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Performance Bound of Ad Hoc Device-to-Device Communications using Cognitive Radio

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***Abstract*—The aim of this paper is to study the achievable throughput of an ad hoc Device-to-Device (D2D) communications with cognitive radio capabilities coexisting with cellular user equipment (UE) in the same macrocell. Specifically, we consider ad hoc D2D systems with non-orthogonal resources sharing instead of D2D with infrastructure support. The main objective is to find out how much throughput a device in a D2D pair can achieve in the presence of another D2D pair and a cellular user over fading channels. A closed-form expression for statistics, the Moment Generating Function (MGF) and Complementary Cumulative Distribution Function (CCDF) of multiple interferers in Nakagami-m fading channels in cellular system are presented. By using these expressions, we derive the device throughput for multiple D2D systems in a cellular system. Furthermore, the upper bound for the probability of false alarm, which is required to achieve a certain throughput is deduced. The results of this paper illustrate how the transmission probability and sensing performance affect the achievable throughput in cognitive D2D systems. In addition, these results serve as guidance for the deployment of cognitive D2D systems without infrastructure support.**

I. INTRODUCTION

D2D communications in a cellular communication system is a process in which physically close UEs under a cellular communication network set up a D2D link pairs using a cellular resources for better spectral utilization. Other D2D communications benefits include increased data rates, power control, extended coverage, improved network capacity and better load balancing [1], [2], [3], [4].

Resources sharing between cellular users and D2D systems as an underlay of cellular systems can either be orthogonal or non-orthogonal [5]. The orthogonal case means D2D communication gets dedicated resources, while the remaining resources are assign to cellular user, under this situation, there is no interference between cellular and D2D systems, while in non-orthogonal, D2D and cellular users re-use the same resources, causing interference to each other but offer improved spectral efficiency. In D2D communications underlaying cellular system, one of the important issues is an efficient interference coordination which prevent generation of harmful interference to cellular system. This will help to achieve throughput enhancement of D2D systems or to guarantee a reliable communication of D2D systems [1], [2], [3], [4]. A mechanism in which the base station (BS) controls the maximum transmit power of the D2D transmitter was proposed in [1]. This method can efficiently manage the D2D interference to cellular system. However, the interference from cellular system to D2D UEs was not considered in [1]. Enhanced throughput can be achieved by using non-orthogonal resource sharing, but there is need for effective interference management to achieve this goal.

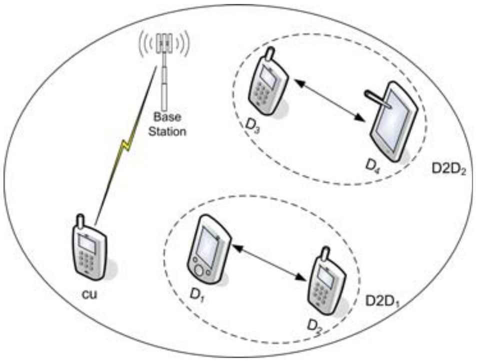

Figure 1: A network scenario, where two pairs of D2D systems coexist with a cellular user (CU) in a macrocell.

In this paper, we consider ad hoc D2D systems with non-orthogonal resources sharing instead of D2D with infrastructure support. To improve the gain from intra-cell spatial reuse of the same resources through interference reduction, we introduced cognitive capabilities into the UEs in a cell. This enables the UEs to establish ad hoc D2D communication links and be able to detect and make decision regarding spectral resources. These cognitive capabilities allow a secondary user to take advantage of the unused spectrum in the primary user spectrum allocation [6].

In Figure 1 the network scenario of cellular communication system of five UEs (CU, D_1, D_2, D_3, D_4) forming two pairs of D2D systems coexisting with CU is demonstrated. The figure shows two pairs D2D systems ($D_1 to D_2$ denotes $D2D_1$ and $D_3 to D_4$ denotes $D2D_2$) and CU as the cellular user operating in the same macrocell. All the five UEs have cognitive capabilities that is only enabled under the D2D mode of operation. Under the cognitive operation, D_1, D_2, D_3 and D_4 represent the secondary users (SU) and CU is the primary

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user (PU) all forming cognitive radio (CR) network. The main problem is that the two pairs of D2D links will interfere with each other in such situations, in addition to yielding to the CU. In this paper we specifically study the achievable throughput of the D2D system, i.e., $D2D_1$ coexisting with $D2D_2$ and CU in the same cellular system.

