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Enhanced Service Delivery for Cognitive Systems within Multiple Antenna Scenarios

Nisreen Hassouneh
EiZ Engineering
Amman, Jordan
n.hassouneh@eiz.jo

Maha Odeh
SnT Centre
University of Luxembourg
maha.alodeh@uni.lu

Nizar Zorba
Qatar Mobility Innovations Center
Doha, Qatar
nizarz@qmic.com

Hossam S. Hassanein
Queen's University
Kingston, Canada
hossam@cs.queensu.ca

***Abstract*— Multiple Input Multiple Output (MIMO) is a well established technology that when jointly considered with Cognitive Radio (CR) it will create interactions that need to be optimized. The capability to provide service to more than one user and the generated interference among them is of crucial importance, where we employ the opportunistic scheduling to increase the system performance. Therefore, along this paper we propose statistical optimization techniques to tackle the joint MIMO-CR scenario, where each user asks for different Quality of Service (QoS) demands. By considering real time applications, we mathematically obtain their QoS behaviour in terms of the maximum allowed scheduling delay and maximum enabled jitter. Computer simulations are run to verify the accuracy of our results, and for both primary (PU) and secondary (SU) users.**

I. Introduction

The radio spectrum is becoming more and more occupied as the demand on wireless applications is explosively increasing, which presents a huge challenge for the operators to obtain the sufficient bandwidth that can handle them. Several operators (e.g., Vodafone, ATT) have recently moved away from the flat-rate data download option, as they cannot offer the requested rate by all the users. On the other hand, recent surveys have revealed that this precious resource is widely underutilized [1].

Cognitive radio techniques appeared to tackle this situation and allow secondary users (low-priority users) to simultaneously access the medium at the same time as the primary users (high-priority users). Such medium sharing is sensitive as the QoS for the PUs should not be affected, therefore, smart scheduling and allocation techniques [2] are needed to guarantee the QoS for PUs by employing spectrum sensing, dynamic frequency selection, transmit power control, etc.

Being proposed 20 years ago, the MIMO technology is currently embedded in all modern wireless communications standards [3] thanks to its increased system throughput, lower error probability and interference cancellation capability. The inclusion of several transmitting/receiving antennas is proved to increase the operator performance, and specially in Multiuser scenarios. MIMO consideration together with CR seems very attractive to enable PU to be served through different antennas/streams from SU users, for what is known as "Spatial Sharing", as long as the SUs does not affect the QoS for the PUs. Several techniques are proposed within the MIMO technology, where the Zero Forcing Beamforming (ZFB) outstands for its excellent performance and seems to be ideal for the Spatial sharing thanks to its interference cancellation capability [3].

The main concept of spatial cognition is the users separation through their spatial signature, while sharing the same time, frequency and code. The operator desire is to service several users at the same time to increase its income, but without affecting the QoS of its PU users. This problem should be optimized and properly identified with all its affecting parameters to achieve the maximum throughput to SUs while keeping the QoS for PUs.

In multiuser scenarios, the inherited systems deal with delay as a very important parameter. [4] evaluates the maximum delay that faces the most unlucky user in the system. Nevertheless, such works do not consider the imposed priority levels by the cognition concept. To date, few studies focus on QoS provisioning in CR systems, as they focus on the secondary user satisfaction from the delay perspective, but very initial results are presented.

The heterogeneity of the users (i.e., PU and SU) and applications imposes different demands on the operator to deal with, and to satisfy its users' needs. The QoS satisfaction metrics are in terms of the minimum guaranteed rate but also the maximum allowed scheduling delay and jitter. Many studies have shown that the user's satisfaction is insignificantly raised by a performance higher than the requested demands, while on the other hand, the satisfaction drastically reduces when the user's requirements are not fulfilled [5]. To satisfy the delay requirements for all the primary and the secondary users, we have to investigate the worst-case delay.

In this paper, spatial cognitive transmission is investigated where multiple primary and secondary users interact with each others in different scenarios. We focus on the cognition in ZFB scenarios where the selection scheme dramatically influences the users' performance. So that the statistical distributions for the Opportunistic based selection are derived to fully judge the feasibility of cognition. The QoS metrics of maximum allowed scheduling delay, mean and maximum enabled jitter are all obtained in closed form expressions, to show the impact of each parameter in the system performance, and to optimize

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it.

