Enabling D2D Transmission Mode with Energy Harvesting and Information Transfer in Heterogeneous Networks

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Abstract. *The concept of energy harvesting-assisted relay has been introduced to support the relaying transmission using Device-to-Device (D2D) communications for enhancing communication reliability. Motivated by the recent advance in Heterogeneous Network (HetNet) using relaying techniques, we consider the D2D communication provided by Energy Harvesting (EH) assisted relay where signal is forwarded from a Base Station (BS) to the conventional cellular user (non-D2D user) and D2D user. We first derive the outage probability by taking into account the SNR and power allocation parameters, and propose the transmission mode for D2D link as well as non-D2D link. After deriving the outage probability of the D2D-HetNet, we explore the effects of the network parameters on the outage probability and throughput.*

Keywords

D2D, energy harvesting, HetNet, throughput analysis.

1. Introduction

Today, the need of strengthening the network capacity via the distribution of small cell BSs (e.g., micro, pico, and femto) underlying the common macro cell BSs, especially HetNet which is increasingly growing up. For example, for carrying a massive amount of throughput and bandwidth in satisfying the network quality in order to meet the fast growth of wireless handsets number, HetNet likely affords to accustom because the wireless handsets network capacity appears to achieve the limit. More and more BSs can be supported by HetNet to be distributed in good location to prevent interference. This provided us with a lot of development about network sufficiency and power employing in comparison with macro BSs. Nevertheless, many actual problems have arisen such as load balancing, traffic management, operation and maintenance etc. BSs network scope also has issues like capacity with low power consumption; therefore, wireless energy harvesting plays a very important role for green network for Fifth Generation (5G) world using infrastructures having sufficient and green energy in HetNet [1]. When using ambient Radio-Frequency (RF) signals with the new source for energy harvesting, one of the appropriate ways to harvest energy is parallel Wireless Information and Power Transfer (SWIPT) by collecting energy from ambient RF signals [2] and [3]. Accordingly, SWIPT helps to make the wireless device which can be obtained higher bandwidth efficiency when considering full-duplex mode in relaying networks [4]. However, the process of SWIPT realization has two main difficulties in the large network scope.

The HetNet helps to build up the network capacity through reusing a greater space [5], but this results in the increased interference [6], [7] and [8]. When BSs were distributed heavily, HetNet becomes more attractive for efficient RF-SWIPT. Then the gap between the Mobile User (MU) and the BS in HetNet is much closer than in homogeneous macro cell networks. Furthermore, the total interference in HetNet could be an additional energy source with full frequency reuse. SWIPT technique with self-maintaining and inexpensive characteristics employing the interference in HetNet can increase the spectrum and energy efficiency.

Although the above details are very vital and made a stable infrastructure for promoting new D2D and K-tier network technologies, the effect of wireless power in such networks with D2D capability is less well evaluated. After studying mentioned result in [9], we analyze the design space of future wireless networks about outage performance and energy efficiency for the D2D networks to which energy harvesting enables. On the other hand, in this paper, the system in large-scale HetNet with an energy limited D2D transmitter will be considered. At first, the D2D transmitter collects energy from BSs. Then it performs transporting to the target D2D receiver which accompanies with different levels.

2. System Model and Protocol Description

We consider a scenario of D2D communications underlaying a cellular network that is shown in Fig. 1, where D_2 intends to exchange information with D_4 in D2D link and D_2 transmit signal from BS to normal cellular user D_3. In this paper, we consider K-tier communication (i.e. considering two tiers) which is assigned for D2D in the first tier and non-D2D transmission mode in the second tier.

2.1. System Model

In this paper, we consider a heterogeneous network, in which the second tier services primary user D_3 by considering the Base Station (BS) wants to transfer information to the primary user D_3. It is noted that in such case D_3 is assigned as non-D2D user. Meanwhile, the D2D user D_2 wants to transfer its own information which intended for the the other D2D user D_4. Therefore, D_2 not only forwards to the user in the tier 2 but also delivers the information in the tier 1 simultaneously. As a result, D_2 plays in role of relay node and it required more energy to serve this duty. In particular, the relay D_2 has the ability to scavenge energy from the received signals. Furthermore, the operation of all devices is half-duplex and every device has one signal antenna.

