Performance Analysis of Time-Switching Energy Harvesting Device-to-Device Link Underlying Small-Cell-Networks

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Abstract. In this paper, we propose an underlying Small-Cell-Networks (SCNs) Device-to-Device (D2D) pair with the use of time-switching Energy Harvesting (EH) techniques. More specifically, we have a D2D transmitter and receiver underlying SCNs operating in closeness to a SCNs primary user (PU). We propose two scenarios, in the first scenario we harvest energy from all of the available SCN base stations (BSs). Whereas in the second scenario we select the best BS link to harvest energy from. Moreover, the transmission is kept under a certain threshold between the D2D pair, so that it does not have any deleterious effect on the PU transmission link.

Keywords: Device-to-Device communication · Small cell networks
Energy harvesting

1 Introduction

Currently, there are more than five billion devices connected to the cellular network and it is predicted that 50 billion devices will be connected by 2020 [3]. This shows the importance of broadband cellular networks in modern life. The tremendous growth in this market has been driven by the introduction of smart phones, tablets and netbook devices and its swiftly developing and rising innovative applications, such as online gaming, mobile social networks applications and virtual and augmented reality in multimedia applications. Correspondingly, there continues to be a significant growth in the demand for data capacity. To address this, various new technologies have been proposed to improve the spectral efficiency in the traditional communication methods of cellular networks and increase its throughput. These include technologies such as, Millimetre waves (MM wave), Massive multiple input and multiple output (MIMO), Small Cell Networks (SCNs) and Device-to-Device communication (D2D) [1]. Furthermore, out of the all aforementioned technologies, D2D communication and SCN technologies arise to be promising concepts. Particularly underlying D2D communication, which is a technology that allows devices that are in close proximity to each other to use cellular resources to communicate with each other without routing the information through the base station (BS).

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D2D communication was first introduced in [2] as an approach to allow multi-hop relays in cellular networks. Subsequently, the authors in [3,4] considered the possibility of using D2D communication networks as a way to enhance the spectral efficiency and diminish communication delay. The reported numerical simulation results show that the proposed D2D scheme improves the cell throughput by 40%. Moreover, different possible D2D use-cases were introduced such as machine-to-machine (M2M) communication [6], peer-to-peer communication [5] and video braodcasting [7].

Recently, Energy Harvesting (EH) in cellular networks has arose as promising concept in providing a different source of energy to power cellular devices [9]. EH allows wireless devices to scavenge an alternative source of energy that is provided by nature or man-made phenomena [12]. The authors in [13], investigated the use of EH based D2D communication and proposed a power transfer and information signal model for secure EH information transmission. In [14], a beamforming design for wireless information and power transfer was suggested to maximize the minimum user rate and minimize the maximum BS transmit power under both the BS transmit power and the user data rate constraints respectively, considering the user harvested energy constraint as well. Furthermore, maximizing the achievable user date rate was studied as well in [15] by suggesting a mutually optimal power and time fraction allocation and optimal power allocation with a fixed time fraction for EH.

Consisting of a number of low cost and power radio access nodes, SCNs introduced to deal with the coverage issues in conventional cellular networks [20]. Later on, their use was extended to replace the traditional cellular network BSs in some cases as a way of increasing the capacity and quality of service (QoS) [21]. This was due to their ability to achieve higher signal-to-interference-plus-noise ratio (SINR) and shorter transmit-receive distance. Moreover, the authors in [22] suggest that SCNs will be a key element in the next generation cellular architecture in regards to minimizing energy consumption and providing a higher end-user data rates.

The rest of this paper is organized as follows. System and channel models are discussed in Sect. 2. The outage probabilities of the proposed system in the both schemes are described in Sect. 3. In Sect. 4, numerical simulations results are presented to validate the correctness of our analyses. Finally, the paper is concluded in Sect. 5.

