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Quality-of-Service Aware Game Theory-Based Uplink Power Control for 5G Heterogeneous Networks

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Abstract

The fifth-generation (5G) mobile communication system is expecting to support users with diverse data rate requirements by densely deploying small cells. The users attached with small cells make use of the same frequency band as the existing macro cell users, that causes severe co-channel interference and degrades the performance. To overcome this challenge, we propose a game theoretical framework for the optimal uplink power allocation for small cells, i.e., femtocell deployed underlaid macrocell. In this paper, femtocell users play a non-cooperative game to choose the optimal power to maximize the sum-rate of the system. Furthermore, an iterative quality-of-service (QoS)-aware game theory based power control (QoS-GTPC) scheme is proposed to optimize the femtocell user power taking into account macrocell user QoS requirements. Simulation results verify that the proposed QoS-GTPC scheme significantly improves the sum-rate and reduces outage and interference, as compared with conventional power control scheme.

Keywords Game-theory · Power control · 5G system · Interference management

1 Introduction

The fifth-generation (5G) mobile communication system is targetting to achieve high data rate and low-latency solutions [1]. This target can be achieved by deploying dense small cells [2–5], permitting device-to-device (D2D) communications [6–8], enabling moving networks [9–11], and using mmWave communications [12]. Among these solutions, small cells (femtocells) deployment is the most reliable and efficient solution because of the fact that the femtocells dense deployment increases the system capacity by reusing the same frequency band. However, its deployment results in severe co-channel interference among femtocell users (FUE) and conventional macrocell user (MUE).

To solve the co-channel interference problem, avrious resource allocation schemes such as quality-of-service (QoS)-aware coordinated scheduling scheme was presented in [13]. This scheme consider coordinated scheduling among users to reduce interference. But this scheme increases the feedback overhead as it demands neighbor base station scheduling information for its successful implementation. Similarly, in [14] the author presented QoS-aware resource allocation scheme to reduce interference among MUE and FUE by enabling fractional frequency reuse. This scheme reduces spectral efficiency because of not reusing the similar frequency bands in the neighbor cells.

To address this challenge, in literature [15, 16] numerous power control solutions exists but unfortunately most of them have high complexity as they need centralized processing. For instance, the power headroom report based power control scheme discussed in [17] needs frequent feedback of remaining power for its implementation. Similarly, in [16] authors discussed the power control scheme that reduces the power based on the neighbor situation that also demand the neighbors information. Hence, the schemes discussed here have high complexity and more feedback burden. To reduce this complexity, user-centric approach is attracting researchers attention. In user-centric approach, the main interest is on user information

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only rather than the network centric approach that requires complete network information, hence have high complexity. Thus, the fusion of these two approaches can generate some interesting results [18].

Numerous power control schemes [17, 19] need centralized information for its successful implementation. To overcome these limitations non-cooperative game theory models can be a best possible solution to optimize the resource allocation in femtocells as it distributes the control among users.

First of all, we would like to discuss the existing schemes as a motivation for proposing iterative quality-of-service (QoS)-aware game theory based power control (QoS-GTPC) scheme. For instance, the non-cooperative game theoretic based resource and power allocation algorithm is proposed [20] to reduce interference for the uplink multi-user frequency division multiple access networks. This scheme targeted the increase in energy efficiency but only for conventional macro cell users. Hence, this solution cannot be adopted for cellular system with dense small cell deployment. In [21], authors proposed the joint resource and power allocation for high power conventional macro cell and low-power small cell base stations. They also targeted to reduce the co-channel interference by allocating the resources based on the user-centric fashion, but with centralized user association criteria. This scheme also neglects users with different QoS priority while allocating resources.

In [22], authors presented non-cooperative game-theory based power control scheme for machine type communications. This scheme focused on reliable communication by considering the power consumption and signal-to-interference-plus-noise-ratio (SINR) constraints. However, this scheme cannot be suitable for the system model considered here. Hence, the presented schemes needs ample enhancements to be adopted in dense small cells environment. Similarly, a role game theory to control the uplink power is proposed in [23] to address this challenge. In this scheme, authors defined diverse roles for users deployed within the cell coverage, and various parameters such as user location, user activity, and service type are considered to design a system throughput maximization utility. However, this technique does not provide the optimal solution because of managing numerous roles at the same time, that in turn enhances the system complexity.

