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Prioritized Cell Association and Power Control in Uplink Heterogeneous Networks

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ABSTRACT A heterogeneous network (HetNet) is a mix of macrocell base stations (MBSs) underlaid by a diverse set of small cell base stations (SBSs) such as microcells, picocells and femtocells. These networks are employed to enhance network capacity, improve network coverage, and reduce power consumption. However, HetNet performance can be limited by the disparity of power levels in the different tiers. Further, conventional cell association approaches cause MBS overloading, SBS underutilization, excessive user interference and wasted resources. Power control and cell association (CAPC) should be determined based on user priority, channel condition and BS traffic load. However, ensuring priority user (PU) requirements while satisfying as many normal users (NUs) as possible is not considered in existing power control algorithms. In this paper, prioritized CAPC is proposed to solve the load balancing problem between MBSs and SBSs and meet the needs of all PUs. Performance results in Additive white Gaussian noise (AWGN) and Rayleigh fading channels are presented which show that the proposed scheme is a fair and efficient solution which reduces power consumption and has faster convergence than other CAPC schemes.

INDEX TERMS Heterogeneous network, priority users, normal users, power control, cell association.

I. INTRODUCTION

There has been a rapid increase in mobile traffic and data rate requirements worldwide due to multimedia applications, personal devices such as smartphones and tablets, and device to device (D2D) communications. As a consequence, network capacity and efficiency must be improved as bandwidth is limited. A conventional macrocellular network is designed assuming uniform coverage and traffic distribution, and so cannot adequately deal with variable traffic and data rate requirements [1]. Possible solutions to handle the growth in mobile data traffic are to improve the macrocell base station (MBS) architecture, increase MBS density, or employ heterogeneous networks (HetNets). Hetnets consist of MBSs and small base stations (SBSs) with lower transmit power and smaller coverage which can be deployed quickly. While MBSs are used to cover large areas with many users, SBSs enhance capacity and energy efficiency in crowded areas such as large buildings, train stations, shopping malls, city centers and at concerts and festivals. HetNets can be used to efficiently accommodate increased traffic and data rate requirements [2]. They have also been employed to reduce the reuse distance (the distance between adjacent BSs), and the communication distance (the distance between a user and BS) which improve the system capacity and energy efficiency [3]. However, disparate BS transmit powers and random SBS locations can result in higher interference among users compared to conventional MBS networks.

With signal strength cell association, users are associated with the BS that provides the highest signal strength. As a result, most users are connected to MBSs and few are associated with SBSs since the strength of a signal from a MBS is typically higher than from SBSs at the same distance [4]. Thus, the available SBS resources may not be fully utilized. Further, users associated with SBSs often receive strong interference from MBSs, which degrades HetNet performance. At the MBSs, this cell association criterion can cause overloading and low data rates due to insufficient MBS resources [5]. Therefore, a more efficient cell association scheme with load balancing is needed to improve HetNet performance. In a cellular network, users who require high and stable data rates, and active users should have a high priority, and so are called priority users (PUs). Active users are defined as currently connected users. Users who require low and variable data rates, and new users are called normal users (NUs). To satisfy data rate requirements and reduce

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power consumption, prioritized cell association and power control (CAPC) in the HetNet uplink can be employed.

User data rates over 1 Gb/s have been proposed for 5G networks. Thus, users who require data rates greater than this can be considered as PUs, and the rest as NUs. In addition, future cellular networks are expected to accommodate flexible requirements, so user target SINRs should be adjusted according to their demands [6]. In enhanced mobile broadband networks there are both BSs and hotspots. The coverage area for a BS is large and a BS is expected to serve many users. Conversely, the coverage area for a hotspot is small and the number of users served is low [7]. In this case, users associated with BSs can be considered as PUs, and users in hotspot areas as NUs. The proposed scheme can also be used for mobile health services. For example, patients and medical staff in urgent care locations can be conisdered as PUs.

Users can be classified as either low or high handoff frequency. Those with high handoff frequency can be designated as PUs and the remainder as NUs [8]. In addition, high mobility users (e.g. speeds greater than 50 km/h) can be considered as PUs so their target SINRs can be satisfied as quickly as possible. Low mobility users have more stable channel conditions and so can be designated as NUs [9].

Ultra dense cellular networks (UDCNs) have been proposed for 5G networks which include macrocells, picocells and femtocells [10], [12]. In addition to cellular traffic, 5G networks support D2D and internet of things (IoT) communications [11]. However, satisfying users in the presence of a large number of interferers is a challenging task. Hence, coexistence through interference management is essential to realizing the potential of 5G networks, and CAPC is a key technology used in cellular networks for this purpose. A UDCN requires additional BS control and/or cooperation. This can be achieved by employing decentralized CAPC at BSs so the requirements of the associated users can be satisfied. Centralized control can be implemented by using an upper tier algorithm in conjunction with the BSs. BSs can also cooperate to improve performance. Regardless of the approach, CAPC will be employed at BSs to provide interference management and load balancing, and as shown here, the proposed algorithm outperforms existing techniques. Further, the concept of PUs and NUs can be used to differentiate between users and devices.

A. PRIORITIZED CELL ASSOCIATION AND POWER CONTROL (CAPC)

In HetNets, there is a need to efficiently assign users to BSs and to effectively control user transmit power to maintain effective communication links with minimal interference. Further, users have different signal strengths and channel conditions from MBSs and SBSs. These problems can be addressed with a suitable cell association and power control (CAPC) scheme. In particular, cell association is used to establish network utility (the sum of the data rates of all users), and connect users with BSs according to the user channel conditions and BS load. Power control is used to ensure that users transmit with appropriate power levels to maintain link quality without imposing excessive interference on other users.

Recently, CAPC in HetNets has attracted significant research interest. In [13], distributed joint CAPC in the uplink of a two tier HetNet was studied. The objective was to mitigate intra tier and inter tier interference and maximize the network utility. A solution for user cell association and power allocation was obtained using the dual decomposition method. Further, the signal to interference plus noise ratio (SINR) requirements of all users were satisfied. In [14], a combined CAPC scheme was investigated for the HetNet uplink in which each channel is used by only one MBS. A distributed iterative CAPC algorithm was proposed and shown to converge to a Nash equilibrium of a noncooperative game.

In [15], joint power control and load aware user association with load balancing in a two tier HetNet was investigated. Load balancing between MBSs and SBSs was used to mitigate intercell interference in the network. Joint user association and power control for load balancing in HetNets was proposed in [16] to maximize the weighted sum of effective (long term) rates. The power update function for users was derived using a two sided scalable function. In [17], joint user association, power control and scheduling in multi cell 5G networks was proposed. The user association employs both network and user centric approaches. With the network centric approach, user association is performed in a centralized manner while in the user centric approach, distributed association is used to reduce the complexity. In [18], a joint BS association and power control optimization problem was proposed using game theory. The objective is to maximize the network utility and minimize the corresponding transmit power.

In [19], a combination of multiple BS association, power control and dynamic interference cancellation in a HetNet was proposed. Prioritized and selective power control in cellular networks was proposed in [20] considering three types of users, namely PUs, satisfied NUs and unsatisfied NUs. However, cell association was not considered and the target SINR was determined solely by user type. To the best of our knowledge, a hybrid prioritized CAPC approach does not exist to improve network utility and reduce power consumption while considering user priority. The goal of the proposed scheme is to satisfy the target SINRs for as many NUs as possible while ensuring the requirements of all PUs are met.

B. CONTRIBUTIONS AND ORGANIZATION

In this paper, the power control problem in HetNets is formulated to maximize the network utility of NUs while limiting the interference to PUs. In [21], [22], each user was associated with the BS offering the highest achievable rate. However, in this paper, different cell association and power control criteria are used for PUs and NUs. The main contributions are as follows.