2 System Model

In this paper, we consider a D2D pair communication underlying SCNs. The D2D pair consists of D2D transmitter (D_{tx}) and D2D receiver (D_{rx}) operating in closeness to a SCNs primary user (PU) as shown in Fig. 1. We propose two scenarios, the first scenario, when D_{tx} harvests energy from all of the SCNs available BSs in order to communicate with D_{rx}. Whereas in the second scenario the best BS link is selected for D_{tx} to harvest energy from. The received signal (y) and harvested energy (e) at D_{tx} can be calculated as:

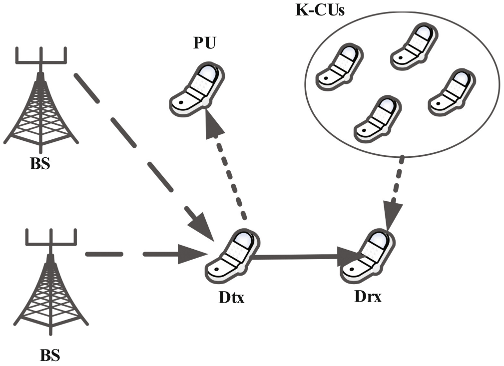

Fig. 1. D2D pair underlying a small cellular network.

$$y = P_o h_1 x + \zeta_o. \tag{1}$$

$$E = P_o |h_1|^2 \eta \alpha T, \tag{2}$$

where

$$|h_1|^2 = \begin{cases} \sum_{i=0}^{M} |h_m|^2 & \text{, EH scenario 1} \\ \max\limits_{m} |h_m|^2 & \text{, EH scenario 2} \end{cases}. \tag{3}$$

Assuming a Rayleigh fading channel, h_1 is the channel coefficient between the D_{tx} and BS, P_o denotes the transmitting power of the BS, x is the transmitted signal from the m-th BS, e$|x|^2$=1, and ζ_o is the additive white Gaussian noise (AWGN) with zero mean and variance N_o. η and α are the EH efficiency coefficient and fraction respectively, and T is the period time for the transmission symbol. K represent the number of SCNs users causing interference to D_{rx} and h_k is the channel coefficient between the D_{tx} and K users. M is the number of SCNs BSs and the channel coefficients between the D_{tx} and D_{rx} is h_2, where it is defined as h_3 between D_{tx} and PU. The transmitted power of D_{tx} is defined as:

$$PD_{tx}^{'} = \frac{E}{(1-\alpha)T} = \frac{P_o |h_1|^2 \eta \alpha}{(1-\alpha)}. \tag{4}$$

Nonetheless, the D2D pair link transmission power is kept under a certain threshold so it could not have any effect on the transmission link of PU. Therefore, D_{tx} will be constrained by a peak interference constraint (I_p) at D_{rx}. Therefore, the transmitted power of D_{tx} is redefined as:

$$PD_{tx} = \min\left(\frac{P_o |h_1|^2 \eta \alpha}{(1-\alpha)}, \frac{I_p}{|h_3|^2} \right). \tag{5}$$

Now, the SINR at D_{rx} can be calculated as:

$$\begin{aligned}\varPsi &= \frac{PD_{tx}|h_2|^2}{\sum_{k=0}^{K} P_I|h_k|^2 + N_0} = \frac{\min\left(\frac{P_o|h_1|^2\eta\alpha}{(1-\alpha)}, \frac{I_p}{|h_3|^2}\right)|h_2|^2}{\sum_{k=0}^{K} P_I|h_k|^2 + N_0} \\ &= \frac{\min\left(P_o|h_1|^2\delta, \frac{I_p}{|h_3|^2}\right)|h_2|^2}{\sum_{k=0}^{K} P_I|h_k|^2 + N_0} = \frac{\min\left(\gamma_o|h_1|^2\delta, \frac{\gamma_p}{|h_3|^2}\right)|h_2|^2}{\gamma_i\sum_{k=0}^{K} |h_k|^2 + 1}. \end{aligned} \tag{6}$$