The hierarchical game with a multiple-leader and multiple-follower is modeled in [24] to reduce co-channel interference. Here, macro and femtocells users' target is to maximize the system capacity utility function. In this game theoretical approach, MUEs are leader while the FUEs are the follower according to the multiple-leader and multiple-follower approach. The iterative power update rule is adopted for MUE and FUE power allocation. However, during power allocation local search technique is adopted which results in high complexity, and also it ingnores user QoS requirements. Similarly, in [25], the Stackelberg game model is considered that also ignores the users QoS requirements and only focuses to enhance the revenue of MUE.

The non-cooperative game is formulated in [26] to find the optimal power in heterogeneous network scenario. Here, author proposed the energy efficient power allocation scheme with duality concept, that is the energy of macro base station is maximized and femtocells SINR is improved. But still this scheme cannot be adopted for scenario where the users' have diverse QoS requirements. Similarly in [27], a cooperative bargaining game-based method for energy management in heterogeneous network is proposed. The proposed scheme design the utility function that jointly considers the spectral efficiency, deployment efficiency, and energy efficiency problem. They tried to reduce the complexity by increasing the system efficiency but neglects the users QoS requirements. Motivated by this, we propose a QoS-aware game theory-based power control (QoS-GTPC) scheme that optimizes the sum-rate of FUE and MUE by using non-cooperative game and also optimize the users' power based on QoS priority. We design a strategy that reaches the Nash equilibrium by taking into account the users' power and QoS priority constraints.

The rest of the paper is organized as follows. In Section 2, we present system model. In Section 3, we discuss the problem formulation. The proposed QoS-GTPC scheme is discussed in Section 4. Section 5 summarizes the simulation results and finally Section 6 concludes the paper.

2 System model

We consider a two-tier heterogeneous network (HetNet) uplink (UL) cellular scenario with underlaid femto eNodeB (FeNB). Two-tier HetNet consists of an enhanced nodeB (eNB), a set of $\mathcal{K} = \{1, ..., K\}$ FeNB that are randomly deployed in the coverage of eNB, and a set of MUEs and FUEs, $\mathcal{U} = \{1, ..., U\}$ as shown in Fig. 1. We assume that initially eNB, FeNB, and all users transmit with a maximum power $P^{\max}$. We also assume that each user u can associate with maximum one cell at a time. We summarized the list of key mathematical symbols used here in Table 1.

In this paper, the received SINR (γ) for the j-th MUE is evaluated as

$$\gamma_m^j = \frac{P_{m,j}^{\text{tx}} |h_{m,j}|^2}{\sum_{k=2,k\neq 1}^{U} |h_{f,k}|^2 P_{f,k}^{\text{tx}} + \sigma^2}, \tag{1}$$

where $|h_{m,j}|^2$ and $|h_{f,k}|^2$ are respectively the channel gains for the j-th MUE and k-th FUE, σ^2 is the variance of

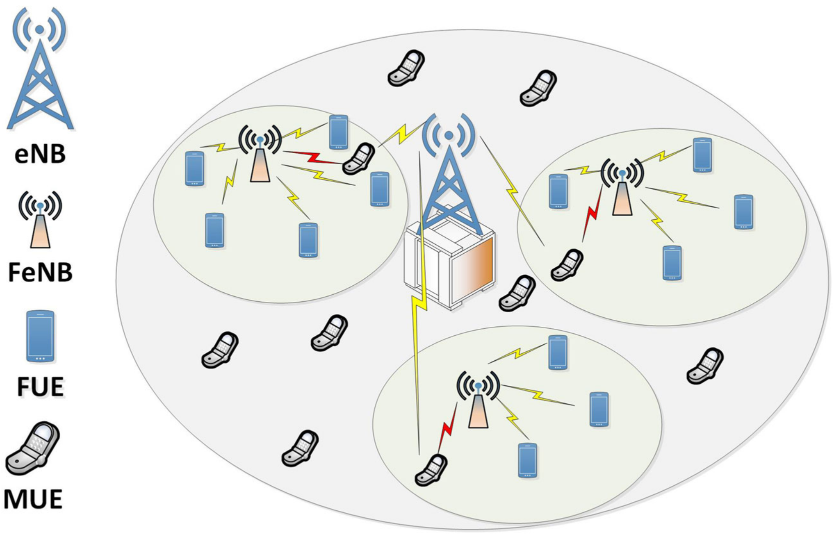

Fig. 1 Heterogeneous network system model

additive white Gaussian noise (AWGN) at the receiver. The channel gain h for MUE and FUE can be expressed as $h = FL$, where F and L are the fading and pathloss models, respectively. In this paper, L for user u connected to eNB and FeNB can be evaluated by using urban pathloss model, respectively as

