Operator Revenue Analysis for Device-to-Device Communications Overlaying Cellular Network

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***Abstract*—Device-to-device (D2D) communications has recently gathered significant research interest due to its efficient utilization of already depleting wireless spectrum. In this article, we considered a scenario where D2D users communicate in the presence of cellular users in an overlay network setup. In order to analyze the revenue of service providers in monetary terms, the paper provides exact expressions of operator profit for both D2D and cellular users. More specifically, we take into account different network parameters including user density, transmit power and channel variations to understand their impact on the total revenue of the operator. Finally, we derive the balancing value of frequency partitioning factor and provide relevant discussion on the analytical expression. Our findings show that D2D communications outperform the conventional cellular communications in terms of revenue generation capability. Our results have been verified by performing extensive simulations.**

***Index Terms*—D2D communications, Frequency partitioning factor, Operator gain.**

I. Introduction

The number of connected devices has increased significantly in past few years. It is expected that more than 50 billion cellular devices will exist in the world by the end of 2020 [1]. These devices will produce a significant amount of data which is expected to grow up to 30.6 Exabyte per month [2]. This implies that meeting the basic demands of cellular users (such as voice calls and text messages) will not be sufficient in the coming years. Advanced cellular applications such as live video streaming, social networking, and online gaming require higher quality-of-service (QoS). The existing cellular infrastructure may not be able to provide support for such a massive number of devices and expected data rate [3]. Thus, in order to meet the future requirements of data transmission, next generation of cellular infrastructure has to adapt according to new strategies, architectures, and methodologies to support the ever-increasing demand of high rate mobile data connectivity [4].

Device-to-device (D2D) communications using the cellular network is a relatively new concept that allows two mobile devices in close proximity to communicate directly with each other without involving base station (BS) [5]. Because of the close proximity of devices, D2D wireless data communication demands fewer resources in comparison to conventional cellular communication devices. This results in enhancing the total cell capacity [6], as D2D communication can be used for local services to meet the expected cellular system demands of higher data rates and spectrum efficiency. Based on the proposed system, mathematical results of D2D underlay communication can be helpful for the availability of more localized services and also increase the spectrum efficiency of the network [7].

For an efficient and cost-effective deployment of advanced mobile communication systems and to assist in planning and management decisions, it is imperative to have a reliable network planning model. Generally, models of cellular network planning are based on two different phase [8]: coverage planning and capacity planning. For the case of coverage planning, the objective is to maximize the service coverage area by increasing antennas and adjusting transmit powers. In the case of capacity planning, frequencies are allocated to the transmitters to enhance the average quality of the received signals without compromising the secrecy of information [9]. Although variables such as antenna bend (angle) or maximum power are inherently continuous, the BS configurations can be determined and discretized by only considering a group of viable parameters [8]. Moreover, due to the uncertainty of key network parameters like the signal path loss and the state of wireless channel [9], these formulations are far off the reach of classical location theory techniques.

The coverage planning stage depends upon the assignment of an available frequency range to each network user so that all data transfer demands can be served with the maximum value of the received signal. The corresponding problem is called frequency assignment problem (FAP). In the 1970s, mobile operators had to pay for every individual assigned frequency they used. The objective was to lower the total number of frequency channels requested by using non-interfering methodologies [8]. This objective can be achieved by carefully maximizing the capacity of wireless links. Also, the problems like power optimization and interference management fall into the domain of capacity planning [10].

A. Related Work

Studies on D2D communication in the cellular networks show that the operators can provide better data rate and services by controlling modes of communication. The technical aspects of operator controlled D2D communications include spectrum reuse, resource allocation and connection establishment between devices [11]. D2D communications allow the mobile operators to control the spectrum and network to provide better data rates which result in good user experience as compared to conventional cellular communication.

Lately, the authors of [12], studied the effects of delayed Wi-Fi offloading for cellular users data. They considered a monopoly market with two providers and modeled a two-stage game to prove that the equilibrium offloading price depends on parameters like the number of users, Wi-Fi density and cellular cost using Nash equilibrium. Numerical results for various parameter changes provide useful insights into the utility of offloading user data through Wi-Fi offloading. In [13], Jiang *et al*. addressed pricing concerns for the cognitive femtocell network and presented a model based on a two-tier pricing game-theoretic framework. The said framework further discusses two mathematical models: static and dynamic pricing models. Simulation results suggested that the dynamic pricing model converges to the Nash equilibrium prices.

