

G C, Deepak, Ladas, Alexandros and Politis, Christos (2015) Inter-cell collaborative spectrum monitoring for cognitive cellular networks in fading environment. In: 2015 IEEE International Conference on Communications. Piscataway, U.S. : Institute of Electrical and Electronics Engineers. ISSN (print) 1550-3607, ISSN (online) 1938-1883 ISBN 9781467364324

Inter-Cell Collaborative Spectrum Monitoring for Cognitive Cellular Networks in Fading Environment

Deepak G. C., Keivan Navaie and Qiang Ni
School of Computing and Communications
Lancaster University, LA1 4YW, UK

Abstract—We propose a novel inter-cell power allocation for multi-carrier cognitive cellular networks. The proposed scheme incorporates the network-wide primary service communication activity into sub-channel power allocation. To model the primary service activity we define sub-channel activity index (SAI). SAI is then evaluated through a simple yet efficient collaborative spectrum monitoring scheme with very low signaling overhead. Corresponding to a secondary user transmission over a sub-channel, a utility function is defined which is a decreasing function of SAI, and an increasing function of the sub-channel achievable rate. Optimal power allocation is then formulated to maximize the total secondary base station (SBS) utility, subject to SBS transmit power, and primary system collision probability constraints. The sub-optimal solutions to the non-convex optimization are then obtained utilizing dual decomposition method. Comparing with a cognitive cellular network with no signalling among the SBSs, where SBS adopts equal sub-channel power allocation, simulation results indicate a significant gain on the achievable rate. We further compare the rate performance with an ideal system in which perfect interference channel state, and spectrum sensing information are available at the SBS and a combination of underlay and overlay access techniques are adopted. Comparing to the ideal system, the proposed method requires significantly lower signaling overhead while its rate performance closely follows the ideal access.

I. INTRODUCTION

In a cognitive cellular network, a secondary cellular network shares the spectrum with a primary legacy cellular network. Such scenario has been considered as a way of improving spectrum efficiency in the cellular band, see, e.g., [1] and references therein. The main challenge in spectrum sharing is to efficiently exploit the under-utilized primary spectrum without compromising primary users' quality-of-service (QoS).

Various access techniques are defined including overlay, underlay and a combination of both [2], [3]. In overlay method, the secondary system accesses the channel only if the channel is idle, whereas in underlay, the secondary system simultaneously uses the channel subject to a received interference constraint at the primary receiver. Ideally, to protect QoS in the primary system, in overlay (underlay) access, accurate spectrum sensing information (perfect channel state information for the channel between the secondary transmitter and the primary receiver) is required. In practice however there is usually no or very limited inter system signaling. This makes acquiring the mentioned information very challenging.

In this paper, we consider a multi-carrier multi-cell cognitive system. In such systems, designing network-wide optimal allocation to coordinate the functions of the neighboring secondary

base stations plays a crucial role in efficient usage of the scarce radio resources [4]. Network-wide resource allocation reduces the impact of intra-system interference on the secondary system performance. It also enables the secondary system to exploit the temporal variations in the available under-utilized spectrum due to variations in the primary system communication activities. Exploiting the primary channel temporal behavior can improve the performance of the radio resource allocation in the secondary network [5]. Nevertheless implementing efficient network-wide resource allocation often requires high signaling overhead which consumes the already scarce radio resources [6].

Alternatively, Poisson based models are proposed in [7], [8] to characterize the primary system activity. Such models however fail to capture instantaneous primary channel activity which has in fact a rather bursty nature [9], [7]. Other researchers propose schemes which are designed to exploit the primary service activity, however it is usually assumed that the activity information is available to the secondary system, either through signaling or a priori, see, e.g., [10]. Yet this assumption is not realistic in practical scenarios.

Here we consider a multi-carrier system. To address the signaling overhead issue we define *sub-channel activity index* (SAI). SAI indicates the level of communication activity in a sub-channel and is equal to one for utilized, zero for unutilized, and between zero and one for under-utilized sub-channels. Under-utilized sub-channels are those in which there is still room, subject to careful power allocation, to accommodate secondary users due to low primary system activity. In a secondary cell covered by a secondary base station (SBS), SAI is a function of the communication activity of the primary users located in that cell as well as the primary users located in the adjacent cells. We then propose a simple, yet efficient, collaborative spectrum monitoring scheme with very low signaling overhead to estimate SAI based on one bit per sub-channel feedback provided by the neighboring SBSs on the sub-channel status.