II. System Model

We consider a multiple-antenna Downlink scenario, where the base station (BS) is equipped with n_t transmit antennas and it offers service to K user terminals, where each one is assumed with a single antenna. We consider a quasi static block fading channel $\mathbf{h}_{[1\times n_t]}$ between the each user and the BS antennas, where the channel from each transmit antenna to a user is characterized by independent and identically distributed (i.i.d.) complex Gaussian entries $\sim \mathcal{CN}(0,1)$. Let $\mathbf{x}(t)$ be the $n_t \times 1$ transmitted vector, while denote $y_k(t)$ as the k^{th} user received signal given by

$$y_k(t) = \mathbf{h}_k(t)\mathbf{x}(t) + z_k(t) \quad (1)$$

where $z_k(t)$ is an additive i.i.d. complex noise component with zero mean and $E\{|z_k|^2\} = \sigma^2$. Any number of antennas n_t can be employed for multiuser service, but due to the generated cross interference, providing service to more than two users at the same time, frequency and code will generate a lot of interference in the system, and needs a lot of signalling overhead [6]; therefore we limit this work to the case of two antennas.

The transmitter delivers service to M users at the same time, where $M \leq n_t$, so that a global system model is formulated by stacking the received signals and the noise components for the set of M selected users as $\mathbf{y}(t) = \mathbf{H}(t)\mathbf{x}(t) + \mathbf{z}(t)$, with $\mathbf{H}(t) = [\mathbf{h}_1(t); ...; \mathbf{h}_M(t)]$ as the compound channel. The transmitted signal $\mathbf{x}(t)$ contains the uncorrelated data symbols $s_m(t)$ to each one of the selected users, where $E\{|s_m|^2\} = 1$ is employed. We assume that full Channel State Information is available at the transmitter side, and the system runs under a total transmission power of $P_t = 1$. For ease of notation, time index is dropped whenever possible.

III. Zero Forcing Beamforming

One of the best techniques within the MIMO technology is the Zero Forcing Beamforming (ZFB), that has been already included in the IEEE 802.16e WiMax standard [7]. Through this technique, the transmitted signals are pre-processed (i.e., transmit beamforming) to transform the downlink channel into orthogonal and independent sub-channels, which is an interesting feature for Spatial Cognition as it will avoid interference among PUs and SUs. The simultaneous transmission to to M users makes the transmitted signal $\mathbf{x}$ to be as

$$\mathbf{x} = \mathbf{B}\mathbf{s} \quad (2)$$

where $\mathbf{s}$ is the vector of transmitting symbols, and $\mathbf{B}$ is the ZFB beamforming matrix, that is obtained through the Penrose Pseudo inverse [8] as

$$\mathbf{B} = \mathbf{H}^H \left(\mathbf{H}\mathbf{H}^H\right)^{-1} \quad (3)$$

Based on the transmitter power restriction $P_t = 1$, then the sum power of the transmitting vectors is normalized through a uniform power allocation strategy as:

$$|\mathbf{B}|^2 = \alpha_i^2 \mathbf{I} \quad (4)$$

where α_i is the normalization parameter defined as

$$\alpha_i^2 = \gamma_i = \frac{1}{n_t\left(\mathbf{H}\mathbf{H}^H\right)^{-1}_{i,i}} \quad (5)$$

so that the equivalent channel ($\mathbf{HB}$) ensures no interference among the serviced users/streams as it is now a diagonal channel as

$$\mathbf{HB} = \mathbf{D} = diag(\alpha_1, \alpha_2, ..., \alpha_M) \quad (6)$$

which delivers a SNR given as [8]

$$SNR_i = \frac{\alpha_i^2}{\sigma_i^2} \quad (7)$$

From above mathematical expressions, ZFB can completely eliminate the interference but lower SNR per stream will be achieved as a lower normalization parameter α is obtained if the channels for the selected users are co-linear. Therefore, the employment of ZFB seems to be more suitable with a pre-selection step that selects the most orthogonal users, to carry out ZFB on their channels as a pre-amended step before the spatial processing, as already being proposed by [3] and as will be discussed throughout this paper.

In the next section, we will show how to employ ZFB within the spatial cognition philosophy and it obtains its performance characterization.

