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Quality of Service Provisioning for D2D Users in Heterogeneous Networks

Tien Hoa Nguyen[1,*], Dang Qua Nguyen[1], Viet Dung Nguyen[2]
[1]School of Electronics and Telecommunications, Ha Noi University of Science and Technology, Ha Noi, Vietnam
[2]Information & Telecommunication Technology Center, University of Kansas, USA

Abstract

This paper investigates power allocation for D2D communications in a Heterogeneous Network (HetNet) which includes a macro cell and pico cells, whereas femto cells are distributed inside. The objective is to minimize the total power consumption of D2D transmitter while satisfying a set of Quality of Service in D2D receivers and cellular users communication interference. To this end, we first obtain expression for the formula of signal to interference plus noise ratio (SINR) and spectral efficiency of each D2D receiver. Then, an optimization problem is formulated to minimize the total transmit power of D2D transmitters subject to QoS constraints. It is shown that this optimization problem is linear programming and it can be solved in polynomial time with standard tools. In addition, the maximization value of D2D pair transmission rates are determined with fixed cellular users parameters.

Keywords: Heterogeneous networks, total transmit p ower minimization, quality of service, D2D communications

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1. Introduction

Recent years have witnessed a significant increase in the number of smart devices and applications which contributes to the considerable growth of mobile data traffic. According to Cisco VNI publication, it is predicted that the number of mobile-ready connections in 2020 is approximately 12 billion [1]. Likewise, the monthly global mobile data traffic will reach a peak of 30.6 exabytes by 2020 [1] with various kinds of mobile network and wireless communication such as wireless sensor networks [2] [3], ultra-dense mobile networks [4], and vehicular ad-hoc networks,. . . . As a result, the next-generation mobile communication networks (5G) need to deploy new technologies to deal with the afore requirements [5].

Specifically, to improve the spectral efficiency, a macro Base Station (BS) can deploy small scale BSs such as pico, femto BSs inside a macro cell [6]. These small BSs have the advantages of inexpensive development, low-power consumption Device-to-Device (D2D) communication is a promising technique to cope with the increasing traffic in the future mobile communication networks [7]. The cell deployment as mentioned above is called heterogeneous networks (HetNets). In addition, enabling device-to-device (D2D) communication to operate in the licensed frequencies occupied by cellular user equipments is another way to deal with these traffic increase [8]. D2D communication paradigm allows two users in a short distance to communicate directly without data transmission through BSs or other core networks. Therefore, this technique can considerably reduce the power consumption of cellular user equipments and end-to-end transmission delay and effectively enhance network spectral efficiency [8]. However, several challenges were pointed out when deployed the D2D communication in cellular networks.In [9], the energy-efficient for maximizing the number of dicovered users was investigated under the major constraint of overlay interference in cellular networks. In addition, the problem of power allocation for energy efficiency and secrecy in D2D communication were considered in various scenarios [10], [11]. Moreover, the D2D user power allocation and beamforming technique can be combined to acheive energy efficient satisfying to QoS constraints in multi-relay communications, [12]. In [13], non-cooperative energy efficient power allocation in D2D communication based on reinforcement learning approach to optimize user experience.

In the downlink (DL) scheme, the D2D receivers suffer interference from the transmission of nearby cellular users and other D2D users. This interference

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[*]Corresponding author. Email: hoa.nguyentien@hust.edu.vn

will result in a high packet error rate and low Quality of Service (QoS) degree. In order to provide customized and personalized services for D2D users which are in coexistence with cellular user equipments in a high-density HetNet, it is important for the network operator to ensure a high QoS for each user while reducing power consumption of cellular user devices. Many interference management and resources allocation techniques for D2D communication have been investigated [14], [15], [16]. In [17], the authors presented a principle to maximize the system throughput while ensuring the QoS requirements of cellular users and D2D users which includes several factors such as mode selection for D2D communication, resource allocation, and power control. Beside, in [18] the authors optimized the total transmit power of all users and illustrated resource allocation methods in a cellular network with the coexistence of nonorthogonal multiple access (NOMA) based D2D pairs simultaneously QoS level requirements of all users. Furthermore, a power distribution approach for D2D communication in an underlaid cellular network based on the stochastic geometry is discussed in [15].