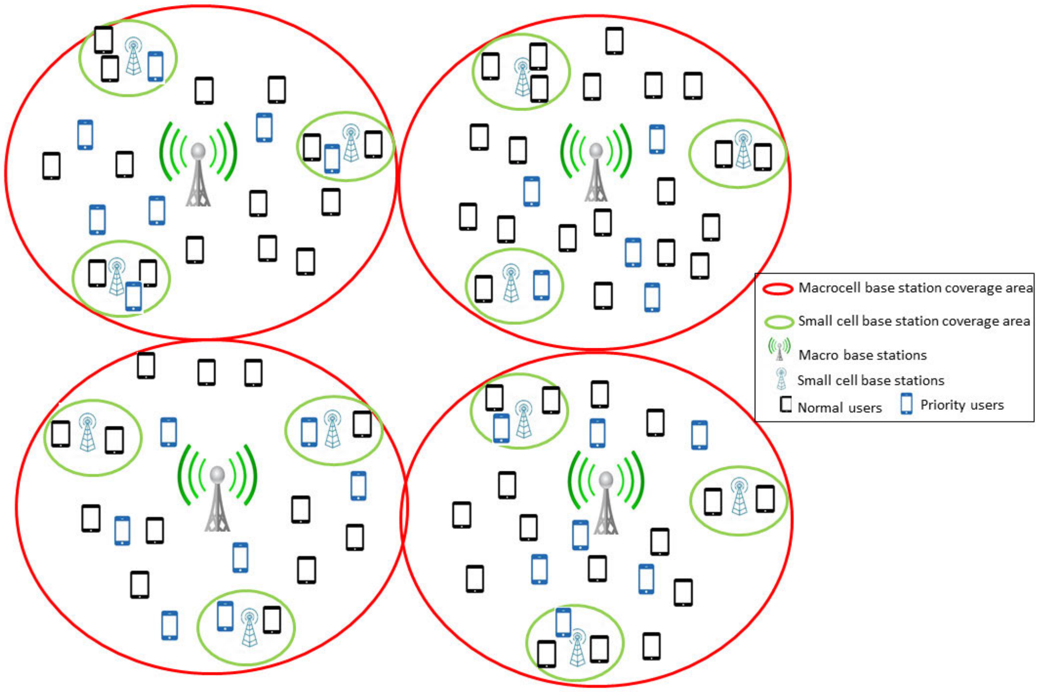

FIGURE 1. The two tier HetNet system model.

1) Two stage CAPC optimization is proposed. The first stage is employed by PUs and NUs and the second stage is employed by the BSs. First, the product of the channel access likelihood (CAL) and channel gain to interference plus noise ratio (GINR) is considered for PU cell association while network utility is considered for NU cell association. Here, CAL is defined as the reciprocal of the BS load. In CAL and GINR cell association, PUs are associated with the BSs that provide the maximum product of CAL and GINR. This implies that PUs are connected to BSs with a low number of users and good channel conditions. NUs are connected to BSs so that the network utility is maximized, and this is achieved using an iterative algorithm. Second, prioritized power control is used to reduce power consumption and satisfy as many NUs with their target SINRs as possible while ensuring that PU requirements are satisfied.
2) The proposed optimization problem is nonconvex. Thus, a two loop algorithm is employed which alternately optimizes the user transmit power and cell association. Specifically, the outer loop performs cell association using Lagrange multipliers, and user transmit power is adjusted in the inner loop using a power update function (PUF).
3) A distributed iterative CAPC algorithm is proposed which uses the Nesterov method and an exponential rule to accelerate the outer and inner loop convergence, respectively.
4) The performance of the proposed schemes is compared with several well-known algorithms in the literature over both AWGN and Rayleigh fading channels. The results obtained show that this scheme provides superior performance.

The rest of the paper is organized as follows. The system model and related work are described in Section II. The prioritized CAPC algorithm is presented in Section III. In Section IV, the performance of the proposed approaches is evaluated and compared with other solutions in the literature. Finally, some concluding remarks are given in Section V.

II. SYSTEM MODEL AND PRELIMINARIES

Fig. 1 illustrates the two tier HetNet system model which consists of multiple MBSs and SBSs. The users and SBSs are randomly distributed in the geographic area of the macrocells [23]. It is assumed that all antennas are omnidirectional. There are N BSs and K users divided into two classes of BSs (MBSs and SBSs) and two types of users (PUs and NUs). The number of MBSs is N_1 and the number of SBSs is N_2, with $N = N_1 + N_2$. It is assumed that the indices of the MBSs are $1, 2, \ldots, N_1$ and the indices of the SBSs are $N_1 + 1, N_1 + 2, \ldots, N$. The number of PUs is K_1 and the number of NUs is K_2, with $K = K_1 + K_2$. It is assumed that the indices of the PUs are $1, 2, \ldots, K_1$ and the indices of the NUs are $K_1 + 1, K_1 + 2, \ldots, K$.

Define the transmit power of user k as p_k, $0 \leq p_k \leq p_{\max}$, where $p_{\max}$ is the maximum transmit power. Then the received power from user k at BS n is $\varphi_{nk} = p_k g_{nk}$ where g_{nk} is the channel gain. The maximum received power is $\varphi_{nk\max} = p_{\max} g_{nk}$. The SINR between BS n and user k is defined as [24], [25]

$$\gamma_{nk} = \frac{p_k g_{nk}}{\sum_{j=1, j\neq k}^{K} p_j g_{nj} + \sigma_n^2} = p_k \Gamma_{nk}, \tag{1}$$

where σ_n^2 is the additive white Gaussian noise (AWGN) power at BS n. The channel gain to interference plus noise ratio (GINR) is denoted as

$$\Gamma_{nk} = \frac{g_{nk}}{\sum_{j=1, j\neq k}^{K} p_j g_{nj} + \sigma_n^2}.$$

The achievable rate of user k associated with BS n is defined as $r_{nk} = \log_2(1+\gamma_{nk})$. The load of BS n is given by $y_n = \sum_{k=1}^{K} x_{nk}$, where $x_{nk} = 1$ if user k is associated with BS n, and $x_{nk} = 0$ otherwise. Thus, the load y_n is the number of users associated with BS n. The reciprocal of y_n is the channel access likelihood (CAL) of BS n. Users are assumed to have the same CAL regardless of the channel conditions [26]. If y_n users are associated with BS n, the effective rate of user k associated with BS n is defined as $R_{nk} = \frac{r_{nk}}{y_n}$. The effective SINR between BS n and user k can then be defined as

$$\begin{aligned}\theta_{nk} &= \frac{p_k g_{nk}}{p_k g_{nk} + \sum_{j=1, j\neq k}^{K} p_j g_{nj} + \sigma_n^2} \\ &= \frac{\gamma_{nk}}{\gamma_{nk}+1} = \frac{p_k g_{nk}}{\rho_{nk}},\end{aligned} \tag{2}$$

where ρ_{nk} is the received power and interference plus noise which characterizes the channel and interference conditions for user k. From (1) and (2), the user transmit power is

$$p_k = \frac{\theta_{nk}\rho_{nk}}{g_{nk}} = \frac{\gamma_{nk}}{\Gamma_{nk}}. \tag{3}$$

The target SINR and target effective SINR for user k are $\hat{\gamma}_k$ and $\hat{\theta}_k$, respectively.

A. CELL ASSOCIATION SCHEMES

Three well-known signal strength cell association schemes are max SINR [27], max reference signal received power (RSRP) [28], and max reference signal received quality (RSRQ) [29]. In these approaches, users are associated with the BS that provides the largest SINR, highest RSRP or maximum RSRQ, respectively. However, due to transmit power differences between MBSs and SBSs, most users will connect to MBSs which can cause overloaded MBSs and underutilized SBSs [30], [31]. Thus, max signal strength with cell range expansion (CRE) [32], [33] was proposed as a solution to this load balancing problem.

In CRE, the cell association condition for users can be formulated as $n^* = \arg\max_n(\gamma_{nk} + \tau_n)$, where τ_n is a positive bias value for BS n. τ_n is in the range [0, 18] dB for SBSs and $\tau_n = 0$ for MBSs. The SBS coverage areas are increased by adding a positive bias to their signal strengths. As a result, more MBS users are transferred to SBSs and thus the load balance is improved compared to other max signal strength schemes. However, users in the CRE region can have a poor quality SBS channel and strong inter tier interference from MBSs.

TABLE 1. Comparison of existing and proposed cell association schemes.

Cell Association Scheme	RSRP [28]	RSRQ [27], [29]	CRE [32], [33]	ABS [34]	Proposed
Objective	Maximize received power	Maximize SINR	Balance load	Maximize SINR Balance load	Maximize SINR Balance load User priority
Application	Uplink Downlink	Uplink Downlink	Downlink	Downlink	Uplink
Association	✓	✓	✓	✓	✓
Channel based	✓	✓	✓	✓	✓
Interference based	x	✓	✓	✓	✓
Load based	x	x	✓	✓	✓
Priority based	x	x	x	x	✓

CRE with almost blank subframe (ABS) [34] uses time domain orthogonalization at the MBSs which leaves some subframes almost blank. This provides a window for SBSs to serve users in the CRE region with reduced inter tier interference. However, this solution wastes MBS subframes and thus resources, and the blank to number of subframes ratio (ABS ratio) needs to be determined carefully. CRE with BS load awareness [29] takes the cell load distribution into consideration. In fact, without incorporating cell load information, the cell association scheme may not be efficient since new users should be associated with an underloaded BS rather than an overloaded BS.

The channel access cell association in [35] considers channel quality indicators and traffic load information from the BSs to improve spectral efficiency and achieve load balancing in HetNets. In [36], load and interference aware cell association was proposed which considers the load and interference for user rate maximization in the uplink of a cellular network. The cell association condition in [35], [36] can be formulated as $n^* = \arg\max_n(\frac{\gamma_{nk}}{y_n})$.