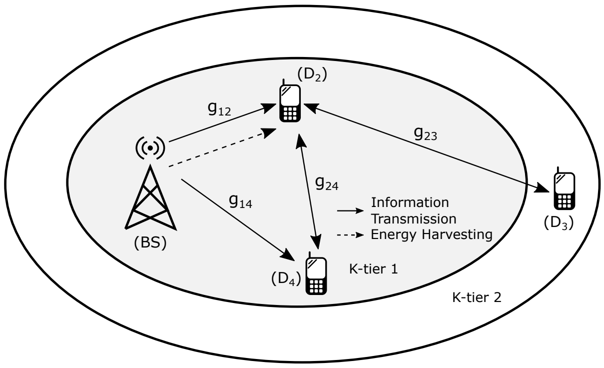

Fig. 1: The structure of two-tier networks for D2D applications.

In Fig. 2, we present a parameter α_1^2 $(0 \leq \alpha_1^2 \leq 1)$ denoting the fraction of the block time allocated for Energy Harvesting (EH) in the block time $T/2$ with T denoted as block time for signal frame processing, node D_2 is assumed as energy harvesting relaying node which uses Power Splitting-based Relaying (PSR) protocol [2], [3], [4] and [10]. We assume that all of the channels are quasi-static fading channels, following Rayleigh fading. Let g_{12}, g_{23}, g_{14}, g_{24} denote as the channel coefficients between BS and D_2, D_2 and D_3, BS and D_4, D_2 and D_4 in the concerned block time, respectively. Also, the channels are modeled as follows: $g_{ij} \sim CN\left(0, \Phi_{ij}\right)$ for $ij = 1, 2, \ldots, 4$. In addition, the transmitted power of BS which is equipped a fixed power supply, i.e. power grid P_{S_1}, whereas there is no fixed energy supply for D_2 and it thus needs to harvest energy from the received signals.

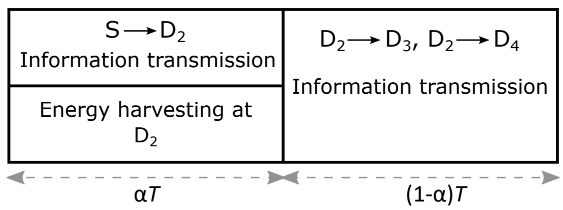

Fig. 2: Illustration of the key parameters in the power splitting protocol for energy harvesting and information processing at D_2.

2.2. The K-Tier Network Structure

In Fig. 1, we show the structure of a two-tier network, in which the first tier includes D2D users D_2 and D_4, while D_3 is considered as in a conventional cellular user. In this paper, the energy harvesting-assisted device D_2 deploys a fraction of power to transmit the primary information from source BS to the normal cellular user and then uses remaining power to transmit signal for D2D link. It is worth noting that each user only detaches related signal and we concern other signals as the unwanted interferers.

2.3. Energy Harvesting and Information Transfer Procedure

In the system model of power splitting-assisted energy harvesting and information transfer protocol includes two phases which are shown in Fig. 2 and it is applied as PSR (Power Splitting-based Relaying) protocol [10]. In phase 1, the BS transmits its information to D_2, energy harvesting of node D_2 and D_4 depends on the EH time of the block time and fraction of information split which is signed by α_1 and α_2, respectively, while power allocation of the second link (including non-D2D and D2D link) is denoted as α_3 $(0 < \alpha_1 < 1; 0 \leq \alpha_2 \leq 1; 0 \leq \alpha_3 \leq 1)$. In principle of PSR, P_{S_1} is transferred the harvested signal at the relay D_2 and the total block time denoted by T, from which half of the time, $T/2$ is occupied for information processing at the first hop of the BS to relay D_2 and the remaining half, $T/2$ is used for the relay to destination D_3, D_4. In particular, the fraction of the received signal power, $\alpha_1 P_{S_1}$ is used for energy harvesting and the remaining received power, $(1-\alpha_1)P_{S_1}$ is used for the source to relay information transmission.

