Impact of Power Allocation and Antenna Directivity in the Capacity of a Multiuser Cognitive Ad Hoc Network

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Abstract. *This paper studies the benefits that power control and antenna directivity can bring to the capacity of a multiuser cognitive radio network. The main objective is to optimize the secondary network sum rate under the capacity constraint of the primary network. Exploiting location awareness, antenna directivity, and the power control capability, the cognitive radio ad hoc network can broaden its coverage and improve capacity. Computer simulations show that by employing the proposed method the system performance is significantly enhanced compared to conventional fixed power allocation.*

Keywords

Power control, cognitive radio, location awareness, antenna directivity.

1. Introduction

Cognitive radio (CR) is a key technology to solve the conflict between the increasing demand of radio spectrum and its underutilization. First proposed in [1], CR has been considered for use by the Federal Communications Commission in [2], due to the imminent need for communication technologies that enable a more flexible and intelligent exploitation of the limited radio resources. Such promising technology is based on dynamic spectrum access techniques which allow the opportunistic use of underutilized frequency bands, increasing the efficiency of spectrum utilization [3]. The basic idea behind this paradigm is to allow unlicensed or cognitive users (secondary users or SUs) to dynamically access certain frequency bands without causing harmful interference to legitimate or licensed users (primary users or PUs). For instance, temporarily idle frequency bands can be allocated to the SUs or the coverage area of the secondary network can be confined within a region, without introducing intolerable interference levels to the PUs. Valuable and updated information on this technology can be found for instance in [4] and [5]. The main challenges associated with the development of CR networks are also presented in [6].

In scenarios where the SUs are sufficiently far from the PUs, they can concurrently transmit without interfering with each other significantly. Based on this principle, some papers propose to establish an ad-hoc network that operates in the same region and frequency band of an infrastructure-based primary network, expecting a significant increase in total system throughput [7], [8], [9]. Therefore, it is quite useful for the SUs to know the PUs positions. However, if the transmit power used by PUs and SUs is the same, such solution is not useful when the separation between the devices is not large enough. In such cases it is of paramount importance to adequately allocate the transmit power [8], [9]. Moreover, location awareness is proposed in [10] and [11] in order to support other location based services and applications.

Several studies have addressed power control in cognitive networks. For instance, Qiant *et al* [12] and Li [13] investigate the issue of energy efficiency. In [14] the relationship between the maximum transmit power and the signal-to-interference-plus-noise ratio (SINR) is addressed. In [15] a system with a mixed CR strategy (overlay and underlay) is presented, while in [16] a non-cooperative model based on the SINR is described and a new objective function is proposed. Both papers are based on game theory. Similar approaches can also be found in [17], [18] and [19]. In [20] power allocation is investigated considering a cognitive radio network scenario where a relay is assigned to mitigate interference to primary users. In [21] the issue of multiple antennas in spectrum sharing is analyzed, in [22] individual SINR requirements are considered and in [23] the robustness of the system for multiple primary and secondary users considering channel uncertainty is discussed.

Nevertheless, the performance of a system with several cognitive pairs operating in the coverage area of the primary network is still a somewhat open issue. The present study aims at determining the impact of efficient power allocation for the CR transmitters on the capacity of the secondary link. First we propose a procedure to optimize the power allocation, while later we exploit antenna directivity in the secondary network. Besides the premise of not affecting the primary, we also aim at maximizing the overall throughput of the secondary network. Our main contribution is to show that the proposed method allows a cognitive radio ad-hoc network (CRAHN) to operate simultaneously in the same frequency band and coverage area of a primary network, without causing unacceptable levels of interference while achieving a significantly increased total capacity.

The rest of this paper is organized as follows. In Section 2 the system model and problem formulation are presented. Section 3 presents an efficient selection algorithm based on optimal power control. Antenna directivity at the SUs is included in an evolved version of this algorithm in Section 4. In Section 5 we present numerical results while Section 6 concludes the paper.