A comparison between the above cell association schemes and the proposed scheme is given in Table 1. Channel based schemes (max RSRP) require knowledge of the instantaneous channel conditions and user received power while interference based schemes (max SINR and max RSRQ) depend on knowledge of the instantaneous interference. Load based schemes (CRE and CRE with ABS) require traffic load information which is the number of users associated with a BS. Priority based schemes require information regarding priority for PUs and NUs.

B. POWER CONTROL SCHEMES

There are three main types of power control schemes, single target SINR, variable target SINR and multiple target SINRs. Single target SINR implies that each user has one target SINR. With a variable target SINR, the user target SINRs are determined based on channel conditions, while with multiple target SINRs there are multiple values for each user. In [37], [38], single target SINR tracking power control (TPC) was considered. The PUF to achieve a target SINR with and without a maximum transmit power constraint is

$$\text{Unconstrained TPC}: p_k(t+1) = \frac{\hat{\gamma}_k}{\Gamma_{nk}(t)}$$

$$\text{Constrained TPC}: p_k(t+1) = \min\left\{\frac{\hat{\gamma}_k}{\Gamma_{nk}(t)}, p_{th}\right\},$$

where t is the iteration index, $\hat{\gamma}_k$ is the target SINR for user k, and p_{th} is the power threshold with $p_{th} \leq p_{\max}$. The goal of user k is to maintain a transmit power which satisfies the target SINR $\hat{\gamma}_k$ so that $\gamma_{nk} \geq \hat{\gamma}_k$. With unconstrained TPC, when this target is not satisfied, users transmit at their maximum power levels $p_{\max}$ which can result in substantial interference to other users and is power inefficient. With constrained TPC, users who cannot attain their target SINRs transmit at the power threshold p_{th} which is more power efficient than unconstrained TPC. However, there can still be significant interference to other users which can increase the number of users who are not satisfied with their target SINRs. Another issue is the single target SINR for all users with unconstrained and constrained TPC, which is typcally not optimum.

To solve the problems with unconstrained and constrained TPC, variable SINR opportunistic power control (OPC) was proposed in [39]. The PUF for OPC is

$$\text{Constrained OPC}: p_k(t+1) = \min\{\xi_k \Gamma_{nk}(t), p_{th}\},$$

where ξ_k is a predefined constant. With this scheme, users with better channel conditions have a higher SINR than other users, and vice versa. Similar to constrained TPC, a power threshold is employed to limit the user transmit power so the interference to others is restricted.

Distributed power control with temporary removal and feasibility check (DFC) is a mixture of TPC and OPC [40]. DFC outperforms OPC and TPC in terms of convergence, number of satisfied users, and power consumption. The PUF for this scheme is

$$p_k(t+1) = \begin{cases} \dfrac{\hat{\gamma}_k}{\Gamma_{nk}(t)}, & \text{if } \dfrac{\hat{\gamma}_k}{\Gamma_{nk}(t)} \leq p_k^{th1} \text{ and } p_k(t) \neq 0 \\ 0, & \text{if } \dfrac{\hat{\gamma}_k}{\Gamma_{nk}(t)} > p_k^{th1} \text{ and } p_k(t) \neq 0 \\ \dfrac{\hat{\gamma}_k}{\Gamma_{nk}(t)}, & \text{if } \dfrac{\hat{\gamma}_k}{\Gamma_{nk}(t)} \leq p_k^{th2} \text{ and } p_k(t) = 0 \\ 0, & \text{if } \dfrac{\hat{\gamma}_k}{\Gamma_{nk}(t)} > p_k^{th2} \text{ and } p_k(t) = 0, \end{cases}$$

where p_k^{th1} and p_k^{th2} are the upper and lower power thresholds for user k which are given by

$$p_k^{th1} = p_{\max} \text{ and } p_k^{th2} = \frac{\sigma_n^2(\widehat{\gamma}_k + 1)}{p_{\max} g_{nk} + \sigma_n^2} p_{\max}.$$

With DFC, users decrease their transmit power level to less than p_k^{th2} when the transmit power required to obtain their target SINR is above p_k^{th1}. Further, they increase their power level if the required transmit power to obtain their target SINR is below p_k^{th2}. There are several advantages to DFC. First, the interference to other users is reduced compared to TPC and OPC. Second, the power consumption is lower and a higher number of users are satisfied with their target SINRs compared to TPC. Third, compared to constrained OPC, users have a lower power threshold which allows them to reach their target SINRs faster while the interference to other users is limited.

TABLE 2. Comparison of existing and proposed power control schemes.

Power Control Scheme	TPC [37], [38]	OPC [39]	DFC (TPC + OPC) [40]	VTPC (DFC + OPC) [41]	Proposed (DFC + OPC or TPC + OPC)
Objective	Minimize power	Maximize throughput	Maximize throughput	Maximize throughput Increase the number of satisfied users	Maximize throughput Increase the number of satisfied NUs Satisfy all PUs
Constraints	SINRs $p_{\max}, p_{th}$	Variable SINRs p_{th}	Target SINRs p_{th1}, p_{th2}	Target SINRs or Variable SINRs p_{th3}	Target SINRs or Variable SINRs $p_{th1}, p_{th2}, \rho_{nk\max}$

Multiple target SINR tracking power control (VTPC) was proposed in [41]. With this approach, the target SINR for user k is adjusted according to

$$\hat{\gamma}_k(t) = \begin{cases} \sqrt{\xi_k \Gamma_{nk}(t)}, & \text{if } p_k(t) \leq p_k^{th3} \\ \hat{\gamma}_k, & \text{if } p_k(t) > p_k^{th3}, \end{cases}$$

where $p_k^{th3} = \frac{p_k^{th1}}{\hat{\gamma}_k}$ and $p_k^{th2} \leq p_k^{th3} \leq p_k^{th1}$. The corresponding PUF is

$$p_k(t+1) = \frac{1}{\Gamma_{nk}(t)} \begin{cases} \sqrt{\xi_k \Gamma_{nk}(t)}, & \text{if } p_k(t) \leq p_k^{th3} \\ \hat{\gamma}_k, & \text{if } p_k(t) > p_k^{th3}. \end{cases}$$

With VTPC, user k updates p_k^{th3} and the PUF is separated into two zones. If $p_k(t) \leq p_k^{th3}$, the target SINR for this user is increased, and if $p_k(t) > p_k^{th3}$, the target SINR is not changed, which is similar to DFC and TPC. The goal of VTPC is to maximize the sum rate and increase the number of satisfied users that attain their target SINRs. A comparison between the above power control schemes and the proposed scheme is given in Table 2.

III. PRIORITIZED CAPC IN THE HETNET UPLINK

In this section, the CAPC optimization problem is formulated and solved with an iterative algorithm using Lagrangian dual decomposition. Further, the convergence rate of the algorithm is accelerated using the Nesterov approach and an exponential rule [42], [43], [45].

A. PRIORITIZED CAL AND GINR CELL ASSOCIATION

Cell association is employed to maximize the network utility while all PUs are associated with BSs. PUs are associated with BSs that provide the maximum CAL and GINR, and NUs are associated with BSs to maximize the network sum rate. The following constraints are considered for the rate maximization problem.

1) The cell association variables are binary, $x_{nk} \in \{0, 1\}$.
2) Each user is associated with at most one BS, $\sum_{n=1}^{N} x_{nk} = 1 \;\; k = 1, 2, \ldots, K$.
3) No more than $y_{\max}$ users are associated with BS n, $y_n \leq y_{\max}, \;\; n = 1, 2, \ldots, N$.
4) The total number of users associated with BS n is $y_n = \sum_{k=1}^{K} x_{nk}, \;\; n = 1, 2, \ldots, N$.

The cell association problem for PU k is

$$\max_{n} \frac{\Gamma_{nk}}{y_n}$$
$$\text{subject to } x_{nk} \in \{0, 1\}$$
$$\sum_{n=1}^{N} x_{nk} = 1, \quad k = 1, 2, \ldots, K_1, \tag{4}$$

and the corresponding cell association problem for NU k is

$$\max_{x_{nk}, y_n} \sum_{n=1}^{N}\sum_{k=1}^{K} x_{nk} \log(R_{nk})$$
$$\text{subject to } x_{nk} \in \{0, 1\}$$
$$\sum_{n=1}^{N} x_{nk} = 1, \quad k = K_1 + 1, K_1 + 2, \ldots, K$$
$$\sum_{k=1}^{K} x_{nk} = y_n, \quad n = 1, 2, \ldots, N. \tag{5}$$

Comparing (4) and (5) indicates that the cell association criteria for NUs is more complex than that for PUs. The main difference between problems (4) and (5) is that PU cell association is based on user requirements while NU cell association is based on network requirements. First, each PU connects to a BS that has good channel conditions and sufficient capacity. This ensures that the PU SINR requirements are satisfied. Then, as many NUs as possible are served by the BSs providing that all PUs are associated.