However, these papers mainly concentrated on the D2D communication model in one or two tiers cellular HetNets. In this paper, we will consider three tiers HetNets which include pico cells, and femto cells distributed in a macro cell. Moreover, we consider that all cellular BSs are equipped with multiple antennas and all users have single antenna for transmission. It is emphasized that the paper focuses on minimizing the total power of D2D transmitters and cellular users are fixed. The contributions of the paper are follows

- We develop a new D2D communication scenario in Heterogeneous Network with the coexistence of cellular users in which Base Stations of cells are equipped multiple antennas and all users are single antenna. From the model description, we formulate and calculate the achievable rate for D2D users.
- Base on the formulated D2D pair transmission rate formulas, we determine the lower and upper bound on the spectral efficiency of D2D receivers.
- We solve the problem of minimizing the total transmit power minimization for D2D transmitters under the limited power budget and spectral efficiency requirements of the D2D receiver. This optimization problem is shown to be a linear program, hence the optimal solution can see in polynomial time.

The rest of this paper is organized as follows. The system model of D2D communication in HetNets is described in Section II. After that, the total transmit power optimization of D2D communication is formulated in Section III. Numerical results are presented in Section IV. Finally, Section V concludes the paper.

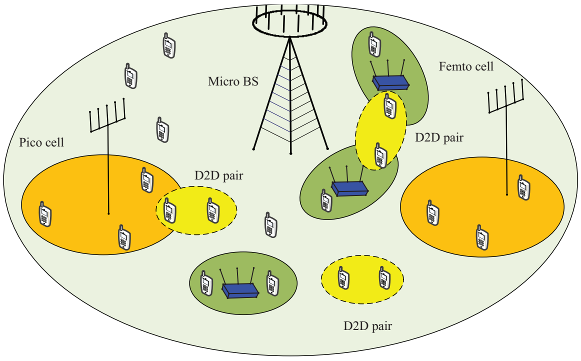

Figure 1. Illustration of the considered heterogeneous network.

2. System Model

As illustrated in Figure 1, we consider a downlink complex single-cell heterogeneous network. Specifically, the model includes a macro base station equipped with N_m antennas and serving U_m single-antenna users which are called macro users. In addition, there are P pico cells that are arbitrarily deployed in the coverage area of the macro base station. Each pico cell consists of one small base station with N_p antennas and transmitting information to U_p single-antenna users. Besides, F femto cells, each utilizing one N_f-antenna base station and delivering information to U_f single-antenna users. Especially, we suppose that there are D pairs of D2D users which are distributed randomly in the network as illustrated in Figure 1. Although the channels change over time and frequency, we partition it into coherence intervals with flat propagation channel. Furthermore, all of the channels between BSs and D2D users are characterized as in Table 1.

Table 1. Propagation channels in the considered system model.

Notation	Type	Expression
$\mathbf{h}_j^0$	$\mathbb{C}^{M_m}$	Macro BS and received D2D device in pair j
$\mathbf{h}_j^i$	$\mathbb{C}^{M_p}$	Pico BS i and received D2D device in pair j
$\hat{\mathbf{h}}_j^i$	$\mathbb{C}^{M_f}$	Femto BS i and received D2D device in pair j
h_j^i	$\mathbb{C}$	D2D device i and received D2D device in pair j