In the SBS, allocating a higher power to sub-channel with a high SAI, may compromise the primary service quality. On the other hand allocating a lower power to a sub-channel with a low SAI results in low utilization of the available spectrum. To model this tradeoff, we adopt concept of utility function [11], [12]. For each secondary user communicating over a sub-channel, we then define a utility function as a decreasing function of the sub-channel index and increasing function of

the achievable rate on that sub-channel.

Optimal power allocation in the SBS is then formulated with the objective of maximizing the total SBS utility subject to maximum SBS transmit power and primary system collision probability constraints which is non-convex. The formulated optimization is an instance of weighted sum-rate maximization which has been extensively studied in the related literature, see, e.g., [4], [13]–[15] although most the previous works require accurate channel estimation and/or spectrum sensing, thus need direct inter-system and heavy intra-system signaling. Dual decomposition method is then adopted to obtain the solutions. In our method however the only required signaling is one bit per sub-channel in each SBS.

The contributions of this paper are as follows:

- Defining SAI to incorporate primary service activity into SBSs' power allocation,
- Proposing a simple yet efficient collaborative spectrum monitoring scheme with very low signaling overhead for estimating sub-channel activity index,
- Defining a new utility function associated to each secondary user and sub-channel and formulating the joint power and sub-channel allocation in the SBS as maximizing the total SBS utility function,
- Proposing a sub-optimal sub-channel power allocation scheme based on dual decomposition technique.

Comparing with a cognitive cellular network with no signalling among the SBSs, where SBS adopts equal sub-channel power allocation, simulation results indicate a significant rate improvement for the proposed scheme. We then compare the rate performance of the proposed method with a system in which an ideal combination of underlay and overlay access techniques is adopted, where perfect interference channel state information and spectrum sensing information are available at the SBS. Simulation results also show that the proposed method closely follows the ideal spectrum access with a slightly lower achievable rate although the required signaling overhead is significantly reduced.

II. SYSTEM MODEL

The considered system includes a cellular CR network (also referred to as the secondary system) co-located with a legacy cellular primary system. A B Hz frequency band is licensed to the primary system which is used to serve $j = 1 \dots J$ primary users (PU). In many legacy 3G systems a reuse factor of one is usually introduced to increase the spectral efficiency. The uplink spectrum in the primary system is shared for the downlink transmission in the CR network. The CR network is a multi-cellular network with M secondary base stations (SBSs). In the central cell, an SBS serves secondary users (SU) indexed by $s = 1 \dots S$. The secondary system utilizes orthogonal frequency division multiple access (OFDMA), where the radio spectrum is divided into N non-overlapping $B_i = B/N$ Hz sub-channels which are indexed by $i = 1 \dots N$.

Time is slotted into frames and SBSs are synchronized in frame level. All transmitters and receivers in the system have single antenna unless otherwise stated. There is no signaling

between the primary system and the CR network. Based on each sub-channel status the secondary service either adopts underlay or overlay spectrum access technique. In underlay access the secondary service can always access to the sub-channel subject to the interference threshold constraint for the primary system. In overlay access, the secondary service senses the sub-channel status and conducts transmission if the spectrum is idle. While implementing OFDMA in CR network, no inter-channel interference occurs because the higher spectral distance and perfect bandpass filter is assumed in the secondary systems. A schematic of the considered network is presented in Fig. 1.

The communication link between the primary transmitter (PT) and primary receiver (PR) (secondary transmitter (ST) and secondary receiver (SR)) is referred to as primary link (secondary link). For sub-channel i , $i = 1 \dots N$, the instantaneous channel gain of primary and secondary links are denoted by $g_{ji}(\nu)$, and $g_{si}(\nu)$, respectively. Similarly the instantaneous channel gain for the interference link between ST to PR is denoted by $g_{sj}(\nu)$. Parameter ν denotes the joint fading state which is dropped hereafter for brevity. We further assume that g_{sj} , $\forall s$, are independent and identically distributed (i.i.d.). Therefore we drop index s and referred to it as g_j . The value of g_{si} is updated through measurement in each time frame by the CR user. Measuring g_j is a challenging task. Here, we assume that it is estimated through the aggregated interference received at the SUs due to primary transmission.

The achievable rate for SU s accessing sub-channel i is:

$$r_{si} = \log_2(1 + P_{si}h_{si}) \text{ bps/Hz}, \quad (1)$$

where, h_{si} is the channel gain to interference plus noise ratio, and P_{si} is the allocated transmission power on sub-channel i at the SBS corresponding to each secondary user s . We also define $\mathbf{r}_s = [r_{s1}, \dots, r_{sN}]$, as the rate vector for secondary user s . The optimal transmit power vector, $\mathbf{P}_i^* = [P_{1i}^*, \dots, P_{si}^*, \dots, P_{Si}^*]$, is directly related to the primary network communication activity on sub-channel i as well as the associated constraints for protecting PU's QoS.