In another work, the authors of [14] discussed two-tier networks that include a macrocell tier (BS to cellular user communications) and a device tier (D2D communications). In [15], Shang *et al*. proposed a D2D offloading framework which encourages some mobile users with an incentive to act as D2D transmitters to broadcast the data of other users in closed range areas. They employed two-stage Stackelberg game to model such interaction analytically. In particular, the mobile operator (leader) defines the incentive price to obtain maximum advantages and D2D transmitters (followers) select suitable traffic volume to be offloaded. Simulation results showed that the mobile operator can fully utilize the available spectrum and considerably improve its profit by incorporating this D2D offloading incentive-based mechanism with conventional communication.

B. Motivation and Contribution

D2D communication using cellular infrastructure has many advantages in the form of efficient resource utilization, less power consumption, and improved cellular coverage area [10]. Although the co-existence of D2D communication in cellular networks has apparent advantages, its exact monetary profit for the service providers has not been studied extensively. This key observation has motivated us to evaluate the monetary gains of D2D communications. As a byproduct of this work, we also focus on the comparative analysis of cellular and D2D communications in terms of pricing benefits to the operators. Main contributions of this article can be summarized as follows:

1) We formulate a network model where cellular and D2D users co-exist in a multi-cell environment. In contrast to previous studies (see [14] and references therein), the multi-cell network is considered more practical than a single cell network. We also analyze the impact of different network parameters like frequency partitioning factor, the density of D2D users and transmit powers on the operators gain.
2) While earlier works have focused on the performance analysis aspect of D2D communication, we have quantified the performance gains in monetary terms. Rather than adopting a game-theoretic approach, which loosely interprets economic gains of operators, our work can be directly applied to estimate the profit to the mobile operators and service providers for D2D communications.

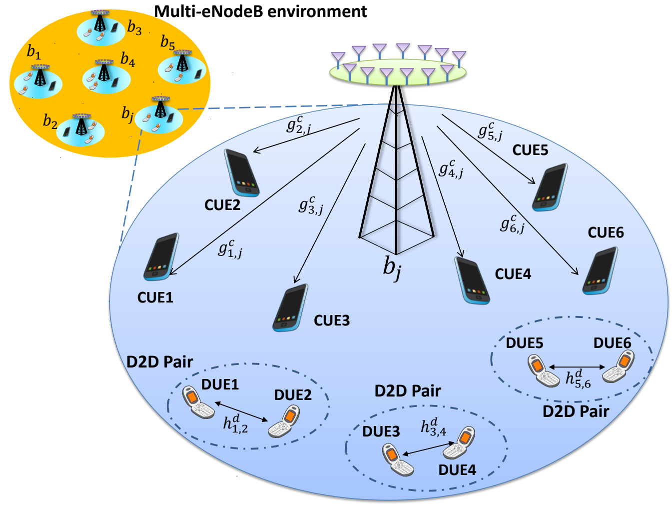


Fig. 1. Illustration of system model.

3) Finally, we derive the closed-form expression of frequency partitioning factor which balances the utility functions of both cellular and D2D users. The balancing value of the frequency partitioning factor can be helpful in characterizing the trade-off between D2D and cellular user monetary gains.

The remainder of the paper is organized as follows. Section II provides a discussion on the system model. Section III gives the mathematical analysis of operator revenue, whereas, Section IV presents the discussion on numerical results. Finally, Section V concludes this work and provides some interesting future research directions.

II. System Model

We consider a multi-cell communication model where D2D users operate in overlay mode, as shown in Figure 1. The eNBs are distributed in the area $\mathbb{R}^2$, with density λ_b (eNBs/m^2). All the eNBs follow a homogeneous Poisson point process (PPP) which is defined as the set of $\Psi_B = \{b_j, j = 0, 1, 2, \ldots\}$. A single cell consists of both cellular and D2D users, also called CUEs and DUEs, respectively. It is considered that both CUEs and DUEs are distributed uniformly in the entire area $\mathbb{R}^2$ with another independent PPP having density of λ_c and λ_d. Here, the set of D2D transmitters (D2D-Txs) is defined by Ψ_D and the set of CUEs is denoted as Ψ_C. Furthermore, the maximum possible transmit power of D2D-Txs is denoted by P_D and the maximum possible transmittable power for every eNB is represented as P_m.

