A Distributed Dynamic Target-SIR-Tracking Power Control Algorithm for Wireless Cellular Networks

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***Abstract*—The well-known fixed-target-signal-to-interference-ratio (SIR)-tracking power control (TPC) algorithm provides all users with their given feasible fixed target SIRs but cannot improve the system throughput, even if additional resources are available. The opportunistic power control (OPC) algorithm significantly improves the system throughput but cannot guarantee the minimum acceptable SIR for all users (unfairness). To optimize the system throughput subject to a given lower bound for the users' SIRs, we present a distributed dynamic target-SIR tracking power control algorithm (DTPC) for wireless cellular networks by using TPC and OPC in a selective manner. In the proposed DTPC, when the effective interference (the ratio of the received interference to the path gain) is less than a given threshold for a given user, that user opportunistically sets its target SIR (which is a decreasing function of the effective interference) to a value higher than its minimum acceptable target SIR; otherwise, it keeps its target SIR fixed at its minimum acceptable level. We show that the proposed algorithm converges to a unique fixed point starting from any initial transmit power level in both synchronous and asynchronous power-updating cases. We also show that our proposed algorithm not only guarantees the (feasible) minimum acceptable target SIRs for all users (in contrast to the OPC) but also significantly improves the system throughput, compared with the TPC. Furthermore, we demonstrate that DTPC, along with TPC and OPC, can be utilized to apply different priorities of transmission and service requirements among users. Finally, when users are selfish, we provide a game-theoretic analysis of our DTPC algorithm via a noncooperative power control game with a new pricing function.**

***Index Terms*—Distributed power control, dynamic target-signal-to-interference-ratio (SIR) allocation, wireless cellular networks.**

I. Introduction

POWER control plays an important role in satisfying the increasing demand for high data rates in wireless data networks. Enhancing the throughput of a user or of the system is highly dependent on how interference is managed. The objective of power control from a user's point of view is to support a user with its minimum acceptable throughput, whereas that from a system's point of view is to maximize the aggregate throughput. These two objectives are completely opposed to one another since, in the former, it is required to compensate for the near–far effect by allocating higher power levels to users with poor channels, compared with users with good channels, and in the latter, high power levels are allocated to a few users with the best channels, and very low (even zero) power levels are allocated to others.

Distributed power control is practically preferred to centralized power control, because, in the former, the transmit power level of a user is decided by the user utilizing local information and minimal feedback from the base station. In contrast, a centralized approach needs to have path gains and throughput requirements for all users at the base station. To satisfy the two stated objectives for power control, two distributed approaches have been considered: 1) the fixed-target-signal-to-interference (SIR) tracking proposed in [1] and 2) the opportunistic approaches proposed in [2]–[4].

In the fixed-target-SIR-tracking power control algorithm (TPC), each user is tracking its own predefined fixed target SIR. The TPC that was proposed in [1] enables users to achieve their fixed target SIRs at minimal aggregate transmit power if target SIRs are feasible. However, there is a major drawback in the original TPC [5]. It causes users to exactly hit their fixed target SIRs in feasible systems, even if additional resources are still available that can otherwise be used to achieve higher SIRs (and better throughput values). In addition, the fixed-target-SIR assignment is suitable only for voice service, for which reaching a SIR value higher than the given target value has no practical effect on service quality (due to the characteristics of the service and human ears). In contrast, for data services, a higher SIR results in a better throughput, which is desirable. Thus, it is important to design a power control algorithm for wireless data networks by which the minimum acceptable target SIRs (assumed to be feasible) are guaranteed for all users, and at the same time, the system throughput is increased to the extent that the required resources are available by increasing the actual SIRs attained by some users.

From the system's point of view, opportunistic power control (OPC) allocates high power to users with good channels (i.e., high path gains and low interference levels) and low power to users with poor channels. In this algorithm, a small difference in path gains between two users may lead to a large difference in their actual throughput values [2], [3]. Since an opportunistic algorithm always favors those users with better channels, it magnifies unfairness. For users with low mobility (when their channels slowly vary or are static), this might lead to long-term unfairness.

The characteristics of existing distributed power control schemes are summarized as follows: TPC can provide all users

Manuscript received January 30, 2009; revised June 9, 2009 and August 24, 2009. First published November 3, 2009; current version published February 19, 2010. This work was supported in part by Tarbiat Modares University (TMU), Tehran, Iran; by Wireless@KTH, Stockholm, Sweden; and by the Iran Telecommunications Research Center, Tehran, under Ph.D. Research Grant TMU 86-07-54. The review of this paper was coordinated by Prof. J. Li.

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Digital Object Identifier 10.1109/TVT.2009.2035627

with their fixed target SIRs when the system is feasible but cannot further improve the system throughput, even if additional resources are available. OPC significantly improves the system throughput but cannot guarantee the minimum acceptable SIRs for some users (unfairness).

Motivated by the aforementioned drawbacks, in this paper, we formally define the problem of system throughput maximization subject to a given feasible lower bound for the achieved SIRs of all users in wireless cellular networks and propose a distributed dynamic power control algorithm to address this problem. We will show that, when the minimum acceptable target SIRs are feasible, the actual SIRs attained by some users can dynamically be increased (to a value higher than their minimum acceptable target SIRs) in a distributed manner; so far, as the required resources are available, and the system remains feasible (meaning that reaching the minimum target SIRs for the remaining users are guaranteed). This would enhance the system throughput (at the cost of higher power consumption), compared with TPC. We will show that our proposed algorithm not only guarantees the (feasible) minimum acceptable target SIRs for all users as in the case of TPC (and in contrast to OPC) but also significantly improves the system throughput, compared with TPC. Furthermore, we discuss the application of the dynamic target-SIR tracking power control algorithm (DTPC) to cognitive radio networks (CRNs) and multiservice networks and provide a game-theoretic analysis of our proposed algorithm.

The rest of this paper is organized as follows: In Section II, we introduce the system model and throughput measure. In Section III, we review the existing distributed power control algorithms, present a formal statement of the problem, and state the objectives. Section IV contains the proposed method and an analysis of its convergence and its improved system throughput. Application of our proposed algorithm to cognitive radio or multiservice networks is discussed in Section V. Section VI provides a game-theoretic analysis of our proposed algorithm. Simulation results and conclusions are presented in Sections VII and VIII, respectively.

II. System Model and Signal-to-Interference Ratio Feasibility

We consider a multicell wireless code-division multiple-access network with K base stations (cells) and M active users denoted by $\mathcal{K} = \{1, 2, \ldots, K\}$ and $\mathcal{M} = \{1, 2, \ldots, M\}$, respectively. Let p_i be the transmit power of user i. Noise is assumed to be additive white Gaussian whose power at the receiver of the base station k is σ_k^2. Let s_i denote the base station to which the user i is assigned. Denote the set of users assigned to the base station k by $\mathcal{C}_k = \{i \in \mathcal{M} | s_i = k\}$.

The receiver is assumed to be a conventional matched filter. Thus, for a given transmit power vector $\mathbf{p} = [p_1, p_2, \ldots, p_M]^T$, the SIR of a user i, which is denoted by γ_i, is

$$\gamma_i(\mathbf{p}) = g_i \frac{h_{s_i i}}{I_i(\mathbf{p})} p_i \tag{1}$$

where g_i is the processing gain for user i (defined as the ratio of the chip rate (or the spreading bandwidth) to the transmit data rate), $h_{s_i i}$ is the path gain from user i to its assigned base station, and $I_i(\mathbf{p}) = \sum_{j \neq i} h_{s_i j} p_j + \sigma_{s_i}^2$ is the interference caused to user i at its assigned base station. The interference $I_i(\mathbf{p})$ can be rewritten as $I_i(\mathbf{p}) = I_i^{\text{int}} + I_i^{\text{ext}} + \sigma_{s_i}^2$, where $I_i^{\text{int}} = \sum_{j \in \mathcal{C}_{s_i}, j \neq i} p_j h_{s_i j}$ and $I_i^{\text{ext}} = \sum_{j \notin \mathcal{C}_{s_i}} p_j h_{s_i j}$ are the intracell interference and the intercell interference, respectively. The effective interference for user i is defined as the ratio of its experienced interference to its path gain [3], which was denoted by R_i, i.e.,

$$R_i(\mathbf{p}) = \frac{I_i(\mathbf{p})}{g_i h_{s_i i}}. \tag{2}$$

The value of R_i represents the channel status for user i, i.e., for a given processing gain, a higher interference and a lower path gain result in a higher R_i, implying a poor channel, compared with a lower interference and a higher path gain, which result in a lower R_i, implying a good channel.