$$L(dB) = \begin{cases} 15.3 + 37.6 \log 10(d) & \text{eNB model} \\ 127 + 30 \log 10(d/1000) & \text{FeNB model,} \end{cases} \quad (2)$$

where d is the distance from user u to base station. The fading F is calculated by using Ped-B model as recommended by International Telecommunications Union (ITU) [28]. The MUE transmit power $P^{\text{tx}}_{m,j}$ in Eq. 1 can be either maximum power $P^{\max}$ or P^{FPC}, where P^{FPC} is determined as

$$P_u^{\text{FPC}}(dB) = \min\{P^{\max}, P_o + \alpha PL\}, \quad (3)$$

where $P_o = P_o^{\text{cell}} + P_o^{\text{UE}}$ is the SINR target control parameter, with P_o^{cell} and P_o^{UE} being the cell-specific and user specific parameters, respectively. Similarly, the SINR of the k-th FUE is evaluated as

$$\gamma_f^k = \frac{P^{\text{tx}}_{f,k}|h_{f,k}|^2}{|h_{m,j}|^2 P^{\max/\text{FPC}}_{m,j} + \sigma^2}. \quad (4)$$

Here, the k-th user is considered to be in the outage if the received SINR ($\gamma^k_{f/m}$) is below the SINR threshold (γ^{th}). Thus, based on it the outage probability is

$$Pr(outage) = 1 - Pr(\gamma^k_{f/m} > \gamma^{th}), \quad (5)$$

where $Pr(\gamma^k_{f/m} > \gamma^{th})$ represents the probability that the receive SINR is higher than the SINR threshold, and hence that user is not in outage state and vice versa. By using Eqs. 1 in 5, the outage probability for femto users can be written as

$$Pr(\text{outage}) = 1 - Pr\left(\frac{P^{\text{tx}}_{f,k}|h_{f,k}|^2}{|h_{m,j}|^2 P^{\max/\text{FPC}}_{m,j} + \sigma^2} > \gamma^{th}\right). \quad (6)$$

Similarly, using Eqs. 4 in 5, the outage probability for macro users can be calculated as

$$Pr(\text{outage}) = 1 - Pr\left(\frac{P^{\text{tx}}_{m,j}|h_{m,j}|^2}{\sum_{k=2,k\neq 1}^{U} |h_{f,k}|^2 P^{\text{tx}}_{f,k} + \sigma^2} > \gamma^{th}\right). \quad (7)$$

In this paper, we consider an N-player non-cooperative game, with $\mathcal{N} := \{1, ..., N\}$ denotes the player set. In this game, the players maximize their utility without caring

Table 1 Important symbols

Symbol	Definition
$\mathcal{K}$	Set of femtocells
$\mathcal{U}$	Set of users involved in communication
$P^{\text{tx}}_{m,j}$	j-th macro user transmit power connected to m-th eNB
$P^{\text{tx}}_{f,k}$	k-th femto user transmit power connected to f-th FeNB
P^{FPC}_u	fractional power control based user transmit power
B	Bandwidth
R	Resource blocks
$\psi_{u,j}$	User association indicator for user u associated with j-th base station
L, F	Pathloss, fading
P_o	Signal-to-noise-ratio (SINR) target control parameter
α	Pathloss compensation factor
δ	Priority indicator
γ	SINR
γ_{th}	SINR threshold

about other players. However, the outcome depends on the strategy of all the players. Here, the decision variable of player u is its transmit power denoted as $p_u \in P_u$, where P_u is the action set of player u. Our utility function is to maximize the sum-rate of the FUEs and the MUEs connected to FeNB by taking into consideration the users QoS and interference constraints.

