On the Optimal Spectrum Partitioning in D2D Enhanced Cellular Sensor Networks

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Abstract. Device-to-Device communication is a key technique in future cellular sensor networks since it provides short range communications between two adjacent devices in terms of power consumption, green communication, and system capacity as compared to conventional homogeneous cellular network. What is more, the D2D protocol not only provides direct communication to various kinds of devices but also bridges together two devices of wireless sensor and cellular device. However, the sensors reuse licensed channels with cellular devices and potential result in severe interference from each other. In this paper, we investigate the problem of optimal spectrum partitioning and the impacts of device density on outage probability in cellular sensor networks. We convert the throughput maximization problem in to an optimal spectrum partitioning problem with signal to interference plus noise ratio constraints. Simulation results show that the proposed algorithm achieves the higher throughput.

Keywords: D2D · Cellular network · Wireless sensor network
Interference management · Resource allocation

1 Introduction

Applications rely on WSNs (wireless sensor networks), such as mobile health (m-Health), military sensing and tracking, real-time road traffic monitoring, have been rapid increase in the past few years. However, there are two drawbacks exist in current WSN networks. One is that long distance wireless communication is not suit for WSNs due to the limited battery life of nodes. The other is no platform can support Internet services to WSNs. However, the future cellular network aims to provide controlled QoS (Quality of Service) and ubiquitous MTC (machine-type communication) to various kinds of devices. D2D (Device-to-Device) or M2M (Machine-to-Machine) communications have been considered as an interface to combine cellular network and sensor network. The details can be find in release 12 of MTC-LTE [1, 2]. The collaborative applications based on sensors would benefit from the ubiquitous coverage

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and Internet services offered by future cellular networks when they equipped the required LTE chip and protocol [3]. Many works have been focus on the technique of connecting sensors to cellular devices, such as smart phones and tablet computers with cellular module [4, 5]. The application of cellular sensor network in environment protection and wearable sensor has been shown in [6, 7]. D2D technique allows two proximity devices directly communicate with each other instead of traversing the BS (Base station) to offload the increasing traffic. It not only improve the spectrum efficiency but also bridge the collected data by the sensors with the cellular network [8]. Although cellular sensor network with in-band D2D communication brought various benefits to sensor applications, it still meets many challenges in resource management due to critical interferences [9].

Recently, many works research on underlay D2D communications in cellular networks focus on co-channel interference management and resource allocation algorithm with in cellular networks [10–16]. In order to mitigate co-channel interferences, most of these works mainly focus on power control or intelligent resource allocation. In [10], the authors reduce interference and optimize the system throughput through power reduction. In [11], the authors defined a SINR (Signal to Interference plus Noise Ratio) threshold to D2D receiver. This result in some cellular devices cannot reuse channels with D2D devices due to severe interference and the interference problem can be alleviated. With regards to interference mitigation solutions based on resource allocation, many of the current works utilize the information of path loss or shadowing to design superior interference alleviated schemes. In [12, 13], the position-based and distance-based interference mitigation schemes are proposed. However, these schemes need to know the locations of devices and result in high control overhead. In [14], a resource allocation scheme which considers QoS (Quality of Service) for D2D communications has been proposed. However, these channel assignment algorithms often with high computational complexity and overhead. It is hard to implement nicely in cellular sensor networks due to considerable investment to develop and deploy [15, 16]. Nowadays, modeling the locations of base station as a PPP model has been proven to be accurate in terms of SINR distribution when compared to hexagonal grid model [17, 18]. Most of current works are based on hexagonal grid network model, which is not a universal mathematical tool for analytical system performance.

In this paper, we focus on the spectrum partitioning on CUEs (cell UE) and DUEs (D2D UEs and sensors) in a PPP (Poisson point process) model. Unlike [19] which only model the locations of UEs with PPP model and not encounter in sensors, i.e., the sensors cannot communicate with base station due to low transmit power. We also claim that sensors only communication with other sensors or CUEs only by using overlay D2D communications. Our objective is to find the optimal spectrum partitioning that maximizes the network throughput. The main contributions of this paper are summarized as follows: first we provide analytical expressions for the UE outage probability and ergodic rate to characterize the performance of UEs. Then, we convert the throughput maximization problem into an optimal spectrum partitioning problem which is expressed by the outage probability and UE ergodic rate.