2.1. Downlink Transmission for D2D Pairs

In the downlink transmission phase, the macro base station sends a complex data signal $x_{0,k} \in \mathbb{C}$ to its macro user k with $\mathbb{E}\{|x_{0,k}|^2\} = 1$. This signal is steered to user k by the beamforming vector $\mathbf{w}_{0,k} \in \mathbb{C}^{M_m}$. Thus the transmitted signal at the macro base station is

$$\mathbf{x}_0 = \sum_{k=1}^{U_m} \sqrt{p_{0,k}}\mathbf{w}_{0,k} x_{0,k} \in \mathbb{C}^{M_m}, \tag{1}$$

where $p_{0,k} \geq 0$ is the power that the macro base station allocates to the data symbol of macro user k. To take advantages in power allocation, we deploy the normalized beamforming vectors in (1) such that $\|\mathbf{w}_{0,k}\| = 1, \forall k = 1, \ldots, K_m$. Similarly, the ith picocell, $i = 1, \ldots, P$, transmits signals to its K_p users as

$$\mathbf{x}_i = \sum_{k=1}^{U_p} \sqrt{p_{i,k}}\mathbf{w}_{i,k} x_{i,k} \in \mathbb{C}^{M_p}, \tag{2}$$

where $x_{i,k}$ is the data symbol that the ith picocell sends to user k and $\mathbb{E}\{|x_{i,k}|^2\} = 1$. The beamforming vector $\mathbf{w}_{i,k} \in \mathbb{C}^{M_p}$ satisfies $\|\mathbf{w}_{i,k}\| = 1$ Similarly, the transmitted signal $\hat{\mathbf{x}}_i$ at the base station of the ith femtocell is defined as

$$\hat{\mathbf{x}}_i = \sum_{k=1}^{U_f} \sqrt{\hat{p}_{i,k}}\hat{\mathbf{w}}_{i,k} \hat{x}_{i,k} \in \mathbb{C}^{M_f}, \tag{3}$$

where the data symbol sent to user k is denoted as $\hat{x}_{i,k}$with$\mathbb{E}\{|\hat{x}_{i,k}|^2\} = 1$, and the corresponding beamforming vector $\hat{\mathbf{w}}_{i,k} \in \mathcal{C}^{M_f}$, $\|\hat{\mathbf{w}}_{i,k}\| = 1$ Finally, the transmitted signal at the ith D2D pair is

$$\tilde{x}_i = \sqrt{\tilde{p}_i}\frac{h_i^i}{|h_i^i|} x_i, \tag{4}$$

where x_i is the data symbol sent by the transmit D2D device in pair i and $\tilde{p}_i$ is the allocated transmit power. Here, $\tilde{p}_i$ is bounded by the power constraint $\tilde{p}_i \leq P_{\max,i} \forall i = 1, 2 \ldots D$. From the above definitions of the transmitted data, the received signal at D2D receiver j is then given as

$$y_j = \mathbf{h}_j^{0,H}\mathbf{x}_0 + \sum_{i=1}^{P} \mathbf{h}_j^{i,H}\mathbf{x}_i + \sum_{j=1}^{F} \hat{\mathbf{h}}_j^{i,H}\hat{\mathbf{x}}_i + \sum_{i=1}^{D} h_j^{i,*}\tilde{x}_i + n_j, \tag{5}$$

where n_j is complex Gaussian noise with distribution $\mathcal{CN}(0, \sigma^2)$.

2.2. Analysis of Downlink Spectral Efficiency

For each D2D pairs, the received signal in (5) can be transformed as follows

$$\begin{aligned} y_j &= \mathbf{h}_j^{0,H}\mathbf{x}_0 + \sum_{i=1}^{P} \mathbf{h}_j^{i,H}\mathbf{x}_i + \sum_{j=1}^{F} \hat{\mathbf{h}}_j^{i,H}\hat{\mathbf{x}}_i + \sum_{i=1}^{D} h_j^{i,*}\tilde{x}_i + n_j \\ &= \sqrt{\tilde{p}_j}\frac{h_j^j h_j^{j,*}}{|h_j^j|}\tilde{x}_j + \sum_{i=1, i\neq j}^{D} \sqrt{\tilde{p}_i}\frac{h_j^{i,*} h_i^i}{|h_i^i|}\tilde{x}_i \\ &+ \sum_{k=1}^{U_m} \sqrt{p_{0,k}}\mathbf{h}_j^{0,H}\mathbf{W}_{0,k} + \sum_{i=1}^{P}\sum_{k=1}^{U_p} \sqrt{p_{i,k}}\mathbf{h}_j^{i,H}\mathbf{w}_{i,k} \\ &+ \sum_{i=1}^{F}\sum_{k=1}^{U_f} \sqrt{\hat{p}_{i,k}}\hat{\mathbf{h}}_j^{i,H}.\hat{\mathbf{w}}_i^k + n_j \end{aligned} \tag{6}$$