In this scenario, the received signals at D_2 can be expressed as:

$$y_{D_2} = \sqrt{P_{S_1}} g_{12} s_1 + n_{D_2}, \quad (1)$$

$$y_{D_4} = \sqrt{P_{S_1}} g_{14} s_1 + n_{D_4}. \quad (2)$$

Here, s_1 is the primary signal intended for D_3 in the different tier. It is assumed that $\mathrm{E}\left\{|s_1|^2\right\} = 1$, where $E\{.\}$ is the expectation operator and $|.|$ is the absolute value operator, and noted that distance of each link is installed as simulation results in the next section.

Applying PSR protocol in energy harvesting, the transmitted power at D_2 after energy harvesting is shown as

$$P_{D_2} = \eta \alpha_1^2 P_{S_1} |g_{12}|^2, \quad (3)$$

where $0 \leq \eta \leq 1$ depicts the energy conversion efficiency and it depends on the rectifier and the energy harvesting.

Similarly, D_4 can be fed by wireless power transfer from the BS. It can be computed the stored energy at the node D_4 is shown as

$$E_h = \frac{1}{2} \eta \alpha_2^2 P_{S1} |g_{14}|^2. \quad (4)$$

During the phase 2, after energy harvesting, D_2 amplifies $\sqrt{1-\alpha_1^2} y_{D_2}$ together with the D2D-assisted information s_2, then forwards it to D_4. Interestingly, we assume that the relay D_2 in phase 2 can split its transmitted power into two parts: $P_{D_2} = \alpha_3^2 P_{D_2} + (1-\alpha_3^2) P_{D_2}$ for normal link (non-D2D) and D2D link. Thus, we have the broadcasting information at D_2 is given by

$$\begin{aligned} s_{D_2} &= \underbrace{G\sqrt{P_{D_2}\alpha_3{}^2}\left(\sqrt{1-\alpha_1^2}y_{D_2} + n_{b1}\right)}_{non-D2D\ signal} \\ &+ \underbrace{\sqrt{(1-\alpha_3^2)P_{D_2}}s_2}_{D2D\ signal}, \end{aligned} \quad (5)$$

where s_2 is the unit-power transmitted information intended for D_4, $n_{b1} \sim CN\left(0, \sigma_{b1}^2\right)$ denotes the white Gaussian noise introduced by the signal conversion from passband to baseband at D_2. The amplifier factor G of D_2 is given by

$$\begin{aligned} G &= \frac{1}{\sqrt{(1-\alpha_1^2)\left(P_{S_1}|g_{12}|^2 + \sigma_1^2\right) + \sigma_{b1}^2}} \\ &\approx \frac{1}{\sqrt{(1-\alpha_1^2)\, P_{S_1}|g_{12}|^2}}. \end{aligned} \quad (6)$$

At the primary receiver D_3, we obtained the received signal at destination D_3, D_4, respectively, as below

$$y_{D_3} = g_{23} s_{D_2} + n_{D_3} and \;\; y_{D_4} = g_{24} s_2 + n_{D_4}, \quad (7)$$

where $n_{D_3} \sim CN(0, \sigma_{D_3}^2)$ and $n_{D_4} \sim CN(0, \sigma_{D_4}^2)$ represents the additive white Gaussian noise (AWGN) introduced at D_3 and D_4, respectively. Here, D_4 want to detach to signal s_1 where does not appear interference from the secondary signal s_2. At D_3, to decode signal s_1, the Signal-to-Interferences-plus-Noise Ratio (SINR) of D_3 can be calculated by

$$\begin{aligned} \gamma_{D_3} &= \frac{\eta\alpha_1^2\alpha_3^2 P_{S_1}|g_{12}|^2|g_{23}|^2\alpha_3^2}{1-\alpha_3^2} \\ &\cdot \frac{1}{\frac{\eta\alpha_1^2|g_{23}|^2\alpha_3^2}{1-\alpha_3^2}\left(\sigma_{D_2}^2\alpha_3^2 + \frac{\sigma_{b1}^2\alpha_3^2}{(1-\alpha_1^2)} + \left(1-\alpha_3^2\right)P_{S_1}|g_{12}|^2\right) + \sigma_{D_3}^2}. \end{aligned} \quad (8)$$