The main objective of this paper is to find out how much throughput a device in a D2D pair can achieve in the presence of another D2D pair and a cellular user over Nakagami-m fading channel. The main contributions of this paper are as follows. We firstly derive the detection model and interference model for coexisting D2D pairs which takes into account spectrum sensing performance. This model is then used to deduce the probability that the received Signal to Interference and Noise Ratio (SINR) is larger than the required threshold for successful reception of a packet. These results are used to find out the device throughput and the bound for the probability of false alarm in case of coexisting D2D pairs. This bound determines whether it is feasible to establish multiple D2D communications in the same region with the required quality-of-service, say, the minimum throughput. We analyze the performance of a device in detail by considering the effects of various CR network parameters such as transmission probability, performance of spectrum sensing (false alarm and detection probabilities), etc.

The paper is organized as follows. First, the used system model with the detection model is defined in Section II. Then, we derive the interference model, the probabilistic device throughput, and the performance bound for a device in coexisting D2D pairs in Section III. Fundamental results and detailed analysis on the performance of a D2D systems with cognitive capabilities in cellular system are presented in Section IV. Section V gives the concluding remarks.

II. SYSTEM MODEL

The presence of CU i.e. the PU, is defined using the following hypotheses. Hypothesis H_0 denotes the case in which the PU is idle and H_1 stands for the case in which the PU is active. We further make the following assumptions:

- D2D systems is a uniformly random system $D2D_i$, without loss of genarality we assume i to range from 1 to 2
- Each D2D system network performs its own spectrum sensing and the corresponding probabilities of detection and false alarm are taken into account in this paper. However, they do not coordinate their sensing nor share the sensing results.
- All the UEs cellular system are homogeneous in the sense that these devices have similar capabilities and behaviors, such as the transmission power.
- Each of the device transmit to and receives from one device, they have smaller transmission ranges and are located closer to each other, we model the channel between D2D nodes with Rayleigh fading.
- We assume Additive White Gaussian Noise (AWGN).

In this paper, we focus on ad hoc D2D systems instead of D2D with infrastructure support.

A. Detection Model

We assume that an existing cellular user and D2D system transmits a pilot signal periodically on a subcarrier if that subcarrier is occupied by itself. Through the detection of the presence of such a pilot signal, newly established D2D system can determine if that particular subcarrier is available or not. The pilot signal is a sinusoid signal, $B_0 cos(\omega_c t)$, $0 \leq t \leq T$, where ω_c is the subcarrier frequency, B_0 is the amplitude of the sinusoid signal. At the detector, pilot signal can be expressed as $Bcos(\omega t + \theta) + n_0(t)$, where $n_0(t)$ is a white gaussian noise with power spectral density (PSD) $N_0/2$, the signal is assumed to be corrupted by a Rayleigh fading process and thus the amplitude B is Rayleigh distributed with average power $2\sigma_B^2$. Then, the detection hypotheses for the received signal $r(t)$ are:

$$\begin{aligned} H_1 : r(t) &= Bcos(wt + \theta) + n_0(t), 0 \leq t \leq T \\ H_0 : r(t) &= n_0(t), 0 \leq t \leq T \end{aligned} \quad (1)$$

Following the same line as in [7], the detector finally reaches a decision rule:

$$\sum_{i=1}^{S} exp\left[\frac{2q_i^2\sigma_B^2}{N_0^2 + N_0\sigma_B^2 T}\right] \geq \psi \quad (2)$$

Where S is number subcarrier in the frequency ω range and q_i is obtained from a fourier analysis complex envelop of the data in the i-th frequency interval, the pilot signal is declared to be present if the sum in (2) exceeds the pre-specified threshold ψ.

III. DEVICE THROUGHPUT AND PERFORMANCE BOUND

We study the problem from the secondary users' (D2D systems) perspective and provide required protection on primary user's (CU's) performance. In this section we first derive the interference model for coexisting D2D systems and cellular system which is then exploited to deduce the device probabilistic throughput for such scenario. Then, we enhance these results by taking into account the sensing parameters, the probability of false alarm and detection. Finally, the performance bound for the probability of false alarm is also derived.