3 Problem formulation

In this section, the non-cooperative game is played to find the FUE transmit power that can maximize the sum-rate of both FUEs and MUEs. The sum-rate utility function of FeNB by considering (1) and (4) is written as

$$U\left(p_u, p_{-u}\right) = \log_2(1+\gamma_m^j) + \log_2(1+\gamma_f^k), \tag{8}$$

where p_u is the transmit power of the u-th user and p_{-u} is the transmit power of all the users except the u-th user. Before problem formulation, we need to check the convexity of the utility function, that is to check whether the problem can be formulated as either maximization or minimization problem. The utility function in Eq. 8 is convex if and only if its 2$^{\text{nd}}$ order derivative is monotonically non-decreasing. By taking its 1$^{\text{st}}$ derivative we have

$$\frac{dU}{dp_{f,k}} = \frac{d}{dp_{f,k}}\left(\log_2(1+\gamma_m^j)\right) + \frac{d}{dp_{f,k}}\left(\log_2(1+\gamma_f^k)\right), \tag{9}$$

$$= \frac{d}{dp_{f,k}}\left(\log_2\left(1+\frac{p_{m,j}^{\max}|h_{m,j}|^2}{\sum_{k=2,k\neq 1}^{U}|h_{f,k}|^2 p_{f,k}+\sigma^2}\right)\right) + \frac{d}{dp_{f,k}}\left(\log_2(1+\frac{p_{f,k}|h_{f,k}|^2}{|h_{m,j}|^2 p_{m,j}+\sigma^2})\right), \tag{10}$$

By proceeding 2$^{\text{nd}}$ derivative with respect to $p_{f,k}$ in Eq. 9 and by some algebraic operations, we obtain

$$\frac{d^2U}{dp_{f,k}^2} = -\frac{|h_{f,k}|^2|h_{f,k}|^2}{\left(p_{m,j}^{\max}|h_{f,k}|^2+\sigma^2+p_{f,k}|h_{f,k}|^2\right)^2} + \frac{p_{m,j}^{\max}|h_{m,j}|^2|h_{f,k}|^2|h_{f,k}|^2}{\left(p_{f,k}|h_{f,k}|^2+\sigma^2+p_{m,j}^{\max}|h_{m,j}|^2\right)^2} \tag{11}$$

From Eq. 11, we conclude that the function is concave, since we have

$$\frac{d^2U}{dp_{f,k}^2} < 0 \tag{12}$$

Thus, due to the concave nature we have the following sum-rate maximization problem (P1)

$$\begin{aligned} \mathbf{P1}: &\max\ U\left(p_u, p_{-u}\right) && (13a)\\ &\text{s.t. } \gamma_f^k \geq \gamma_{th}, && (13b)\\ &\quad \gamma_m^j \geq \gamma_{th} && (13c)\\ &\quad p_u^{\text{FPC}} \leq p_u^{\text{tx}}(t) \leq p_u^{\max}. && (13d) \end{aligned}$$

Here, the SINR at the MUE and FUE (13b, 13c) and power constraints (13c) are crucial to guarantee the user reliability. The solution to the problem (P1) can be found when each player u achieves the Nash equilibrium. The player in a non-cooperative game can achieve the Nash equilibrium when

$$U\left(p_u^*, p_{-u}^*\right) \geq U\left(p_u, p_{-u}^*\right); \forall p_u \in P_u \tag{14}$$

To find the solution of P1 problem, recall (9) and let $\frac{dU}{dp_{f,k}} = 0$, we have

$$\frac{dU}{dp_{f,k}} = \frac{d}{dp_{f,k}}\left(\log_2\left(1+\frac{p_{m,j}^{\max}|h_{m,j}|^2}{\sum_{k=2,k\neq 1}^{U}|h_{f,k}|^2 p_{f,k}+\sigma^2}\right)\right) + \frac{d}{dp_{f,k}}\left(\log_2\left(1+\frac{p_{f,k}|h_{f,k}|^2}{|h_{m,j}|^2 p_{m,j}+\sigma^2}\right)\right) = 0, \tag{15}$$

By performing some algebraic operations of Eq. 15, we obtain

$$-\frac{p_{m,j}^{\max}|h_{m,j}|^2|h_{f,k}|^2}{\left(p_{f,k}|h_{f,k}|^2+\sigma^2\right)+\left(p_{f,k}|h_{f,k}|^2+\sigma^2+p_{m,j}^{\max}|h_{m,j}|^2\right)} + \frac{|h_{f,k}|^2}{p_{m,j}^{\max}|h_{f,k}|^2+\sigma^2+p_{f,k}|h_{f,k}|^2} = 0 \tag{16}$$