At the secondary receiver D_4, the received signal from the source along with the information intended for D_4 can be written as

$$\begin{aligned} y_{D_4} &= g_{24} s_{D_2} + n_{D_4}, \\ &= \sqrt{(1-\alpha_1^2)\,\alpha_3^2 P_{D_2} P_{S_1}}\, G g_{12} g_{24} s_1 + \\ &+ \sqrt{(1-\alpha_1^2)\, P_{D_2}}\, G g_{24} n_{D_3} + \\ &+ \sqrt{P_{D_2}}\alpha_3 G g_{24} n_{b1} s_2 + \\ &+ \sqrt{(1-\alpha_3^2)\, P_{D_2}}\, G g_{24} + n_{D_4}. \end{aligned} \quad (9)$$

On the other hand, when $\alpha_2 = 1$, the BS only transfer power to the D2D user. It means that all the harvested power is allocated to harvest energy during all time and no information processing in the link BS-D_4. This leads to a result that D_3 and D_4 have the primary interference to treat s_1 as interference and after D_3 and D_4 decode the secondary information s_1.

It is noted that $\alpha_2^2 = 1$, it can be computed the SNR expression as below

$$\gamma_{D_4} = \frac{\frac{\eta\alpha_1^2(1-\alpha_3^2)P_{S_1}|g_{12}|^2|g_{24}|^2\alpha_3}{1-\alpha_3}}{\beta_1\left[P_{S_1}|g_{12}|^2\alpha_3^2 + \sigma_{D_2}^2\alpha_3 + \frac{\sigma_{b1}^2\alpha_3}{(1-\alpha_1^2)}\right] + \sigma_{D_4}^2}, \quad (11)$$

where

$$\beta_1 = \frac{\eta\alpha_1^2|g_{24}|^2\alpha_3}{(1-\alpha_3)}. \quad (12)$$

We assume that the antenna noise power is zero, i.e. $\sigma_{D_2}^2 = \sigma_{D_4}^2 = 0$. Thus, we have $\sigma_{D3}^2 = \sigma_{D4}^2 = \sigma_{b1}^2 = \sigma_0^2$ as a result from Eq. (8), Eq. (11). We can rewrite the received SNR of the node D_3 and D_4 as follows

$$\gamma_{D_3} = \frac{\frac{\eta\alpha_1^2\alpha_3^2P_{S_1}|g_{12}|^2|g_{23}|^2\alpha_3}{(1-\alpha_3)}}{\frac{\eta\alpha_1^2\alpha_3^2\sigma_0^2|g_{23}|^2\alpha_3}{(1-\alpha_3)(1-\alpha_1^2)} + \frac{\eta\alpha_1^2(1-\alpha_3^2)P_{s_1}|g_{12}|^2|g_{23}|^2}{(1-\alpha_3)\alpha_3^{-1}} + \sigma_0^2}. \quad (13)$$

Similarly, SNR at device D_4 can be expressed by

$$\gamma_{D_4} = \frac{\frac{\eta\alpha_1^2(1-\alpha_3^2)P_{s_1}|g_{12}|^2|g_{24}|^2\alpha_3}{(1-\alpha_3)}}{\frac{\eta\alpha_1^2|g_{24}|^2\alpha_3}{(1-\alpha_3)}\left(P_{s_1}|g_{12}|^2\alpha_3^2 + \frac{\sigma_0^2}{(1-\alpha_1^2)}\alpha_3\right) + \sigma_0^2}. \quad (14)$$