The solution of (4) can be expressed as

$$n^* = \arg\max_{n} \frac{\Gamma_{nk}}{y_n}, \quad k = 1, 2, \ldots, K_1 \text{ and } n = 1, 2, \ldots, N.$$

For convenience, let Φ denote the feasible region corresponding to the constraints in (5). The objective function for NU k is then

$$\max_{x_{nk}, y_n \in \Phi} F(x_{nk}, y_n) = \sum_{n=1}^{N}\sum_{k=1}^{K} x_{nk} \log(R_{nk}). \tag{6}$$

$F(x_{nk}, y_n)$ can be rewritten as

$$\begin{aligned} F(x_{nk}, y_n) &= \sum_{n=1}^{N}\sum_{k=1}^{K} x_{nk} \log(R_{nk}) \\ &= \sum_{n=1}^{N}\sum_{k=1}^{K} x_{nk} \log(r_{nk}) - \sum_{n=1}^{N}\sum_{k=1}^{K} x_{nk} \log(y_n) \\ &= \sum_{n=1}^{N}\sum_{k=1}^{K} x_{nk} \log(r_{nk}) - \sum_{n=1}^{N} y_n \log(y_n). \end{aligned} \tag{7}$$

The coupling constraint in (5) is $\sum_{k=1}^{K} x_{nk} = y_n$, $n = 1, 2, \ldots, N$. The Lagrangian dual decomposition approach in [42] is employed to relax this constraint using the Lagrange multiplier λ_n. The dual problem is then

$$\begin{aligned} \max_{\lambda_n} F(\lambda_n) &= \sum_{n=1}^{N}\sum_{k=1}^{K} x_{nk} \log(r_{nk}) - \sum_{n=1}^{N} y_n \log(y_n) \\ &\quad - \sum_{n=1}^{N} \lambda_n \Big(\sum_{k=1}^{K} x_{nk} - y_n\Big) \\ &= \sum_{n=1}^{N}\sum_{k=1}^{K} x_{nk} \log(r_{nk}) - \sum_{n=1}^{N}\sum_{k=1}^{K} x_{nk} \lambda_n \\ &\quad + \sum_{n=1}^{N} y_n \lambda_n - \sum_{n=1}^{N} y_n \log(y_n) \\ &= F_{x_{nk}}(\lambda_n) + F_{y_n}(\lambda_n), \end{aligned} \tag{8}$$

where $F_{x_{nk}}(\lambda_n)$ is the first subproblem and $F_{y_n}(\lambda_n)$ is the second subproblem. The optimization problem for NUs is nonconvex [43] and so there may be a nonzero duality gap. However, using an approach similar to that in [44], this gap can be shown to be zero. Thus, the solution can be obtained in an iterative manner as given below.

Subproblem 1

$$F_{x_{nk}}(\lambda_n) = \sum_{n=1}^{N}\sum_{k=1}^{K} x_{nk} \log(r_{nk}) - \sum_{n=1}^{N}\sum_{k=1}^{K} x_{nk} \lambda_n$$
$$\text{subject to } x_{nk} \in \{0, 1\}$$
$$\sum_{n=1}^{N} x_{nk} = 1, \; k = K_1 + 1, K_1 + 2, \ldots, K. \tag{9}$$

This is implemented at the user side using the following steps.

Step 1: Obtain the load information $y_n(t)$ and Lagrange multiplier $\lambda_n(t)$ broadcast by BS n, and compute the GINR $\Gamma_{nk}(t)$.

Step 2: PU k selects the BS n^* given by

$$n^* = \arg\max_{n} \frac{\Gamma_{nk}(t)}{y_n(t)}, \; k = 1, 2, \ldots, K_1 \text{ and } n = 1, 2, \ldots, N,$$

and NU k selects the BS n^* given by

$$n^* = \arg\max_{n} (\log(r_{nk}(t)) - \lambda_n(t)),$$
$$k = K_1 + 1, K_1 + 2, \ldots, K \text{ and } n = 1, 2, \ldots, N. \tag{10}$$

Subproblem 2

$$F_{y_n}(\lambda_n) = \sum_{n=1}^{N} y_n \lambda_n - \sum_{n=1}^{N} y_n \log(y_n). \tag{11}$$

This is implemented at the BS side. After all users have been associated, BS n updates y_n and its Lagrange multiplier λ_n using the following steps and then λ_n is broadcast to the users. The steps are as follows.

Step 1: The maximum of (11) is found by taking the derivative with respect to y_n and setting it to 0. The optimal value is

$$y_n(t + 1) = e^{(\lambda_n(t) - 1)}, \tag{12}$$

and adding the constraint $y_n \leq y_{\max}$ gives

$$y_n(t + 1) = \min\{y_{\max}, e^{(\lambda_n(t) - 1)}\}. \tag{13}$$

Step 2: The Lagrange multiplier is updated using the Nesterov accelerated subgradient method with step size $\mu_n(t)$ where $0 \le \mu_n(t) \le (|\frac{\partial F(\lambda_n(t))}{\partial \lambda_n(t)}|)^{-1}$ [45] which gives

$$\bar{\lambda}_n(t) = \lambda_n(t) - \mu_n(t)\left(\frac{\partial F(\lambda_n(t))}{\partial \lambda_n(t)}\right)$$
$$\frac{\partial F(\lambda_n(t))}{\partial \lambda_n(t)} = -\sum_{k=1}^{K} x_{nk}(t) + y_n(t)$$
$$\beta_n(t+1) = \frac{1+\sqrt{1+4\beta_n^2(t)}}{2}$$
$$\lambda_n(t+1) = \bar{\lambda}_n(t) + \frac{\beta_n(t)-1}{\beta_n(t+1)}\big(\bar{\lambda}_n(t) - \bar{\lambda}_n(t-1)\big), \quad (14)$$

where $\beta_n(t)$ is the momentum parameter. The multiplier $\lambda_n(t)$ represents the traffic load at BS n and can be interpreted as the price of the BS determined by the load. It can be positive or negative. The higher the value of $\lambda_n(t)$, the more traffic the BS has. Thus, when BS n has a high load, $\lambda_n(t)$ will increase and fewer users will associate with this BS. Conversely, if BS n has a small load, the price will decrease to attract additional users.

B. PRIORITIZED POWER CONTROL

In cellular networks, users require a variety of data rates for real time and non real time services. Some users are licensed while others can be unlicensed. Further, active and new users may exist in the network. Active and licensed users should be given a higher level of service than new and unlicensed users. Therefore, different priorities should be assigned to users when determining the power control. In this section, three priority based power control approaches are proposed. First, we have the following assumptions.

Assumption 1: $\rho_{nk\max}$ is the maximum received power and interference plus noise for NU k so that the target SINRs for all PUs are satisfied. The upper limit for NU k is given by

$$\begin{aligned}\rho_{nk\max} &= \{\rho_{nk} \mid 0 \le p_k \le p_{\max}\} \\ &= \left\{\rho_{nk} \mid 0 \le \frac{\theta_{nk}}{g_{nk}}\rho_{nk} \le p_{\max}\right\} \\ &= \min\left\{\frac{\varphi_{nk\max}}{\hat{\theta}_k}\right\}, \end{aligned} \quad (15)$$

where $\varphi_{nk\max} = p_{\max} g_{nk}$, and $k = K_1+1, K_1+2, \ldots, K$. From (2), $\hat{\theta}_k = \frac{\gamma_{nk}}{\gamma_{nk}+1}$ when the target SINR for NU k is satisfied. Combining (2), (3) and (15), the maximum target SINR for NU k is

$$\hat{\gamma}_{k\max} = \frac{\varphi_{nk}}{\left|\left(\min\left(\frac{\varphi_{nk\max}}{\hat{\theta}_k}\right) - \varphi_{nk}\right)\right|}, \quad (16)$$

and the corresponding maximum transmit power is

$$p_{k\max}^{th1} = \frac{\hat{\gamma}_{k\max}}{\Gamma_{nk}}. \quad (17)$$

Assumption 2: To keep the NU SINR below the maximum allowable SINR, a power tuning parameter is used which is given by

$$\Upsilon_k(\gamma_{nk}) = \begin{cases} \frac{\hat{\gamma}_{k\max}}{\gamma_{nk}}, & \text{if } \gamma_{nk} > \hat{\gamma}_{k\max} \\ 1, & \text{if } \gamma_{nk} \le \hat{\gamma}_{k\max}. \end{cases} \quad (18)$$

When the required SINR of NU k is higher than the maximum allowable SINR, the PUF of this user is reduced by a factor $\frac{\hat{\gamma}_{k\max}}{\gamma_{nk}}$. Otherwise, the PUF of user k is left unchanged.