For the sake of simplicity, we consider that each cellular user establishes a connection to its nearest eNB ($b_j \in \Psi_B$) while cell area of eNB b_j, to which a cellular device has been connected, is defined as [16]

$$V_j = \left\{ x \in R^2, ||x - b_j|| \leq ||x - b_n||, b_n \in \frac{\Psi_B}{b_j} \right\}, \quad (1)$$

where $||a-b||$ represents the distance between two points a and b. For establishing connection between two DUEs, the i-th D2D user $u_{i,k}^{d}$ has to connect to the k-th D2D-Tx, i.e., (u_k^{DT}) for data transmission. The connectivity of these devices is subject to two conditions; otherwise, the user chose to connect to the closest eNB in cellular mode. First condition is that the distance between user $u_{i,k}^{d}$ and D2D-Tx u_{DT}^{k} is within the limits of D2D communications possible range, defined by the radius $\mathbb{R}_D$. Second condition is that the user's required content to be transmitted must be available with u_k^{DT}. Considering the first required condition, the communication region of user u_k^{DT} is defined as

$$\Omega_k^{DT} = \left\{ x \in \mathbb{R}^2 || x - u_k^{DT} || \leq \mathbb{R}_D, u_k^{DT} \in \Psi_D \right\}, \quad (2)$$

where $\mathbb{R}_D$ represents the radius of a circular area centered at u_k^{DT}. The circumference of the circle is defined as the possible communication area for the DUE where QoS can be ensured for other users.

A. Radio Resources

The total bandwidth available to the mobile operator is denoted by B in MHz. Here, the cellular downlink bandwidth is defined by B_C in MHz, and the bandwidth for DUEs is defined by B_D in MHz. The bandwidth of cellular communication system is $B_C = (1-\omega)B$, and for DUEs $B_D = \omega B$, where ω is the frequency partitioning factor with $0 < \omega \leq 1$.

B. Cellular Communications

Users within cell V_j are represented as a set of $\Psi_{u,j}^{c}$, where $|\Psi_{u,j}^{c}| = N_c^j$ gives the number of cellular users in V_j. In each cell, the downlink bandwidth is denoted as B_C and the user has been represented as $u_{i,j}^{c}$ (i.e., the i-th cellular user in the j-th cell). The bandwidth of a user $u_{i,j}^{c}$ is written as $B_{i,j}^{c} = \frac{u_{i,j}^{c} B_c}{N_j^C}$ MHz. We consider that each eNB can perform adaptive power control based on the feedback of channel state information (CSI) from users [16]. According to Shannon's theorem, eNB b_j uses the transmit power $P_{i,j}^{B}$ for user $u_{i,j}^{c}$ to achieve the required user data rate $R_{i,j}^{c}$ given below

$$R_{i,j}^{c} \leq B_{i,j}^{c} \log_2 \left(1 + \frac{P_{i,j}^{B} g_{i,j}^{c} || u_{i,j}^{c} - b^j ||^{-\alpha}}{I_{c,l,j}^{C} + \sigma^2} \right), \quad (3)$$

where the channel power gains from eNB b_j to cellular user $u_{i,j}^{c}$ is represented as $g_{i,j}^{c}$, $I_{c,l,j}^{C} = \sum_{l \neq j}^{N_l^C} P_l^C h_l^C || u_j^C - u_l^C ||^{-\alpha}$ denotes the total received interference power at $u_{i,j}^{c}$ from cellular networks, α is the path-loss exponent, and σ^2 is the variance of additive white Gaussian noise with zero mean. For b_j, the total downlink transmit power for the N_j^c cellular users is written as

$$P_j^B = \sum_{i \in \Psi_{u,j}^{c}} P_{i,j}^{B}. \quad (4)$$

C. D2D Communications

For a D2D user $u_{i,k}^{d}$, the transmit power P_k^D to achieve the required data rate is given as

$$R_{i,k}^{d} \leq B_D \log_2 \left(1 + \frac{P_k^D h_{i,k}^{d} || u_{i,k}^{d} - u_k^{DT} ||^{-\alpha}}{I_{d,l,k}^{D} + \sigma^2} \right), \quad (5)$$

where B_D is the transmission bandwidth for every D2D-Tx, and $h_{i,k}^{d}$ denotes the channel power gain and $I_{d,l,k}^{D} = \sum_{l \neq i}^{N_l^D} P_l^D h_l^d || u_i^d - u_l^{DT} ||^{-\alpha}$ represents the total received interference power at $u_{i,k}^{d}$ from D2D communications.