The rest of this paper is organized as follows. Section 2 describes the D2D enhanced cellular network model and frame structure. In Sect. 3, we derive the UE outage probabilities that help us to control the D2D interference and communication coverage of D2D. In addition, the ergodic rate of UEs is derived to analyze the network throughput. In Sect. 4, we propose a method that makes an appropriate spectrum partitioning to optimize the system throughput. Then we give the numerical results and analysis. Concluding remarks are given at last.

2 System Model and Assumptions

Here we consider a multi-cell downlink cellular sensor network with D2D communications, as shown in Fig. 1. Each node of WSN can be thought as an UE (user equipment) in cellular sensor network. We refer to a device which communication with BS as a CUE (cellular user equipment) and a device which adopt D2D communication with other device as a DUE (D2D user equipment). Therefore, two kinds of links exist in the network. Links between BS and CUE are called direct links and links between DUEs are called D2D links. A D2D communication represents a DUE pair (i.e. a D2D transmitter and a D2D receiver) in which two DUEs work in the D2D mode. BSs are modeled as a homogeneous PPP Φ_b with density λ_b, the spatial distribution of CUEs and transmitter DUE are also generated according to another PPP with density λ_c and λ_d that is independent of Φ_b. The distance between two D2D communications DUEs follows a uniformed distribution on (0, b) and the transmit powers of BSs and DUEs are P_b and P_D. α_C and α_D are the path loss exponents for direct link and D2D link. We consider a full load scenario in which the bandwidth is always fully occupied by CUEs or DUEs.

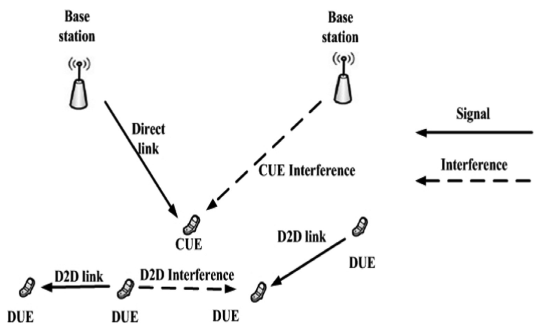

Fig. 1. System model.

In order to avoid interferences between CUEs and DUEs, disjoint spectrum allocation algorithms are adopted. As shown in Fig. 2, the total available system spectrum divided in to N orthogonal channels and each channel has a bandwidth of k Hz. A spectrum partitioning approach is considered in which the DUEs are active on η fraction of the resources in the frequency domain. i.e., the network allocates ηN channels to D2D links and allocates the rest channels to CUEs. Note that direct links operate on $(1-\eta)N$ fraction of channels, which are protected from DUE interferences. We further assume that each D2D pair randomly shares N_D channels in ηN and all D2D links can reuse the same channels simultaneously. Recall that if it has $\eta N = N_D$, all DUEs share the same channels. If it has $\eta N > N_D$, each DUE will randomly select N_D channels form ηN fraction of channels and then the assigned channels of D2D links will not always identical. Therefore, the suffered interferences among DUEs are alleviated.

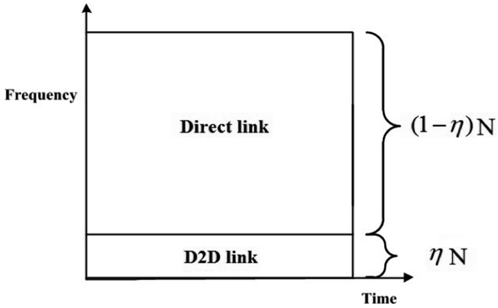

Fig. 2. Frame structure.

3 Outage Probability and Average Ergodic Rate

In this section, we derive the expressions for the outage probability and ergodic rate for CUEs and DUEs to characterize the performance of UEs which will be then used for formulating the network optimization problem.

We consider a cell association approach based on maximum received power, where a CUE is associated with the node which provides the highest reference signal receive power (RSRP). The probability that a typical UE is associated with BS is

$$A_C = \frac{\lambda_C}{\lambda_C + \lambda_D}. \tag{1}$$

The probability that a typical UE use D2D communication is

$$A_D = \frac{\lambda_D}{\lambda_C + \lambda_D}. \tag{2}$$

The average number of CUEs associates with a BS is

$$N_{CUE} = \frac{\lambda_C}{\lambda_b}. \tag{3}$$

The outage probability of a typical UE is defined as the probability that the received SINR of that UE below a certain threshold.