Spectrum sensing is implemented at the SBSs. Corresponding to sub-channel i in SBS m , spectrum sensing returns a decision variable d_{mi} . If sub-channel i is busy (idle), then $d_{mi} = 1$ ($d_{mi} = 0$). Sensing vector, $\mathbf{d}_m = [d_{m1}, \dots, d_{mN}]$, indicates the status of the sub-channels in SBS m .

III. INTER-CELL COLLABORATIVE SPECTRUM MONITORING

For a sub-channel i in an SBS with $(M - 1)$ neighboring SBSs, *sub-channel activity index* (SAI) is defined as:

$$\hat{d}_i = \frac{1}{M} \left(\sum_{m=1}^M d_{m,i} \right), \quad \forall i. \quad (2)$$

The activity index vector for an SBS is also defined as:

$$\hat{\mathbf{d}} = [\hat{d}_1, \dots, \hat{d}_N], \quad (3)$$

where according to (2), $0 \leq \hat{d}_i \leq 1$, $\forall i$.

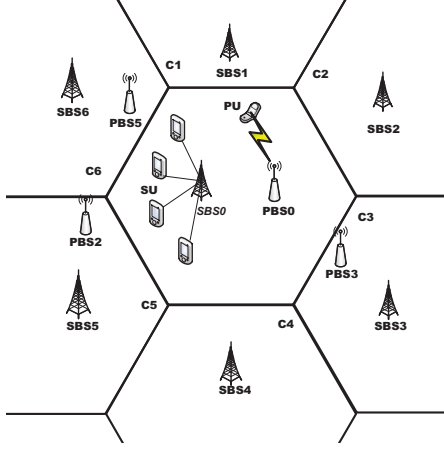


Fig. 1. Schematic of the cognitive cellular network.

To obtain sub-channel activity index by each SBS, 1-bit information per sub-channel is required to feedback by the neighboring SBSs. In the proposed method in this paper each SBS broadcasts its $\hat{\mathbf{d}}$ at the beginning of each time frame which is received and recognized by all its neighboring SBSs. Therefore, obtaining sub-channel activity index for all N sub-channels in an SBS with $M-1$ neighboring cells only requires $(M-1) \times N$ bits of feedback.

A. Spectrum Access

Availability of a sub-channel in an SBS is directly related to the value of \hat{d}_i . In the proposed method in this paper SBS decides about the access technique on each sub-channel based on its corresponding activity index.

We consider three possible cases: i) $\hat{d}_i = 0$, ii) $\hat{d}_i = 1$, and iii) $0 < \hat{d}_i < 1$. If $\hat{d}_i = 0$, there is no PU transmission detected sub-channel i both within the SBS and in the neighboring cells. In such cases, overlay sub-channel access is adopted for transmission over sub-channel i . In cases where $\hat{d}_i = 1$, it implies that sub-channel i is busy both in the SBS and its neighboring cells, therefore secondary transmission on this sub-channel is not possible. If $0 < \hat{d}_i < 1$ an underlay access technique is adopted by the secondary system. The larger the value of \hat{d}_i , the higher is the current interference in sub-channel i , the lower should be the transmit power of the SBS to prevent further interference on the primary receivers. Here, we propose an optimal power allocation scheme in which incorporating \hat{d}_i , the transmit power of the SBS is obtained to maximize the achievable rate of the secondary network subject to the maximum SBS transmit power and the QoS constraints in the primary network. The proposed spectrum access method at the SBS based on SAI is summarized in Fig. 2.

B. Optimal Power Allocation for $0 < \hat{d}_i < 1$

Here we propose an analytical framework for optimal sub-channel power allocation based on \hat{d}_i . As it is seen in (1), the achievable rate for user s on sub-channel i , is a function of h_{si} , where $h_{si} = |g_{si}|^2 / (N_0 + I_{pi})$, N_0 is the variance

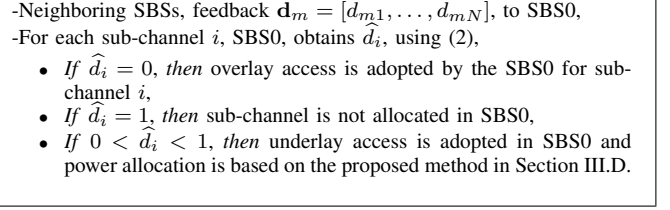


Fig. 2. Inter-Cell Collaborative Spectrum Monitoring Scheme at SBS0.

of the AWGN at the secondary receiver, I_{pi} is the aggregated interference due to simultaneous transmissions by PUs. On the other hand, the higher the value of \hat{d}_i , the higher is the activity of the primary system over sub-channel i . Therefore, to keep r_{si} at the same level a higher P_{si} is required.