A. Spatial Cognition in Zero Forcing Beamforming

The MIMO technology is already implemented in all modern broadband communication standards (e.g., WLAN and LTE), so that the proposal of Spatial Cognition is a recommended choice for operators, thanks to its increased throughput and lower delay performance, as more than one user are serviced at the same time, frequency and code. Taking into consideration its QoS guarantee to the PU users, it seems as a perfect technique for its implementation. We should remind that the latter point is of great importance as the QoS satisfaction for PU is of crucial importance to the operator, and the SU will not be scheduled if the PU won't achieve its QoS demands (defined as a minimum guaranteed SNR value [4]) when the SU is provided service.

An important concept for all wireless systems is outage [4] that has a major impact on the QoS satisfaction. In traditional single user service, if the channel shows deficient performance and the SNR is below the minimum detection threshold, the user is declared in outage. The same situation applies to the cognitive scenario, but also keeping in mind that providing service to a SU should not increase the PU outage, so that a study to the cognition impact on the PU's QoS satisfaction is required. In order to obtain then, the SNR distributions are required. To do that, a reformulation to the SNR in Eqn.(5) gives

$$\gamma_i = \alpha_i^2 = \frac{det\left(\mathbf{H}\mathbf{H}^H\right)}{n_t A_{ii}} \quad (8)$$

where det(.) denotes the determinant, and A_{ii} the determinant resulting from striking out the i^{th} row and the i^{th} column of $det\left(\mathbf{H}\mathbf{H}^H\right)$ as

$$det(\mathbf{H}\mathbf{H}^H)=\|\mathbf{h}_1\|^2\|\mathbf{h}_2\|^2-|\mathbf{h}_1^h\mathbf{h}_2|^2=\|\mathbf{h}_1\|^2\|\mathbf{h}_2\|^2(1-\delta^2) \quad (9)$$

with $\delta^2 = \frac{|\mathbf{h}_1^h\mathbf{h}_2|^2}{\|\mathbf{h}_1\|^2\|\mathbf{h}_2\|^2}$ as the normalized scalar product between $\mathbf{h}_1$ and $\mathbf{h}_2$, $0 \leq \delta^2 \leq 1$, where 1 occurs when the users are totally colinear and 0 when they are orthogonal. Therefore, the resultant SNR value will be

$$\gamma_1 = \frac{\|\mathbf{h}_1\|^2(1-\delta^2)}{2} \quad (10)$$

Notice that the impact of SU on PU is identified by the interaction of each term of $\|\mathbf{h}_1\|^2$ and $1-\delta^2$, which need a further study of Eqn.(10). We start with $\|\mathbf{h}_1\|^2$ that is the addition of two i.i.d complex gaussian random variables and it has a $\Gamma(2,\gamma_\circ)$ distribution while $\gamma_\circ$ is the average system SNR, which its PDF be expressed as follows [10]:

$$q_\gamma(\gamma) = \frac{\gamma}{\gamma_\circ^2}e^{-\frac{\gamma}{\gamma_\circ}} \quad (11)$$

and its corresponding CDF is obtained as

$$Q_\gamma(\gamma) = 1 - e^{-\frac{\gamma}{\gamma_\circ}}(1+\frac{\gamma}{\gamma_\circ}) \quad (12)$$

δ^2 has been deduced to be Beta distribution $\beta(i, n_t - i)$ in [3], with the corresponding PDF [10]:

$$f_\delta(\delta; i, n_t - i) = \frac{\delta^{i-1}(1-\delta)^{n_t-i-1}}{\int_0^1 \delta^{i-1}(1-\delta)^{n_t-i-1}} \quad (13)$$

where i is the number of each scheduled user.

Consequently, the CDF is a regularized incomplete beta function $I_\delta(i, n_t - i)$

$$I_\delta(i, n_t - i) = \frac{\beta(\delta, i, M-i)}{\beta(i, M-i)} \quad (14)$$

In order to proceed, we should now characterize the above distributions and to know if they match any widely known distribution. A main characteristic of the Beta distribution is if X has $\beta(a,b)$ then $1-X$ has $\beta(b,a)$. For the case of $n_t = 2$, δ^2 and $1-\delta^2$ has $\beta(1,1)$. The distribution of the multiplication of the two terms is obtained from the relation between Beta and Gamma distributions; if X and Y are independently distributed with $\Gamma(a,\gamma_\circ)$ and $\Gamma(b,\gamma_\circ)$ respectively, their addition $X+Y$ has the distribution of $\Gamma(a+b,\gamma_\circ)$, which is represented by $\|\mathbf{h}_1\|^2$. Another important transformations of the Gamma distribution is that $\frac{X}{Y+X}$ has $beta(a,b)$ [9]. With all these obtained results, since $\|\mathbf{h}_1\|^2$ has $\Gamma(2,\gamma_\circ)$ distribution and $(1-\delta^2)$ has $\beta(1,1)$, their multiplication will have $\Gamma(1,\gamma_\circ)$, which presents an exponential distribution; so that the term $\frac{\|\mathbf{h}_1\|^2(1-\delta^2)}{2}$ will have the following PDF and CDF:

$$f_\gamma(\gamma) = \frac{2}{\gamma_\circ}e^{-2\frac{\gamma}{\gamma_\circ}} \quad (15)$$

$$F_\gamma(\gamma) = 1 - e^{-\frac{2\gamma}{\gamma_\circ}} \quad (16)$$

It can be viewed from the previous formulations that PU loses a degree of freedom when adding an SU to the system, which jeopardizes the provided service to PU. To overcome this obstacle, a limitation to the correlation among the scheduled users is desired, to boost the system performance (i.e., especially PUs), as shown later in the following parts.

B. Opportunistic Transmission in ZFB cognitive scenarios

Within multiuser scenarios, the throughput-optimal scheme is the opportunistic transmission [5], where the base station extracts all the multiuser gain by selecting the user with the best channel condition for transmission. The opportunistic transmission has been extended to spatial dimension as in [11]; where n_t beams are generated, and each user sends his Signal to Noise and Interference Ratio (SNIR) to each one of them, and then the base station selects the user whose SNIR is the highest for each beam. This concept is not the same for all beamforming techniques (i.e., ZFB) where the selection of the users with highest channel norm $\|\mathbf{h}\|^2$ may show deficient performance because of the spatial correlation among the serviced users. To beat this hurdle, a pre-selection among the users is required to choose the set of user with least co-linearity among them [3]. Therefore, to improve our proposed scheme behaviour, we need for the opportunistic selection as a pre-step to ZFB. The scheduling scheme can be addressed as follows:

- Schedule the primary user (in case of more than one PUs) with the highest channel norm $\|\mathbf{h}_{PU}\|^2$
- Calculate $\delta_s^2 = \frac{|\mathbf{h}_{PU}^h\mathbf{h}_{SU}|^2}{\|\mathbf{h}_{PU}\|^2\|\mathbf{h}_{SU}\|^2}$ for all the SUs.
- Choose the users S who meets the condition $\delta_s \leq \delta_\circ$; where $\delta_\circ$ is the correlation threshold (usually predefined by the system administrator).
- Pick the user with highest $\|\mathbf{h}_s\|^2(1-{\delta_s}^2)$ among all the users who satisfy the previous step.

to guarantee the selection of the set of users with lowest correlation and highest channel characteristics, therefore, improving the system performance.

To analyze the orthogonality based selection, we need their PDF and CDF formulations we derived from (10) by imposing $\delta_s \in [0, \delta_\circ]$. The SNR statistical characteristic are changed due to the scheduling modifications; as the term $1-\delta^2$ in (9) has no longer $\beta(1,1)$ distribution due to the restriction limits; and now it follows a uniform distribution $U(1-\delta_\circ^2, 1)$ as presented in [10], making the SNR distribution to be as

$$Y_\gamma(\gamma) = 1 + \frac{1-{\delta_\circ}^2}{{\delta_\circ}^2}e^{-\frac{2\gamma}{\gamma_\circ(1-{\delta_\circ}^2)}} - \frac{1}{{\delta_\circ}^2}e^{-\frac{2\gamma}{\gamma_\circ}} \quad (17)$$

with its related PDF as

$$y_\gamma(\gamma) = \frac{2}{{\delta_\circ}^2\gamma_\circ}\left(e^{-\frac{2\gamma}{\gamma_\circ}} - e^{-\frac{2\gamma}{\gamma_\circ(1-{\delta_\circ}^2)}}\right) \quad (18)$$