The cumulative distribution function (CDF) of h_1 is:

$$F_{h_1}(x) = [1 - \exp(-\lambda_1 x)]^M. \tag{7}$$

The probability density function (PDF) of h_1 is:

$$f_{h_1}(x) = \sum_{m=0}^{M} C_M^m (-1)^m \exp(-m\lambda_1 x). \tag{8}$$

The CDF of X is:

$$F_X(x) = \frac{1}{\varGamma(K)}\varUpsilon(K, x\lambda_4) = 1 - \exp(-\lambda_4 x)\sum_{k=0}^{K-1}\frac{x^k\lambda_4^k}{k!}. \tag{9}$$

The achievable rate of the D2D link is:

$$C = (1-\alpha)\log_2\left(1 + \frac{\min\left(\gamma_o|h_1|^2\delta, \frac{\gamma_p}{|h_3|^2}\right)|h_2|^2}{\gamma_i\sum_{k=0}^{K}|h_k|^2 + 1}\right). \tag{10}$$

3 Outage Probability

The outage probability of the D2D communication link is the probability that the achievable rate of the D2D communication link falls below a certain threshold (R_{th}).

$$\begin{aligned}P_{out} &= P_r C < R_{th} = P_r\varPsi < 2^{\frac{R_{th}}{(1-\alpha)}} \\ &= P_r\left(|h_2|^2 < \frac{(\gamma_i x + 1)\beta}{\min(\gamma_o|h_1|^2\delta, \frac{\gamma_p}{|h_3|^2})}\right) \\ &= 1 - \int_0^\infty \exp\left(\frac{\lambda_2(\gamma_i x + 1)\beta}{\underbrace{\min(\gamma_o|h_1|^2\delta, \frac{\gamma_p}{|h_3|^2})}_{\mathcal{U}}}\right) f_X(x)dx \\ &= 1 - \lambda_4^K \exp\left(\frac{-\lambda_2\beta}{\mathcal{U}}\right)\left(\frac{\mathcal{U}}{\lambda_4\mathcal{U} + \lambda_2\beta\gamma_I}\right)^K, \end{aligned} \tag{11}$$

where

$$\mathcal{U} = \begin{cases} \frac{\gamma_P}{|h_3|^2}, & \text{if } \ |h_1|^2 > \frac{\gamma_p}{\gamma_p \delta |h_3|^2} \\ \gamma_P \delta |h_3|^2, & \text{if } \ |h_1|^2 < \frac{\gamma_p}{\gamma_p \delta |h_3|^2} \end{cases} . \tag{12}$$

Now, (11) can be rewritten as:

$$\begin{aligned} P_{out} = 1 &- \left(\frac{\gamma_p}{\lambda_4 \gamma_p + \lambda_2 \beta \gamma_i h_3} \right)^K \\ &\times \int_{\frac{\gamma_p}{\gamma_o \delta h_1}}^{\infty} \lambda_4^K \exp\left(\frac{-\lambda_2 \beta h_3}{\gamma_p} \right) f_{h_3}(h_3) dh_3 \\ &- \left(\frac{\gamma_o \delta h_1}{\lambda_4 \gamma_o \delta h_1 + \lambda_2 \beta \gamma_i} \right)^K \\ &\times \int_0^{\frac{\gamma_p}{\gamma_o \delta h_1}} \lambda_4^K \exp\left(\frac{-\lambda_2 \beta}{\gamma_o \delta h_1} \right) f_{h_3}(h_3) dh_3, \end{aligned} \tag{13}$$

$$\begin{aligned} = 1 - &\underbrace{\int_{\frac{\gamma_p}{\gamma_o \delta h_1}}^{\infty} \lambda_4^K \exp\left(\frac{-\lambda_2 \beta h_3}{\gamma_P} \right) \mathcal{A} \lambda_3 \exp(-\lambda_3 h_3) dh_3}_{\mathcal{J}_1} \\ &- \lambda_4^K \exp\left(\frac{-\lambda_2 \beta}{\gamma_o \delta h_1} \right) \left(\frac{\gamma_o \delta h_1}{\lambda_4 \gamma_o \delta h_1 + \lambda_2 \beta \gamma_i} \right)^K \\ &\left(1 - \exp\left(-\lambda_3 \frac{\gamma_p}{\gamma_o \delta h_1} \right) \right), \end{aligned} \tag{14}$$