Assume that for a user s two sub-channels i, k , provide the same achievable rate, $r_{si} = r_{sk}$. If $d_i < d_k$, then $I_{pi} < I_{pk}$. Therefore, according to (1) a higher transmit power is required to provide the same rate, i.e., $P_{si} < P_{sk}$. In other words, the “cost” of providing the same rate to user s on sub-channels i is lower for the secondary system than that of sub-channel k .

To quantify the impact of \hat{d}_i on the system performance at the SBS when deciding for the access method and P_{si} on sub-channel i , here we define utility function u_{si} as the following

$$u_{si} = \frac{r_{si}}{\hat{d}_i} \alpha_{si}, \quad (4)$$

where α_{si} is the weight parameter assigned by the secondary system for traffic prioritization. For a user s , the larger u_{si} for a sub-channel the lower is the cost of transmission on that sub-channel. Total secondary system utility, U is defined as

$$U = \sum_{s=1}^S \sum_{i=1}^N u_{si}. \quad (5)$$

If $0 < \hat{d}_i < 1$, the SBS adopt underlay access. Thus interference is induced at the primary receivers. Transmission collision may then occur at the primary receiver if the inflicted interference by the secondary transmission, $I_{ji} = \sum_{s=1}^S P_{si} g_j$, is getting higher than a predefined threshold $Q_{ji}, \forall j, i$. To protect the QoS in the primary system, the radio resource allocation is often designed so that the probability of collision in the primary system is kept below η_{ji} , which is a primary system parameter related to the primary QoS [15]. The optimal radio resource allocation is then formulated as:

Problem \mathcal{A}_1 :

$$\max_{\mathbf{P}} U, \quad (6a)$$

$$\text{s.t.} \quad \sum_{s=1}^S \sum_{i=1}^N P_{si} \leq P_T, \quad (6b)$$

$$\Pr \left\{ \sum_{s=1}^S P_{si} g_j > Q_{ji} \right\} \leq \eta_{ji}, \quad \forall j, i, \quad (6c)$$

where P_{si} is the allocated transmission power for SU s on sub-channel i , \mathbf{P} is a $S \times N$ matrix, $\mathbf{P} = [\mathbf{P}_1 | \dots | \mathbf{P}_S]$, and $\mathbf{P}_s = [P_{s1}, \dots, P_{sN}]^T$. Constraint (6b) ensures that the total transmit power in the SBS is always smaller than its maximum transmit power, P_T . Furthermore, (6c) is to keep the collision probability for the primary users below η_{ji} . Hereafter, for brevity we assume the same QoS requirements for all users over all sub-channels, i.e., $Q_{ji} = \bar{Q}$, and $\eta_{ji} = \bar{\eta}$.

If the channel distribution information (CDI) for the channel between ST and PR, g_j , or an estimation of that, is known to the SBS, then (6c) can be written as

$$\begin{aligned} \Pr \left\{ g_j > \frac{\bar{Q}}{\sum_{s=1}^S P_{si}} \right\} &= 1 - \Pr \left\{ g_j \leq \frac{\bar{Q}}{\sum_{s=1}^S P_{si}} \right\}, \\ &= 1 - F_{g_j} \left[\frac{\bar{Q}}{\sum_{s=1}^S P_{si}} \right], \\ &\leq \bar{\eta}, \quad \forall j, i. \end{aligned} \quad (7)$$

C. Rayleigh Distributed Interference Link

If g_j follows a Rayleigh distribution with parameter r , then (7) is further simplified to

$$\exp \left(\frac{-\bar{Q}}{2r^2 \sum_{s=1}^S P_{si}} \right) \leq \bar{\eta}, \quad \forall i. \quad (8)$$

For Rayleigh distributed g_j , using (8), (6c) is substituted by

$$\sum_{s=1}^S P_{si} \leq \frac{\bar{Q}}{2r^2 \left(\ln \frac{1}{\bar{\eta}} \right)}, \quad \forall i. \quad (9)$$

Therefore, \mathcal{A}_1 is equivalent to the following optimization:

Problem \mathcal{A}_2 :

$$\max_{\mathbf{P}} U, \quad (10a)$$

$$\text{s.t.} \quad \sum_{s=1}^S \sum_{i=1}^N P_{si} \leq P_T, \quad (10b)$$

$$\sum_{s=1}^S P_{si} \leq \frac{\bar{Q}}{2r^2 \left(\ln \frac{1}{\bar{\eta}} \right)}, \quad \forall i. \quad (10c)$$

Hereafter, for brevity we assume $\alpha_{si} = 1 \quad \forall i, s$.