Therefore, the number of users that can survive the $\delta_\circ$ selection, using the large number law [10]:

$$S_i \approx N_{SU}\left({\delta_\circ}^2\right)^i \quad (19)$$

and for $n_t = 2$ it gives the exact result of

$$S = N_{SU}{\delta_\circ}^2 \quad (20)$$

From these equations, it is seen that a random value for $\delta_\circ$ is impractical, as it is lower bounded to ensure orthogonality in the selection as

$$\delta_\circ \geq \sqrt{\frac{1}{N_{SU}}} \quad (21)$$

As the scheduled user has an SNR value which is the maximum over all other users' SNR, then we derive the PU's CDF from the CDF expression in Eqn.(17) as

$$OY_{\gamma}^{PU}(\gamma) = \left(1 + \frac{1-{\delta_\circ}^2}{{\delta_\circ}^2} e^{-\frac{2\gamma}{\gamma_\circ(1-{\delta_\circ}^2)}} - \frac{1}{{\delta_\circ}^2} e^{-\frac{2\gamma}{\gamma_\circ}}\right)^{N_{PU}} \quad (22)$$

where a value of $n_t = 2$ has been considered. While the distributions for the opportunistic selection are above obtained for the PU users. Related to the SU users, their distributions are similar to previous ones with the exception of replacing N_{PU} by S.

IV. Delay Performance in Spatial Cognitive Scenarios

All modern communications systems need to guarantee the QoS offered to the customers, which is a challenging request specially due to the applications' heterogeneity, where each application demands for different QoS requirements. QoS can be characterized by several metrics but this paper will concentrate on the real-time applications that currently consume a large portion of available wireless resources, and present QoS in terms of the maximum tolerable delay, average jitter and maximum jitter. We should remind the reader about the difficulty to guarantee QoS in spatial cognitive scenarios, where the PU has strict QoS demands, while the SUs demands are satisfied when it is possible.

As previously discussed, the concept of outage [4] is present whenever we deal with wireless communications due to the channel fading characteristics that may drive the SNR value below the minimum detection threshold. Therefore, QoS can not be ensured for 100% of the time, and for both PU and SU. This paper deals with the access delay outage that refers to the channel opportunistic access instant and if it is within the maximum tolerable time delay K.

A. Access Delay Outage

Round Robin scheduling is the delay optimal strategy [12] delivering a maximum (and average) delay of n time slots when n users are considered for scheduling. But the deficient data rate performance of the round robin strategy has motivated new and sophisticated schemes that are more suitable for broadband communication. We previously said that the opportunistic scheduling is optimal in terms of throughput, but we should also consider its delay performance for practical consideration. Remind that a user is scheduled if it shows the best channel characteristics over all available users, so that the access and service acquisition are not guaranteed, and this is critical for the SU since PU satisfaction has larger priority than awarding service to SU.

A very important QoS indicator for real-time applications is the maximum access delay, which is defined as the largest number of the slots that a user's packet is waiting since it is ready to be transmitted till the user is served [13]. If the user is not scheduled within this period, the user is declared to be in delay outage. Then the probability that a maximum of K time slots are needed to select a certain user from a group of users, follows a geometric distribution [10] [13], as

$$Prob[X \leq K] = 1 - (1 - P_{ac})^K \quad (23)$$

Then the access outage ζ_{ac} is defined as follows

$$\zeta_{ac} = (1 - P_{ac})^K \quad (24)$$

where P_{ac} is the probability to access the channel, that in cognitive scenario depends on the kind of served user and the chosen threshold for both PU and SU. This work separately obtains the faced delay by PU and SU, then a joint metric is formulate to judge the overall performance of the whole system.

From Eqn.(24), the maximum scheduling delay over all the users (PUs and SUs) can be expressed as:

$$K = \frac{\log_2(\zeta_{ac})}{\log_2(1 - P_{ac})} \quad (25)$$

The access outage for the primary users, P_{ac}^{PU}, does not only rely on the number of the PUs, it also depends on the selection scheme, whether it is just round robin or opportunistic selection. We consider the opportunistic scheduling for its high performance, so that the probability of access outage, $P_{ac}^{PU_{OPP}}$, is now obtained from Eqns.(12) and (24) as

$$P_{ac}^{PU_{OPP}} = \frac{1 - \left(1 - e^{-\frac{\gamma_{th}^{PU}}{\gamma_\circ}}(1 + \frac{\gamma_{th}^{PU}}{\gamma_\circ})\right)^{N_{PU}}}{N_{PU}} \quad (26)$$