2. System Model

The system model is illustrated in Fig. 1. The n cognitive radio transmitters (CTx) are represented by stars while the n cognitive radio receivers (CRx) are represented by circles. We consider that the CRAHN operates in the uplink of the infra-structured primary network, so that in the figure are also shown the primary transmitter or primary mobile station (PMS) and the primary receiver, which is a fixed base station or access point (BS). The BS is at the origin while the location of the mobile devices (primary or secondary) is represented in polar coordinates as (r_j, θ_j), within the BS coverage area (πR^2). We assume that the cognitive devices know their relative or absolute locations as well as those of the PMS, assisted by positioning techniques such as GPS or by systems based on measuring the received signal strength, angle of arrival and/or time of arrival. Methods available for doing that can be found in [24], [25] and [26]. Moreover, location information can be broadcasted through geographical routing protocols [27], [28] and [29].

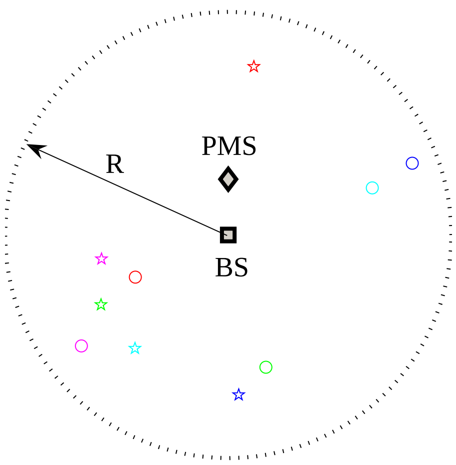

Fig. 1. CRAHN operating in the coverage region of an infrastructure-based primary network. The devices belonging to the same pair are represented with the same color; CTx's are represented by "stars" and CRx's by "circles".

Our main goal, while guaranteeing the primary network performance, is to maximize the overall Shannon capacity [30] of the secondary network

$$C_a = W \sum_{k=1}^{n} \log_2 \left(1 + \mathrm{SINR}_{ak}\right) \tag{1}$$

where SINR_{ak} denotes the SINR of the k-th cognitive pair and W denotes the bandwidth of each link, which will be assumed to be equal for all secondary links and for the primary link.

The capacity of the primary link, (C_i), is used as a quality metric, and must be always greater than or equal to a predefined threshold (σ_i), according to the minimum information transmission rate required by the primary link:

$$C_i = W \log_2 \left(1 + \mathrm{SINR}_i\right) \geq \sigma_i \tag{2}$$

where SINR_i denotes the SINR of the primary link. Therefore, our problem can be formally stated as:

$$\begin{aligned} \max_{\{P_{ts1}\ P_{ts2}\ \cdots\ P_{tsn}\}} \quad & C_a \\ \text{subject to} \quad & C_i \geq \sigma_i \\ & P_{tsk} \leq P_{max} \end{aligned} \tag{3}$$

where P_{tsk} is the transmit power of the k-th secondary transmitter and P_{max} is a maximum power constraint per secondary user.

Finally, we consider the two-ray propagation model between transmitter and receiver [31]. Therefore, the power of the received signal can be expressed as $P_r = \frac{P_t h_r^2 h_t^2 G_r G_t}{r^4}$, where P_r and P_t represent the received and transmitted powers, respectively, h_r and h_t are the receive and transmit antenna heights, G_r and G_t the corresponding antenna gains, and r is the distance between the receiver and transmitter.

3. Power Control

We assume that each CTx can adjust its transmit power according to its position and those of other mobile stations involved in the scenario. The following is a long-term average analysis, taking into account the effect of large-scale fading [31]. Let $a_k = \frac{P_{tsk}}{P_{tp}}$ be the power control factor associated with the k-th CTx, where P_{tp} is the transmit power of the primary transmitter. If the height of the antennas of all mobile stations are considered to be equal and their gains as unity, the SINR for the primary link is

$$\mathrm{SINR}_i = \frac{P_{rpp}}{N + \sum_{j=1}^{n} P_{rpj}} = \frac{\frac{1}{r_p^4}}{f_n + \sum_{j=1}^{n} \frac{a_j}{r_j^4}} \tag{4}$$