D. Sub-Optimal Power Allocation in SBS

Optimisation problem \mathcal{A}_2 is non-convex. Here we adopt dual decomposition approach [16], to obtain its solutions. There is a duality gap between the obtained solutions using dual decomposition method and the actual optimal solutions. However, it is shown in [17] that if the number of sub-channels is sufficiently large, the duality gap is very close to zero. Note that the obtained U using dual decomposition is a lower bound on the maximum total secondary system utility.

To derive the dual problem we need Lagrange function, \mathcal{L} , corresponding to optimization problem \mathcal{A}_2

$$\begin{aligned} \mathcal{L}(\mathbf{P}, \lambda, \boldsymbol{\mu}) &= \sum_{i=1}^N \frac{1}{\hat{\mathbf{d}}_i} \sum_{s \in \mathcal{S}} \log_2 \left(1 + \frac{|g_{si}|^2 P_{ji}(\hat{\mathbf{d}}_i)}{N_0 + I_{pi}} \right) \\ &\quad + \lambda \left(\sum_{s=1}^S \sum_{i=1}^N P_{si} \leq P_T \right) \\ &\quad + \sum_{i=1}^N \boldsymbol{\mu}_i \left(\sum_{s=1}^S P_{si}(\hat{\mathbf{d}}_i) \leq \frac{\bar{Q}}{2r^2 \left(\ln \frac{1}{\bar{\eta}} \right)} \right), \end{aligned} \quad (11)$$

where, $\lambda \geq 0$ is Lagrangian multiplier associated with constraint (10b) and $\boldsymbol{\mu} \geq 0$ is Lagrangian vector associated with constraint (10c). The dual function is then defined as [16]:

$$\mathcal{D}(\lambda, \boldsymbol{\mu}) = \max_{\mathbf{P}} \mathcal{L}_a(P, \lambda, \boldsymbol{\mu}). \quad (12)$$

Therefore, the corresponding dual function is [16]:

$$\begin{aligned} \mathcal{D}(\lambda, \boldsymbol{\mu}) &= \max_{\mathbf{P}} \sum_{i=1}^N \frac{1}{\hat{\mathbf{d}}_i} \sum_{s \in \mathcal{S}} \log_2 \left(1 + \frac{|g_{si}|^2 P_{si}(\hat{\mathbf{d}}_i)}{N_0 + I_{pi}} \right) \\ &\quad - \lambda \sum_{i=1}^N \sum_{s=1}^S P_{si}(\hat{\mathbf{d}}_i) - \sum_{i=1}^N \boldsymbol{\mu}_i \sum_{s=1}^S P_{si}(\hat{\mathbf{d}}_i), \end{aligned} \quad (13)$$

and the dual optimization problem is:

$$\begin{aligned} \min \quad &\mathcal{D}(\lambda, \boldsymbol{\mu}), \\ \text{s.t.} \quad &\lambda \geq 0, \quad \boldsymbol{\mu} \geq 0. \end{aligned} \quad (14)$$

The optimal transmission power obtained from (14) maximizes the total system utility, however it needs to adjust $\lambda, \boldsymbol{\mu}$, which are in fact the prices associated with the constraints in \mathcal{A}_2 .

The Lagrangian multipliers $(\lambda, \boldsymbol{\mu})$ are iteratively estimated using the sub-gradient method [18] in such a way that the algorithm will gradually find the suitable direction of $(\lambda, \boldsymbol{\mu})$. This reduces the computational complexity and the value of λ and $\boldsymbol{\mu}$ are calculated iteratively as follows:

$$\begin{aligned} \lambda(m+1) &= \left(\lambda_i(m) + \Delta_s(m) \left(P_T - \sum_{s=1}^S \sum_{i=1}^N P_{si} \right) \right)^+, \\ \mu_i(m+1) &= \left(\mu_i(m) + \Delta_s(m) \left(\frac{\bar{Q}}{2r^2 \left(\ln \frac{1}{\bar{\eta}} \right)} - \sum_{s=1}^S P_{si}(\hat{\mathbf{d}}_i) \right) \right)^+, \end{aligned} \quad (15)$$

where, $\Delta_s(m)$ is the step size at the m^{th} iteration state. The step size is initialized as $\Delta_s(m) \geq 0$, $\sum_{m=1}^{\infty} \Delta_s^2(m) < \infty$ and $\sum_{m=1}^{\infty} \Delta_s(m) \rightarrow \infty$.