Lemma 1. If the CUE prescribed SINR threshold is T_C, the outage probability is given as

$$\mathbb{P}[SINR_C < T_C] = 1 - 2\pi\lambda_b \int_0^{\infty} x \exp\left\{ -\frac{T_C}{SNR_C} - \pi x^2 \lambda_b [1 + \mathcal{Z}(T_C, \alpha_C, 1)] \right\} dx \quad (4)$$

where $\mathcal{Z}(T_C, \alpha_C, 1) = T_C^{\frac{2}{\alpha_C}} \int_{(\frac{1}{T_C})^{2/\alpha_C}}^{\infty} \frac{1}{1 + t^{\alpha_C/2}} dt$.

Proof: If x is the distance between a random CUE and its serving BS, then we have

$$\mathbb{P}[SINR_C < T_C] = 1 - \int_0^{\infty} \mathbb{P}[SINR_C > T_C] f_C(x) dx. \quad (5)$$

The probability density function of x can be expressed as

$$f_C(x) = e^{-\pi\lambda_b x^2} 2\pi\lambda_b x. \quad (6)$$

This is because macro BS follows a 2D Poisson process with density λ_b in area S and its PDF is $\exp(-\lambda_b S)$.

In order calculate $\mathbb{P}[SINR_C > T_C]$, we first study the sum of interferences for the typical CUE. Let the CUE locate at the origin and its serving BS is denoted as b_0. The suffered interferences come from the BSs which follow PPP Φ_b with density λ_b. Thus, the suffered sum interferences can be expressed as

$$I_C = P_b \sum_{\Phi_b \backslash b_0} H_x d_C^{-\alpha_C} \quad (7)$$

where d_C is the distance between the typical CUE and BSs and H_x is the channel gain. According to [20], the Laplace transform of I_C is

$$\begin{aligned}
\mathcal{L}_{I_C}(s) &= E_{I_C}[\exp(-sI_C)] \\
&= E_{\Phi_b}[\exp(-sP_b \sum_{\Phi_b \backslash b_0} H_x d_C^{-\alpha_C})] \\
&= \exp(-2\pi\lambda_b \int_z^{\infty} \{1 - \mathcal{L}_{H_x}(sP_b r^{-\alpha_C})\} r dr) \\
&= \exp(-2\pi\lambda_b \int_z^{\infty} \frac{r}{1 + (sP_b)^{-1} r^{\alpha_C}} dr) \\
&= \exp(-2\pi\lambda_b \int_z^{\infty} \frac{sP_b r}{sP_b + r^{\alpha_C}} dr)
\end{aligned} \quad (8)$$

where z is the distance between the typical CUE and the closest interferer BS and

$$\begin{aligned}\mathbb{P}[SINR_C > T_C] &= \mathbb{P}\left[P_b H_x x^{-\alpha_C}/I_C + \sigma^2 > T_C\right] \\ &= \mathbb{P}[H_x > x^{\alpha_C} P_b^{-1} T_C (I_C + \sigma^2)] \\ &= \exp\left\{-\frac{T_C}{SNR_C}\right\} \mathcal{L}_{I_C}(x^{\alpha_C} P_b^{-1} T_C)\end{aligned} \tag{9}$$

where SNR_C is the Signal-to-Noise Ratio for CUEs and $SNR_C = \frac{P_b x^{-\alpha_C}}{\sigma^2}$. Plugging (8) into (9) gives the result

$$\mathbb{P}[SINR_C > T_C] = \exp\left\{-\frac{T_C}{SNR_C}\right\} \exp(-2\pi\lambda_b \int_d^{\infty} \frac{T_C x^{\alpha_C} r}{T_C x^{\alpha_C} + r^{\alpha_C}} dr). \tag{10}$$

Employing a change of variables $t = x^{-2} r^2 T_C^{-2/\alpha_C}$, we obtain

$$\mathbb{P}[SINR_C > T_C] = \exp\left\{-\frac{T_C}{SNR_C} - \pi\lambda_b \mathcal{Z}(T_C, \alpha_C, 1) x^2\right\} \tag{11}$$

where $\mathcal{Z}(T_C, \alpha_C, 1) = T_C^{\frac{2}{\alpha_C}} \int_{(\frac{1}{T_C})^{2/\alpha_C}}^{\infty} \frac{1}{1 + t^{\alpha_C/2}} dt$.