and for the k-th secondary link

$$\mathrm{SINR}_{ak} = \frac{P_{rkk}}{N + P_{rkp} + \sum_{\substack{j=1 \\ j \neq k}}^{n} P_{rkj}} = \frac{\frac{a_k}{d_{kk}^4}}{f_n + \frac{1}{d_{pk}^4} + \sum_{\substack{j=1 \\ j \neq k}}^{n} \frac{a_j}{d_{jk}^4}} \tag{5}$$

where P_{rpp} and P_{rpj} are the powers received by the BS from the PMS and the j-th CTx, respectively; P_{rkk}, P_{rkp} and P_{rkj} are the powers received by the k-th CRx from the k-th CTx, the PMS and the j-th CTx, respectively; N is the noise power; f_n represents the noise factor that depends on the noise power as

$$f_n = \frac{W\kappa T}{P_{tp}h_r^2 h_t^2} = \frac{N}{P_{tp}h_r^2 h_t^2};$$

T is the noise temperature; $\kappa = 1.38 \times 10^{-23}$ J/K is the Boltzmann constant; r_p and r_j are the distances from the PMS and the j-th CTx to the BS, respectively; d_{pk}, d_{kk} and d_{jk} are the distances from the PMS, the k-th CTx and the j-th CTx to the k-th CRx, respectively. When the polar coordinates of the devices are known, these distances are calculated as

$$d_{kj} = \sqrt{\left(r_k^2 + r_j^2 - 2r_k r_j \cos\left(\theta_k - \theta_j\right)\right)}.$$

For practical reasons the power control factors a_k can take values from a finite set of m values $\{-\infty\,\text{dB}, a_{min}, a_{min}+\Delta a, \cdots, a_{min}+(m-3)\Delta a, a_{max}\}$, where

$$\Delta a = \frac{a_{max} - a_{min}}{m-2},$$

(a_{max} and a_{min} are both in dB). For example, considering $m = 4$, $a_{min} = -9$ dB and $a_{max} = 9$ dB implies that a_k takes values from $\{-\infty\,\text{dB}, -9\,\text{dB}, 0\,\text{dB}, 9\,\text{dB}\}$. In addition, note that the maximum power constraint per secondary user is therefore $P_{max} = a_{max}P_{tp}$.

Through Algorithm 1, Transmitter Selection with Power Control (TS-PC), it is possible to determine the power control vector $\mathbf{a}^\star = [a_1, \ldots, a_n]$ which ensures the maximum sum rate of the secondary network. Once the coordinates of all mobile devices are updated, the algorithm generates the $m^n \times n$ matrix $\mathcal{A}$ whose rows represent all possible combinations of power control vectors that can be used by the n cognitive transmitters based on the m distinct power levels under consideration. From this data a column vector $\mathbf{s}_{BS}$ is constructed whose entries are the SINR ratio perceived at the BS for each of the m^n distinct combinations of cognitive transmit powers, according to (4). Then, the capacity of the primary network can be estimated for each transmit power combination, according to (2). By discarding the rows in matrix $\mathcal{A}$ for which $C_i < \sigma_i$, we construct a new matrix $\mathcal{A}'$. Using $\mathcal{A}'$ we calculate matrix $\mathcal{S}_{CR}$ whose rows contain the values of SINR perceived at the secondary receivers for each power control vector, according to (5). Finally, after calculating the capacity of the secondary links for each row in $\mathcal{S}_{CR}$ using (1), the maximum overall secondary capacity value is identified and the corresponding power control vector becomes $\mathbf{a}^\star$ which is then used by the secondary transmitters.

For the sake of better illustrating the impact of the proposed secondary power control scheme, in our numerical results we also consider two variants of the TS-PC algorithm. In the first one, Transmitters Selector with Fixed Power (TS-FP), we assume an on-off power control scheme where the CTx either transmit with the same power as the PMS or do not transmit at all. Note that in TS-FP, due to the on-off power control scheme, $\mathcal{A}$ is a $2^n \times n$ matrix. The second variant, One Transmitter with Fixed Power (OT-FP), is even simpler and considers a single CTx at fixed power. If the target capacity of the primary network is guaranteed, then the cognitive pair can establish its communication, otherwise the secondary transmitter remains silent. In OT-FP the interference seen at the CRx comes only from the primary link, as there is only one active CTx.