The optimal power allocation for each sub-channel which maximizes the total utility in the SBS is then given by water-filling solution [16]:

$$P_{si}^* = \left(\frac{1/\ln 2}{\hat{\mathbf{d}}_i(\lambda + \sum_i \mu_i)} - \frac{N_0 + I_{pi}}{|g_{si}|^2} \right)^+, \quad (17)$$

where, $(a)^+ = \max\{0, a\}$. Note that where for sub-channel i $\frac{N_0 + I_{pi}}{|g_{si}|^2} > \frac{1/\ln 2}{\hat{\mathbf{d}}_i(\lambda + \sum_i \mu_i)}$, $\forall s, i$, (17) returns $P_{si}^* = 0$.

TABLE I
SIMULATION PARAMETERS

Channel Model	Rayleigh with $r = 1$.
Number of Sub-Channels (N)	32
Sub-Channel Bandwidth (B_i)	125KHz
Number of The Secondary Users (S)	6
Interference Threshold \bar{Q}	0.15
Collision Probability Threshold ($\bar{\eta}$)	0.1-0.6
Maximum SBS Transmit Power (P_T)	20dBm

The optimum transmission power on the available set of sub-channels is obtained as shown in (17). As it is seen in (17) $P_{s_i}^*$ is independent of $\bar{\eta}$ and \bar{Q} . Therefore, the constraint (10c) needs to be re-evaluated as a further requirement of sub-optimum transmission power.

In OFDMA based cognitive radio system only one SU, s^* , access the sub-channel i , therefore the maximum transmission power for the case of free sub-channel is calculated as the maximum value of constraint (10c), therefore:

$$P_{s^*i}^* = \frac{\bar{Q}}{2r^2 \left(\ln \frac{1}{\bar{\eta}} \right)}. \quad (18)$$

The minimum value of (17) or (18) is taken as the optimal transmission power because this does not violate other constraints and also fulfills the QoS requirements of primary systems. Therefore, the optimum transmission power is

$$P_{s_i}^{opt} = \min \{ \max(0, P_{s_i}^*), \max(P_{s^*i}^*, 0) \}, \forall s, i. \quad (19)$$

The optimized transmission power maintains the collision probability requirement for all the PUs as well as the transmission power constraint for the SBSs.

IV. SIMULATION RESULTS

A. Simulation Setting

We simulate a multi-cell OFDMA based cellular CR network as in Fig. 1. SBS0 follows the proposed scheme presented in Section. III. Both PUs and SUs are uniformly distributed in the coverage area of SBS0. In each time frame SAI, $0 < \hat{d}_i \leq 1, \forall i$, is modeled by uniformly distributed random variable with a fixed mean. We assume that SAI is identically distributed for all sub-channels, therefore we drop sub-channel index i in the following. Unless otherwise stated, the simulation parameters are as in Table I. Here in addition to investigating the impact of system parameters on the performance of the proposed method, we also compare its performance with two reference systems, SYS-I and SYS-II. The investigated performance metric is the total achievable rate defined as $\sum_{s=1}^S \sum_{i=1}^N r_{s_i}$.

SYS-I is a stand-alone SBS0 with no signaling with the adjacent SBSs. SYS-I adopts the same system parameters as in Table. I, however SBS0 adopts equal power allocation on the available sub-channels without considering their corresponding activity. SYS-II is an ideal spectrum sharing system in which both accurate spectrum sensing information and perfect interference channel state are available to the SBS. SYS-II

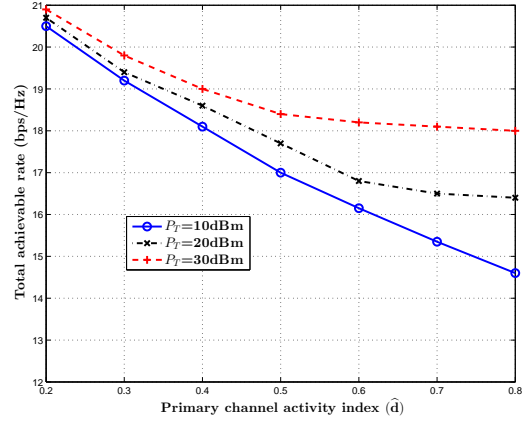


Fig. 3. Total achievable rate of the SBS vs. \hat{d} for $P_T = 10, 20, 30$ dBm.

is then utilized overlay spectrum access for unutilized sub-channels, and underlay access for under-utilized sub-channels. For underlay access, the power allocation maximizes SBS achievable rate subject to collision probability constraint and maximum SBS transmit power.