A. Interference Modeling and Probabilistic Throughput

Devices in the D2D systems are distributed independently in an area according to a Poisson Point Process (PPP). Device density within the cellular system is denoted by λ. We consider Rayleigh fading, x_0 with $E\{x_0^2\} = 1$. The cartesian coordinates of a device are denoted by X and Y. These random variable are independent of the other devices location and uniformly distributed in $[-L, L]$. By setting the device density $\lambda = N/(4L^2)$, where N is the number of devices, the probability of finding k devices in an area A in the plane is given by

$$\Pr\{k \in A\} = \frac{e^{-\lambda A}\,(\lambda A)^k}{k!} \quad (3)$$

Also, the received SINR γ at each device can be expressed as

$$\gamma = \frac{x_0^2 R^{-\alpha} P_0}{\sum x_i^2 {r_i}^{-\alpha} \mathcal{P}_i + \sigma_n^2} \tag{4}$$

P is the D2D node transmission power, R the distance between a D2D transmitter and a receiver and σ_n^2 is the noise power. We use a deterministic distance-dependent path loss $r^{-\alpha}$ as a channel model, where r is the distance between the interfering transmitter and its victim receiver and α is the path loss exponent. x_i, $i = 1, 2, ..., K$ are independent gamma distributed RVs that represent the squared fading gains of the Nakagami-m fading. The Nakagami-m distribution, parameterized by fading severity parameter m, can model different flat fading environment, it reduces to Rayleigh fading model for $m = 1$ and describes less severe fading condition as m increases. γ is a ratio of mixture of large number of RVs, for which closed-form expression for its Complementary Cumulative Distribution Function (CCDF) is generally difficult to obtain, if not impossible. Therefore, we derived a closed form expression $\mathcal{M}(z) = \mathbb{E}[e^{-yz}]$ for the MGF of $\sum x_i^2 {r_i}^{-\alpha} \mathcal{P}_i$ expressed as

$$\mathcal{M}(z) = \mathbb{E}[e^{-z \sum_{i=1}^{K} x_i^2 {r_i}^{-\alpha} \mathcal{P}_i}] \tag{5}$$

Consider the interference generated in an area A around the victim receiver, where K is distributed as a Poisson RV with average $\lambda(L^2 - d_0^2)$. We define d_0 as the near field cut-off radius which defines the distance in which other devices in a network cannot transmit, r_i, $i = 1, 2, ..., K$ are independent and distributed according to the following pdf

$$f(r) = \begin{cases} \frac{2r}{(L^2 - d_0^2)}, & d_0 < r < L \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

x_i, $i = 1, 2, ..., K$ are independent gamma distributed RVs that represent the squared fading gains of the Nakagami-m fading

$$f(x) = \frac{x^{m-1}}{\Gamma(m)} m^m e^{-mx} \tag{7}$$

We seek asymptotic $\mathcal{M}(z)$, therefore, we take the limit of (5) as $L \to \infty$

$$\mathcal{M}(z) = \lim_{L \to \infty} \mathbb{E}[e^{-z \sum_{i=1}^{K} x_i^2 {r_i}^{-\alpha} \mathcal{P}_i}] \tag{8}$$

we conditioned on K in order to compute (8) [8]

$$\begin{aligned} \mathcal{M}(z/K) &= \lim_{L \to \infty} \prod_{i=1}^{K} \mathbb{E}[e^{-z x_i^2 {r_i}^{-\alpha} \mathcal{P}_i}] \\ &= \lim_{L \to \infty} (\mathbb{E}[e^{-z x_1^2 {r_1}^{-\alpha} \mathcal{P}_1}])^K \end{aligned} \tag{9}$$

on averaging out K, we obtain

$$\begin{aligned} \mathcal{M}(z) &= \lim_{L \to \infty} \sum_{\kappa=0}^{\infty} \frac{e^{-\lambda(L^2 - d_0^2)} (\lambda(L^2 - d_0^2))^\kappa}{\kappa!} \\ &\times (\mathbb{E}[e^{-z x_1^2 {r_1}^{-\alpha} \mathcal{P}_1}])^\kappa \end{aligned} \tag{10}$$

Further simplification gives

$$\mathcal{M}(z) = \lim_{L \to \infty} e^{-\lambda(L^2 - d_0^2)(1 - (\mathbb{E}[e^{-z x_1^2 {r_1}^{-\alpha} \mathcal{P}_1}]))} \tag{11}$$