To improve convergence of the TPC, DFC and proposed schemes, an exponential rule is employed with the weighted average of the current and previous transmit powers. Since an exponential function decays faster than a linear function, power control with an exponential rule will converge faster than with the linear functions in TPC and DFC. The exponential rule is

$$p_k(t+1) = \psi e^{\kappa(\hat{\gamma}_k - \gamma_{nk})} p_k(t) + (1-\psi)p_k(t-1), \quad (19)$$

where ψ is in the range (0, 1], and $p_k(t)$ is the transmit power at iteration t. The convergence control parameter is given by

$$\kappa = \frac{\log(p_k^*) - \log(p_k)}{\hat{\gamma}_k - \gamma_{nk}}, \quad (20)$$

where $p_k^* = \frac{\hat{\gamma}_k}{\Gamma_{nk}}$. With user priority, the goal of the algorithm is to satisfy all PU requirements while satisfying as many NUs as possible. The following approaches are proposed to achieve this goal.

Approach 1: The PUs and NUs adjust their target SINRs using constrained TPC and DFC, respectively. Constrained TPC is employed by the PUs so they transmit at power levels which satisfy their target SINRs. DFC is employed by the NUs which implies that some NUs may have to reduce their transmit power level to reduce the interference to other users. However, employing TPC for PUs and DFC for NUs separately may result in some NUs transmitting at the maximum power level even though their target SINRs are not attained, which can cause significant interference to the PUs. To ensure this does not occur, the target SINRs of the NUs are reduced. Thus, their transmit power is adjusted to restrict the interference to PUs. The PUF for PU k is then

$$p_k(t+1) = \max\left\{p_k^{th2}, \min\left\{\psi e^{\kappa(\hat{\gamma}_k - \gamma_{nk})} p_k(t) + (1-\psi)p_k(t-1), p_k^{th1}\right\}\right\}, \quad k = 1, 2, \ldots, K_1, \quad (21)$$

and the PUF for NU k is

$$p_k(t+1) = \begin{cases} \max\left\{p_k^{th2}, \min\left\{\psi e^{\kappa(\hat{\gamma}_k - \gamma_{nk})} p_k(t) + (1-\psi)p_k(t-1), p_k^{th1}\right\}\right\}, & \text{if } p_k(t) \le p_k^{th1} \\ 0, & \text{if } p_k(t) > p_k^{th1}. \end{cases} \quad (22)$$

Equations (21) and (22) indicate that PUs and NUs increase their transmit powers until the target SINRs are reached if

$\gamma_{nk} < \hat{\gamma}_k$. Conversely, the transmit powers are reduced until the target SINRs are reached if $\gamma_{nk} > \hat{\gamma}_k$. Thus, convergence occurs when $\gamma_{nk} = \hat{\gamma}_k$. The power threshold p_k^{th1} is used to manage the NU interference to PUs. NUs with a transmit power that exceeds this threshold must reduce their transmit power to 0.

Approach 2: The PUs employ constrained TPC so that PU SINR requirements are satisfied as quickly as possible. The NUs employ either constrained TPC or OPC depending on the channel conditions and PU interference. The PUF for PU k is

$$p_k(t+1) = \max\left\{p_k^{th2}, \min\left\{\psi e^{\kappa(\hat{\gamma}_k-\gamma_{nk})}p_k(t) +(1-\psi)p_k(t-1), p_k^{th1}\right\}\right\}, k = 1, 2, \ldots, K_1,$$

and the PUF for NU k is

$$p_k(t+1) = \max\left\{p_k^{th2}, \min\left\{\frac{e^{\kappa(\xi_k+\gamma_{nk})}}{p_k(t)} + (1-\psi)p_k(t-1), \psi e^{\kappa(\hat{\gamma}_k-\gamma_{nk})}p_k(t) + (1-\psi)p_k(t-1), p_k^{th1}\right\}\right\}, \quad (23)$$

where ξ_k is in the range (0, 1).

Approach 3: The PUs and NUs both employ constrained TPC. However, a tuning parameter is used in the NU PUF which depends on the channel conditions and interference to PUs. The PUF for PU k is

$$p_k(t+1) = \max\left\{p_k^{th2}, \min\left\{\psi e^{\kappa(\hat{\gamma}_k-\gamma_{nk})}p_k(t) + (1-\psi)p_k(t-1), p_k^{th1}\right\}\right\}, \ k = 1, 2, \ldots, K_1,$$

and the PUF for NU k is

$$p_k(t+1) = \max\left\{p_k^{th2}, \min\left\{\Upsilon_k(\Gamma_{nk})e^{\kappa(\hat{\gamma}_k-\gamma_{nk})}p_k(t) + (1-\psi)p_k(t-1), p_k^{th1}\right\}\right\}. \quad (24)$$

The computation of $p_k(t+1)$ requires knowledge of $p_k(t)$, $p_k(t-1)$, $\hat{\gamma}_k$, Γ_{nk}, κ, and Υ_k. However, $p_k(t)$, $p_k(t-1)$ and $\hat{\gamma}_k$ are available locally at the PUs and NUs. Further, κ and Υ_k are determined by the BS based on the channel conditions and traffic load. These parameters are used to maintain the PU and NU target SINRs according to the corresponding criteria. Finally, Γ_{nk} can easily be estimated at the BS and sent to the corresponding use via the return downlink channel. Therefore, the proposed approaches to power control can be implemented in a fully decentralized manner. The proposed CAPC algorithm is summarized in Algorithm 1. As before, the PUs are considered first, and then the NUs. The timescales are assumed to be the same so that cell association and power control can be done sequentially.

Algorithm 1 Proposed CAPC Algorithm

Stage 1: User side

Obtain the load information $y_n(t)$, Lagrange multiplier $\lambda_n(t)$, and $p_{k\,\max}^{th1}$ broadcast by BS n.

Measure the GINR $\Gamma_{nk}(t)$.

Loop 1: Cell association

PU k selects BS n^* given by

$$n^* = \arg\max_n \frac{\Gamma_{nk}(t)}{y_n(t)},$$
$$k = 1, 2, \ldots, K_1 \text{ and } n = 1, 2, \ldots, N.$$

NU k selects BS n^* given by

$$n^* = \arg\max_n (\log(r_{nk}(t)) - \lambda_n(t)),$$
$$k = K_1+1, K_1+2, \ldots, K \text{ and } n = 1, 2, \ldots, N.$$

Loop 2: Power control

PU k updates its transmit power using

$$p_k(t+1) = \max\left\{p_k^{th2}, \min\left\{\psi e^{\kappa(\hat{\gamma}_k-\gamma_{nk})}p_k(t) + (1-\psi)p_k(t-1), p_{k\,\max}^{th1}\right\}\right\}.$$

NU k updates its transmit power using one of the proposed power control approaches.

Stage 2: BS side

Find the maximum $y_n(t+1)$ at BS n by taking the derivative of (11).

Update the Lagrange multiplier $\lambda_n(t)$ associated with BS n using the Nesterov subgradient method.

IV. PERFORMANCE RESULTS

In this section, Monte Carlo simulation is used to evaluate the proposed algorithms. As in the related literature [46]–[48], the channel gain is $g_{nk} = hd_{nk}^{-\alpha}$, where $h = 0.97$ is a constant, d_{nk} is the distance between user k and BS n, and $\alpha = 3$ is the path loss exponent which corresponds to urban and suburban environments. The noise power at BS n is $\sigma_n^2 = 0.01$ W, and all initial transmit powers are set to 1 W which is the maximum transmit power for each user. The results are given below.

A. CELL ASSOCIATION

The proposed cell association scheme is evaluated using a two tier system model and four different scenarios. The performance is compared using Jain's fairness index [49] which is given by

$$J = \frac{(\sum_{n\in N} y_n)^2}{N\sum_{n\in N} y_n^2},$$

where $J \in [\frac{1}{N}, 1]$. This index reflects the equality of user association to BSs [50]. The closer J is to 1, the better the traffic load distribution and the more fairly users are associated with MBSs and SBSs. When $J = \frac{1}{N}$, the traffic load is the most imbalanced and all users are associated with one BS [51].

In the first scenario, there is one MBS (BS9), 8 SBSs (BS1 to BS8), 10 PUs, and 40 NUs. The MBS is located in the center of a square geographic area with dimensions 40 km × 40 km and origin (0, 0). The MBS is denoted by (x_{MBS}, y_{MBS}) which here is (20, 20) km. The SBSs, PUs and NUs are uniformly distributed in the geographic area. Table 3 gives the load distribution and Jain's fairness index for the max signal strength, CRE and proposed cell association schemes averaged over 10000 trials.