where $\mathcal{A} = \left(\frac{\gamma_p}{\lambda_4 \gamma_p + \lambda_2 \beta \gamma_I h_3} \right)^K$, and $\mathcal{J}_1$ are calculated as:

$$\begin{aligned} \mathcal{J}_1 = \mathcal{N}_3 \Bigg[&\left(\exp \frac{-\gamma_p}{\gamma_o \delta h_1} \mathcal{N}_1 \right) \sum_{k=1}^{K-1} \frac{(k-1)! (\mathcal{N}_1)^{K-k-1}}{(K-1)! (\frac{\gamma_p}{\gamma_o \delta h_1} + \mathcal{N}_2)^k} \\ &- \frac{-\mathcal{N}_1{}^{K-1}}{(k-1)!} \exp(\mathcal{N}_2 \cdot \mathcal{N}_1) E_i \left(-\left(\frac{\gamma_p}{\gamma_o \delta h_1} + \mathcal{N}_2 \right) \mathcal{N}_1 \right) \Bigg], \end{aligned} \tag{15}$$

where $\mathcal{N}_1 = (\frac{\lambda_2 \beta}{\gamma_p} + \lambda_3), \mathcal{N}_2 = (\frac{\lambda_4 \gamma_p}{\gamma_i \lambda_2 \beta}), \mathcal{N}_3 = ((\gamma_i \lambda_2 \beta)^K)$.

Now with the use of (13) and $\mathcal{N}_1, \mathcal{N}_2, \mathcal{N}_3$:

$$\begin{aligned} P_{out} = 1 - \mathcal{N}_3 &\sum_{k=1}^{K-1} \frac{(k-1)! (\mathcal{N}_1)^{K-k-1}}{(K-1)!} \\ &\underbrace{\int_0^{\infty} \frac{(\gamma_o \delta h_1)^k}{(\gamma_p + \gamma_o \delta h_1 \mathcal{N}_2)^k} f_{h_1}(h_1) dh_1}_{\mathcal{J}_2} \\ &+ \frac{\mathcal{N}_3 (-\mathcal{J}_1)^{K-1}}{(K-1)!} \exp(\mathcal{N}_1 \mathcal{N}_2) \end{aligned}$$

$$\begin{aligned}
&\int_0^\infty \underbrace{E_i(-\mathcal{N}_1[\frac{\gamma_p}{\gamma_o\delta h_1}+\mathcal{N}_2])f_{h_1}(h_1)dh_1}_{\mathcal{J}_3}\\
&-\lambda_4^K(\lambda_o\delta)^K\\
&\int_0^\infty \underbrace{\exp(\frac{-\lambda_2\beta}{\lambda_o\delta h_1})\frac{h_1^K}{(\lambda_4\gamma_o\delta h_1+\lambda_2\beta\gamma_i)^K}f_{h_1}(h_1)dh_1}_{\mathcal{J}_4}\\
&+\lambda_4^K\int_0^\infty \underbrace{\exp(-\frac{1}{h_1}(\mathcal{N}_4))\mathcal{B}f_{h_1}(h_1)dh_1}_{\mathcal{J}_5}, \qquad (16)
\end{aligned}$$

where $\mathcal{N}_4=\left(\frac{\lambda_1\beta}{\gamma_o\delta}+\frac{\lambda_3\gamma_p}{\gamma_o\delta}\right)$, $\mathcal{B}=\left(\frac{(\gamma_o\delta h_1)^K}{(\lambda_4\gamma_o\delta h_1+\lambda_2\beta\gamma_i)^K}\right)$.