Using matrix notations, the relation between the transmit power vector and the SIR vector can be rewritten as

$$\mathbf{p} = \mathbf{G} \cdot \mathbf{p} + \boldsymbol{\eta} \tag{3}$$

where the (i, j)th component of $\mathbf{G}$ is $G_{i,j} = (h_{s_i j} \gamma_i)/(g_i h_{s_i i})$ if $i \neq j$ and $G_{i,j} = 0$ if $i = j$, and the ith component of $\boldsymbol{\eta}$ is $\eta_i = (\sigma_{s_i}^2 \gamma_i)/(g_i h_{s_i i})$. A SIR vector $\boldsymbol{\gamma}$ is feasible if a power vector $\mathbf{p} \geq \mathbf{0}$ that satisfies (3) exists. It was shown in [6] that the necessary and sufficient condition for feasibility of a given SIR vector $\boldsymbol{\gamma}$ is $\rho(\mathbf{G}) < 1$, where $\rho(\mathbf{G})$ is the spectral radius (maximum eigenvalue) of the matrix $\mathbf{G}$.

From (3) and with some mathematical manipulations, a one-to-one relation between a transmit power vector and the achieved SIR vector is obtained [4], [7], [8], i.e.,

$$p_i = \frac{\gamma_i}{h_{s_i i}(\gamma_i + g_i)} \times \frac{\sigma_{s_i}^2 + I_i^{\text{ext}}}{1 - \sum\limits_{j \in \mathcal{C}_{s_i}} \frac{\gamma_j}{\gamma_j + g_j}} \quad \text{for all } i \in \mathcal{M}. \tag{4}$$

Thus, a SIR vector is feasible if

$$\sum_{j \in \mathcal{C}_k} \frac{\gamma_j}{\gamma_j + g_j} < 1 \quad \text{for all } k \in \mathcal{K}. \tag{5}$$

The interesting and useful point from the feasibility constraint (5) is that feasibility can individually be checked in each cell by checking the sum of $\gamma_j/(\gamma_j + g_j)$ for all users in that cell. Note that, for checking the feasibility, using (5) is simpler, compared with checking $\rho(\mathbf{G}) < 1$, which requires calculation of the spectral radius of the matrix $\mathbf{G}$.

The left side of the inequality (5) is the Pareto efficiency measure for the users' SIR allocations in the sense that, for a given base station k, as $\sum_{j \in \mathcal{C}_k} (\gamma_j/(\gamma_j + g_j))$ approaches 1, the SIR of no user assigned to that base station (i.e., C_k) can further be increased without decreasing the SIRs of some other users in C_k. In other words, a value of $\sum_{j \in \mathcal{C}_k} (\gamma_j/(\gamma_j + g_j))$ closer to 1 for each $k \in \mathcal{K}$ means a more-Pareto-efficient use of resources and a higher system throughput, and a value farther from 1 means that more resources are available to increase the users' SIRs.

Similar to [4], [7], [9], and [10], we use an information-theoretic approach to define the throughput for each user i by

$$T_i(\mathbf{p}) = W \log_2 (1 + \gamma_i(\mathbf{p})) \tag{6}$$

where W is the channel bandwidth. The system throughput (the sum of achievable rates by users) is

$$T(\mathbf{p}) = \sum_i T_i(\mathbf{p}). \tag{7}$$

III. Problem Formulation and Background

A. Existing Distributed Power Control Algorithms

In a distributed power control algorithm, each user i updates its transmit power by a power-updating function $f_i(\mathbf{p})$, i.e., $p_i(t+1) = f_i(\mathbf{p}(t))$, where $\mathbf{p}(t)$ is the transmit power vector at time t. The fixed point of the power-updating function, which is denoted by $\mathbf{p}^*$, is obtained by solving $\mathbf{p}^* = \mathbf{f}(\mathbf{p}^*)$. If a distributed power control algorithm converges to an equilibrium state, it will be a fixed point of the corresponding power-updating function.

The power-updating function of TPC is

$$f_i^{(T)}(\mathbf{p}(t)) = \widehat{\gamma}_i R_i(\mathbf{p}(t)) \tag{8}$$

where $\widehat{\gamma}_i$ is the given target SIR for user i. It was shown in [1] and [11] that, if the target-SIR vector $\widehat{\boldsymbol{\gamma}}$ is feasible, then TPC either synchronously or asynchronously converges to a fixed point at which users attain their target SIRs with minimum aggregate transmit power, i.e., its fixed point solves the following optimization problem:

$$\begin{aligned} &\min_{\mathbf{p}\geq \mathbf{0}} \sum_i p_i \\ &\text{subject to } \gamma_i(\mathbf{p}) \geq \widehat{\gamma}_i \qquad \forall i \in \mathcal{M}. \end{aligned} \tag{9}$$

In OPC, the transmit power levels are updated in a manner opposed that in TPC, i.e., it is increased when the channel is good and decreased when the channel is poor. The power-updating function of OPC is

$$f_i^{(O)}(\mathbf{p}(t)) = \frac{\eta_i}{R_i(\mathbf{p}(t))} \tag{10}$$

where η_i is a constant for user i. In this algorithm, each user i tries to keep the product of its transmit power and its effective interference to a constant η_i called the target signal-interference product (SIP). This algorithm is convergent, and although it does not guarantee optimal system throughput defined by

$$\max_{\mathbf{p}\geq \mathbf{0}} \sum_i T_i(\mathbf{p}) \tag{11}$$

it significantly enhances the system throughput by transmission at high power levels by users with good channels and transmission at low power levels by users with poor channels but leads to unfairness as well. In TPC and OPC, each user sets its own target SIR and its own target SIP, respectively, meaning that each user requires only to know its SIR measured at the base station (i.e., minimal feedback information). Note that each user i can obtain the value of $R_i(\mathbf{p}(t))$ in (8) and (10) by knowing its achieved SIR at its assigned base station by using $R_i(\mathbf{p}(t)) = p_i(t)/\gamma_i(\mathbf{p}(t))$.

B. Problem Statement and Objectives

We now introduce the problem of system throughput optimization subject to a given feasible lower bound for the users' SIRs as

$$\begin{aligned} &\max_{\mathbf{p}\geq \mathbf{0}} \sum_i T_i(\mathbf{p}) \\ &\text{subject to } \gamma_i(\mathbf{p}) \geq \widehat{\gamma}_i \qquad \forall i \in \mathcal{M}. \end{aligned} \tag{12}$$

The constraint on SIR, i.e., $\gamma_i(\mathbf{p}) \geq \widehat{\gamma}_i$, is equivalent to a constraint on throughput, i.e., $T_i(\mathbf{p}) \geq \widehat{T}_i$, where $\widehat{T}_i = W \log_2(1 + \widehat{\gamma}_i)$. It can be shown that the preceding optimization problems is nonconvex, and thus, it cannot be solved by using the conventional methods. Our focus in this paper is to design a distributed convergent power control algorithm that can significantly improve the system throughput while guaranteeing the minimum acceptable target SIRs for all users.

IV. Proposed Method: Dynamic Allocation of Target Signal-to-Interference Ratios

When the minimum acceptable target SIRs are feasible, the actual target SIRs tracked by some users with better channels should dynamically be set to a value higher than their minimum acceptable target SIRs to the extent that the required resources are available, and the system remains feasible (i.e., the constraint (5) is satisfied). This will enhance the system throughput (at the cost of consuming more power).