With max signal strength cell association, the largest average loads are 34.8% at BS9 and 15.6% at BS8. The average load is the percentage of users associated with a BS averaged over the trials. Thus, BS9 (MBS) and BS8 are highly loaded compared to BS1 to BS7. The average loads for BS1 to BS7 range from 6.87% to 7.84%, which means these BSs are underloaded. There is a difference of 27.9% between the largest and smallest loads, which is a significant imbalance between the MBS and SBSs so that $J = 0.44$. Most users are associated with BS9 (MBS) because it provides the largest signal strength.

With CRE cell association, the loads are more balanced than with the max signal strength scheme. The average load at BS9 is 4.33%, which is the smallest, and the average loads at BS1 to BS8 range from 11.9% to 12.1%. The difference between the largest and smallest loads is only 7.77% and $J = 0.84$. Fewer users are associated with BS9 because a positive bias was added to the SBS signal strengths to make them more attractive to users.

The load distribution with the proposed cell association scheme is the fairest as $J = 0.87$ which is the highest. The average load at BS9 is 11.6%, and the average SBS load (BS1 to BS8) ranges from 10.9% to 11.1%, so the difference is just 0.71% which is the smallest.

In the second scenario, there are 4 MBSs, 20 SBSs, 40 PUs, and 160 NUs. The geographic area of 40 km × 40 km is split into four zones of size 20 km × 20 km. An MBS is located in the center of each zone. The SBSs, PUs and NUs are uniformly distributed in the four zones but with 25% in each zone. Table 4 gives Jain's fairness index for the max signal strength, CRE and proposed cell association schemes averaged over 10000 trials. For a fair comparison, the same channel conditions were used for each scheme in a given trial. These results show that the prioritized CAL and GINR scheme gives the highest fairness index of $J = 0.91$. CRE is next with $J = 0.81$ which is much better than the max signal strength scheme with $J = 0.54$.

In the third scenario, the PUs and NUs are again uniformly distributed in the four zones, but the percentage of SBSs in the zones is [24.7 24.3 24.8 26.2]. Table 5 gives Jain's fairness index for the max signal strength, CRE and proposed cell association schemes averaged over 10000 trials. For a fair comparison, the same channel conditions were used for each scheme in a given trial. Again the prioritized CAL and GINR scheme gives the highest fairness index of $J = 0.91$. CRE is next with $J = 0.82$, which is much better than the max signal strength scheme with $J = 0.54$.

In the fourth scenario, the percentage of SBSs in the four zones is [26.1 24.4 24.6 24.9] and the percentage of PUs and NUs in the four zones is [26.3 23.8 25.4 24.5]. Table 6 gives

TABLE 3. Average loads and Jain's fairness index with one MBS and eight SBSs.

Cell Association Scheme	Jain's Fairness Index	BS	Average Load (%)
Max signal strength	0.44	BS1	6.95
		BS2	6.99
		BS3	6.98
		BS4	6.87
		BS5	7.00
		BS6	6.93
		BS7	7.84
		BS8	15.6
		BS9	34.8
CRE	0.84	BS1	12.0
		BS2	12.0
		BS3	11.9
		BS4	12.0
		BS5	12.0
		BS6	11.9
		BS7	12.1
		BS8	11.9
		BS9	4.33
Prioritized CAL and GINR	0.87	BS1	11.1
		BS2	11.1
		BS3	10.9
		BS4	11.1
		BS5	11.0
		BS6	11.1
		BS7	11.0
		BS8	11.0
		BS9	11.6

TABLE 4. Jain's fairness index with uniform SBS and user distributions.

Cell Association Scheme	Jain's Fairness Index
Max signal strength	0.54
CRE	0.81
Prioritized CAL and GINR	0.91

TABLE 5. Jain's fairness index with nonuniform SBS and uniform user distributions.

Cell Association Scheme	Jain's Fairness Index
Max signal strength	0.54
CRE	0.82
Prioritized CAL and GINR	0.91

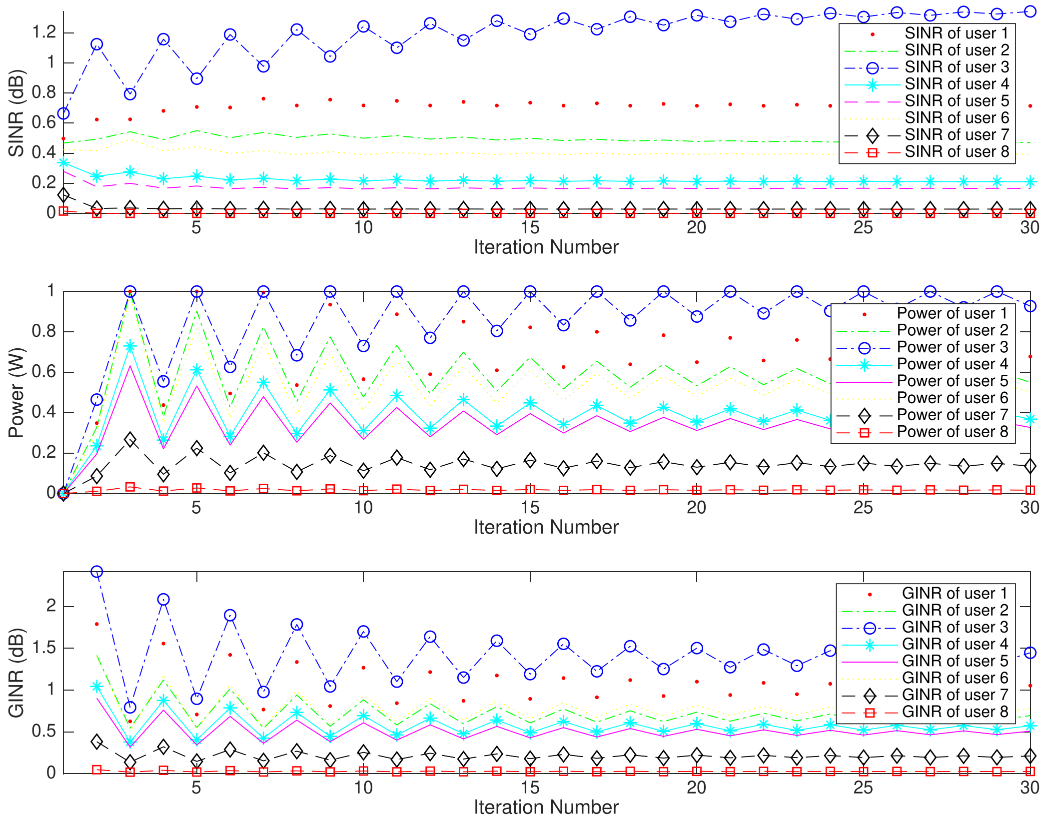

FIGURE 2. Transmit power, SINR and GINR for one trial with the OPC scheme.

TABLE 6. Jain's fairness index with nonuniform SBS and user distributions.

Cell Association Scheme	Jain's Fairness Index
Max signal strength	0.53
CRE	0.83
Prioritized CAL and GINR	0.91

Jain's fairness index for the max signal strength, CRE and proposed cell association scheme averaged over 10000 trials. For a fair comparison, the same channel conditions were used for each scheme in a given trial. These results show that the prioritized CAL and GINR scheme gives the highest fairness index of $J = 0.91$, followed by CRE with $J = 0.83$ and the max signal strength scheme with $J = 0.53$.

The results in Tables 3 to 6 show that the proposed scheme provides a fairer traffic load distribution and higher fairness index than the max signal strength and CRE schemes.

B. POWER CONTROL IN AWGN CHANNELS

To evaluate the performance of the proposed power control approaches, simulation results are presented with 2 PUs (users 1 and 2) and 6 NUs (users 3 to 8) associated with a BS in an AWGN channel. The target SINRs for the users are

$$\hat{\gamma}_k = [0.27, 0.31, 0.48, 0.35, 0.15, 0.20, 0.16, 0.11] \text{ dB},$$

with an average SINR of 0.26 dB. The performance of the proposed power control approaches is compared with that of power control based on power consumption, average SINR and number of iterations. The solutions with these techniques are obtained iteratively, so the number of iterations is used to evaluate the computational complexity. Results were obtained for 100 trials with different distances between the users and BS in each trial.