III. Operator Revenue Analysis

In this section, we provide operator utility functions for both cellular and D2D users. Subsequently, we derive close form expression of balancing frequency partitioning factor.

A. Economic Utility

In order to evaluate the economic utility function and for the sake of mathematical tractability, certain assumptions have been made with respect to the cellular network. Firstly, we consider that the data rate requirement for all the cellular users is same which is R_u i.e., $R_{i,j}^{c} = R_u$, $\forall u_{i,j}^{c} \in \Psi_U$. This assumption helps to focus on the system-level performance and provides network design statistics for multi-cell networks. For instance, the cumulative data rate for cellular users can be calculated as

$$R_c = \frac{(1-\omega)(\sum_{j=1}^{K} \sum_{i=1}^{N_j^c} R_{i,j}^{c})}{\sum_{j=1}^{K} N_j^c}, \quad (6)$$

where $N_j^c = |\Psi_{u,j}^{c}|$ represents the number of cellular users in cell V_j and K denotes the number of cells in the region of interest. In a similar way, the cumulative data rate for D2D users can be given as

$$R_D = \frac{\omega(\sum_{j=1}^{K} \sum_{i=1}^{N_j^c} R_{i,j}^{d})}{\sum_{j=1}^{K} N_j^d}, \quad (7)$$

where N_j^d represents the number of D2D users.

In [17] and [18], the economic efficiency has been computed using the financial award of the mobile network operator (in monetary unit per second). More specifically, the power consumption is considered as cost of the network since the mobile operator has to pay electricity bills. So, the utility function or profit function for mobile operator $U_{Operator}$ for CUEs can be given as the difference between the operating income of mobile operator and its total cost, as given below

$$U_{Operator}^{C} = \mathbb{O}^C - \mathbb{P}^C. \quad (8)$$

In (8), $\mathbb{O}^C$ is the mobile operator's income per unitary area which is charged from mobile users, and $\mathbb{P}^C$ represents the power cost at eNBs. In particular, we have

$$\mathbb{O}^C = \lambda_c \tau R_c \ (Pence/m^2/s), \tag{9}$$

and

$$\mathbb{P}^C = \lambda_b c_B \eta P_B^{total} \ (Pence/m^2/s), \tag{10}$$

where τ (Pence/Mbit/user) denotes the mobile operator income per Mbit per user and R_c (in Mbps) is the average required data rate of mobile users. Moreover, in (10), c_B (Pence/Joule/eNB) shows a cost factor at the eNB with respect to power consumption, P_B^{total} (in Watt) represents the total power consumption at the eNB and $0.5 < \eta \leq 1$ is the portion of total power consumed for providing services to cellular users and is called power allocation factor.

Similarly, the utility function for mobile operators for DUEs can be given as

$$U_{Operator}^D = \mathbb{O}^D - \mathbb{P}^D = \lambda_d \tau R_D - \lambda_b c_B \hat{\eta} P_B^{total}, \tag{11}$$

where $\hat{\eta} = 1 - \eta$ represents the fraction of total power used for providing services to DUEs. It is worth noting that the amount of eNB's power consumed by DUEs would be used for operations like authentication and transferring of control messages. The power used for performing these tasks is significantly lower than the power used for transmitting actual data. Thus, it can be easily deduced that for a particular value of η, we always have $\hat{\eta} < \eta$.