It is well known that, for enhancing the system throughput, users with good channels should transmit at higher power levels, compared with other users [2], [3]. On the other hand, reducing the outage necessitates that users with poor channels also transmit at just enough power to at least reach their minimum acceptable SIRs. Based on these observations, we propose that users with good channels set their power levels in an opportunistic manner and users with poor channels transmit in a minimum-acceptable-target-SIR-tracking manner. This can be done in a distributed manner if each user i updates its transmit power according to the following algorithm:

$$f_i^{(D)}(\mathbf{p}(t)) = \begin{cases} \frac{\eta_i}{R_i(\mathbf{p}(t))}, & \text{if } R_i(\mathbf{p}(t)) < R_i^{\text{th}} \\ \widehat{\gamma}_i R_i(\mathbf{p}(t)), & \text{if } R_i(\mathbf{p}(t)) \geq R_i^{\text{th}} \end{cases} \tag{13}$$

where R_i^{th} is the effective interference threshold, η_i is a constant, and $\widehat{\gamma}_i$ is the minimum acceptable target SIR for user i. Note that this algorithm is a generalized selective scheme of either OPC or TPC. At the extreme cases where $R_i^{\text{th}} \to 0$ or $R_i^{\text{th}} \to \infty$, the proposed power-updating function turns into either TPC or OPC, respectively.

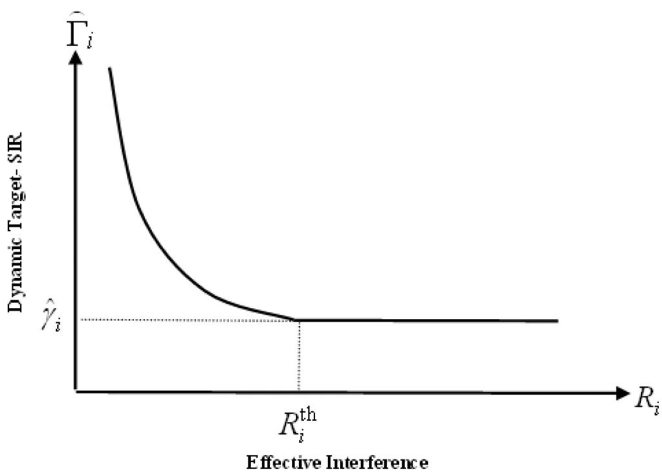

Fig. 1. Dynamic target SIR versus effective interference in DTPC.

Our proposed DTPC algorithm is explained here. We rewrite (13) as the DTPC power-updating function, i.e.,

$$f_i^{(D)}\left(\mathbf{p}(t)\right) = \widehat{\Gamma}_i\left(\mathbf{p}(t)\right) R_i\left(\mathbf{p}(t)\right) \tag{14}$$

in which $\widehat{\Gamma}_i(\mathbf{p}(t))$ is a target SIR dynamically set as

$$\widehat{\Gamma}_i\left(\mathbf{p}(t)\right) = \begin{cases} \frac{\eta_i}{R_i^2(\mathbf{p}(t))}, & \text{if } R_i\left(\mathbf{p}(t)\right) < R_i^{\rm th} \\ \widehat{\gamma}_i, & \text{if } R_i\left(\mathbf{p}(t)\right) \geq R_i^{\rm th}. \end{cases} \tag{15}$$

For DTPC to be continuous, its three parameters are adjusted as follows: For a given $\widehat{\gamma}_i$ and η_i, the value of $R_i^{\rm th}$ is set as

$$R_i^{\rm th} = \sqrt{\frac{\eta_i}{\widehat{\gamma}_i}}. \tag{16}$$

The minimum acceptable target SIR in (14) is set exactly to the same value as that of the fixed target SIR that was set in (8). We use *fixed target SIR* and *minimum acceptable target SIR* interchangeably throughout this paper. As shown in Fig. 1, by using DTPC, a given user sets its target SIR at the minimum acceptable value when the channel is not good. (The value of the effective interference is higher than the threshold.) When its channel is good, it opportunistically sets its target SIR at a value that is higher than the minimum acceptable value. When the set of minimum target SIRs is feasible in a non-Pareto-efficient manner (i.e., additional resources are available that can be used to further enhance the users' SIRs, meaning that the sum of $\gamma_j/(\gamma_j + g_j)$ is far from 1), some users with better channels reach higher SIRs, compared with the minimum acceptable value, and the remaining users exactly hit their minimum target SIRs. This means that the system throughput is increased while the users' minimum target SIRs are guaranteed, as we will show in the following. Such enhancement on the system throughput causes all users to consume more power, compared with the fixed (minimum acceptable)-target-SIR-tracking scheme.

A. Convergence of DTPC

A framework for examining the convergence of the so-called standard power-updating functions such as TPC was provided in [11]. This framework was generalized to a new framework in [2], which is applicable to a wider range of distributed power control algorithms (covering both TPC and OPC) with a two-sided scalable power-updating function. Our proposed DTPC falls into this generalized framework. Using the key properties of a two-sided scalable function, we will show that the DTPC's power-updating function has a unique fixed point to which it converges. To show this, we define the two-sided scalable function as in [2] and prove that the DTPC's power-updating function (14) is two-sided scalable.

Definition 1: A power-updating function $\mathbf{f}(\mathbf{p}) = [f_1(\mathbf{p}), f_2(\mathbf{p}), \ldots, f_M(\mathbf{p})]^T$ is two-sided scalable if, for all $a > 1$, $(1/a)\mathbf{p} \leq \mathbf{p}' \leq a\mathbf{p}$ implies

$$\frac{1}{a} f_i(\mathbf{p}) \leq f_i(\mathbf{p}') \leq a f_i(\mathbf{p}) \quad \text{for all } i \in \mathcal{M}. \tag{17}$$

Theorem 1: The DTPC's power-updating function $\mathbf{f}^{(D)}(\mathbf{p})$ in (14) is two-sided scalable.

Proof: It has been shown in [2] that, for the given two-sided scalable functions $\mathbf{f}(\mathbf{p})$ and $\mathbf{f}'(\mathbf{p})$, their componentwise maximum or minimum, i.e., $\max\{\mathbf{f}(\mathbf{p}), \mathbf{f}'(\mathbf{p})\}$ or $\min\{\mathbf{f}(\mathbf{p}), \mathbf{f}'(\mathbf{p})\}$, respectively, are two-sided scalable. Since the power-updating functions corresponding to the fixed-target-SIR tracking and the opportunistic power control algorithms are two-sided scalable [2] and since the proposed power-updating function can be rewritten as $f_i^{(D)}(\mathbf{p}(t)) = \max\{(\eta_i/R_i(\mathbf{p}(t))), \widehat{\gamma}_i R_i(\mathbf{p}(t))\}$, then this theorem is proven. ■

Theorem 2: If there exists a fixed point for the proposed power-updating function, i.e., if there exists a $\mathbf{p}^{*(\rm D)}$ so that $\mathbf{p}^{*(\rm D)} = \mathbf{f}(\mathbf{p}^{*(\rm D)})$, then the following two parts hold.

1) This fixed point is unique.
2) For any initial power vector, the power control algorithm $\mathbf{p}(t+1) = \mathbf{f}(\mathbf{p}(t))$ converges to this unique fixed point.

Proof: This theorem is directly concluded from Theorem 1 as a key property of a two-sided scalable function [2]. ■

Theorem 3: There exists a fixed point for the DTPC's power-updating function $\mathbf{f}^{(D)}(\mathbf{p})$ if the minimum acceptable target-SIR vector $\widehat{\boldsymbol{\gamma}}$ is feasible.

