implementations with large network topologies would result in longer computations necessitating powerful high speed processing servers to be used as CNCs. Additionally, more realistic scenarios would require that the sharing scheme is performed dynamically and repetitively on a precisely estimated time periods in order to prevent performance decrease due to the system changes in time varying networks.

Future work will include adoption of a more complex propagation model, investigation of cooperation techniques among the SUs, Common Control Channel (CCC) signaling overhead analysis, performance evaluation through introducing several different secondary systems/technologies etc.

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