B. Balancing Frequency Partitioning Factor

We now derive the expression of frequency partitioning factor which maximizes both $U_{Operator}^D$ and $U_{Operator}^C$, i.e.,

$$\omega^* = \arg\max_{\omega} \{U_{Operator}^C, U_{Operator}^D\}. \tag{12}$$

The motivation for deriving (12) comes from the fact that the utility functions of both DUEs and CUEs are a function of achievable data rate and the data rates of both DUEs and CUEs depend on the value of frequency partitioning factor ω. It can be seen from (7) that the data rate of D2D users increases with an increase in ω. In contrast, the data rate of the cellular users decreases with an increase in frequency partitioning factor ω. This implies that $U_{Operator}^C$ is a decreasing function of ω, whereas, $U_{Operator}^D$ is an increasing function of ω. In other words, it can be observed that

$$As\ \omega \to 0,\ \max_{\omega}\{U_{Operator}^C, U_{Operator}^D\} \approx \max_{\omega}\{U_{Operator}^C\}, \tag{13}$$

and

$$As\ \omega \to 1,\ \max_{\omega}\{U_{Operator}^C, U_{Operator}^D\} \approx \max_{\omega}\{U_{Operator}^D\}. \tag{14}$$

Thus, we can concluded that there exists an ω^* where $U_{Operator}^C = U_{Operator}^D$. Using (8) and (11), we can write

$$\lambda_c \tau R_c - \lambda_b c_B \eta P_B^{total} = \lambda_d \tau R_D - \lambda_b c_B \hat{\eta} P_B^{total}. \tag{15}$$

Replacing the values of R_c and R_D from (6) and (7), and solving for the value of ω, we get

$$\omega^* = \frac{-c_B \eta \lambda_b P_B^{total} + c_B \hat{\eta} \lambda_b P_B^{total} + \lambda_c \gamma_c \tau}{(\lambda_c \gamma_c + \lambda_d \gamma_D)\tau} \tag{16}$$

where $\gamma_c = \frac{(\sum_{j=1}^{K} \sum_{i=1}^{N_j^c} R_{i,j}^c)}{\sum_{j=1}^{K} N_j^c}$ and $\gamma_D = \frac{(\sum_{j=1}^{K} \sum_{i=1}^{N_j^c} R_{i,j}^d)}{\sum_{j=1}^{K} N_j^d}$. The expression in (16) can be further simplified as

$$\omega^* = \frac{(1 - 2\eta) c_B \lambda_b P_B^{total} + \lambda_c \gamma_c \tau}{(\lambda_c \gamma_c + \lambda_d \gamma_D)\tau}. \tag{17}$$

IV. Results and Discussion

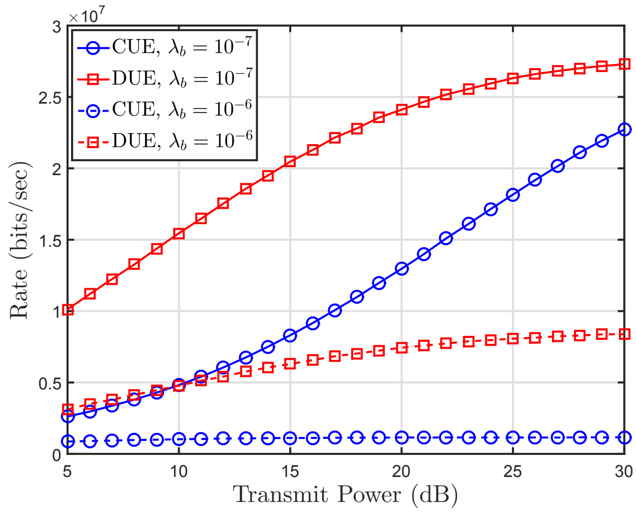
This section provides numerical results based on the analysis of Section III. Unless mentioned otherwise, simulation parameters in Table I have been used to generate the results in this section.

TABLE I
SIMULATION PARAMETERS.

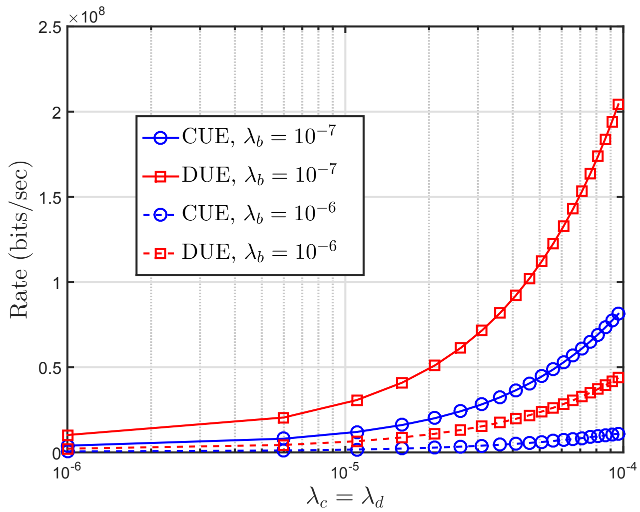
S No.	Parameter	Value
1.	Max UE Tx power	0 to 20 dB
2.	Path Loss exponent for cellular link	2
3.	Path loss exponent for D2D link	2
4.	Channel Bandwidth	1MHz
5.	Noise Figure	-150 dB
6.	Channel realizations	10^5
7.	Frequency partitioning factor, ω	0.5
8.	Density of eNBs, λ_b	$10^{-6}/m^2$
9.	Density of D2D pairs in each eNB, λ_d	$10^{-6}/m^2$
10.	Density of cellular users in each eNB, λ_c	$10^{-6}/m^2$
11.	Power allocation factor, η	0.8