Combining (5), (6) and (11) gives the desired result in (4) in which the outage probability is independent of λ_b and P_b. This property is also observed in [21].

Lemma 2. If the DUE prescribed SINR threshold is T_D, the outage probability is given as

$$\mathbb{P}[SINR_D < T_D] = 1 - \frac{1}{b} \int_0^b \exp\left\{-\frac{T_D}{SNR_D} - \pi N_D \lambda_D \mathcal{Z}(T_D, \alpha_D, 1) x^2/\eta N\right\} dx. \tag{12}$$

Proof: For a random DUE, if the communication distance is r, the probability density of r can be expressed as

$$f_d(r) = 1/b. \tag{13}$$

This is because r follows a uniformed distribution on (0, b). In practical cellular networks, a lot of D2D communications required to meet the application requirements. When a D2D UE receives signals from multiple D2D transmitters at the same time and on the same channels, the achieved SINR can be significantly reduced. Based on the above described disjoint spectrum partitioning setting, the interference for a receiver DUE is from other transmitter DUEs which reuse the same channels. The probability that a transmitter DUE use the same channels with a random receiver DUE is $N_D/\eta N$.

The derivation of DUE outage probability has a similar process as CUEs. Because a DUE suffers interferences from all the D2D pair with density $\lambda_D N_D/\eta N$. By following a similar mathematical derivation shown above, the access probability for DUEs is

$$\mathbb{P}[SINR_D > T_D] = \int_0^b \exp\left\{-\frac{T_D}{SNR_D} - \pi\lambda_D N_D \mathcal{Z}(T_D, \alpha_D, 1)x^2/\eta N\right\}dx \tag{14}$$

and the outage probability is

$$\mathbb{P}[SINR_D < T_D] = 1 - \int_0^b \mathbb{P}[SINR_D > T_D] f_D(x)dx. \tag{15}$$

Combining (13), (14) to (15), we obtain the DUE outage probability in (12). The obtained result shows that as the D2D transmission distance increases, the outage probability decrease due to high path loss. If the system allocates more sources to DUE, the outage probability can be decreased.

Lemma 3. If BSs allocate equal resources to its serving CUEs (i.e. Round Robin algorithm). The average ergodic rate of a typical CUE is

$$R_c = 2\pi\lambda_b \int_{r>0}\int_{t>0} \exp\left\{-\frac{e^t-1}{SNR_C} - \pi\lambda_b r^2[\mathcal{Z}(e^t-1, \alpha, 1)+1]\right\} r\,dt\,dr. \tag{16}$$

Proof: The average ergodic rate of a CUE is defined as the data rate average over the communication distance x when all cell channels allocated to that CUE. According to Shannon's theory,

$$R_C = E_x[E_{SINR_C}[\ln(1+SINR_C(x))]] \tag{17}$$

where

$$\begin{aligned} E_{SINR_C}[\ln(1+SINR_C(x))] &= \int_0^\infty \mathbb{P}[\ln(1+SINR_C(x)) > t]dt \\ &= \int_0^\infty \exp\left\{-\frac{e^t-1}{SNR_C}\right\}\mathcal{L}_{I_C}(x^{\alpha_C}P_b^{-1}(e^t-1))dt \\ &= \int_0^\infty \exp\left\{-\frac{e^t-1}{SNR_C} - \pi\lambda_b x^2 \mathcal{Z}(e^t-1, \alpha_C, 1)\right\}dt. \end{aligned} \tag{18}$$

Plugging (18) to (17), we have

$$R_C = \int_0^\infty E_{SINR_C}[\ln(1+SINR_C(x))] f_c(x)dx. \tag{19}$$

After plugging (6) into (19), we get the desired result in (16). By following a similar mathematical derivation shown above, the average ergodic rate of a typical DUE is

$$\begin{aligned} R_D &= \int_0^\infty E_{SINR_D}[\ln(1+SINR_D(x))]f_D(x)dx \\ &= \frac{1}{b}\int_0^b \int_0^\infty \exp\left\{-\frac{e^t-1}{SNR_D} - \frac{\lambda_D N_D r^2}{\eta N}\mathcal{Z}(e^t-1,\alpha_D,1)\right\}dtdr \end{aligned} \tag{20}$$

where SNR_D is the Signal-to-Noise Ratio for DUEs and $SNR_D = \frac{P_D x^{-\alpha_D}}{\sigma^2}$. Obviously, the average ergodic rates of DUE can be determined by the parameter η which denoted the amount of channel resources assign to D2D links. This indicates that the appropriate channel partitioning can improve the network throughput.