Now concerned with the SUs, their study is more challenging in the spatial cognition scheme as the SU's activities should not impact PU's transmission even if the SU shows good channel condition, and no delivered service for this user as long as PU can not afford the service. Therefore, the SU access outage P_{access}^{SU}, depends on a larger amount of variables: the service for the PU, the minimum detection values and the number of SU in the system. With $\delta_\circ$ as the previous defined correlation threshold, the access outage for SUs in the opportunistic scheduling strategy, $P_{ac}^{SU_{OPP}}$, using Eqns.(22) and (24) can be displayed as

$$P_{ac}^{SU_{OPP}} = \frac{1}{N_{SU}} \left(1 - \left(1 + \frac{1-{\delta_\circ}^2}{{\delta_\circ}^2} e^{-\frac{2\gamma_{th_{PU}}}{\gamma_\circ(1-{\delta_\circ}^2)}} - \frac{1}{{\delta_\circ}^2} e^{-\frac{2\gamma_{th_{PU}}}{\gamma_\circ}}\right)^{N_{PU}}\right) \left(1 - \left(1 + \frac{1-{\delta_\circ}^2}{{\delta_\circ}^2} e^{-\frac{2\gamma_{th_{SU}}}{\gamma_\circ(1-{\delta_\circ}^2)}} - \frac{1}{{\delta_\circ}^2} e^{-\frac{2\gamma_{th_{SU}}}{\gamma_\circ}}\right)^{S}\right) \quad (27)$$

To identify the whole system delay through a single QoS indicator, a unification procedure is needed to obtain the average performance [10] as

$$\widetilde{n} = \sum_i P_i N_i = P_{ac}^{PU} N_{PU} + P_{ac}^{SU} N_{SU} \quad (28)$$

making the resultant total scheduling delay for the cognitive scenario to be presented using Eqns.(25) and (28) as follows

$$K_{res} = \frac{\log_2(\zeta_{ac})}{\log_2(1 - \frac{\widetilde{n}}{N_{PU}+N_{SU}})} \tag{29}$$

As the probability of cognition in the case of orthogonality based opportunistic selection surmounts the random one, $\widetilde{n}$ in the first case excels the random selection. As a consequence, the user in the second system will suffer higher delay for the same threshold requirement.

B. Access Jitter in Cognitive MIMO Scenarios

Delay jitter is the variation of the delays that packets suffer while traveling on a network until they reach their destination. In multiuser systems, employing real time application (i.e., VoIP) can be a bit challenging since the packets should be received in order, to make the voice stream continuous to the user. As defined in [13] [14], the maximum jitter is the maximum time that can exist between two consecutive packets

$$maximum\ jitter = K_{max} \tag{30}$$

where for our cognitive case, the PUs face less jitter in comparison with SUs as they have the priority to be scheduled first.

Despite this relation is pessimistic, it is beneficial for network designing and scaling. A more optimistic relation is the average jitter, as the user is not scheduled each K_{max}; s/he can be scheduled in any time $\in (1, K_{max})$ so the average jitter j can be stated as follows [10]

$$j = \sum_{k=1}^{K_{max}} k\, P_{ac}(1 - P_{ac})^{k-1} \tag{31}$$

where P_{ac} is the general one, so that for each kind (i.e., PU or SU) and for each scheduling philosophy (i.e., RAN or OPP), we can substitute the specific P_{ac} value. With further mathematical manipulations, previous equation can be reformulated as

$$j = \frac{1-(1-P_{ac})^{K_{max}+1}}{P_{ac}} - (K_{max}+1)(1-P_{ac})^{K_{max}} \tag{32}$$

obtaining a closed form expression of the resultant system jitter.

V. Simulations and Results

The spatial cognition scheme is presented through simulations and mathematical formulations, in a wireless scenario where the impact of the several parameters is visualized. The QoS performance for delay and jitter are tackled by taking into consideration that PUs have strict demands to be satisfied while SUs are served as long as PU is pleased, PUs do not necessarily share the same minimum rate QoS (i.e., SNR threshold) with SUs. The proposed scheme is analyzed by computer simulations in a wireless broadband system with $n_t = 2$ transmitting antenna and a variable number of single-antenna users. A total transmitted power $P_t = 1$ and noise power $\sigma^2 = 1$ are considered. Outage is allowed due to the wireless channel conditions.