In Figure 2 (a), the achievable data rate has been shown as a function of the transmit power for different CUEs and DUEs densities. It can be seen that the data rate generally increases with the increase in transmit power. However, with an increase in λ_b, the data rate for both D2D and cellular users decreases and vise versa. It can also be noticed that the difference between the data rates of DUEs and CUEs is more prominent at higher values of transmit power as compared to its lower values. Additionally, Figure 2 (b) shows the rate against increasing values of λ_c and λ_d. One can also observe that the data rate increases with the increase in user densities, however, this increase is more prominent for smaller densities of eNBs due to reduced interference.

In Figure 3, the operator gain (Pence/Mbit/sec) for CUEs and DUEs has been shown against the increasing values of power allocation factor. This figure shows that for an increase in η, the operator gain increases for DUE and decreases for the CUE. It is because, at larger values of η, more power is allocated for DUEs as compared to CUEs. The impact of η thus becomes more prominent at larger values of transmit power.



(a)



(b)

Fig. 2. Achievable rate against (a) Transmit Power (b) $\lambda_c = \lambda_d$.

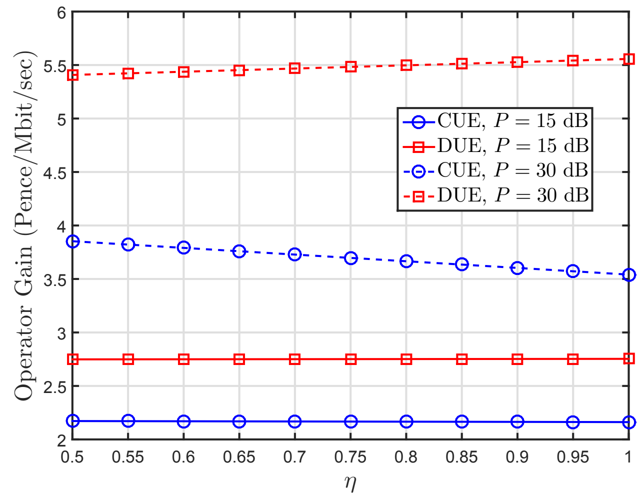


Fig. 3. Operator gain as a function of power allocation factor.

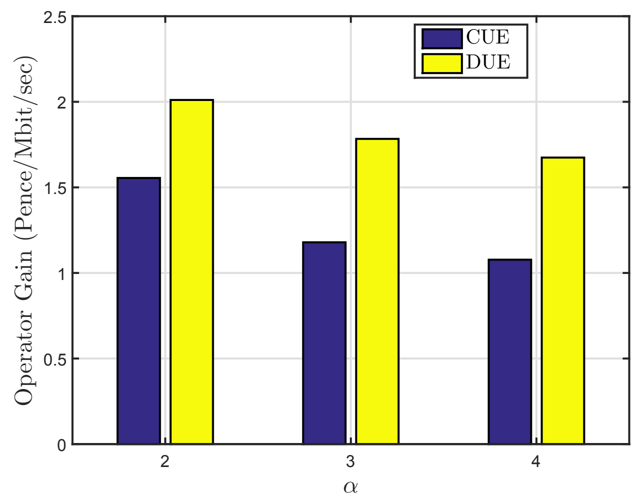


Fig. 4. Operator gain vs path loss exponent.

Figure 4 illustrates a bar graph of operator gain for different values of path loss factor (α) of CUEs and DUEs. The same figure demonstrates that the operator gain decreases when path loss factor is increased for both CUE and DUE. However, we notice that the operator gain for DUE always remains higher when compared with the operator gain of the CUE. This trend can be seen for all the values of path loss exponent.