Proof: It has been proven in [2] that, if $\mathbf{f}(\mathbf{p})$ is two-sided scalable, continuous, and $\mathbf{f}(\mathbf{p}) \leq \mathbf{u}$ for all $\mathbf{p}$ (i.e., $\mathbf{f}(\mathbf{p})$ is upper bounded) for $\mathbf{u} > \mathbf{0}$, then a fixed point for $\mathbf{f}$ exists. Since the proposed power-updating function is two-sided scalable and continuous, by employing (16), the existence of a fixed point for the proposed power-updating function is guaranteed if it is upper bounded. Now, we show that, when $\widehat{\boldsymbol{\gamma}}$ is feasible, the DTPC's power-updating function is upper bounded. When $\widehat{\boldsymbol{\gamma}}$ is feasible, a fixed point denoted by $\mathbf{p}^{*(T)}$ exists for the power-updating function of TPC in (8). If $R_i(\mathbf{p}^{*(T)}) \geq R_i^{\rm th}$ for all $i \in \mathcal{M}$, then $\mathbf{p}^{*(T)}$ is also the fixed point of the proposed power-updating function for DTPC denoted by $\mathbf{p}^{*(D)}$, i.e., $\mathbf{p}^{*(D)} = \mathbf{p}^{*(T)}$. This means that, at the fixed point of DTPC, all users are in the TPC mode. Otherwise, at the fixed point of DTPC, there exist some users (at least one user) operating in the OPC mode, i.e., for which $R_i(\mathbf{p}^{*(D)}) < R_i^{\rm th}$, and the remaining users are operating in the TPC mode. For TPC, the existence of a fixed point depends only on path gains and target SIRs and does not depend on the level of background noise [12]. On the other hand, the transmit power of users operating in the OPC mode appears as the background noise to users operating in the TPC mode. The transmit power levels set by users in the OPC mode are upper bounded, because the OPC's power-updating function is always upper bounded, and those in the TPC mode are also upper bounded, because the set of their fixed target SIRs is feasible. ■

B. Improvement in System Throughput by Using DTPC

In the following theorem, we will show that, by using DTPC for a given feasible set of minimum target SIRs, the system throughput is improved, compared with using TPC, while guaranteeing that all users are supported at least with their minimum target SIRs.

Theorem 4: Given a feasible target-SIR vector $\widehat{\boldsymbol{\gamma}}$, let $\mathbf{p}^{*(\mathrm{T})}$ and $\mathbf{p}^{*(\mathrm{D})}$ be the fixed points of TPC and DTPC, respectively. We have $\gamma_i(\mathbf{p}^{*(\mathrm{D})}) \geq \widehat{\gamma}_i$ for all $i \in \mathcal{M}$, and thus, $T(\mathbf{p}^{*(\mathrm{D})}) \geq T(\mathbf{p}^{*(\mathrm{T})})$. More specifically, the following two parts hold.

1) If and only if $R_i(\mathbf{p}^{*(\mathrm{T})}) \geq R_i^{\mathrm{th}}$ for all i, then $\gamma_i(\mathbf{p}^{*(\mathrm{D})}) = \widehat{\gamma}_i$ for all $i \in \mathcal{M}$, and thus, $T(\mathbf{p}^{*(\mathrm{D})}) = T(\mathbf{p}^{*(\mathrm{T})})$.
2) If and only if there exists at least one user with $R_i(\mathbf{p}^{*(\mathrm{T})}) < R_i^{\mathrm{th}}$, then for a nonempty set of users, we have $\gamma_i(\mathbf{p}^{*(\mathrm{D})}) > \widehat{\gamma}_i$, and for the remaining users, we have $\gamma_i(\mathbf{p}^{*(\mathrm{D})}) = \widehat{\gamma}_i$; thus, $T(\mathbf{p}^{*(\mathrm{D})}) > T(\mathbf{p}^{*(\mathrm{T})})$.

Proof: If $R_i(\mathbf{p}^{*(\mathrm{T})}) \geq R_i^{\mathrm{th}}$ for all i, then, from (8) and (14), it is easy to see that the fixed point of TPC is the same as the fixed point of DTPC, i.e., $\mathbf{p}^{*(\mathrm{D})} = \mathbf{p}^{*(\mathrm{T})}$. Thus, in this case, we have $\gamma_i(\mathbf{p}^{*(\mathrm{D})}) = \gamma_i(\mathbf{p}^{*(\mathrm{T})})$ for all $i \in \mathcal{M}$, which proves Part 1. For Part 2, the (nonempty) set of users with $R_i(\mathbf{p}^{*(\mathrm{T})}) < R_i^{\mathrm{th}}$ is denoted by $\mathcal{N} \neq \emptyset$. In this case, there exists a nonempty subset of users in $\mathcal{N}$, which is denoted by $\mathcal{L}$, for which we have $\widehat{\Gamma}_i(\mathbf{p}^{*(\mathrm{D})}) > \widehat{\gamma}_i$, i.e., $R_i(\mathbf{p}^{*(\mathrm{D})}) < R_i^{\mathrm{th}}$ for all $i \in \mathcal{L}$. If this is not true, then we have $R_i(\mathbf{p}^{*(\mathrm{D})}) \geq R_i^{\mathrm{th}}$ for all $i \in \mathcal{M}$, meaning that $\mathbf{p}^{*(\mathrm{D})} = \mathbf{p}^{*(\mathrm{T})}$, and consequently, $R_i(\mathbf{p}^{*(\mathrm{T})}) \geq R_i^{\mathrm{th}}$ for all $i \in \mathcal{M}$, which contradicts the existence of at least one user with $R_i(\mathbf{p}^{*(\mathrm{T})}) < R_i^{\mathrm{th}}$. Thus, from this and from (8) and (14), we conclude that $\gamma_i(\mathbf{p}^{*(\mathrm{D})}) > \gamma_i(\mathbf{p}^{*(\mathrm{T})})$ for each user $i \in \mathcal{L}$ and that $\gamma_i(\mathbf{p}^{*(\mathrm{D})}) = \gamma_i(\mathbf{p}^{*(\mathrm{T})})$ for each user $i \in \mathcal{M} \setminus \mathcal{L}$, which proves Part 2. ■

V. Application of DTPC to Cognitive Radio Networks or Multiservice Networks

It is important to employ proper distributed power-control schemes for different service requirements (e.g., real-time versus nonreal-time services) or for different network paradigms (e.g., a network with only primary users versus that with both primary and secondary users). In this section, we demonstrate that DTPC, along with TPC and OPC, can properly be employed to apply different priorities of transmission and service requirements.

A. Application of DTPC to CRNs

Cognitive radio is a promising technique for improving the efficiency of using the scarce frequency spectrum. This technique allows unlicensed (secondary) users to opportunistically access the frequency spectrum concurrently with licensed (primary) users, provided that the interference caused by secondary users would not deny any primary user its throughput requirements. In other words, primary users have a higher priority of transmission, compared with secondary users.

In previous sections, we assumed equal priority of transmission for all users. Now, we consider a CRN in which primary and secondary users coexist. Let us denote the sets of primary and secondary users by $\mathcal{P}$ and $\mathcal{S}$, respectively. We adjust the effective interference threshold in DTPC for primary and secondary users so that primary users are protected against all secondary users, and at the same time, secondary users can opportunistically use the available resources. In the following theorem, we show that, when the minimum-target-SIR requirements for primary users are feasible, if DTPC is utilized by primary users and OPC is utilized by secondary users, then secondary users do not prevent primary users from attaining their target SIRs.

Theorem 5: Suppose that each primary user applies DTPC with its given effective interference threshold and that each secondary user employs OPC. If minimum target SIRs for primary users are feasible, then for any number of secondary users, the following two parts hold.

1) A unique fixed point exists, to which the set of transmit power levels for all users converge.
2) All primary users are supported at least with their minimum target SIRs, i.e., $\gamma_i(\mathbf{p}^{*(\mathrm{D})}) \geq \widehat{\gamma}_i$, and for secondary users, we have $\gamma_i(\mathbf{p}^{*(\mathrm{D})}) = \widehat{\Gamma}_i(\mathbf{p}^{*(\mathrm{D})})$.

Proof: Since the power-updating function corresponding to either DTPC or OPC is two-sided scalable, as shown in Theorem 3 and in [2], respectively, we conclude that, if there exists a fixed point to which the set of transmit power levels for all primary and secondary users converge, then it is unique. Thus, to prove Part 1, we only need to show the existence of a fixed point. This can be proven similar to Theorem 2 by noting that the transmit power levels of secondary users operating in the OPC mode appear as the background noise to primary users, and for DTPC, the existence of the fixed point does not depend on the background noise. Part 2 can easily be proven as follows: Since primary users employ DTPC, thus, at the fixed point (whose existence and uniqueness is guaranteed as shown in Part 1), each primary user obtains a SIR higher than its minimum acceptable target SIR, i.e., $\gamma_i(\mathbf{p}^{*(\mathrm{D})}) \geq \widehat{\gamma}_i$. In addition, since each secondary user employs OPC, a given secondary user i obtains a SIR that is equal to $\eta_i/R_i^2(\mathbf{p}^{*(\mathrm{D})})$, which may be higher or lower than its minimum SIR. ■

In the preceding scheme, so long as the set of minimum acceptable target SIRs for primary users is feasible, each primary user is satisfied, and a given secondary user, depending on its path gain and actual interference at its base station (which, in turn, depends on the number of active primary users and their transmit power), obtains an acceptable or a nonacceptable SIR. We will see in simulation results that, as the number of primary users is decreased (increased), the transmit power levels and the achieved SIRs for secondary users are increased (decreased).