Figs. 2 and 3 present the SINR, transmit power and GINR for the OPC and VTPC schemes, respectively, for one trial. These results show that when the channel conditions are good, higher SINRs are attained, as expected. In Fig. 2, the power and GINR with OPC oscillate. The reason is that OPC is a variable SINR scheme, while VTPC is a variable target SINR scheme. Convergence with OPC requires 40 iterations. The resulting user SINRs are

$$\gamma_k = [0.72, 0.47, 1.35, 0.21, 0.17, 0.39, 0.03, 0.01] \text{ dB}.$$

The average SINR is 0.42 dB and average user power is 0.75 W. However, the average power for users 1 and 3 is greater than 0.7 W, which is high. In addition, users 4, 5, 7 and 8 are not satisfied with their target SINRs, and one PU (user 2) does not reach the target SINR. Fig. 3 shows that convergence with the VTPC scheme requires 30 iterations, which is less than with OPC. The resulting user SINRs are

$$\gamma_k = [0.59, 0.48, 0.92, 0.29, 0.23, 0.43, 0.06, 0.01] \text{ dB}.$$

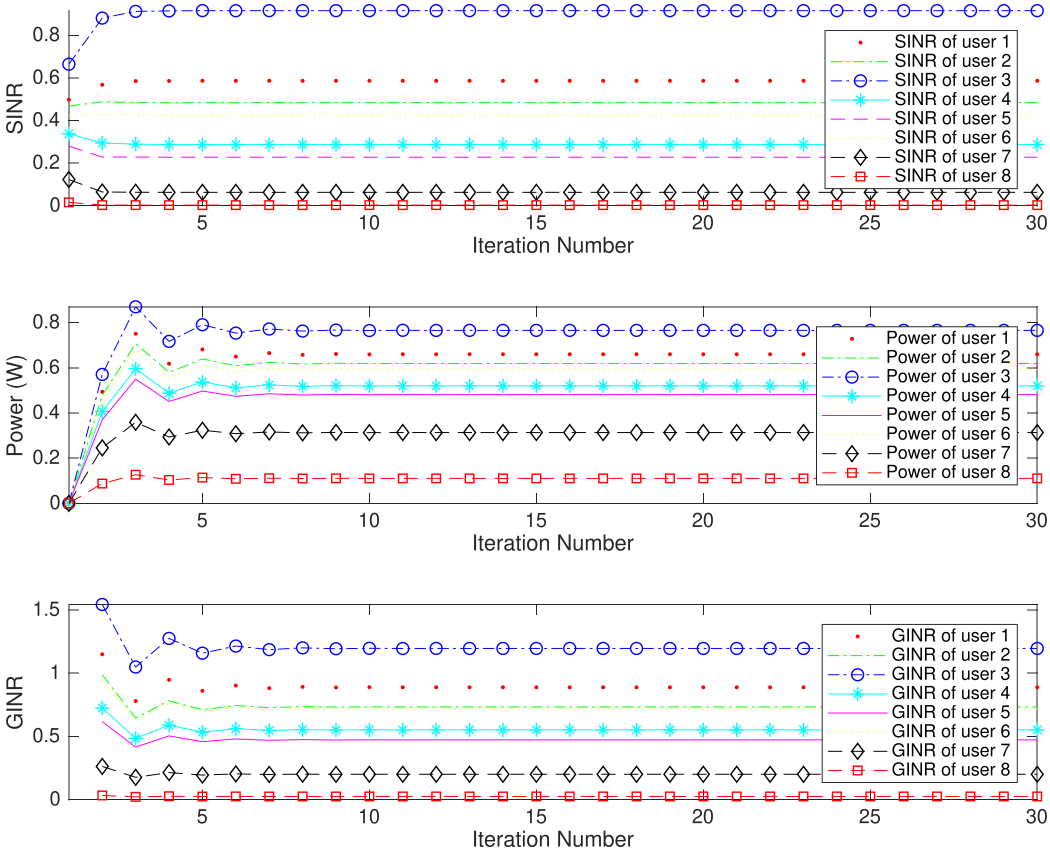

FIGURE 3. **Transmit power, SINR and GINR for one trial with the VTPC scheme.**

The average SINR is 0.37 dB and the average user power is 0.7 W, so VTPC is more power efficient than OPC. In addition, all PUs are satisfied with their target SINRs, but two NUs (users 7 and 8) are not satisfied.

Fig. 4 gives the SINR, transmit power and GINR for one trial with proposed approach 1. This shows that this power control technique converges faster than VTPC. The corresponding user SINRs are

$$\gamma_k = [0.28, 0.32, 0.48, 0.36, 0.16, 0.20, 0.16, 0.11] \text{ dB}.$$

The average SINR is 0.26 dB and the average user power is 0.35 W. In addition, all PUs and NUs are satisfied with their target SINRs. These results indicate that this approach is much better than OPC and VTPC. The results obtained with proposed approaches 2 and 3 are similar and so are omitted.

Table 7 shows the average number of iterations, user power and SINR for the TPC, OPC, DFC, VTPC and proposed approaches averaged over 100 trials. With TPC, an average of 51 iterations is required for convergence with an average user power of 0.45 W. With DFC, the target SINRs for the users were attained after an average of 33 iterations with an average user power of 0.35 W, which is better than TPC. In addition, the number of users not satisfied with their target SINRs is less than with TPC. With proposed approach 1, all users attain their target SINRs and an average of 29 iterations was required. The average user power is 0.35 W. Proposed approach 2 required an average of 22 iterations and the average user power is 0.67 W, while proposed approach 3 required an average of 20 iterations and the average user power is 0.7 W. Thus, proposed approach 1 outperforms TPC, OPC, DFC and VTPC in terms of user power and number of iterations. Proposed approaches 2 and 3 have faster convergence, but require more power.

TABLE 7. **Average number of iterations, user power and SINR for the TPC, OPC, DFC, VTPC and proposed power control approaches averaged over 100 trials.**

Power Control Scheme	Average Number of Iterations	Average User Power (W)	Average SINR (dB)
TPC	51	0.45	0.26
DFC	33	0.38	0.26
OPC	40	0.75	0.42
VTPC	30	0.70	0.37
Proposed 1	29	0.35	0.26
Proposed 2	22	0.67	0.26
Proposed 3	20	0.70	0.26

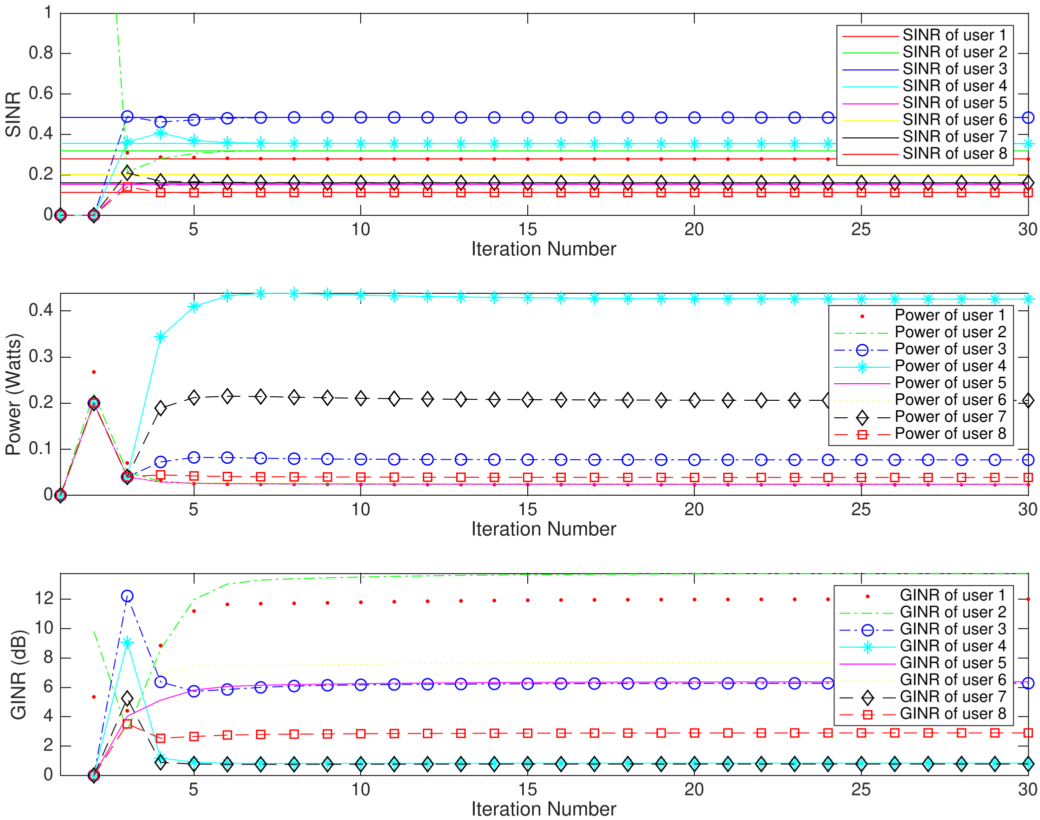

FIGURE 4. Transmit power, SINR and GINR for one trial with proposed approach 1.