B. Impact of SBS Maximum Transmit Power

Fig. 3 presents the total achievable rate of the SBS vs. \hat{d} , for different values of the maximum SBS transmit power, P_T . As expected, by increasing primary users' activity, \hat{d} the achievable rate is decreased. Interestingly however, it is observed that for a less active primary network, $\hat{d} < 0.5$, increasing P_T results in a very limited increase in the achievable rate. This is mainly because for lower \hat{d} , where a large number of primary channels are available, by increasing P_T the allocated per-channel transmission power remains almost the same due to maintaining the collision probability constraint.

C. Impact of Collision Probability Constraint

In Fig. 4, the total achievable rate of the SBS is plotted vs. $\bar{\eta}$ for the proposed method in this paper as well as SYS-II. As expected, a higher maximum transmission power results in a higher achievable rate. However, as it is seen 1000 time increase in P_T results in a improvement to the achievable rate. Corresponding to a larger P_T , a greater rate improvement is observed for larger values of $\bar{\eta}$. Since a system with a larger $\bar{\eta}$ has a higher tolerance to the secondary interference, thus the SBS can allocate a higher power thus achieves a higher rate.

Fig. 4 also indicates that the rate performance of the proposed method closely follows SYST-II's. Note that comparing to SYS-II, the proposed method requires a significantly lower signaling overhead. In other words, the lower level of required signaling in the proposed method is associated with a reasonable cost on rate.

D. Comparison with SYS-I and SYS-II

The achievable rate of the proposed system along with SYS-I and SYS-II are presented in Fig. 5 versus the traffic

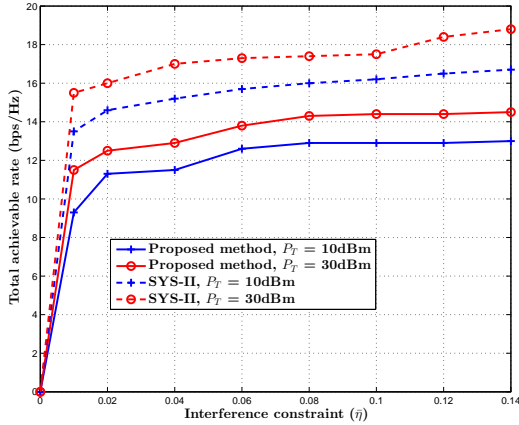


Fig. 4. Total SBS achievable rate vs. collision probability threshold for $P_T = 10, 30$ dBm for the proposed method and SYS-II for $d = 0.6$.

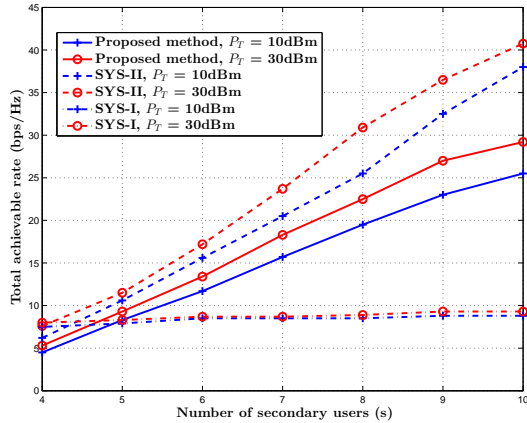


Fig. 5. Total achievable rate of the secondary systems vs. the total number of the secondary users for different scenarios and P_T values.

demand in the secondary system represented by the number of secondary users, S , for different values of $P_T = 10, 30$ dBm. As expected, SYS-II achieves the highest rate, whereas SYS-I has the lowest. The proposed scheme however achieves a significantly higher rate than that of SYS-I. This is due to exploiting primary system activity provided by incorporating SAI in the power allocation. It is also seen that the proposed method closely follows the ideal access (SYS-II) with a slightly lower rate but significantly lower signaling overhead.