B. Application of DTPC to Multiservice Networks

Service requirements for voice and data applications are different with respect to their tolerance against delay and bit error rates. We consider the following three classes of service:

1) Class 1 (voice service): tolerant to bit error rates and sensitive to delays;
2) Class 2 (real-time data services): sensitive to both bit error rates and delays;
3) Class 3 (nonreal-time data services): sensitive to bit error rates and tolerant to delays.

For a data service that is sensitive to bit error rates, its target SIR is higher than that of a voice service. For users of voice service, TPC is suitable. In contrast, for data services, a higher SIR results in a better throughput. We consider two types of data services: real time (e.g., online video) or nonreal time (e.g., email). A real-time data service and voice service have transmission priority, compared with a nonreal-time data service, implying that, if the system is not feasible, the users in Class 3 should be softly removed (i.e., decrease their target SIRs) in favor of users in Classes 1 and 2. Thus, to satisfy transmission priority and SIR requirements, users in Classes 1–3 should apply TPC, DTPC, and OPC, respectively.

VI. Game-Theoretic Analysis of DTPC

In this section, we deal with selfish users who do not cooperatively follow a predefined strategy (in contrast to what we have assumed so far) unless their own utilities are maximized. In the following, assuming selfish and noncooperative users, we investigate how and with what pricing scheme, at the Nash equilibrium (NE) of the power control game, the system throughput is improved similar to DTPC.

Game theory is a powerful mathematical tool to model and analyze such selfish and interactive decision making. In a game-theoretic view of the power control problem [4], [13], [14], users are players. Each user $i \in \mathcal{M}$ chooses its strategy by setting its own transmit power level from its strategy space $P_i = [0, \infty)$, resulting in a utility value that represents the throughput of that user, as well as its associated costs, which is denoted by $U_i(p_i, \mathbf{p}_{-i})$, where $\mathbf{p}_{-i}$ denotes the transmit power vector for all users, except user i. The commonly used concept in solving game-theoretic problems is the NE at which no user can improve its utility by unilaterally changing its transmit power.

It is well established that, in contrast to the case in which no pricing is applied, the pricing scheme could affect the individual user's decision in such a way that the efficiency of NE from a given goal's point of view (e.g., from fairness or the system's point of view) is improved. In [4], for a concave throughput function that is increasing with respect to SIR, we have shown that the SIR-based pricing can be utilized to satisfy some specific goals (such as fairness, aggregate throughput optimization, or trading off between these two goals) at NE. In [2] and [3], it was shown that the best response function for the utility function $U_i(p_i, \mathbf{p}_{-i}) = \sqrt{\gamma_i} - \alpha_i p_i$ corresponds to the opportunistic power-control scheme. Note that the throughput function defined in [2] and [3] has no physical meaning.

A pricing-based utility function for a given user i in many noncooperative power control games (NPCGs) is

$$U_i(p_i, \mathbf{p}_{-i}) = T_i(p_i, \mathbf{p}_{-i}) - c_i(p_i, \mathbf{p}_{-i}) \tag{18}$$

where T_i is the function representing user i's throughput, and c_i is its pricing function. We use the logarithmic function of SIR as the throughput defined in (6), but our results can be applied to any other throughput function that is an increasing and concave function of SIR. In the following, we set up an NPCG with a pricing scheme that is linearly proportional to SIR and analytically show that, with a proper choice of pricing (proportionality constant), its outcome is the same as that of our proposed DTPC, implying that, at NE, the system throughput is improved similar to DTPC.

We propose a SIR-based pricing scheme in which the utility function for user i is

$$U_i(p_i, \mathbf{p}_{-i}) = T_i(p_i, \mathbf{p}_{-i}) - \alpha_i \gamma_i(p_i, \mathbf{p}_{-i}) \tag{19}$$

where $\alpha_i \geq 0$ is the price per unit of the actual SIR at the base station for user i. We will show that this pricing scheme enables us to adequately influence the best response function of each user for improving the throughput (similar to DTPC) by a proper choice of pricing introduced in the following theorem:

Theorem 6: In NPCG, $G = \langle \mathcal{M}, (P_i), (U_i) \rangle$, in which U_i is defined by (19), the best response of user $i \in \mathcal{M}$ to a given power vector $\mathbf{p}_{-i}$ is the same as our proposed power-updating function of DTPC in (14) with the given values of $\widehat{\gamma}_i$ and R_i^{th} if pricing for each user i is set to

$$\alpha_i = \begin{cases} \frac{kR_i^2}{R_i^2 + \widehat{\gamma}_i \cdot (R_i^{\mathrm{th}})^2}, & \text{if } R_i \leq R_i^{\mathrm{th}} \\ \frac{k}{1+\widehat{\gamma}_i}, & \text{if } R_i > R_i^{\mathrm{th}} \end{cases} \tag{20}$$

where $k = W/\ln 2$. Thus, a unique NE for this game exists and is the fixed point of DTPC, i.e., the fixed point of DTPC denoted by $\mathbf{p}^*$ is the solution to

$$\max_{p_i \in P_i} T_i\left(p_i, \mathbf{p}_{-i}^*\right) - \alpha_i \gamma_i\left(p_i, \mathbf{p}_{-i}^*\right) \quad \text{for all } i \in \mathcal{M}. \tag{21}$$

Proof: To obtain the best response function denoted by $b_i(\mathbf{p}_{-i})$, we use the first and second derivatives of the pricing-based utility with respect to p_i, i.e.,

$$\frac{\partial U_i}{\partial p_i} = \frac{1}{R_i}\left(\frac{k}{1+\gamma_i} - \alpha_i\right) \tag{22}$$

$$\frac{\partial^2 U_i}{\partial p_i^2} = -\frac{1}{{R_i}^2}\frac{k}{(1+\gamma_i)^2}. \tag{23}$$

For a given R_i, we note from (22) that $\partial U_i/\partial p_i = 0$ has a unique root, i.e., $p_i = ((R_i^{\mathrm{th}})^2/R_i)\widehat{\gamma}_i$ if $R_i \leq R_i^{\mathrm{th}}$ and $p_i = \widehat{\gamma}_i R_i$ if $R_i > R_i^{\mathrm{th}}$. From (23), we note that $\partial^2 U_i/\partial p_i^2 < 0$, which means that the unique root of $\partial U_i/\partial p_i = 0$ globally maximizes U_i. Thus, the best transmit power in response to $\mathbf{p}_{-i}$ that maximizes U_i is also unique and is given by

$$b_i(\mathbf{p}) = \begin{cases} \frac{(R_i^{\mathrm{th}})^2}{R_i}\widehat{\gamma}_i, & \text{for } R_i \leq R_i^{\mathrm{th}} \\ \widehat{\gamma}_i R_i, & \text{for } R_i > R_i^{\mathrm{th}} \end{cases} \tag{24}$$

which is the same as in DTPC, and its fixed point is the NE for $G = \langle \mathcal{M}, (P_i), (U_i) \rangle$. As there exists a unique fixed point in DTPC, the NE exists and is unique. Thus, the fixed-point of DTPC is the unique solution to (21). ■

Note that the proposed pricing in (20) implies that, when the effective interference for a given user is below the threshold, its pricing is increased as its effective interference is increased to discourage selfish users from transmitting at high power levels until a threshold for the effective interference is reached upon which its pricing is fixed.