C. POWER CONTROL IN RAYLEIGH FADING CHANNELS

To evaluate the performance of the proposed approach in Rayleigh fading, results are obtained with different numbers of users associated with a BS. The target SINRs were randomly chosen from a uniform distribution between 0.1 dB and 0.9 dB. The performance of the proposed power control scheme is compared with that of the DFC, TPC, OPC and VTPC approaches in terms of power consumption, number of iterations for convergence and SINR. The PUs and NUs are uniformly distributed in the geographic area of a cell. The Rayleigh fading channel has T taps where $T = [4, 8, 16, 32, 64]$ [52]. The real and imaginary parts of the channel coefficients are randomly chosen from a Gaussian distribution. The magnitude is then Rayleigh distributed and the phase is uniformly distributed between 0 and 2π. Results are obtained for 100 trials for each number of users with the user locations changed each trial and $\epsilon = 0.001$.

In the first scenario, there is one femtocell with 1 PU and 3 NUs. This cell is located at the center of a square geographic area with dimensions 50 m × 50 m. With TPC and DFC, the target SINRs for the users are

$$\hat{\gamma}_k = [0.29 \;\; 0.16 \;\; 0.31 \;\; 0.41] \text{ dB},$$

which were randomly chosen. With the proposed power control scheme, the first value is for the PU and the others are for the NUs. Table 8 gives the average number of iterations, user power and SINR for the OPC, VTPC and proposed power control approach with 4 users. The TPC and DFC algorithms did not converge so no results are given. This shows that the proposed scheme has the lowest average user power which is 0.29 W. The average number of iterations is 5 which is also the lowest. The average user power for OPC is 2.64 W which is lower than VTPC, but the average number of iterations with OPC is 7 which is higher than VTPC. The average SINR for OPC is 1.60 dB, which is the highest followed by VTPC with 0.82 dB. This is because when the channel conditions are good, the user target SINR values are higher resulting in high transmit powers. These results show that the proposed scheme provides a better balance between the required transmit power and user target SINRs compared to OPC and VTPC.

TABLE 8. Average number of iterations, user power and SINR for the OPC, VTPC and proposed power control approaches with 4 users.

Power Control Scheme	Average Number of Iterations	Average User Power (W)	Average SINR (dB)
OPC	7	2.64	1.60
VTPC	6	2.80	0.82
Proposed	5	0.29	0.29

In the second scenario, there is one femtocell with 2 PUs and 6 NUs. The femtocell is located at the center of a square

TABLE 9. Average number of iterations, user power and SINR for the OPC, VTPC and proposed power control approaches with 8 users.

Power Control Scheme	Average Number of Iterations	Average User Power (W)	Average SINR (dB)
OPC	8	7.07	1.53
VTPC	8	6.90	1.54
Proposed	6	0.13	0.26

geographic area with dimensions 50 m × 50 m. With TPC and DFC, the user target SINRs are

$$\hat{\gamma}_k = [0.28\ \ 0.32\ \ 0.48\ \ 0.36\ \ 0.15\ \ 0.20\ \ 0.16\ \ 0.11]\ \text{dB},$$

which were randomly chosen. With the proposed power control scheme, the first two values are for the PUs and the others are for the NUs. Table 9 gives the average number of iterations, user power and SINR for the OPC, VTPC and proposed power control approaches with 8 users. The TPC and DFC algorithms did not converge so no results are given. This shows that the proposed scheme again has the lowest average user power and number of iterations. The average required power and number of iterations with the proposed scheme are 0.13 W and 6, respectively. The average SINR of the proposed approach is 0.26 dB, while for OPC and VTPC it is 1.53 and 1.54, respectively.

In the third scenario, there is one picocell with 6 PUs and 10 NUs. The picocell is located at the center of a square geographic area with dimensions 300 m × 300 m. With TPC and DFC, the user target SINRs are

$$\hat{\gamma}_k = [0.31\ \ 0.51\ \ 0.28\ \ 0.39\ \ 0.53\ \ 0.37\ \ 0.28\ \ 0.17\ \ 0.19\ \ 0.44\ \ 0.45\ \ 0.24\ \ 0.58\ \ 0.22\ \ 0.51\ \ 0.17]\ \text{dB},$$

which were randomly chosen. With the proposed power control scheme, the first six correspond to the PUs and the last ten to the NUs. Table 10 gives the average number of iterations, user power and SINR for the OPC, VTPC and proposed power control approaches with 16 users. As before, the TPC and DFC algorithms did not converge so no results are given. The proposed scheme again has the lowest average user power and number of iterations which are 0.83 W and 26, respectively. The performance with OPC and VTPC is almost the same. The average number of iterations is 30 for OPC and 34 for VTPC, and the corresponding average user power is 9.33 W and 10.31 W. The average SINR for OPC and VTPC is 2.68 dB and 2.60 dB, respectively.

In the fourth scenario, there is one picocell with 12 PUs and 20 NUs. The picocell is located at the center of a square geographic area with dimensions 300 m × 300 m. With TPC, DFC and the proposed scheme, the target SINRs are randomly chosen between 0.1 dB and 0.6 dB, and the average target SINR is 0.36 dB. The same values were used with the three schemes for a fair comparison. Table 11 gives the average number of iterations, user power and SINR for the OPC, VTPC and proposed power control approaches with 32 users. Again, TPC and DFC did not converge so no results are given. This table shows that the proposed scheme has a lower power consumption and number of iterations than OPC and VTPC, which are 2.56 W and 36, respectively. The average user power with OPC and VTPC is 15.02 W and 16.81 W, respectively, which is approximately five times higher than with the proposed scheme, and the corresponding average number of iterations is 40 and 45. The average SINR with the proposed scheme is 0.52 dB which is reasonable as the target SINR is 0.36 dB. These results show that the proposed scheme provides a better balance between the required transmit power and target SINRs compared to OPC and VTPC. Further, the performance with OPC is slightly better than VTPC.

TABLE 10. Average number of iterations, user power and SINR for the OPC, VTPC and proposed power control approaches with 16 users.

Power Control Scheme	Average Number of Iterations	Average User Power (W)	Average SINR (dB)
OPC	34	9.33	2.68
VTPC	30	10.31	2.60
Proposed	26	0.83	0.30

TABLE 11. Average number of iterations, user power and SINR for the OPC, VTPC and proposed power control approaches with 32 users.

Power Control Scheme	Average Number of Iterations	Average User Power (W)	Average SINR (dB)
OPC	40	15.02	4.39
VTPC	45	16.81	4.35
Proposed	36	2.56	0.52

TABLE 12. Average number of iterations, user power and SINR for the OPC, VTPC and proposed power control approaches with 64 users.

Power Control Scheme	Average Number of Iterations	Average User Power (W)	Average SINR (dB)
OPC	56	26.39	5.44
VTPC	56	30.32	5.37
Proposed	38	6.32	0.39

In the fifth scenario, there is one macrocell with 24 PUs and 40 NUs. The macrocell is located at the center of a square geographic area with dimensions 500 m × 500 m. With TPC, DFC and the proposed scheme, the target SINRs are randomly chosen in the range 0.1 to 0.9 dB. Table 12 shows the average number of iterations, user power and SINR for the OPC, VTPC and proposed power control approaches with 64 users. The TPC and DFC algorithms did not converge so no results are given. The proposed scheme again has a lower average user power than OPC and VTPC. The average user power and number of iterations for this scheme are 6.32 W and 38, respectively. The average user power with OPC is

26.4 W which is lower than VTPC, but the average SINR of 5.44 dB is higher than that of VTPC.

V. CONCLUSION

In this paper, an efficient cell association and power control (CAPC) scheme was proposed. With cell association, the product of the channel access likelihood (CAL) and channel gain to interference plus noise ratio (GINR) was considered for priority user (PU) cell association while network utility was considered for normal user (NU) cell association. Results were obtained which show that this provides a fairer load distribution between MBSs and SBSs, and a higher fairness index, than the max SINR and cell range expansion (CRE) schemes. In AWGN channels, DFC outperforms TPC and VTPC and is much better than OPC. Further, the PU target SINRs are not all satisfied with OPC. Many NUs are not satisfied with their target SINRs with VTPC and TPC, and the target SINRs for the NUs are not always satisfied with DFC.

Three new power control approaches were proposed. The results for these methods show that the target SINRs for all PUs are satisfied while a large number of NUs are satisfied. In addition, the proposed approaches require fewer iterations to converge than the TPC, DFC, OPC and VTPC schemes. Approach 1 requires the lowest average user power, while approaches 2 and 3 require a higher average user power than TPC and OPC. In Rayleigh fading channels, the TPC and DFC schemes did not converge to a solution while OPC and VTPC provided similar performance. The proposed approach provided the best performance for all scenarios in these channels.

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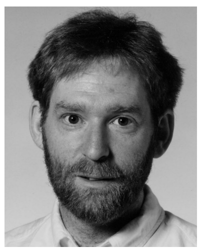

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