Accordingly, from formula of the obtained SNR of the non-D2D user D_3 and the D2D user D_4, we can calculate the instantaneous rate at D_3 and D_4 as follows

$$R_{D_3} = \frac{1}{2}\log_2(1-\gamma_{D_3}); R_{D_4} = \frac{1}{2}\log_2(1-\gamma_{D_4}). \quad (15)$$

3. Outage Probability and Throughput Analysis

3.1. Outage Probability

The outage probability is defined that the data rate of the D2D user D_3 and the cellular user D_4 falls below the predetermined threshold target rate. Therefore, the outage probability for a given target rate F_i is given by

$$\mathrm{P}_{out}(R_i < F_i) = \Pr(\gamma_i < f_i), \quad (16)$$

where $i = D_3$ or $i = D_4$. Here, we set $f_i = 2^{2F_i} - 1$. F_i is the fixed source transmission. According to Eq. (14), we have the following propositions.

Proposition 1: Let denote

$$\lambda = \frac{\alpha_3}{1-\alpha_3}, \quad (17)$$

$$l = \frac{\eta\alpha_1^2\alpha_3^2P_{S_1}}{\sigma_0^2}\lambda, \quad (18)$$

$$m = \frac{\eta\alpha_1^2\left(1-\alpha_3^2\right)P_{s_1}\lambda}{\sigma_0^2}, \quad (19)$$

$$k = \frac{\eta\alpha_1^2\alpha_3^2\lambda}{(1-\alpha_1^2)}. \quad (20)$$

The outage probability of D_3 can be expressed as

$$P_{out}^{D_3} = 1 - \exp\left\{-\frac{kf_{D_3}}{\Phi_1(l-mf_{D_3})}\right\}\sqrt{\frac{4f_{D_3}}{\Phi_1\Phi_2(l-mf_{D_3})}} \times K_1\left\{\sqrt{\frac{4f_{D_3}}{\Phi_1\Phi_2(l-mf_{D_3})}}\right\}, \quad (21)$$

where $K_1(.)$ is the modified Bessel function of the second kind. Interestingly in this paper, the outage probability of D_4 can be calculated as Proposition 1.

Proof: Let $X = |g_{12}|^2$, $Y = |g_{24}|^2$ and define

$$N = \frac{qXY}{wXY + gY + 1}, \quad (22)$$

where we use the definition the CDF of N (i.e. $F_N(n)$) can be easily derived through some algebraic manipulation. Finding out, we have $P_{out}^{D_3} = F_N(f_{D_3})$. The detailed derivation can be seen in [9].

Because of the secondary interference from the information transmission processing in the secondary network and the receiver antenna, the signal converts from pass-band to baseband at the secondary user D_2. It is quite easy to obtain from Eq. (13) that $\lim_{P_{S1}\to\infty}\gamma_{D_3} = \frac{\alpha_3^2}{1-\alpha_3^2}$.

Therefore, $\gamma_{D_3} \to \frac{\alpha_3^2}{1-\alpha_3^2}$ the outage event of the secondary user D_3 occurs all the time if $f_{D_3} \ge \frac{\alpha_3^2}{1-\alpha_3^2}$ and the α_3^2 factor is chosen exactly, the equation $P_{out}^{D_3} = 1$ will happen.

The outage probability the secondary user D_4 can be written as following expression Eq. (10).

In this case, the secondary user can not remove the primary interference from BS when $\alpha_2^2 = 1$, yielding $\lim_{P_{S1}\to\infty}\gamma_{D_4} = \frac{1-\alpha_3^2}{\alpha_3^2}$. As a result, we can calculate the exact expression of $P_{out}^{D_4}$. Likewise, we have $P_{out}^{D_4} = 1$ if $f_{D_4} \ge \frac{(1-\alpha_3^2)}{\alpha_3^2} \approx \frac{1-\alpha_3^2}{\alpha_3^2}$ and $\alpha_2^2 = 1$. This indicates a difficult problem how to choose the factor α_3^2 to satisfy this condition. Note that, when the α_3^2 decreases, $P_{out}^{D_4}$ decreases, but results in $P_{out}^{D_3}$ increasing. Otherwise, if the α_3^2 decreases, $P_{out}^{D_4}$ increases, but results in $P_{out}^{D_3}$ decreasing.