Another important property of the proposed pricing scheme is that it depends on the information pertinent to that user only. This enables each user to compute its pricing in (20) in a distributed and iterative manner by

$$\alpha_i(t+1) = \begin{cases} \frac{k p_i^2(t)}{p_i^2(t) + \gamma_i(t) \cdot \widehat{\gamma_i} \cdot \left(R_i^{\mathrm{th}}\right)^2}, & \text{if } \frac{p_i(t)}{\gamma_i(t)} \leq R_i^{\mathrm{th}} \\ \frac{k}{1+\widehat{\gamma_i}}, & \text{if } \frac{p_i(t)}{\gamma_i(t)} > R_i^{\mathrm{th}} \end{cases} \tag{25}$$

which is obtained from (20) by using $R_i(\mathbf{p}(t)) = p_i(t)/\gamma_i(\mathbf{p}(t))$. This is in contrast to the pricing schemes developed in [13] and [14] that require the base station to announce the pricing to each user.

VII. Simulation Results

Now, we provide simulation results to get an insight into how our proposed DTPC improves the system throughput while guaranteeing a minimum value for the individual user's throughput. We assume a processing gain of 100. The additive white Gaussian noise power at the receiver, i.e., σ^2, is assumed to be -113 dBm. As in [14], we adopt a simple model $h_i = k d_{s_i i}^{-4}$ for the path gain, where $d_{s_i i}$ is the distance between user i and its base station s_i, k is the attenuation factor that represents power variations, and $k = 0.09$. In our simulations, for DTPC, we take the target SIP $\eta_i = 1$ (as in [2] and [15]) for all users. The values of $\widehat{\gamma_i}$ are the same in TPC and DTPC.

We first consider a single cell to investigate how our proposed algorithm works, compared with TPC and OPC. Then, we consider multicell networks, i.e., first a two-cell network to investigate how DTPC deals with the users' movements and finally four-cell networks, each with a different number of users for two separately simulated cases (with and without a cognitive network). In this way, we see the performance of DTPC in multicell networks for different numbers of users for a primary network only and for a cognitive (secondary) radio network.

A. Single-Cell Network

Consider four users indexed from 1 to 4 with the same minimum target SIR of 13 dB in a single-cell environment where their distance vector is $\mathbf{d} = [300, 530, 740, 860]^T$ m, in which each element is the distance of the corresponding user from the base station. Figs. 2–4 show the transmit power and the received SIR in each iteration (power-updating step) for users when TPC, OPC, and DTPC are applied, respectively. In TPC (see Fig. 2), all users reach their minimum target SIRs. In OPC (see Fig. 3), the user with the best channel (user 1) transmits at high power and obtains a high SIR, but other users obtain very low SIRs, which are much lower than their minimum target SIR. As we see in Fig. 4, in our proposed DTPC, in contrast to OPC, the minimum target SIR for each user is guaranteed, and the system throughput is notably improved compared with TPC. Specifically, by using DTPC, user 1, which has the best channel, utilizes the additional available resource (power) and obtains a SIR of 20 dB, which is 7 dB higher than its minimum

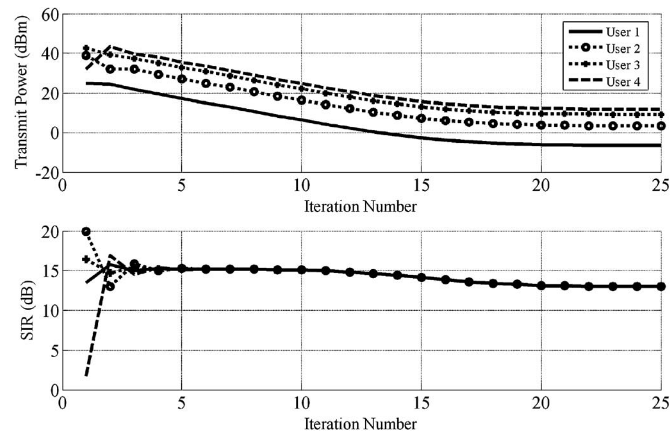

Fig. 2. Transmit power and SIRs for each user in TPC.

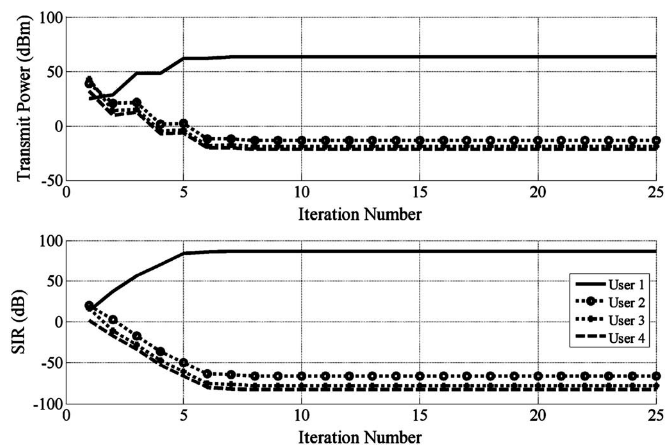

Fig. 3. Transmit power and SIRs for each user in OPC.

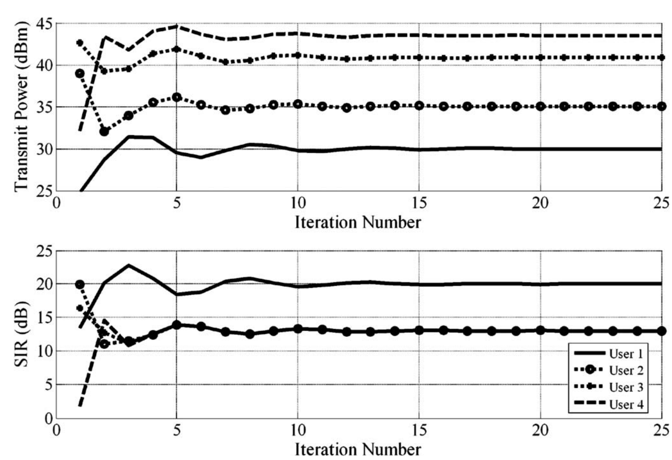

Fig. 4. Transmit power and SIRs for each user in DTPC.

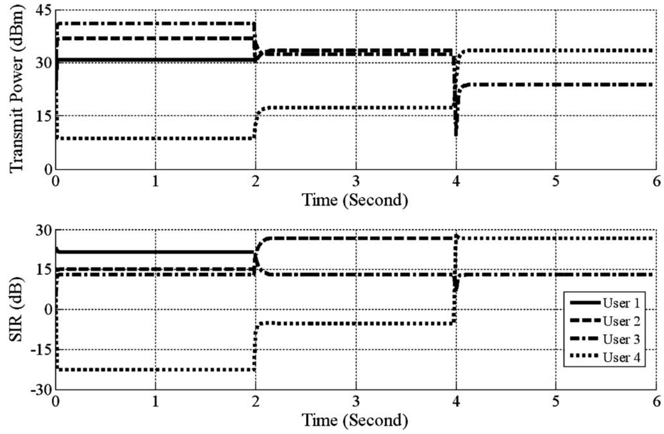

Fig. 5. Transmit power and SIRs for each user with a different service in DTPC.

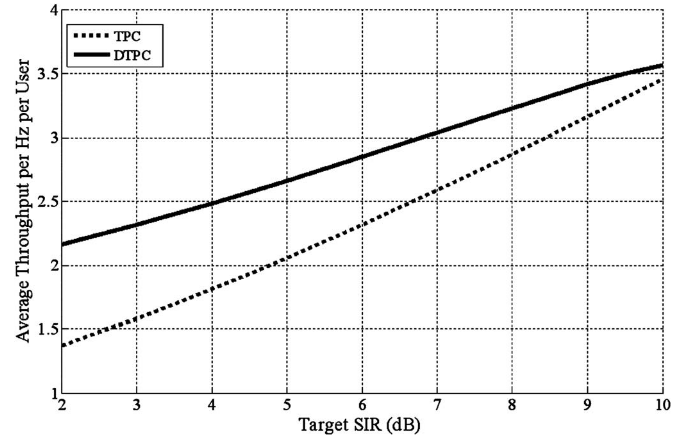

Fig. 6. Average system throughput per hertz per user $\left(\sum_i(\log_2(1+\gamma_i))/W/M\right.$, where W and M are the allocated bandwidth and the total number of transmitting users, respectively$\left.\right)$ achieved by TPC and DTPC versus target SIR.

target SIR by dynamically increasing its target SIR, and at the same time, other users hit their minimum target SIRs of 13 dB.