By further simplification, we can rewrite (16) as

$$\frac{p_{m,j}^{\max}|h_{m,j}|^2|h_{f,k}|^2}{|h_{f,k}|^2} \times \left(1+\frac{p_{f,k}|h_{f,k}|^2+\sigma^2}{p_{m,j}^{\max}|h_{f,k}|^2}\right) = 0 \tag{17}$$

It can be further simplified as

$$\frac{|h_{m,j}|^2\left(p_{m,j}^{\max}|h_{f,k}|^2+\sigma^2+p_{f,k}|h_{f,k}|^2\right)}{|h_{f,k}|^2} = 0 \tag{18}$$

Using some trigonometric rules, we further simplified it to get the FUE power as

$$p_{f,k} = \frac{-(2\sigma^2) \pm \sqrt{(2\sigma^2)^2 - 4|h_{m,j}|^2(-c)}}{2|h_{m,j}|^2}, \tag{19}$$

Since, power cannot be negative. So, FUE power can be calculated as

$$p_{f,k} = \frac{-(2\sigma^2) + \sqrt{(2\sigma^2)^2 + 4|h_{m,j}|^2(c)}}{2|h_{m,j}|^2}, \tag{20}$$

where

$$c = \frac{(p_{m,j}^{\max})^2 |h_{m,j}|^2 |h_{f,k}|^4 - |h_{f,k}|^2 \sigma^2}{|h_{m,j}|^2 |h_{f,k}|^2}. \tag{21}$$