The exponent of (11) can be evaluated in the limit as $L \to \infty$

$$\lim_{L \to \infty} \lambda(L^2 - d_0^2)(1 - (\mathbb{E}[e^{-z x_1^2 {r_1}^{-\alpha} \mathcal{P}_1}]))$$

$$= \lambda \int_{d_0}^{\infty} [1 - e^{-z x_1^2 {r_1}^{-\alpha} \mathcal{P}_1}] 2 r_1 d r_1$$

$$= \lambda[-d_0^2 + d_0^2 e^{-z x_1^2 \mathcal{P}_1 {d_0}^{-\alpha}} - (z \mathcal{P}_1)^{\frac{2}{\alpha}} \Gamma(1 - \frac{2}{\alpha}, z x_1^2 \mathcal{P}_1 {d_0}^{-\alpha})(x_1^{\frac{4}{\alpha}})] \tag{12}$$

From (12), and using eq.(3.381.9) of [9], viz.

$$\mathbb{E}[x_1^{\frac{2}{\alpha}}] = \int_{d_0}^{\infty} x^{\frac{2}{\alpha}} \frac{x^{m_1 - 1}}{\Gamma(m_1)} m_1^{m_1} e^{-m_1 x} dx = \frac{\Gamma(m + \frac{2}{\alpha}, m d_0)}{m^{\frac{2}{\alpha}} \Gamma(m)} \tag{13}$$

$$\mathbb{E}[x_1^{\frac{4}{\alpha}}] = \int_{d_0}^{\infty} x^{\frac{4}{\alpha}} \frac{x^{m_1 - 1}}{\Gamma(m_1)} m_1^{m_1} e^{-m_1 x} dx = \frac{\Gamma(m + \frac{4}{\alpha}, m d_0)}{m^{\frac{4}{\alpha}} \Gamma(m)} \tag{14}$$

We arrive at the following closed form expression for $\mathcal{M}(z)$

$$\begin{aligned} \mathcal{M}(z) &= \exp - \Bigg\{ \lambda \Bigg(-d_0^2 + d_0^2 e^{-z P_1 d_0^{-\alpha} \left(\frac{\Gamma(m + \frac{2}{\alpha}, m d_0)}{m \Gamma(m)} \right)} \\ &- (z P_1)^{\frac{2}{\alpha}} \Gamma \left(1 - \frac{2}{\alpha}, z P_1 d_0^{-\alpha} \left(\frac{\Gamma(m + \frac{2}{\alpha}, m d_0)}{m^{\frac{4}{\alpha}} \Gamma(m)} \right) \right) \\ &\times \left(\frac{\Gamma(m + \frac{4}{\alpha}, m d_0)}{m^{\frac{4}{\alpha}} \Gamma(m)} \right) \Bigg) \Bigg\} \end{aligned} \tag{15}$$

From (4), we can calculate the probabilistic throughput

$$\begin{aligned} \Pr\{\gamma > \theta\} &= \Pr \left\{ \frac{x_0^2 P_0 R^{-\alpha}}{\sum x_i {r_i}^{-\alpha} \mathcal{P}_i + \sigma_n^2} > \theta \right\} \\ &= \Pr \left\{ x_0^2 > \frac{\theta(\sum x_i^2 {r_i}^{-\alpha} \mathcal{P}_i + \sigma_n^2) R^\alpha}{P_0} \right\} \end{aligned} \tag{16}$$

where θ is the required SINR for successful reception (threshold). By denoting $w = x^2$ and $y = \sum x_i^2 {r_i}^{-\alpha} \mathcal{P}_i$ this can be deduced to the following form

$$\begin{aligned} \Pr\{\gamma > \theta\} &= E \left\{ F_{c,w} \left(\frac{\theta(y + \sigma_n^2)}{P_0 R^{-\alpha}} \right) \right\} \\ &= E \left\{ \exp \left(\frac{-\theta(y + \sigma_n^2)}{P_0 R^{-\alpha}} \right) \right\} \end{aligned} \tag{17}$$

where $F_c(.)$ stands for the CCDF. Moreover, note that w is an exponential random variable and $F_{c,w}(w) = e^{-w}$. The expectation is taken over the Gamma distribution which gives

$$\Pr\{\gamma > \theta\} = \exp \left(\frac{\theta \sigma_n^2}{P_0 R^{-\alpha}} \right) \left(\mathcal{M}_y \left(\frac{\theta}{P_0 R^{-\alpha}} \right) \right) \tag{18}$$