4 Problem Formulation

In this section, we derive the overall system throughput in terms of outage probability and ergodic rate. Our objective is to find the optimal spectrum partitioning parameter η that maximizes the network throughput with the constraint of UE SINR threshold. The throughput of a typical CUE and DUE is given below:

$$T_{CUE} = \mathbb{P}[SINR_C > T_C]R_c\frac{(1-\eta)Nk}{N_{CUE}} \tag{21}$$

where $(1-\eta)N/N_{CUE}$ represents the number of channels allocated to each CUE in average and

$$T_{DUE} = \mathbb{P}[SINR_D > T_D]R_D N_D k. \tag{22}$$

Using (21) and (22), we are able to calculated the per cell throughput which is the sum of CUEs and DUEs throughput in a cell, that is

$$T_{total} = A_C T_{CUE} + A_D T_{DUE} \tag{23}$$

Note that ηN must be an integer. The optimal spectrum partitioning parameter η^* can be get by calculate by

$$\eta^* = \begin{cases} \arg\limits_{\eta} T_{total}(\lfloor \eta N \rfloor) & if \quad T_{total}(\lfloor \eta N \rfloor) \geq T_{total}(\lceil \eta N \rceil) \\ \arg\limits_{\eta} T_{total}(\lceil \eta N \rceil) & if \quad T_{total}(\lfloor \eta N \rfloor) < T_{total}(\lceil \eta N \rceil) \end{cases} \tag{24}$$

where $\lceil x \rceil$ is the smallest integer bigger that x and $\lfloor x \rfloor$ is the biggest integer small than x. Thus, the problem of maximize network throughput convert to a spectrum partitioning problem which is shown in (23) and the optimal channel partitioning parameter η^* can be calculated according to (24).

5 Simulation Results and Analysis

We present numerical results on the performance of the proposed approach under different network scenarios. In all the results that follow, the transmit powers are P_b = 46 dBm, P_D = 8 dBm and channel bandwidth k is 1000 Hz. The number of total channels is 100. Assumed densities are $\lambda_b = 1/\pi 500^2$ m^2 and path loss exponents are $\alpha_C = 3.5, \alpha_D = 4$.

Figure 3 shows the outage probability under different DUE communication distance b. It can be observed that at any SINR threshold, as DUE communication distance increases, the outage probability also increases. Fewer D2D communications can be provided due to high path loss. This verified that communication distance is a key factor that affects the system performance. We adopt b = 25 m in the following studies. Because it seems make an appropriate tradeoff between outage probability and communication distance.

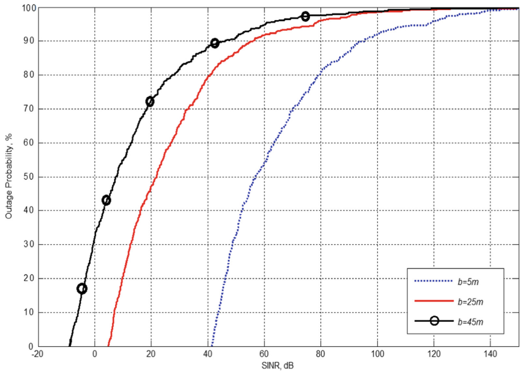

Fig. 3. Outage probability comparison under different DUE communication distance.

We set the SINR threshold T_C = 2 dB and T_D = 8 dB. The impact of UE density on outage is shown in Fig. 4. The x-axis indicated the CUE density and DUE density. We first observe no obvious changes in outage probability for increasing CUE density. Because adding CUEs to network cannot make interference to each other. This validates (4) that adding CUE to the network does not change the SINR distribution of CUEs. For DUEs, as the DUE density increases, the outage probability also increases because the interferences are increasing. This implies that D2D interference is a dominant factor in system performance. This shows that deployment D2D communications with high density are more likely to suffer from D2D interference, which will actually limit the achievable system throughput.

Figure 5 shows the DUE outage probability when b = 25 m and the density of DUE is 5 * λ_b. As the value of ηN increases, the outage probability of DUE decrease. This figure further confirms that the reduction interference can improve the DUE SINR distribution.