Algorithm 1 QoS-GTPC Iterative Algorithm

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Initialization: $t = 1, \delta \in \{0, 1\}$
Assumptions: Initially, HII($\phi$) = 0, $p_{f,k} = p_{f,k}^{\max}$
while ($\gamma^{m/f} \geq \gamma^{\text{th}}$ or $t$ = maxTTI) do
    Allocate the FUE power using the following
    $p_{f,k}(t) = \min\left(\frac{-(2\sigma^2)+\sqrt{(2\sigma^2)^2+4|h_{m,j}|^2(c)}}{2|h_{m,j}|^2}, p^{\max}\right)$
    if $\delta = 0$ (MUE has high priority) then
        if $\phi = 1$ then
            $p_{f,k}^*(t) = p_{f,k}(t) - \Delta p$
            until $\gamma^m \geq \gamma^{\text{th}}$
        else
            $p_{f,k}^*(t) = p_{f,k}(t) + \Delta p$
            until $\gamma^f \geq \gamma^{\text{th}}$ or $\phi = 1$
        end
    else
        $p_{f,k}^*(t) = p_{f,k}(t)$
    end
end
```

4 Proposed iterative QoS-GTPC scheme

In this section, we propose the iterative QoS-GTPC scheme to optimize the FUE transmit power in Eq. 20. The main steps are summarized in Algorithm 1 and briefly discussed here.

In QoS-GTPC, initially we allocate maximum power to FUE. But the maximum power allocation to FUE generates severe UL co-channel interference which in turn decreases MUE SINR below the threshold, i.e., $\gamma^m < \gamma^{th}$. Hence, at this moment eNB will broadcast the high-interference indicator (HII (ϕ) = 1) alert to FUE in the surroundings. Based on HII, the FUE transmit power is decreased by amount Δp to optimize the FUE transmit power, that is $p_{f,k}^*(t) = p_{f,k}(t) - \Delta p$, where t is the transmission time interval (TTI). Here, Δp is calculated using bisection search optimization algorithm.

If eNB continuously broadcasts HII, then FUE and MUE QoS priorities are compared before further reducing the FUE transmit power. The QoS priorities among the users are decided based on the QoS control indicator (QCI) parameter described in Table 2. However, in this paper we only modeled two QoS as an example. That is, the users are either using using voice services or sending data. So, the user using voice services (QCI=1) are considered as high priority and the other as low-priority user (QCI=8). In Table 2, GBR stands for guaranteed bit-rate (GBR) which shows that the connection is guaranteed for real-time voice service whereas non-GBR type connection is used for data services.

If MUE has high priority than FUE (i.e., $\delta = 1$), so reduce FUE power by step Δp to achieve the Nash equilibrium. Otherwise, if no HII is reported, FUE power increase by Δp till HII is reported or $\gamma^f < \gamma^{th}$. Furthermore, if FUE has priority then it can continue using power calculated using (20). This process will keep going on till one of the two conditions are satisfied, that is ($\gamma^{m/f} \geq \gamma^{\text{th}}$ or t = maxTTI). Here, maxTTI represents the number of simulated subframes.

5 Simulation results

In this section, we present the simulation results of our proposed QoS-GTPC scheme using different simulation parameters summarized in Table 3. The performance is evaluated under the HetNet scenario described in Section 2 and with 1 × 1 single-input and single-output (SISO) scenario.

5.1 Sum-rate under QoS-GTPC

Firstly, we compare the user sum-rate performance under the proposed QoS-GTPC and the conventional fractional

Table 2 Standardized QCIs for LTE

QCI	Resource type	Priority	Packet delay budget(ms)	Packet error loss rate	Example services
1	GBR	2	100	10^{-2}	Conversational voice
2	GBR	4	150	10^{-3}	Conversational video (live streaming)
3	GBR	5	300	10^{-6}	Non-conversational video (buffered streaming)
4	GBR	3	50	10^{-3}	Real-time gaming
5	Non-GBR	1	100	10^{-6}	IMS signaling
6	Non-GBR	7	100	10^{-3}	Voice, video (live streaming), interactive gaming
7	Non-GBR	6	300	10^{-6}	Video (buffered streaming)