B. $D2D_1$ Device Throughput

Spectral resources availability within the cellular system is not fixed, availability is base on the number of cellular users, therefore, the D2D system must use resources in the cellular system in an opportunistic manner. Access to available resources can be duplicated by $D2D_1$ and $D2D_2$. Denote n is the number of available spectral resources and m the number of established D2D communication pairs, then the probability that no D2D pair choose the same spectral resource as any other pair is

$$Pr\{no\ duplicate\} = Pr_{nd}\{n,m\} = \frac{n!}{(n-m)!n^m} \tag{19}$$

Then

$$\begin{aligned} Pr\{duplicate\} &= Pr_d\{n,m\} \\ &= 1 - \frac{n!}{(n-m)!n^m} \\ &= 1 - \frac{n \times (n-1) \times ... \times (n-m+1)}{n^m} \\ &= 1 - [(1-\frac{1}{n}) \times (1-\frac{2}{n}) \times ... \\ &\times (1-\frac{m-1}{n})] \end{aligned} \tag{20}$$

using the inequality $(1-x) \leq e^{-x}$, we arrive at an approximation for (20)

$$\begin{aligned} Pr_d\{n,m\} &> 1 - \left[(e^{-\frac{1}{n}}) \times (e^{-\frac{2}{n}}) \times ...(e^{-\frac{m-1}{n}})\right] \\ &= 1 - e^{-\left[(\frac{1}{n})+(\frac{2}{n})+(\frac{m-1}{n})\right]} \\ &= 1 - e^{-\frac{k(m-1)}{2n}} \end{aligned} \tag{21}$$

In our case with $m = 2$, we have

$$Pr_{nd}\{n,2\} = \frac{n!}{(n-2)!n^2} \tag{22}$$

and

$$Pr_d\{n,2\} \approx 1 - e^{-\frac{1}{n}} \tag{23}$$

The received interference in CR networks depends on the sensing results. In case of the two pairs of D2D system with cognitive capabilities in a cellular system, the operations of one could affect the performance of the other. We denote the miss detection and false alarm probabilities of $D2D_1$ system as $P_{m,1}$, $P_{d,1}$ and $P_{f,1}$ and $D2D_2$ system as $P_{m,2}$, $P_{d,1}$ and $P_{f,2}$, idle CU as $P(H_0)$ and active CU as $P(H_1)$. We have multiple transmission scenarios depending on whether the two pairs of D2D system duplicate resources or not as shown in (22) and (23), it also depends on whether CU is idle or active [10]. If $D2D_1$ alone wants to transmit when PU is idle, the spectrum sensing result is $(1-P_{f,1})P_{f,2}P(H_0)$ and when PU is active the spectrum sensing result $P_{m,1}P_{d,2}P(H_1)$. The following achievable throughput of $D2D_1$ can be obtained for different transmission scenarios highlighted above.

1) CU is idle and no duplicate of resources:

$$\begin{aligned} &Pr_1\{\gamma > \theta\} = (1-P_{f,1})P_{f,2}P(H_0) \\ \times\ &Pr_{nd}\{n,m\} \Pr\left\{\frac{x_0^2 P_0 R^{-\alpha}}{\sum x_i^2 {r_i}^{-\alpha}\mathcal{P}_i + \sigma_n^2} > \theta\right\} \end{aligned} \tag{24}$$

2) CU is idle and there is duplicate of resources:

$$\begin{aligned} &Pr_2\{\gamma > \theta\} = (1-P_{f,1})(1-P_{f,2})P(H_0) \\ \times\ &Pr_d\{n,m\} \Pr\left\{\frac{x_0^2 P_0 R^{-\alpha}}{\sum x_i^2 {r_i}^{-\alpha}\mathcal{P}_i + \sigma_n^2} > \theta\right\} \end{aligned} \tag{25}$$

3) CU is active and no duplicate of resources:

$$\begin{aligned} &Pr_3\{\gamma > \theta\} = P_{m,1}P_{d,2}P(H_1) \\ \times\ &Pr_{nd}\{n,m\} \Pr\left\{\frac{x_0^2 P_0 R^{-\alpha}}{\sum x_i^2 {r_i}^{-\alpha}\mathcal{P}_i + \sigma_n^2} > \theta\right\} \end{aligned} \tag{26}$$