4. Power Control and Antenna Directivity

Suppose now a reduced mobility environment in which the CTx has the ability to electronically adjust its antenna beam pattern, so that the CTx can form a directed beam towards its CRx, according for instance to the radiation pattern of Fig. 2, which is given by [32]:

$$G(\phi) = -\min\left(12\left(\frac{\phi}{\phi_{3\text{dB}}}\right)^2, A_{\max}\right) \tag{6}$$

where $G(\phi)$ is the antenna gain in dBi depending on the direction ϕ, $-180^\circ \leq \phi \leq 180^\circ$, $\phi_{3\text{dB}}$ is the 3dB beamwidth and $A_{\max}$ is the maximum attenuation.

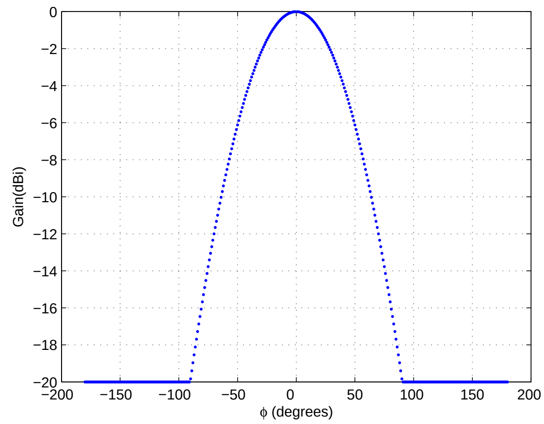

Fig. 2. Radiation pattern of an antenna with beamwidth $\phi_{3\text{dB}} = 70^\circ$ and $A_{\max} = 20$dB, according to (6).

Now, the SINR for each link including the effect of antenna directivity can be expressed as:

$$\text{SINR}_i = \frac{\frac{1}{r_p^4}}{f_n + \sum_{j=1}^{n} \frac{a_j g_{jp}}{r_j^4}}, \tag{7}$$

$$\text{SINR}_{ak} = \frac{\frac{a_k g_{kk}}{d_{kk}^4}}{f_n + \frac{1}{d_{pk}^4} + \sum_{\substack{j=1 \\ j\neq k}}^{n} \frac{a_j g_{jk}}{d_{jk}^4}} \tag{8}$$

where g_{jp} is the directive gain of the j-th CTx in the direction of the BS; g_{kk} is the directive gain of the k-th CTx in the direction of the k-th CRx; and g_{jk} is the directive gain of the j-th CTx in the direction of the k-th CRx. The directive gain

Algorithm 1 Transmitter Selection with Power Control (TS-PC)

1. update $r_p, \theta_p, r_k, \theta_k$ // $k = 1, \ldots, n$.
2. generate $\mathcal{A}$ // $m^n \times n$ matrix
3. calculate column vector $\mathbf{s}_{BS}$ // equation (4)
4. calculate C_i for each value in $\mathbf{s}_{BS}$ // equation (2)
5. construct $\mathcal{A}'$ by discarding the rows in $\mathcal{A}$ for which $C_i < \sigma_i$ // primary link protection
6. calculate $\mathcal{S}_{CR}$ based on $\mathcal{A}'$ // equation (5)
7. calculate C_a for each row in $\mathcal{S}_{CR}$ // equation (1)
8. find the maximum C_a // secondary network capacity
9. determine $\mathbf{a}^\star$ and config the cognitive transmitters // final power allocation

is calculated as $g_{jk} = 10^{\frac{G(\phi)}{10}}$ where in this case, ϕ represents the angle between the line connecting the j-th cognitive pair and the line joining the j-th CTx and the k-th CRx.

The second proposed algorithm, Transmitter Selection with Directional Antenna and Power Control (TS-DAPC), is similar to Algorithm 1 (TS-PC), with the difference that for computing the SINR seen at the BS or at the CRx's we include the directivity of the CTx's antennas. More specifically, now we utilize (7) instead of (4) for calculating $\mathbf{s}_{BS}$, and (8) instead of (5) for calculating $\mathcal{S}_{CR}$.