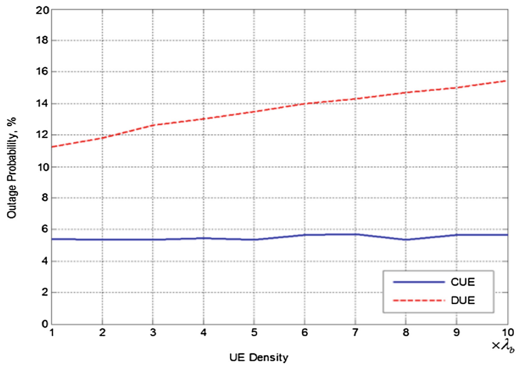

Fig. 4. Outage probability for varying density of CUEs and DUEs.

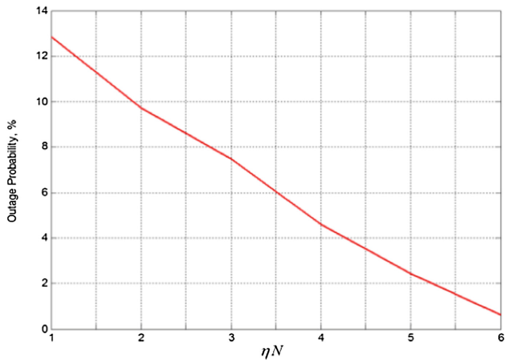

Fig. 5. The DUE outage probability under different value of ηN.

Figure 6 shows the varying value of η versus the total throughput of CUEs and DUEs. The density of CUEs is $5 * \lambda_b$ and the density of DUEs is $10 * \lambda_b$. We first observe that the CUE throughput linearly increase with the value of η since the SINR distribution of CUEs is independent with η. The throughput of DUE decreases as the value of η increases, but the rate of decrement increases due to the more D2D interferences generated in the network as the number of candidate channel is limited by the value of η.

Figure 7 shows the total system throughput under different UE density and the optimal value obtained according to (24). The system gets the maximum throughput only and only if it has $\eta = \eta^*$. When it has $\lambda_C = \lambda_D = \lambda_b$, the total throughput increases as the value of η increases. When $\lambda_C = \lambda_D = 5\lambda_b$ and $\lambda_C = 5\lambda_b, \lambda_D = 10\lambda_b$, the total system throughput increases at first but then decreases for a sufficiently large value of η. It can be observed that different UE density corresponding different optimal η and the value of η^* decrease with increasing DUE density. These results can be explained by noting that increasing DUE density increases D2D interferences and more resources are needed to reduce these interferences, leading to a decrease in η^*.

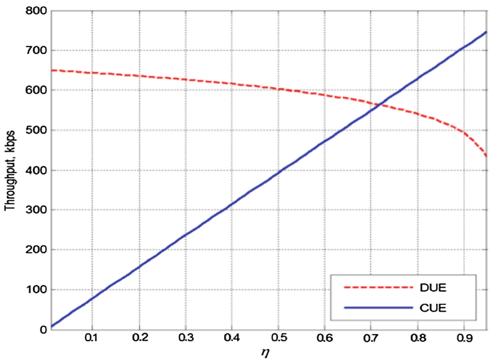

Fig. 6. Throughput with varying values of η.

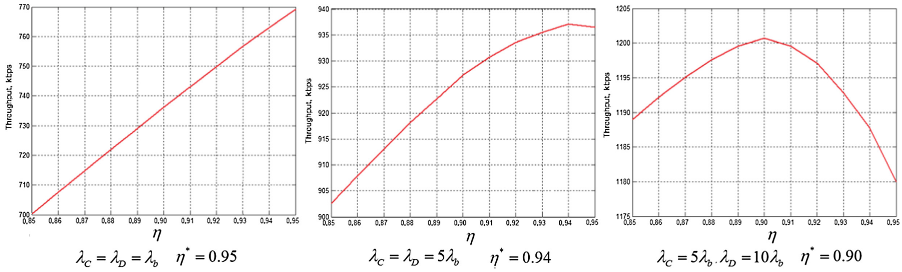

Fig. 7. Optimal value of η under varying UE density.

6 Conclusion

This paper provides an analytical framework for frequency partitioning in D2D enhanced cellular sensor networks. We convert the throughput maximization problem in to an optimal spectrum partitioning problem with SINR constraints and propose an optimal resource partitioning algorithm with UE SINR constraints. Simulation results show that the channel allocation schemes and DUE density strongly affects the overall system throughput due to interference and our proposed scheme effectively optimize the network throughput.

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