which is obtained by applying (1), (2), (3), (4) for (5). The very first part of (6) is the desirable signal from the D2D transmitter to the D2D receiver. The second part is the interference from other D2D pairs. Finally, the remaining parts are the interference from macro base station, pico base station and femto base station and additive noise. We now provide the spectral efficiency of D2D receiver j as in Lemma 1

Lemma 1. The spectral efficiency of an arbitrary D2D receiver in the heterogeneous network is given by

$$R_j = \log_2\left(1 + \mathrm{SINR_j}\right) [\mathrm{b/s/Hz}], \tag{7}$$

where the $SINR_j$ is given in (8).

Proof. From equation (6) , the received signal at D2D receiver j is given by

$$\begin{aligned} y_j = &\underbrace{\sqrt{\tilde{p}_j}|h_j^j|\tilde{x}_j}_{\text{desirable signal}} + \underbrace{\sum_{i=1, i\neq j}^{D} \sqrt{\tilde{p}_i}\frac{h_j^{i,*} h_i^i}{|h_i^i|}\tilde{x}_i}_{\text{D2D interference}} \\ &+ \underbrace{\sum_{k=1}^{U_m} \sqrt{p_{0,k}}\mathbf{h}_j^{0,H}\mathbf{W}_{0,k}}_{\text{Macro interference}} + \underbrace{\sum_{i=1}^{P}\sum_{k=1}^{U_p} \sqrt{p_{i,k}}\mathbf{h}_j^{i,H}\mathbf{w}_{i,k}}_{\text{Pico interference}} \\ &+ \underbrace{\sum_{i=1}^{F}\sum_{k=1}^{U_f} \sqrt{\hat{p}_{i,k}}\hat{\mathbf{h}}_j^{i,H}.\hat{\mathbf{w}}_i^k}_{\text{Femto interference}} + n_j \end{aligned} \tag{9}$$

□

3. Total Transmit Power Minimization

This section formulates and solves the total transmit power minimization problem of D2D users in the

$$\mathrm{SINR}_j = \frac{\tilde{p}_j|h_j^j|^2}{\underbrace{\sum_{k=1}^{U_m} p_{0,k}|\mathbf{h}_j^{0,H}\mathbf{w}_{0,k}|^2}_{\text{Macro interference}} + \underbrace{\sum_{i=1}^{P}\sum_{k=1}^{U_p} p_{i,k}|\mathbf{h}_j^{i,H}\mathbf{w}_{i,k}|^2}_{\text{Pico interference}} + \underbrace{\sum_{i=1}^{F}\sum_{k=1}^{U_f} \hat{p}_{i,k}|\hat{\mathbf{h}}_j^{i,H}\hat{\mathbf{w}}_{i,k}|^2}_{\text{Femto interference}} + \underbrace{\sum_{\substack{i=1\\ i\neq j}}^{D} \tilde{p}_i|h_j^i|^2}_{\text{D2D interference}} + \sigma^2} \tag{8}$$

heterogeneous network. We will solve this optimization problem with under the quality of service constraints and limited power budget at all D2D transmitter, while other parameters of macro cell, pico cells, and femto cells are fixed.