5. Numerical Results

In this section we investigate the performance of the proposed algorithms TS-DAPC and TS-PC, as well as the variants of the latter, TS-FP and OT-FP. We determine the maximum sum rate of the secondary network depending on: the number n of cognitive pairs allowed to operate in the coverage area of the primary network; the number m of power control factors used on the power control scheme; the minimum capacity σ_i required by the primary link; and the distance r_p between the PMS and the BS.

All experiments were performed using MATLAB® and the results shown next correspond to the average of 5000 randomly selected topologies, in which the n cognitive pairs were uniformly distributed within the circular coverage area of the BS. Each topology corresponds to a different relative position between nodes. As the SINR depends only on the allocated power and on the relative position between nodes, for each topology we determine the primary and secondary capacity – using equations (1) and (2) – and the concurrent transmission probability with and without the proposed power control algorithm. This process is repeated for each different random topology and then the average performance is computed.

Moreover, next we consider the following parameters: normalized bandwidth ($W = 1$ Hz); ambient temperature $T = 300$ K; PMS transmit power of $P_{tp} = 20$ dBm; if power control is used then $a_{min} = -9$ dB and $a_{max} = 9$ dB; BS antenna height $h_{BS} = 10$ m; CTx's and PMS antenna height $h_m = 1.5$ m; maximum transmit antenna attenuation $A_{\max} = 20$ dB; transmit and receive antenna gains of $G_t = G_r = 0$ dBi except when the TS-DAPC algorithm is used for which the gains are calculated based on (6) considering $\phi_{3\mathrm{dB}} = 70°$[1].

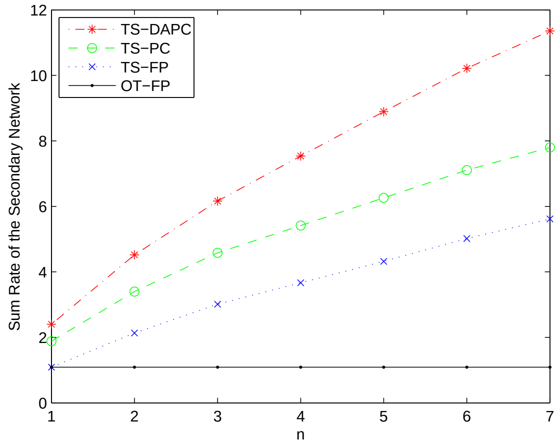

Fig. 3. Sum rate of the secondary network as a function of the number n of CR pairs, for $r_p = 25$ m, $m = 6$, $\sigma_i = 3$ bps and $\phi_{3\mathrm{dB}} = 70°$.

Fig. 3 shows the sum rate of the secondary network as a function of the number of CR pairs. The secondary sum rate increases with n, while TS-DAPC outperforms all other methods. While increasing n the sum rate is also increased when the three intelligent algorithms are used because then it will be more likely to find CR pairs in appropriate (or non-interfering) locations. Note that when $n \leq 3$ the inclusion of power control is relatively more impacting than the inclusion of antenna directivity in terms of sum-rate, as the gain of TS-PC over TS-FP is greater than the gain of TS-DAPC over TS-PC. However, for $n > 3$ the inclusion of antenna directivity is more impacting than the inclusion of power control. Moreover, note that the performance of the OT-FP algorithm does not depend on n, since this algorithm always considers a single CR pair.

Fig. 4 shows the average number of concurrently active secondary links as a function of n. Recall that during the execution of the power control algorithm a CTx can be allocated zero transmit power ($a_k = 0$). Two interesting conclusions

[1]We investigated the performance of TS-DAPC as a function of $\phi_{3\mathrm{dB}}$, and we noticed that it is basically the same for $30° \leq \phi_{3\mathrm{dB}} \leq 90°$. For the sake of brevity we decided to show results for $\phi_{3\mathrm{dB}} = 70°$ only.