4) CU is active and there is duplicate of resources:

$$\begin{aligned} &Pr_4\{\gamma > \theta\} = P_{m,1}P_{m,2}P(H_1) \\ \times\ &Pr_d\{n,m\} \Pr\left\{\frac{x_0^2 P_0 R^{-\alpha}}{\sum x_i^2 {r_i}^{-\alpha}\mathcal{P}_i + \sigma_n^2} > \theta\right\} \end{aligned} \tag{27}$$

We define the throughput of a device in the D2D system such that the transmitter has a packet to transmit while a receiver is idle, i.e., the receiver does not have a packet to transmit. This can be formulated as follows

$$J = p(1-p)Pr_T\{\gamma > \theta\}. \tag{28}$$

where $\Pr_T\{\gamma > \theta\} = \Pr_1\{\gamma > \theta\} + \Pr_2\{\gamma > \theta\} + \Pr_3\{\gamma > \theta\} + \Pr_4\{\gamma > \theta\}$ and p is the transmission probability.

C. Performance Bound on Spectrum Sensing of $D2D_1$

By analyzing $\Pr_1\{\gamma > \theta\}$, $\Pr_2\{\gamma > \theta\}$, $\Pr_3\{\gamma > \theta\}$, and $\Pr_4\{\gamma > \theta\}$ we have concluded that in practice $\Pr_3\{\gamma > \theta\}$ and $\Pr_4\{\gamma > \theta\}$ have negligible influence on the performance of $D2D_1$ devices, since both the miss rate and the probability of CU being active are small. In addition, it is not practical to design D2D system to duplicate the spectral resources CU. Therefore, we use the following approximation

$$\begin{aligned} J &\geq \hat{J} \Rightarrow \\ \hat{J} &\leq p(1-p)(1-P_{f,1})P_{f,2}P(H_0)Pr_{nd}\{n,m\} \\ &\times \Pr\left\{\frac{x_0^2 P_0 R^{-\alpha}}{\sum x_i^2 {r_i}^{-\alpha}\mathcal{P}_i + \sigma_n^2} > \theta\right\} \\ &+ p(1-p)(1-P_{f,1})(1-P_{f,2})P(H_0)Pr_d\{n,m\} \\ &\times \Pr\left\{\frac{x_0^2 P_0 R^{-\alpha}}{\sum x_i^2 {r_i}^{-\alpha}\mathcal{P}_i + \sigma_n^2} > \theta\right\} \end{aligned} \tag{29}$$

The inequality derived above shows the maximum achievable throughput for a device in $D2D_1$ given the CU activity and the spectrum sensing performance of $D2D_1$ and $D2D_2$.

Furthermore, let us define

$$\xi_1 = P(H_0)Pr_{nd}\{n,m\}\,\Pr\left\{\frac{x_0^2 P_0 R^{-\alpha}}{\sum x_i^2 {r_i}^{-\alpha}\mathcal{P}_i+\sigma_n^2}>\theta\right\} \tag{30}$$

$$\xi_2 = P(H_0)Pr_{d}\{n,m\}\,\Pr\left\{\frac{x_0^2 P_0 R^{-\alpha}}{\sum x_i^2 {r_i}^{-\alpha}\mathcal{P}_i+\sigma_n^2}>\theta\right\} \tag{31}$$

and assume that both D2D pairs have the same spectrum sensing performance, i.e., $P_{f,1}=P_{f,2}=P_f$. Then,

$$\hat{J}\le p(1-p)(1-P_f)[P_f\xi_1+(1-P_f)\xi_2] \tag{32}$$

It is observed that when the false alarm probability P_f is very small, the achievable throughput approaches $p(1-p)\xi_2$, also, the achievable throughput will decrease when P_f increases.

If the spectrum sensing performance of $D2D_2$ is given *a priori*, then we can find out the maximum probability of false alarm of $D2D_1$ for achieving a certain throughput $\hat{J}$.

$$P_{f,1}\le 1-\frac{\hat{J}}{(P_{f,2}\xi_1+(1-P_{f,2})\xi_2)p(1-p)}. \tag{33}$$

In other words, Equation (33) defines the upper bound for the probability of false alarm of $D2D_1$.