8,9	Non-GBR	8,9	300	10^{-6}	TCP-based), chat, FTP, p2p file sharing

Table 3 Simulation parameters

Parameters	Values
Frequency	2 GHz
Bandwidth (B)	10 MHz
Resource blocks (R)	50
Number of eNB and FeNB	1, 8
FeNB Deployment	Outdoor
UEs per eNB & FeNB	10, 3
Noise Spectral Density	–175 dBm/Hz
SINR threshold γ_{th}	5dB
No. of subframes (maxTTI)	1000
Simulation drops	20

power control (FPC) scheme. It can be clearly seen that the user edge rate is increased from 2.8 Mbps to 4.1 Mpbs, and thus around 46% improvement is achieved under the proposed QoS-GTPC scheme as shown in Fig. 2. Similarly, the average sum-rate is compared, and we notice that the proposed QoS-GTPC rate is elevated from 8.7 Mbps to 15.4 Mbps when compared at 50% of cumulative distributive function (CDF), where it achieves approximately 76% gain. The main reason behind this improvement is that QoS-GTPC optimizes the FUE transmit power by caring users' QoS requirements.

5.2 Interference reduction under QoS-GTPC

Secondly, we compare the user receive interference among the proposed QoS-GTPC scheme and the conventional FPC scheme. We found that interference in the proposed scheme is around 5 dBm less as compared to conventional FPC when compared at 50% of CDF as depicted in Fig. 3. It proves that proposed scheme decreases a substantial amount of interference.

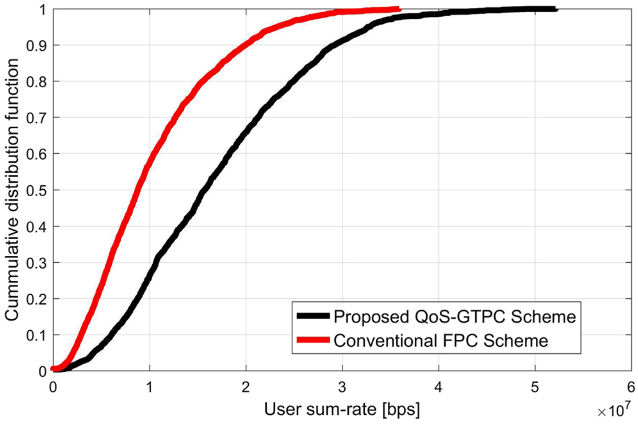

Fig. 2 User sum-rate under proposed QoS-GTPC

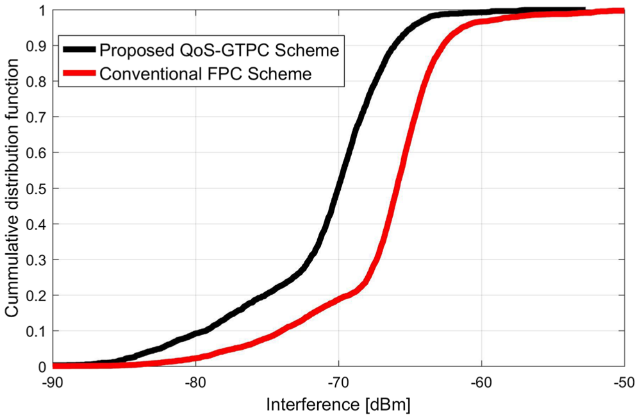

Fig. 3 Interference reduction under the proposed QoS-GTPC

5.3 SINR improvement under QoS-GTPC

In Fig. 4, the SINR is compared among the proposed QoS-GTPC and conventional FPC scheme. The SINR is measured for cell edge and the cell center users. We compared at the SINR at 5% of CDF for cell edge users, the results clearly indicates that with the proposed QoS-GTPC scheme cell edge users' SINR improves around 1.3 dB as compared with C-FPC. Moreover, around 61% SINR gain is achieved for cell center users for the proposed QoS-GTPC scheme when compared at 50% of CDF. These gains are achieved because QoS-GTPC scheme optimally allocate the resources among users by caring users' QoS priority.

5.4 Outage reduction under QoS-GTPC

The outage performance of the proposed QoS-GTPC and C-FPC schemes are compared at 5 dB SINR threshold. From Fig. 5 we can clearly notice that there is an outage around 63% for users using the C-FPC scheme. This outage reduces

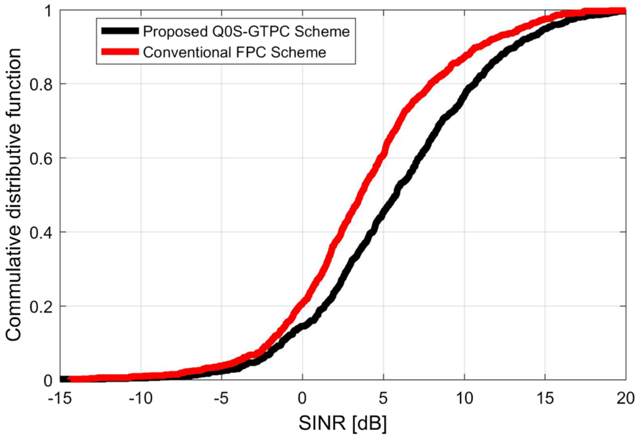

Fig. 4 SINR comparison for the proposed QoS-GTPC and C-FPC schemes

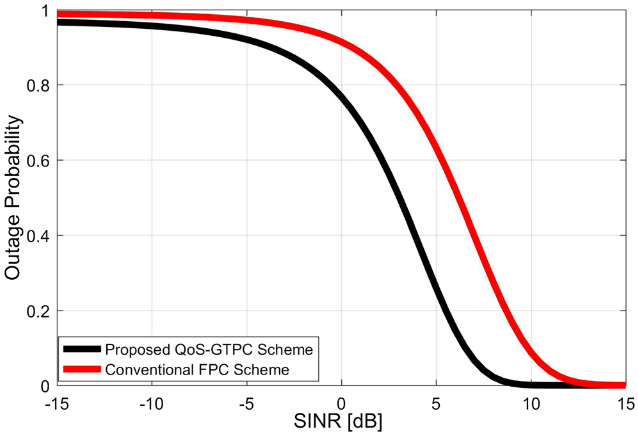

Fig. 5 Outage probability under the proposed QoS-GTPC

to around 26% users when we employ the proposed QoS-GTPC scheme. This proves that users under QoS-GTPC are getting much better channel condition which results in outage reduction. This trend also continues for other threshold values, and hence the proposed scheme is suitable for cell edge users as well as for center users based on the mentioned benefits.

6 Conclusion

In this paper, we proposed a QoS-aware game theory-based power control scheme which optimizes the femtocell users' power to reduce the co-channel interference. We also derived the femtocell users power using game theory, that in turn maximize the system sum-rate and also reduce interference in HetNet scenario. Simulations results proved that the proposed scheme provides us 76% sum-rate gain and decrease the substantial amount of interference as compared to the existing conventional fractional power control (C-FPC) scheme. By this scheme, we also achieves around 61% average SINR improvement as compared with C-FPC scheme. Similarly, the outage decreases by 31% in the proposed QoS-GTPC scheme. These improvements proves that the QoS-GTPC scheme can be adopted for the 5G mobile system.

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