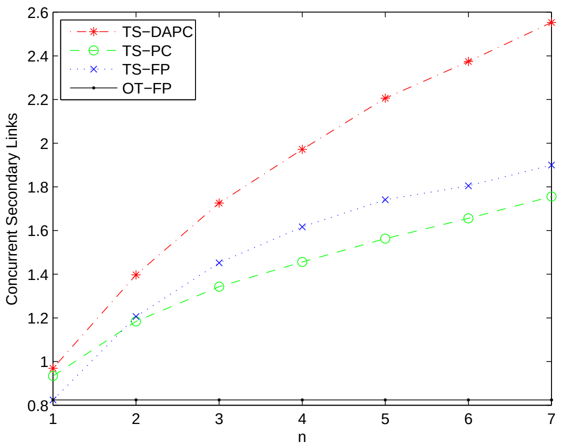

Fig. 4. Concurrent secondary links versus n, for $r_p = 25$ m, $m = 6$, $\sigma_i = 3$ bps and $\phi_{3\mathrm{dB}} = 70°$.

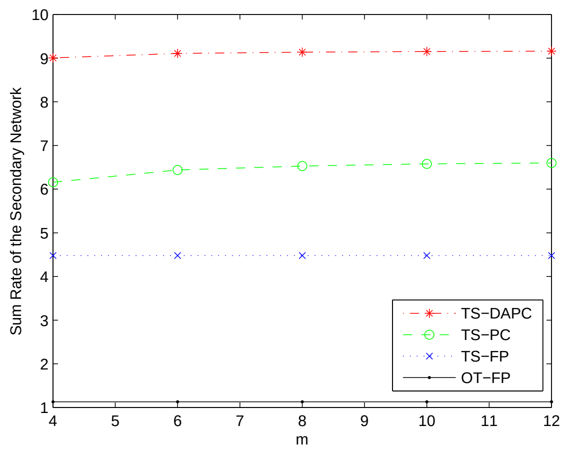

Fig. 5. Sum rate of the secondary network versus the number m of power control factors, for $r_p = 25$ m, $n = 5$, $\sigma_i = 3$ bps and $\phi_{3\mathrm{dB}} = 70°$.

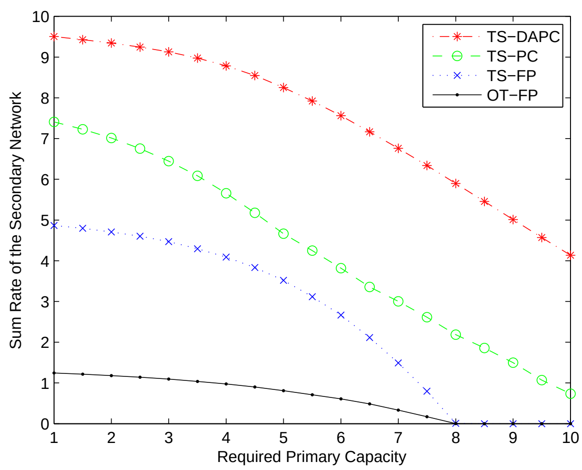

Fig. 6. Impact of the required primary capacity σ_i in the achievable sum rate of the secondary network, for $r_p = 25$ m, $n = 5$, $m = 6$ and $\phi_{3\mathrm{dB}} = 70°$.

can be obtained from this figure. The first one is that TS-DAPC allows more CR pairs to communicate than the other algorithms, showing an interesting effect of the exploitation of antenna directivity. The second conclusion is that TS-FP allows for more communicating CR pair than TS-PC. That is because in TS-PC we are able to allocate more power to a single CTx than in TS-FP (recall than $a_{max} = 9$ dB), so that it may be more advantageous in terms of interference and sum rate to allocate more power to a single pair than to allow two pairs to use less power.

In the analysis that follows we assume the presence of five cognitive pairs ($n = 5$) within the BS coverage area. The impact of the number m of power control factors used by TS-DAPC and TS-PC is shown in Fig. 5. As we can see there is an increase in the sum rate achieved by these two algorithms when m increases. However, the increase in performance is somewhat limited while by increasing m we require a larger computational cost, therefore next we assume a reasonable value of $m = 6$.