3.1. Problem Formulation

The total power minimization problem for D2D transmitters can be formulated as

$$\begin{aligned} &\underset{\{\tilde{p}_i\geq 0\}}{\text{minimize}} \quad \sum_{i=1}^{D}\tilde{p}_i \\ &\text{subject to} \\ &\qquad R_i \geq \xi_i, \forall i = 1,\ldots,D, \\ &\qquad \tilde{p}_i \leq P_{\max,i}, \forall i = 1,\ldots,D. \end{aligned} \tag{10}$$

By setting $\tilde{\xi}_i = 2^{\xi_i} - 1$, Problem (10) can be transformed to the following problem

$$\begin{aligned} &\underset{\{\tilde{p}_i\geq 0\}}{\text{minimize}} \quad \sum_{i=1}^{D}\tilde{p}_i \\ &\text{subject to} \\ &\qquad \mathrm{SINR}_i \geq \tilde{\xi}_i, \forall i = 1,\ldots,D, \\ &\qquad \tilde{p}_i \leq P_{\max,i}, \forall i = 1,\ldots,D. \end{aligned} \tag{11}$$

It is emphasized that Problem (11) and (10) are equivalent with the same optimal solution.

3.2. Optimal Solution for Given Quality of Services

Theorem 1. For a given quality of services set, the global solution to problem (11) is attained in polynomial time since this is a linear program.

Proof. First of all, as mentioned above, all parameters of the cellular base station such as transmit power, beamforming vector. As the objective is to minimize the transmit powers of D2D pairs, we can consider the sum of macro interferences, pico interferences, femto interference in (8) as a constant, denoted by $N_{\text{cellular},j}$. Consequently, the constraint function on the SINR_i in (11) can be written as

$$\mathrm{SINR}_i = \frac{\tilde{p}_i|h_i^i|^2}{N_{\text{cellular},j} + \sum_{j=1,j\neq i}^{D}\tilde{p}_j|h_i^j|^2 + \sigma^2} \geq \tilde{\xi}_i \tag{12}$$

The above is equivalent to

$$\tilde{p}_i|h_i^i|^2 \geq \tilde{\xi}_i \sum_{j=1,j\neq i}^{D}\tilde{p}_j|h_i^j|^2 + \tilde{\xi}_i N_{\text{cellular},j} + \tilde{\xi}_i\sigma^2 \tag{13}$$

or

$$\tilde{p}_i|h_i^i|^2 - \tilde{\xi}_i \sum_{j=1,j\neq i}^{D}\tilde{p}_j|h_i^j|^2 - \tilde{\xi}_i N_{\text{cellular},j} - \tilde{\xi}_i\sigma^2 \geq 0 \tag{14}$$

This is a linear function constraint, as a result, the optimization problem in (11) is equivalent to the following linear programming problem, which also means that its global optimum can be found in polynomial time.

$$\begin{aligned} &\underset{\{\tilde{p}_i\geq 0\}}{\text{minimize}} \quad \sum_{i=1}^{D}\tilde{p}_i \\ &\text{subject to} \\ &\qquad \tilde{p}_i|h_i^i|^2 - \tilde{\xi}_i \sum_{j=1,j\neq i}^{D}\tilde{p}_j|h_i^j|^2 - \tilde{\xi}_i N_{\text{cellular}} - \tilde{\xi}_i\sigma^2 \geq 0 \\ &\qquad \forall i = 1,\ldots,D, \\ &\qquad \tilde{p}_i \leq P_{\max,i}, \forall i = 1,\ldots,D. \end{aligned} \tag{15}$$

□

Theorem 2. The spectral efficiency of an arbitrary D2D receiver in the heterogeneous network is bounded by the following inequalities

$$0 \leq R_j \leq \log_2\left(1 + \frac{P_{\text{max,j}}|h_j^j|^2}{N_{\text{cellular,j}} + \sigma^2}\right) \tag{16}$$

Proof. First of all, it is clear that $1 + \mathrm{SINR}_j \geq 1$. Beside, $\log_2(x)$ is an increasing function with $x \in [1, +\infty)$. So $R_j \geq \log_2(1)$ *i.e.* $R_j \geq 0$. The equality hold when the D2D user does not work as D2D receiver.

Secondly, the D2D interference part in (8) $\sum_{i=1,i\neq j}^{D}\tilde{p}_i|h_j^i|^2 \geq 0$ and $\tilde{p}_j \leq P_{\text{max,j}}$. Therefore $\mathrm{SINR}_j \leq \frac{P_{\text{max,j}}|h_j^j|^2}{N_{\text{cellular,j}}+\sigma^2}$, hence $R_j \leq \log_2\left(1 + \frac{P_{\text{max,j}}|h_j^j|^2}{N_{\text{cellular,j}}+\sigma^2}\right)$.