In Figure 5, the operator gain with respect to power allocation factor is shown for different values of user densities (i.e. λ_c and λ_d). The figure shows that the operator gain increases when user densities are increased for D2D users. It can also be observed that the difference between the gains of DUEs and CUEs increases at higher values of λ_c and λ_d. On the contrary, at lower values of densities, the difference between operator gains of CUEs and DUEs is almost negligible.

In Figure 6, we have shown the operator gain as a function of frequency partitioning factor (ω) for different user densities. One can observe that with an increase in frequency division factor, the operator gain also increases for DUEs. However, in the case of operator gain of CUEs, the graph shows a decreasing trend. The balancing value of ω^* lies at the point where the curves of both CUE and DUE intersect each other. With an increase in the density of cellular and D2D users, ω^* decreases and shifts towards the left-hand side. The same can also be corroborated through (17) which shows λ_c and λ_d in the denominator. It also confirms that the balancing point of operator gain is dependent on the frequency partitioning factor.

V. Conclusions

In this work, a D2D overlay communication scenario has been considered to evaluate the amount of revenue generated from DUEs and CUEs in the cellular network. In particular, we have explored the impact of different parameters such as

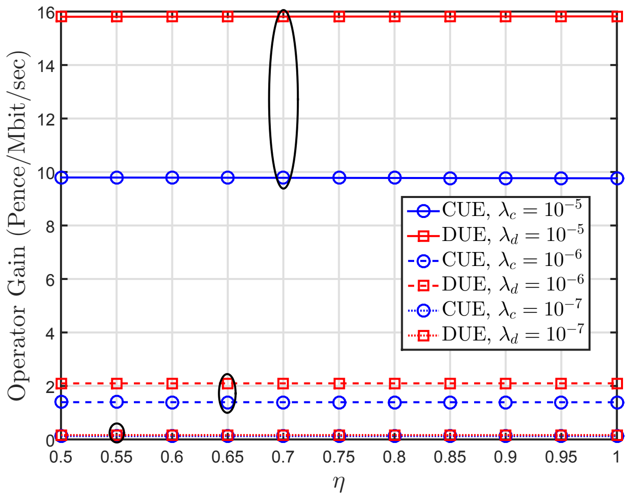


Fig. 5. Operator gain as a function of η.

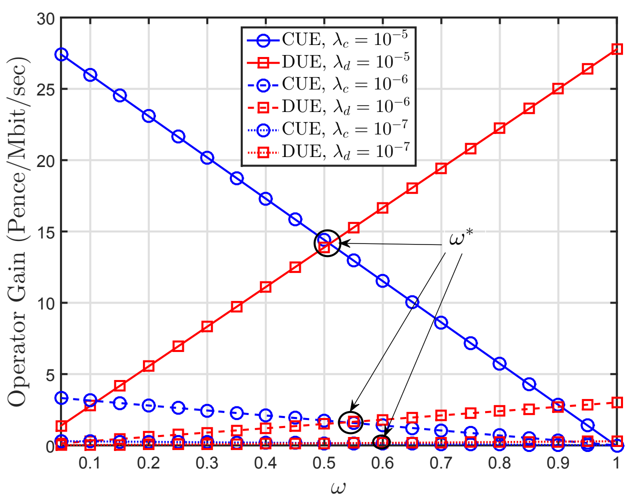


Fig. 6. Operator gain against frequency partitioning factor.

the densities of cellular and D2D users, path loss exponent and frequency partitioning factor on the revenue generation of the cellular communication system. Our findings have shown that D2D communications outperform conventional cellular communications in terms of revenue generation. It was also illustrated that for an increase in the transmit power, the data rate of the cellular and D2D users also increases. In the end, we have proved that an increase in the density of CUEs and DUEs results in decreasing ω^*. This implies that a smaller value of frequency partitioning factor is more desirable as the number of users increases in the network.

Several future research directions can be derived from our results. For once, the system model can be extended for cooperative D2D communications and the impact of helper DUEs on operators' revenue can be explored. Moreover, we have considered the system where D2D and cellular users are equipped with single antennas only. However, it would be interesting to extend the case for multi-antenna D2D users which can bring considerable improvements in data rates. These interesting and challenging problems will be addressed in the future work.

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