The performance of the proposed algorithms depends on the capacity requirements of the primary networks, as shown in Fig. 6. It is evident that if the primary network requirement increases, the total sum rate of the secondary network decreases. Again, the proposed algorithms with power control (TS-DAPC and TS-PC) considerably outperform TS-FP and OT-FP. Moreover, TS-DAPC is again the best performing scheme, its advantage over TS-PC is more notable when the required primary capacity is high.

Fig. 7 shows the sum rate of the secondary network depending on the distance between the PMS and the BS. Note that all algorithms display their best performance when the PMS is as close as possible to the BS, since in this case the power received at the primary link is high and thus the chance that the primary network meets its quality requirement, even under the interference of the secondary network is also higher. Moreover, the algorithms without power control are not effective when the PMS is more than 40 m apart from the BS, however those who use power control are effective even when the PMS is on the boundary of the coverage area. Finally, Fig. 8 shows that the use of directional antennas (TS-DAPC) allows a higher average number of concurrent secondary links until the boundary of the coverage area, which ensures a greater number of CR pairs communicating simultaneously.

6. Conclusion

The proposed algorithms, TS-PC and TS-DAPC, are able to increase the achievable sum-rate of a CRAHN with multiple CR pairs without affecting the performance of the primary network. The proposed schemes consider a practical power control approach, utilizing only a finite number of possible transmit power levels. Moreover, we showed the advantages of exploiting the CTx antenna directivity in terms of the performance of the CRAHN. The proposed TS-DAPC

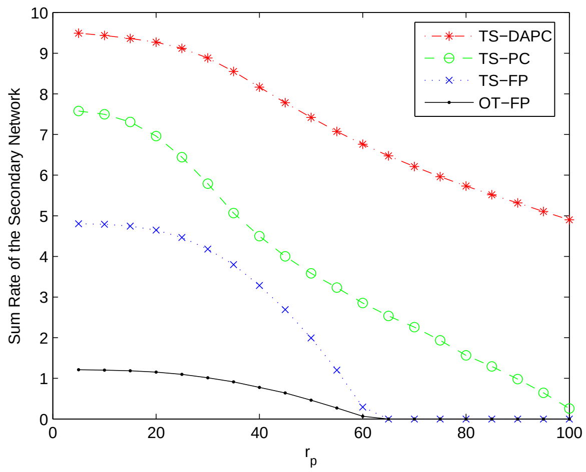

Fig. 7. Sum rate of the secondary network as a function of the distance between the PMS and the BS, for $n = 5$, $m = 6$, $\sigma_i = 3$ bps and $\phi_{3\text{dB}} = 70°$.

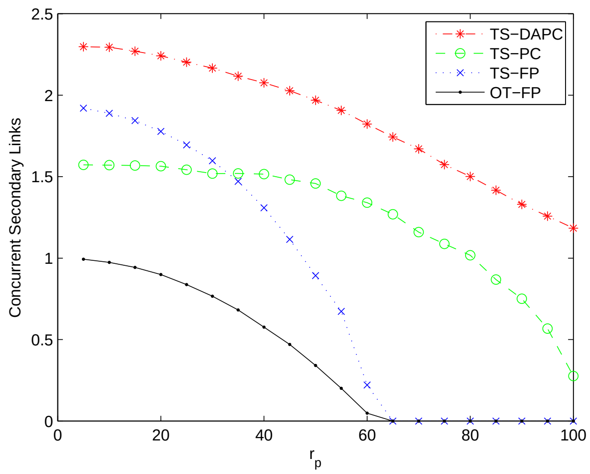

Fig. 8. Concurrent secondary links versus the distance between the PMS and the BS, for $n = 5$, $m = 6$, $\sigma_i = 3$ bps and $\phi_{3\text{dB}} = 70°$.

scheme not only outperforms TS-PC in terms of sum-rate, but also allows for more opportunities for different CR pairs to communicate. TS-DAPC is more robust than TS-PC, and its variants TS-FP and OT-FP, in terms of the primary network capacity constraint and on the position of the PMS with respect to the BS.

Acknowledgements

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