Now, consider that the aforementioned four users are running different services with different target SIRs. Suppose that user 3 utilizes a voice service for 6 s with $\widehat{\gamma}_1 = 13$ dB, users 1 and 2 utilize a real-time data service with $\widehat{\gamma}_2 = \widehat{\gamma}_4 = 15$ dB for 2 and 4 s, respectively, and user 4 utilizes a nonreal-time data service with $\widehat{\gamma}_3 = 18$ dB for 6 s. All users are active from the start time $(t = 0)$, and each user stops its transmission immediately after its respective activity time elapses, i.e., users 1–4 are active in the time intervals of [0,6], [0,2], [0,4], and [0,6], respectively. Note that, when all users are active, the system is infeasible (because $\sum_{i=1}^{i=4}(\widehat{\gamma}_i/(\widehat{\gamma}_i+g_i))=1.03>1$), meaning that the minimum acceptable target SIRs of users are not reachable at the same time. As stated in Section V-B, in accordance with the users' service requirements, users 1–4 set their transmit power levels according to DTPC, DTPC, TPC, and OPC, respectively. Each user updates its transmit power every 1 ms (1 kHz). Fig. 5 shows the transmit power and received SIR versus time for users 1–4. Note that, for the time interval [0,2] s during which all users are active, the voice-service user obtains its target SIR; the two real-time data service users, i.e., users 1 and 2, obtain SIRs equal to and higher than their minimum target SIRs, respectively; and the nonreal-time data service user obtains the low SIR of -22.76 dB. During this interval, the three real-time (voice and data) service users are prioritized with respect to the nonreal-time data service user. When user 1 leaves the system (at $t = 2$), the interference is decreased, and the remaining real-time data user (i.e., user 2) and the nonreal-time data service user (i.e., user 4) immediately increase their transmit power and obtain higher SIRs while the voice-service user continues to receive its target SIR. Similarly, when user 2 leaves the system $(t = 4)$, user 4 obtains an acceptable SIR. Such prioritization is applied in a distributed and automatic manner, as each user employs an appropriate distributed power control algorithm in accordance with its service and priority requirements.

To show that similar improvements in system throughput are obtained for different snapshots of the users' locations and different values of target SIRs, we consider a single-cell network with a radius of 250 m and with ten fixed users. The minimum target SIRs are considered to be the same for all users, ranging from 2 to 10 dB with a step size of 0.5 dB. For each target SIR, we average the corresponding values of the system throughput at equilibrium, where the algorithm converges for both TPC and DTPC, for 1500 independent snapshots from a uniform distribution of the users' locations within a single cell.

Fig. 6 shows the average system throughput per hertz per user, i.e., the $\sum_i(\log_2(1+\gamma_i))/W/M$ obtained by TPC and DTPC versus target SIRs. The average system throughput obtained by OPC is 50. Although this is very high, compared with TPC and DTPC, it does not guarantee an average SIR for all users, and only users with better channels obtain acceptable SIRs.

In Fig. 6, we observe that DTPC results in an improved system throughput, compared with TPC, as was proven in Theorem 4. At the same time, all users are supported by utilizing DTPC at least with their minimum target SIRs, which is not the case when OPC is employed. As expected, increasing the minimum acceptable target SIRs for users results in decreasing the difference between system throughput values of DTPC and TPC. The reason is that, when the minimum acceptable target SIR $\widehat{\gamma}_i$ for each user i is increased, then $\sum_i(\widehat{\gamma}_i/(\widehat{\gamma}_i+g_i))$ is increased, and the feasible system approaches an infeasible system, meaning that target SIRs cannot further be increased, because otherwise, we may have $\sum_i(\widehat{\gamma}_i/(\widehat{\gamma}_i+g_i))>1$, i.e., the system becomes infeasible. In other words, for high values of minimum target SIRs (e.g., values close to 10 dB in our simulation), after providing all users with their minimum target SIRs, the remaining resources are not sufficient to further improve the system throughput. For instance, for a target SIR of 10 dB, we have $\sum_i(\widehat{\gamma}_i/(\widehat{\gamma}_i+g_i)) = 0.91$, which means that very little is available to further improve the system throughput, compared with the target SIR of 6 dB, which corresponds to $\sum_i(\widehat{\gamma}_i/(\widehat{\gamma}_i+g_i)) = 0.38$.

B. Multicell Networks

1) Two-Cell Networks: To show how DTPC works when users move, we assume a two-cell network with nine users, as

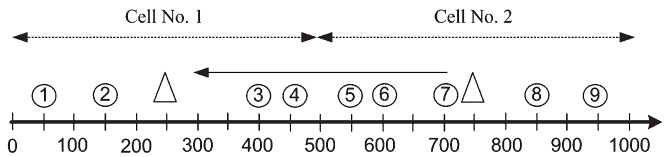

Fig. 7. Distribution of users and base stations in a two-cell network. Users are marked by "○," and base stations are marked by "△." Users 1–6, 8, and 9 are fixed, and user 7 at $t = 0$ starts moving from the starting point $x = 700$ m in cell 2 toward the end point $x = 300$ in cell 1 along the illustrated line at a uniform speed of 20 m/s (72 km/h).

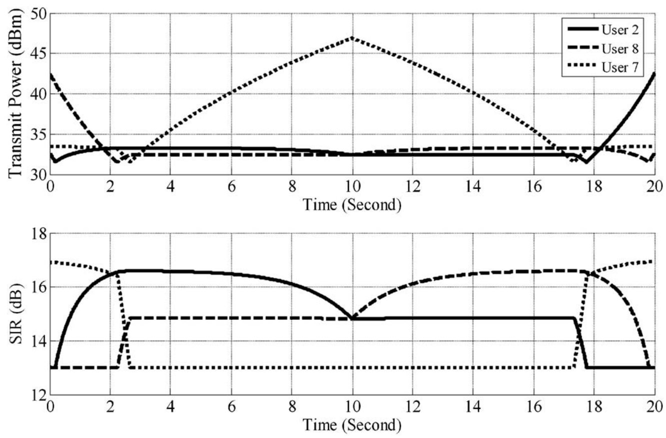

Fig. 8. Transmit power and SIRs versus time for users 2, 7, and 8 using DTPC in the two-cell network in Fig. 7.

shown in Fig. 7. The minimum target SIR for all users is 13 dB. Suppose that users 1–6, 8, and 9 are fixed, and user 7 at $t = 0$ starts moving from its starting point in cell 2 toward cell 1 along the line in Fig. 7 at a uniform speed of 20 m/s (72 km/h). The movement of user 7 from the starting point to the end point lasts 20 s. Each user updates its transmit power every 1 ms (1 kHz) employing DTPC. When user 7 enters cell 1, i.e., at $t = 10$, base station 1 is assigned to that user. Excluding the moving user 7, we note that user 2 in cell 1 and user 8 in cell 2 are the closest users to the base station in their corresponding cells. Fig. 8 shows transmit power levels and received SIRs versus time for users 2, 7, and 8.

As we observe in Fig. 8, for the interval in which user 7 is the closest user to the base station in cell 2 (i.e., [0, 2]), it obtains the highest SIR (greater than its minimum acceptable target SIR), and other users in that cell, including user 8, receive their minimum acceptable target SIRs. At the same time, in cell 1, user 2 obtains the highest SIR, and other users in that cell obtain their minimum acceptable target SIRs. As user 7 moves farther from base station 2 and user 8 becomes the closest user to that base station, user 8 increases its transmit power and obtains a SIR higher than its minimum acceptable target SIR, and user 7 decreases its transmit power and hits its minimum acceptable target SIR. When user 7 enters cell 1 (i.e., at $t = 10$ s), as the number of users in that cell is increased (in contrast to cell 2 in which the number of users is decreased), the system throughput values for cells 1 and 2 are decreased (as per the reduced SIR for user 2) and increased (as per the increased SIR for user 8), respectively. Finally, when user 7 becomes the closest user to base station 1, it obtains the highest SIR in cell 1, whereupon user 2 receives its minimum acceptable target SIR. These show

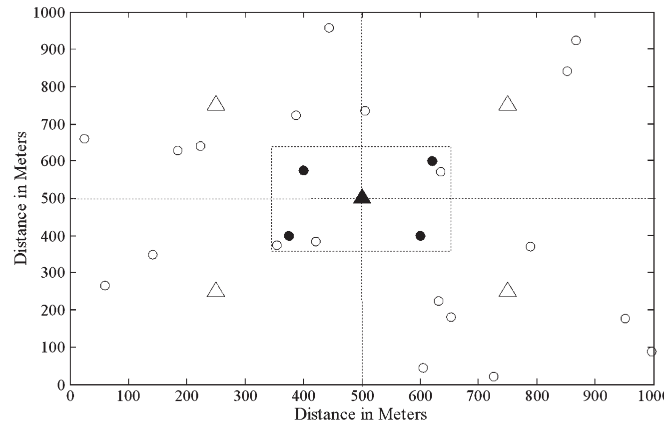

Fig. 9. Example of the users' and base stations' locations in a four-cell primary network with a CRN. Primary and secondary users are marked by "○" and "●," respectively, and primary and secondary base stations are marked by "△" and "▲," respectively.