3.2. Throughput Analysis

Proposition 1 Derives the outage probability at the D_3 and D_4, respectively. In this paper, we con-

$$P_{out}^{D_4} = Pr\left[\gamma_{D_4} < f_{D_4}\right] = P\left[\frac{m|g_{12}|^2|g_{24}|^2}{\left(l|g_{12}|^2|g_{24}|^2 + k\frac{1}{\alpha_3^2}|g_{24}|^2 + 1\right)} < f_{D_4}\right]. \quad (10)$$

sider both the secondary and primary network. The throughput at D_3 and D_4 is given by

$$\tau_m = \left(1 - P_{out}^m\right) F_m, \quad (23)$$

where achievable throughput τ_m with m is D_3 or D_4. Here, the transmitter communicates with fixed rate F_m (bps·Hz^{-1}). This number illustrates effective communication capability from the source node to the destination node in the block of time T seconds.

4. Numerical Results

In this paper, we consider outage performance of D2D link and non-D2D link with the help of energy harvesting-assisted relay node D_2 to transfer information to D2D user in tier 1 and non-D2D in tier 2. In this section, we verify the accuracy of the proposed expressions by the simulation to demonstrate the performance of the proposed wireless energy harvesting and information transfer in HetNet. In the simulation, we set the distances of each link which are normalized. Let d_1 denote the distance between BS and D_2, the distance between D_2 and D_3 are denoted by d_2. Similarly, we define d_3 as the distance between BS and D_4, and the distance between D_2 and D_4 represented by d_4, and hence the average channel gains as $\Phi_1 = 1/d_1$, $\Phi_2 = 1/d_2$, and $\Phi_3 = 1/d_3$, $\Phi_4 = 1/d_4$, for g_{12}, g_{23}, g_{14} and g_{24}, respectively.

In Fig. 3, the analytical results for outage probability are examined. For either D2D user and cellular user, the analytical expressions are confirmed. We observe that the analytical results match well with simulation results for cellular user D_3. Also, we find that outage performance of each type of link is different due to different power allocation. Besides, the floor value of outage probability remains stable level, especially at high SNR, which verifies our theoretical derivation.

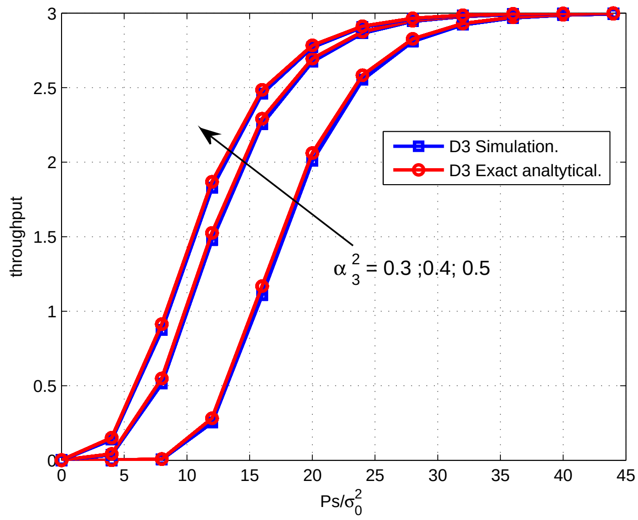

Fig. 4: Simulation based and analytical throughput at D_3. Here, $F_{D_3} = F_{D_4} = 3$ (bps·Hz^{-1}); $d_1 = d_2 = 0.5; d_3 = 0.75\,; \alpha_1 = 0.92\,; \alpha_3 = 0.58$.