IV. RESULTS AND ANALYSIS

The performance of coexisting D2D pairs is studied by investigating the effects of different parameters on the throughput of $D2D_1$. In this section, we use the following practical values for network parameters: $d_0 = 100$ m, $R = 50$ m, $P = 30$ dBm, $\sigma_n = -70$ dBm, $\theta = 10$ dB, $L = 500$ m, $\alpha = 4$, $p_1 = p_2 = 0.5$, and $N = 100$. Furthermore, used CR parameters are: $P_{f,1} = P_{f,2} = 0.1$, $P_m = 0.05$, and $P(H_0) = 0.7$. We vary these parameters to demonstrate their impact.

We can determine the maximum value for the probability of false alarm that is required to achieve a certain throughput by exploiting Equation (33), this is shown in Figure 2. Figure 2 also shows the effect of Nakagami parameter m and transmission probability p on the throughput of a device in D2D mode in cellular system, the results imply that throughput reduces for higher m because the interferer experiences less severe fading condition as m increases, but throughput increases as p increases until an optimal p is reached when increase in p has no effect on throughput.

In Figure 3, the effect of sensing performance on the throughput in case of coexisting D2D systems is shown. This figure captures the fundamental nature of coexisting D2D CR networks. As we had thought, the sensing performance of both $D2D_1$ and $D2D_2$ has an effect and it seems that both networks have equal and linear influence on the throughput of $D2D_1$. From these results, we conclude that D2D users would like to have as low probability of false alarm as possible to achieve the best performance. While, the false alarm probability of the interfering device should be high such that the D2D system in question would be able to access and use the spectrum alone as often as possible.

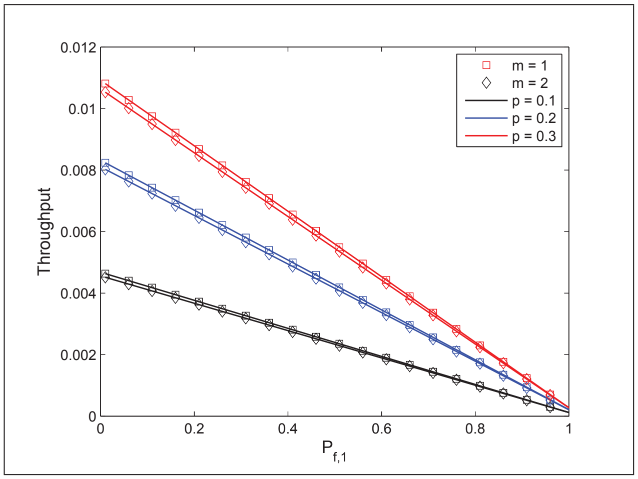

Figure 2: Throughput as a function of false alarm probability and the effect of m and p on throughput of $D2D_1$.

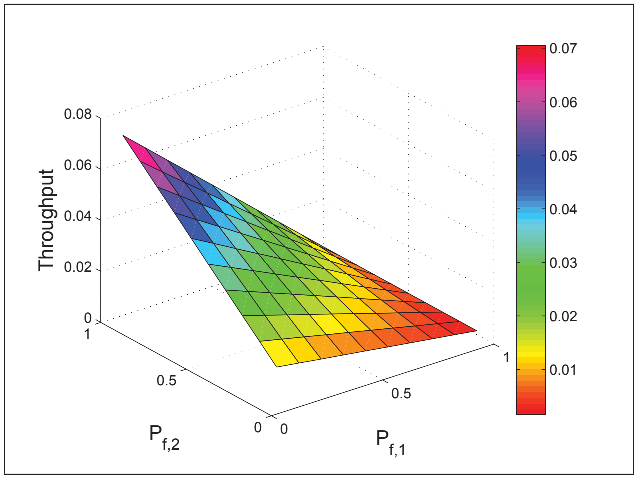

Figure 3: Effect of false alarm probabilities on the throughput of $D2D_1$.

In figure 4, the effect of the transmission probability of $D2D_2$ on the performance of $D2D_1$ is shown. From this figure, We can determine the optimal transmission probability for $D2D_1$, therefore, the optimal transmission probability of $D2D_1$ is independent of the transmission probability of $D2D_2$. However, an increase in the network load, leads to decrease in the throughput of $D2D_1$. The false alarm probability of $D2D_2$ ($P_{f,2}$) has a reversed effect on the performance of $D2D_1$, if $P_{f,2}$ is increased, $D2D_2$ will transmit more rarely which means that it is not as active from the perspective of $D2D_1$. Therefore, $D2D_1$ performance is enhanced by having as low p_2 and as high $P_{f,2}$ as possible.