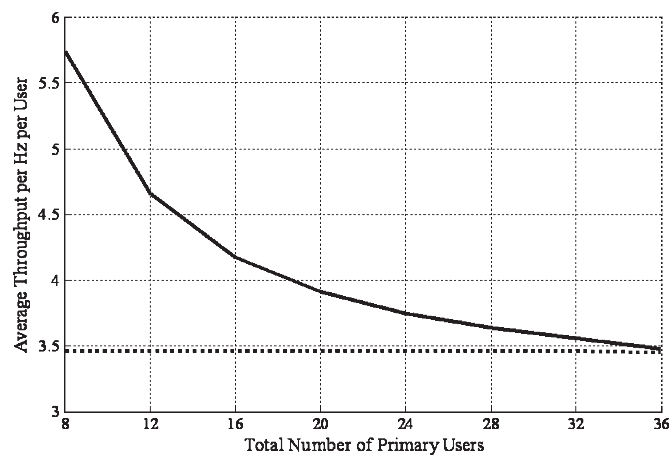

Fig. 10. Average system throughput per hertz per user $\left(\sum_i (\log_2(1+\gamma_i))/W/M\right)$ achieved by TPC and DTPC versus the number of primary users.

that DTPC works well when users move. This is achieved by dynamically assigning high target SIRs to user(s) with better channels and assigning at least the minimum acceptable SIR to the remaining users in a distributed manner.

2) Four-Cell Primary Network With and Without a CRN: We consider a four-cell network to see the performance of DTPC in multicell networks and CRNs. We first consider a four-cell network with no secondary user (all users are primary with equal priority) and then consider the same four-cell primary network along with a CRN. An example of such a four-cell network and a CRN is shown in Fig. 9.

Primary users are distributed in an area measuring 1000 m × 1000 m covered by four base stations each covering a 500 m × 500 m cell. The minimum acceptable target SIR for each primary user is 10 dB. We consider the range of one primary user/cell (a total of four users) to nine primary users/cell (a total of 36 users) with a step size of four users. For each snapshot, TPC and DTPC are separately applied, and their corresponding system throughput is computed at the equilibrium. We average the corresponding values of system throughput for 1500 snapshots of uniform distribution of the users' locations. Fig. 10 shows the average system throughput per hertz per user (the

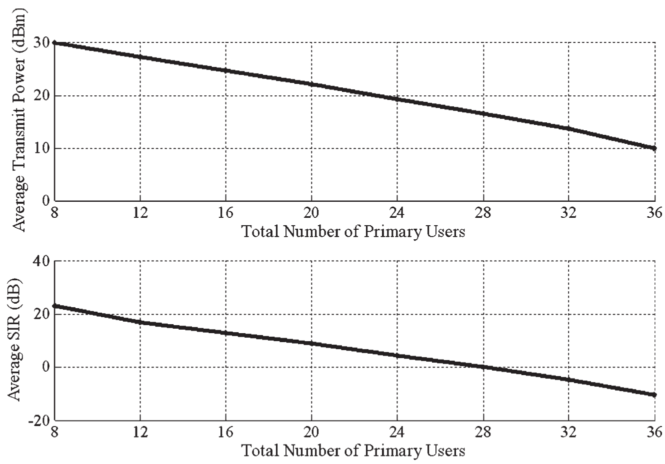

Fig. 11. Average transmit power and average SIRs for four secondary users (the sum of transmit power consumed and the sum of SIRs received by secondary users divided by the total number of secondary users, respectively) versus the number of primary users when primary and secondary users employ DTPC and OPC, respectively.

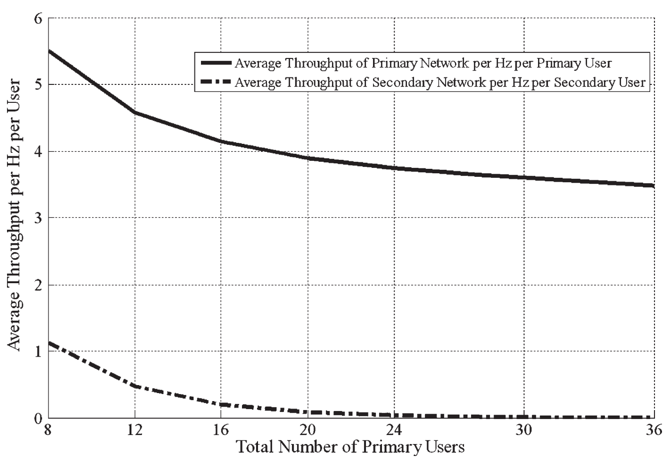

Fig. 12. Average system throughput of the primary network per hertz per primary user (the sum of throughput values for all primary users divided by the allocated bandwidth and the total number of primary users) and the average system throughput of the CRN per hertz per secondary user (the sum of throughput values for all secondary users divided by the allocated bandwidth and the total number of secondary users) versus the total number of primary users when primary and secondary users employ DTPC and OPC, respectively.

sum of the throughput values for all primary users divided by the allocated bandwidth and the corresponding total number of users) versus the total number of users for TPC and DTPC. As can be seen, DTPC outperforms TPC in terms of system throughput.

Now we consider the same primary network together with a single base station (located at the center of the whole area) with four secondary users (who coexist with primary users). In this scenario, primary users employ DTPC and secondary users employ OPC, as discussed in Section V. Fig. 11 shows the average transmit power and SIR for each secondary user. Fig. 12 shows the average system throughput for the primary network and for the CRN versus the total number of primary users. Note that, as the number of primary users increases, secondary users sense it by experiencing an increased effective interference at their base station and consequently reduce their transmit power levels in accordance with OPC, resulting in lower SIRs and a lower system throughput. Note that, by comparing the average system throughput achieved for the two cases (with and without the CRN shown in Figs. 10 and 12, respectively), we see that secondary users do not prevent primary users from obtaining their expected system throughput.

VIII. Conclusion

We have studied the problem of system throughput optimization subject to a given lower bound for the users' SIRs in cellular networks. To address this problem in a distributed manner, we have introduced our proposed DTPC. In the proposed DTPC, when the effective interference for a given user is less than a given threshold, that user dynamically sets its target SIR, which is a decreasing function of the effective interference, to a value higher than the minimum acceptable target SIR; otherwise, it keeps its target SIR fixed at its minimum acceptable value.

We have shown that the proposed algorithm converges to a unique fixed point starting from any initial transmit power in both synchronous and asynchronous power-updating cases. We have also shown that our proposed algorithm not only guarantees the (feasible) minimum acceptable target SIRs for all users as in the case of TPC (and in contrast to OPC) but also significantly improves the system throughput, compared with TPC. Furthermore, we have discussed the application of DTPC, along with OPC, to CRNs and cellular networks with different services. For the case in which users are assumed to be selfish, a game-theoretic analysis of our DTPC algorithm has been presented via an NPCG with a new pricing function. It has been shown that the best response function for each user is the same as our proposed power-updating function of DTPC.

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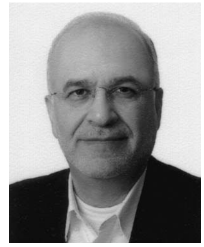

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