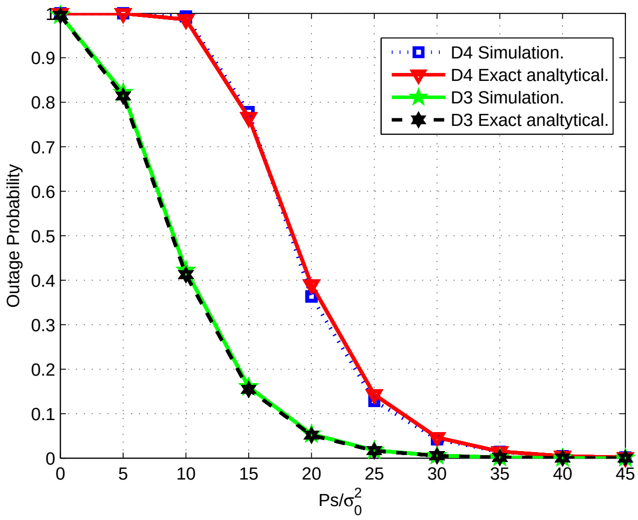

Fig. 3: Simulation based and analytical outage performance at D_3 and D_4. Here,$F_{D_4} = F_{D_3} = 3$ (bps·Hz^{-1}), $d_1 = d_2 = 0.5; d_3 = 0.75\,; \alpha_1 = 0.62\,; \alpha_3 = 0.58$.

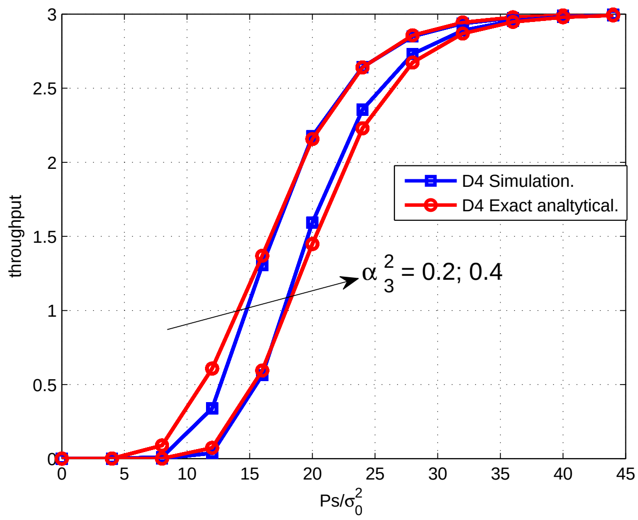

Fig. 5: Simulation based and analytical throughput at D_4. Here, $F_{D_3} = F_{D_4} = 3$ (bps·Hz^{-1}); $d_1 = 0.6; d_2 = 0.4; d_3 = 0.75\,; \alpha_1 = 0.62\,; \alpha_3 = 0.7$.

In Fig. 4, we compare the result of simulation and exactly analysis at D_3 in case of the increase from 0.3 to 0.5 of α_3^2, we can see the throughput which will be better when the power allocation coefficient of the second link (including link assigned for non-D2D and D2D link), .i.e. α_3^2 increases to 0.5, we obtain the highest throughput among concerned values. Besides, the simulation and exactly analysis have the same result.

Similarly, the throughput at node $D4$ is considered in Fig. 5, the throughput is low and it increases very slowly at SNR from 0 dB to 10 dB, but it increases quickly at SNR from 15 dB to 45 dB. Furthermore, when α_3^2 increases, the throughput at node D_4 will increase very slowly.

5. Conclusion

In this paper, a tractable analytical framework for the evaluation of outage of D2D and non-D2D link in a general K-tier heterogeneous cellular networks has been developed. In particular, we have obtained simple expressions for the non-D2D user in terms of outage probability. Beside that, we have presented some guides to design energy harvesting-based multi-tier cellular networks and evaluate their performance under impacts of power allocation fractions for each kind of D2D link. The numerical results based on the analysis show that RF energy harvesting can enable technology to power cellular devices. In addition, the simulation results validate the derived expressions, which are efficiently computed numerically.

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