Table 2. Parameters in Numerical Evaluation

Parameter	Value
Macro cell radius	1 km
Pico cell radius	0.1 km
Femto cell radius	0.03 km
D2D maximum transmission distance	0.02 km
Macro BS transmit power	40 dBm
Pico BS transmit power	30 dBm
Femto BS transmit power	20 dBm
D2D transmit power	10 dBm
Small-scale fading distribution	$\mathcal{CN}(0,1)$
Pathloss at distance d (km) (d > 40 m)	$148.1 + 37.6\log_{10}(d)$ dB
Pathloss at distance d (km) ($d \leq 40$ m)	$127 + 30\log_{10}(d)$ dB
Noise variance σ^2	-126 dBm

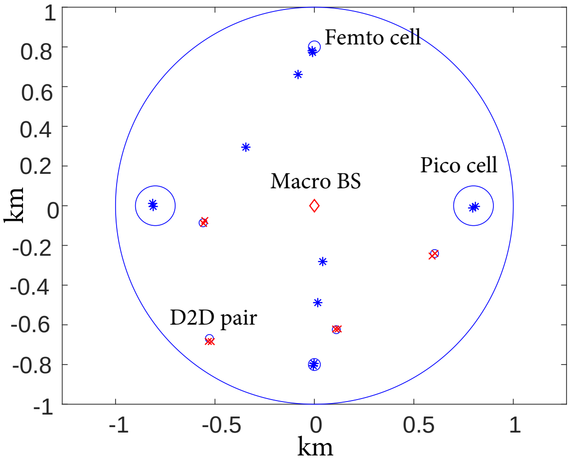

Figure 2. HetNet simulation model

The equality holds when only D2D pair j communicates and other D2D pairs do not transmit data. Consequently, all D2D pairs transmission cannot reach the highest rate simultaneously. ☐

4. Simulation Results

In this section, we provide three sets of numerical results. The first set calculates the spectral efficiency of D2D communication and its maximum values for each D2D receivers. The second set evaluates the total power consumption of D2D transmitters with the QoS degrees in D2D receivers are greater or equal a threshold. The last set evaluates the QoS of each D2D receiver with different number of cellular BS in the model. To begin with, we initiate a HetNet model as in Figure 2 which includes 1 macro cell, 2 pico cells, 2 femto cells with the number of antennas in each type cell is 8, 4, and 2, respectively. We consider 4 cellular users in macro cell, 2 cellular users in each pico cell, and 2 cellular users in each femto cell. In addition, we study 4 pairs of D2D communications in the macro cell which do not belong to any small cells. It is important to point out that all users in the considered model are distributed randomly. Furthermore, the macro BS is located at $(0,0)$; two pico BSs are located at $(0.8,0)$, $(-0.8,0)$; and two femto cells are located at $(0,0.8)$, $(0,-0.8)$. Moreover, the radius of each cell and the transmit power of each BS are described in Table 2. The small-scale fading channel in simulations is modeled as $\mathcal{CN}(0,1)$ while the large-scale fading is calculated as in [19] with the formula given in Table 2. In order to reduce the computation complexity, we implement the Maximum Ratio Transmission (MRT) as in [20] to generate the beamforming vector in Equation (8).

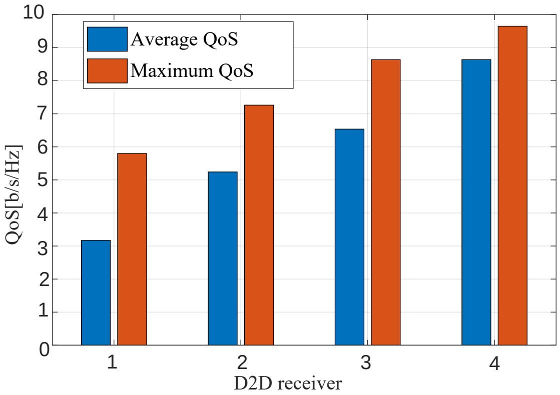

Figure 3. Average QoS and Maximum QoS of D2D receivers

The results of first set is shown in figure 3. Specifically, the average spectral efficiency of each D2D user and its maximum value are calculated based on (8) (16) over 1000 iterations of channel realization. The difference between the average QoS of the D2D receiver and its maximum value is caused by the interference from other D2D pairs. As a result, it can be inferred from Figure 3 that the interference from other D2D pairs have a minor effect on the QoS of a D2D receiver.