V. CONCLUSION

We defined SAI to incorporate primary system communication activity in sub-channel power allocation. A simple collaborative spectrum monitoring scheme with very low signaling overhead was then designed to evaluate SAI. We then obtained sub-optimal power allocation in the SBS with the objective of maximizing the total SBS utility, defined

based on SAI, subject to maximum SBS transmit power and primary system collision probability constraints. Simulations confirmed that the proposed scheme exploited the variations in the primary system communication activity to improve the secondary system achievable rate in return of a slight decrease of the rate comparing to the ideal case. The ideal system however requires direct inter-system signaling and heavy intra-system signaling, whereas the proposed method only requires one bit per sub-channel feedback.

VI. ACKNOWLEDGMENT

This work was partly supported by the UK Eng. & Phy. Sciences Research Council (EPSRC) under grant EP/K/022725/1, and EU Marie Curie CIG S3isE.

REFERENCES

- [1] M. G. Khoshkholgh, *et al.*, "Achievable capacity in hybrid DS-CDMA/OFDM spectrum-sharing," *IEEE Trans. Mobile Comput.*, vol. 9, no. 6, pp. 765–777, 2010.
- [2] —, "Access strategies for spectrum sharing in fading environment: overlay, underlay, and mixed," *IEEE Trans. Mobile Comput.*, vol. 9, no. 12, pp. 1780–1793, 2010.
- [3] K. Shashika Manosha, *et al.*, "Overlay/underlay spectrum sharing for multi-operator environment in cognitive radio networks," in *Proc. IEEE VTC Spring 2011*, 2011, pp. 1–5.
- [4] L. Liu, *et al.*, "Achieving global optimality for weighted sum-rate maximization in the k-user Gaussian interference channel with multiple antennas," *IEEE Trans. Wireless Commun.*, vol. 11, no. 5, pp. 1933–1945, 2012.
- [5] J. Zou, *et al.*, "Optimal power allocation for hybrid overlay/underlay spectrum sharing in multiband cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 62, no. 4, pp. 1827–1837, 2013.
- [6] K. Navaie, "On the interference management in wireless multi-user networks," *Telecommunication Systems*, vol. 46, pp. 135–148, 2011.
- [7] M. G. Khoshkholgh, *et al.*, "On the impact of the primary network activity on the achievable capacity of spectrum sharing over fading channels," *IEEE Trans. Wireless Commun.*, vol. 8, no. 4, pp. 2100–2111, 2009.
- [8] X. Tan, *et al.*, "Achievable transmission rate of the secondary user in cognitive radio networks with hybrid spectrum access strategy," *IEEE Commun. Lett.*, vol. 17, no. 11, pp. 2088–2091, 2013.
- [9] D. Willkomm, *et al.*, "Primary users in cellular networks: A large-scale measurement study," in *Proc. DySPAN 2008.*, 2008, pp. 1–11.
- [10] G. Bansal, M. Hossain, *et al.*, "Subcarrier and power allocation for OFDMA-based cognitive radio systems with joint overlay and underlay spectrum access mechanism," *IEEE Trans. Veh. Technol.*, vol. 62, no. 3, pp. 1111–1122, 2013.
- [11] F. P. Kelly, "Charging and rate control for elastic traffic," *European Trans. Telecommun.*, vol. 8, pp. 33–37, 1997.
- [12] M. Katoozian, *et al.*, "Utility-based adaptive radio resource allocation in OFDM wireless networks with traffic prioritization," *IEEE Trans. Wireless Commun.*, vol. 8, no. 1, pp. 66–71, 2009.
- [13] J. Kaleva, *et al.*, "Weighted sum rate maximization for interfering broadcast channel via successive convex approximation," in *Proc. IEEE GLOBECOM 2012*, 2012, pp. 3838–3843.
- [14] L. Zhang, *et al.*, "Cognitive multiple access channels: optimal power allocation for weighted sum rate maximization," *IEEE Trans. Commun.*, vol. 57, no. 9, pp. 2754–2762, 2009.
- [15] N. Mokari, *et al.*, "Downlink radio resource allocation in OFDMA spectrum sharing environment with partial channel state information," *IEEE Trans. Wireless Commun.*, vol. 10, no. 10, pp. 3482–3495, 2011.
- [16] S. P. Boyd and L. Vandenberghe, *Convex optimization*. Cambridge university press, 2004.
- [17] W. Yu and R. Lui, "Dual methods for nonconvex spectrum optimization of multicarrier systems," *IEEE Trans. Wireless Commun.*, vol. 54, no. 7, pp. 1310–1322, 2006.
- [18] D. Palomar and M. Chiang, "A tutorial on decomposition methods for network utility maximization," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 8, pp. 1439–1451, 2006.