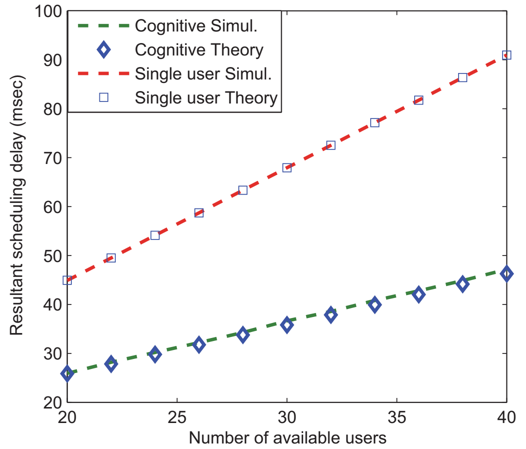

Fig. 1. *Resultant scheduling delay for a variable number of users in the system, both for the spatial cognitive and the single user service.*

Fig.(1) presents the comparison the benchmark single user case and the proposed spatial cognitive scheme with a $\gamma_{th} = 1$ and an allowed access outage of 10%. The figure displays that for an increasing number of users, the delay will be larger as we obtain a lower probability for each user to be selected. This is not the only issue being displayed in the figure, it also provides a comparison between the spatial cognition and the single user for the same number of users in the system. As expected, the cognition induces less delay which enhances the capabilities of the system by supporting different QoS demands. As the mathematical results in this paper do not consider approaximations, we obtain a tight match with simulation results. The same match will be shown in all the obtained results along this section.

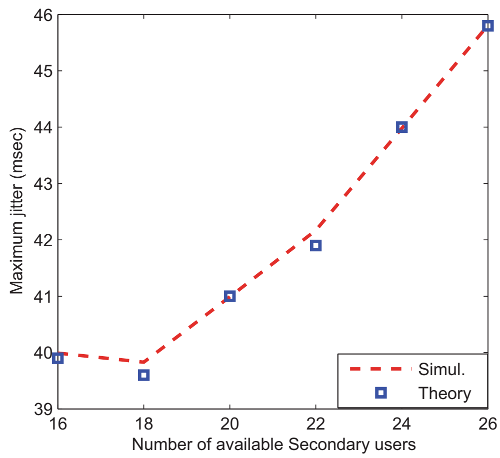

Fig. 2. *The maximum obtained jitter for each SU for a variable number of SUs.*

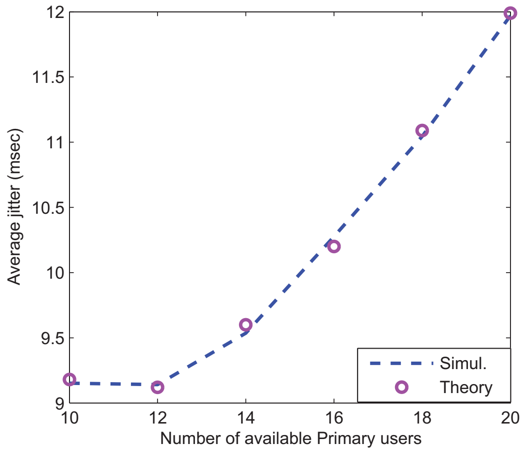

Fig. 3. *The average obtained jitter for each PU for a variable number of PUs.*

Dealing with an alternative scenario where we consider the total outage of the system to be fixed, and all the users in each subsystem suffer from the same total outage. The objective is to investigate the maximum jitter performance of each subsystem, and it can be viewed from Fig.(2) that the maximum jitter shows very small values at certain number of users and for a given threshold value (i.e., the optimum number of secondary users for a given threshold). This concept is very beneficial in network scaling through determining the number of the SUs that can exist in the cell. This has resulted from the conflict of the access outage and the rate outage; as increasing the number of the users will reduce rate outage value while surmounting the access outage. This work has been extended in Fig.(3) for the case of PU users, as the average jitter is implemented where similar performance is obtained, but with different values for the threshold, mainly due to the larger access delay for the SU users.

VI. Conclusion

The MIMO availability in all modern broadband communication systems enables the application of Cognitive Radio in an alternative approach: the Spatial Cognition. Its consideration is recommended for wireless operators due to its outstanding QoS performance in terms of rate rate, delay and jitter. Along this paper we concentrated on the delay and jitter metrics, and we obtained mathematical formulations for the maximum delay, average jitter and maximum jitter. Such formulations are obtained for both the Primary (i.e., VIP) users and the Secondary (i.e., best effort) users. Computer simulations are displayed to check on the system performance as well as on the validity of the obtained closed form expressions.

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