However, it should be noted that the optimal value of p_1 depends on the amount of intra-network interference. With these parameters the term $p(1-p)$ in Equation (28) dominates the performance of $D2D_1$ since the throughput is maximized when $p_1 = 0.5$, whereas, if the amount of received intra-

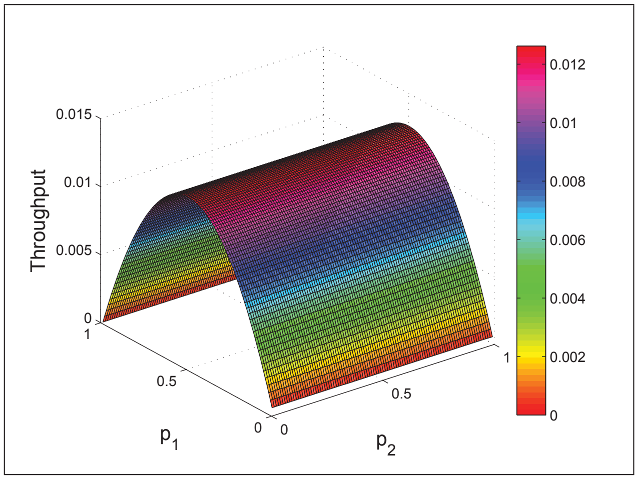

Figure 4: Impact of transmission probabilities of D2D systems on the throughput of $D2D_1$.

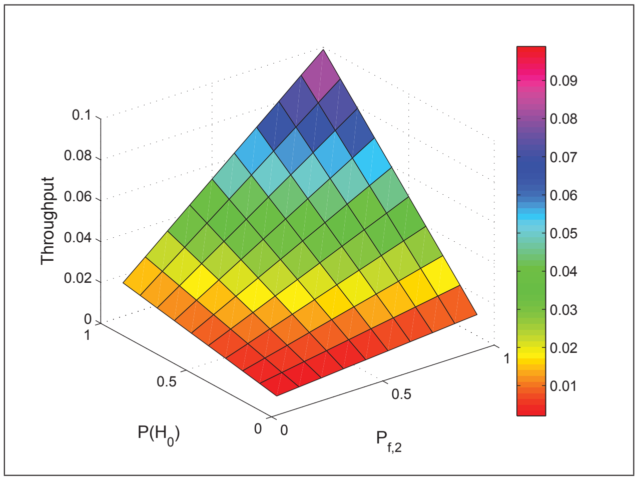

Figure 5: Combined effect of primary user's activity and false alarm probability of $D2D_2$ on the performance of $D2D_1$.

network interference is larger, i.e., the number of D2D systems within the cellular system is high, $\Pr\{\gamma > \theta\}$ becomes dominant. Therefore, smaller values of p_1 will give the best performance in that case.

In case of secondary spectrum usage, the activity of the CU determines the amount of transmission opportunities for D2D systems. Even though there would be large portions of available spectrum in time, high false alarm probabilities of D2D users will restrict the achievable throughput. This is shown in Figure 5 where the throughput of $D2D_1$ is plotted as a function of $P(H_0)$ and $P_{f,2}$. If the CU is active for the most of the time, high probabilities of false alarm have only a minor effect on the throughput. However, if the CU is inactive often, the probability of false alarm affects the performance significantly. In any case it is beneficial for $D2D_1$ to have as high $P(H_0)$ and $P_{f,2}$ as possible for throughput maximization.

V. CONCLUSIONS

This paper studied the performance of ad hoc cognitive D2D systems sharing spectrum with cellular users in a macrocell without infrastructure support. We evaluated the performance of D2D system over Nakagami-m fading channel by investigating the achievable device throughput. A close form expression for statistics, the Moment Generating Function (MGF) and Complementary Cumulative Distribution Function (CCDF) of multiple interferers in Nakagami-m fading channels in cellular system are presented. By using these expressions, we derive the device throughput for multiple D2D systems in a cellular system. Furthermore, the upper bound for the probability of false alarm, which is required to achieve a certain throughput is deduced. The results of this paper illustrate how the transmission probability and sensing performance affect the achievable throughput in cognitive D2D systems. In addition, these results serve as guidance for the deployment of cognitive D2D systems without infrastructure support.

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