In the second set of simulation results, we minimize the total transmit power of all D2D transmitters such that every D2D receiver has QoS greater than or equal to 1, 2, 3, and 4, (b/s/Hz) respectively. The results of this simulation are presented in Figure 4. To provide every D2D receiver's QoS minimum is 4 (b/s/Hz), the total transmit power of D2D transmitters equals 28.3 (dBm) while it requires 12.1 (dBm) to provide the QoS minimum of every D2D receivers equal 1(b/s/Hz).

In the final set of simulation results, we examine the effect of number of cellular BS on the QoS of each D2D receiver by computing the QoS value in various cases of number of cellular BSs in model. Specifically, 3, 5, 7, and 9 BSs in the model equivalents to 1 macro BS and two small cell BSs, 4 small cell BSs, 6 small cell

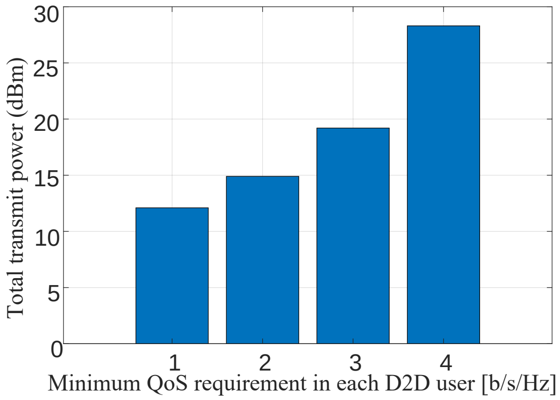

Figure 4. Total transmit power for minimum QoS requirement

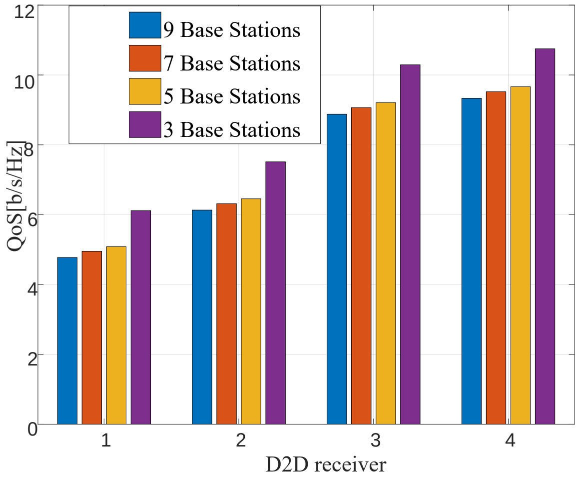

Figure 5. QoS of each D2D user in various number of BSs

BSs, and 8 small cell BSs. The results of this simulation are illustrated in Figure 5. The more cellular BS in the model, the more decrease in the QoS value of each D2D receiver.

5. Conclusion

In this paper, we investigated the spectral efficiency of D2D communication in HetNets with the coexistence of cellular users in macro cell, pico cells, and femto cells. Specifically, a total transmit power minimization problem is formulated to maintain the QoS of D2D users by satisfying constraints on the minimum QoS degree and power consumption budgets. The first simulation results are presented to illustrate the spectral efficiency of D2D communication when all D2D transmitters are equally provided with 10 (dBm) transmit power. The second simulation minimized the total transmit power to obtain the targets QoS of each D2D users are greater than or equal to 1, 2, 3, and 4 (b/s/Hz). The last simulation examine the effect of number of cellular BS on the QoS value of each D2D receiver.

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