Furthermore, $\mathcal{J}_2, \mathcal{J}_3, \mathcal{J}_4$ and $\mathcal{J}_5$ are calculated as:

$$\mathcal{J}_2=\sum_{m=1}^{M}C_M^m(-1)^{m+1}m\lambda_1\times\int_0^\infty\frac{(h_1)^k}{\mathcal{N}_2^K(\frac{\gamma_p}{\gamma_o\delta\mathcal{N}_2}+h_1)^k}\exp(-m\lambda_1h_1)dh_1.$$

$$\mathcal{J}_3=\int_0^\infty E_i\left(-\mathcal{N}_1[\frac{\gamma_p}{\gamma_o\delta h_1}\mathcal{N}_2]\right)\times\sum_{m=1}^{M}C_M^m(-1)^{m+1}m\lambda_1\exp(-m\lambda_1h_1)dh_1.$$

$$\begin{aligned}
\mathcal{J}_4=\sum_{m=1}^{M}C_M^m(-1)^{m+1}\frac{m\lambda_1}{\lambda_4\gamma_o\delta}\int_0^\infty\exp\left(\frac{-\lambda_2\beta}{\gamma_o\delta h_1}-m\lambda_4h_1\right)\\
\times\left(\frac{(h_1)^k}{\left(h_1+\underbrace{\frac{\lambda_2\beta\gamma_i}{\lambda_4\gamma_i\delta}}_{\mathcal{N}_5}\right)^K}\right)dh_1. \qquad (17)
\end{aligned}$$

$$\begin{aligned}
\mathcal{J}_5=&\sum_{m=1}^{M}C_M^m(-1)^{m+1}m\lambda_1\\
&\times\int_0^\infty\exp(\frac{-\mathcal{N}_4}{h_1}-m\lambda_1h_1)\frac{(h_1)^k}{\lambda_4^K(h_1+\mathcal{N}_5)^K}dh_1. \qquad (18)
\end{aligned}$$

4 Numerical Results

Figure 2 shows the theoretical and simulation results of the outage probability of the D2D link when harvesting energy from all of the SCNs BSs, under different peak interference constraints I_p values. We set α= 0.7, η= 0.8 and the number of the SCNs users that cause interference to the D_{rx} to K= 4 with the power of P_I= 5 dB. Furthermore, we set number of SCNs BSs M to 10, $\lambda_1=\lambda_3=\lambda_4=1$, $\lambda_2=0.1$ and $R_{th}=0.4$. As we can see, the simulation results

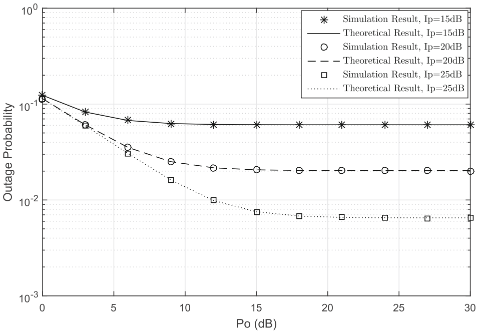

Fig. 2. Outage probability of the D2D link when harvesting energy from All BSs. $\eta = 0.8$, $\alpha = 0.7$, $M = 10$, $K = 4$, $P_I = 5$ dB, $\lambda_1 = \lambda_3 = \lambda_4 = 1$, $\lambda_2 = 0.1$, $R_{th} = 0.4$.

are almost matched perfectly with the theoretical results. Moreover, the outage probability of the D2D link decreases and then saturates when the transmit power of the BS increases. Further, when the transmit power of the BSs is small, the D2D transmitter will also have a small transmit power, smaller than the peak interference constraint which leads the outage probability of the D2D link to improve when the BSs power is increased.

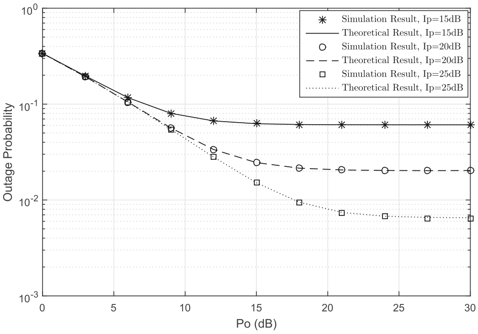

Fig. 3. Outage probability of the D2D link when harvesting energy from the best BS link. $\eta = 0.8$, $\alpha = 0.7$, $M = 10$, $K = 4$, $P_I = 5$ dB, $\lambda_1 = \lambda_3 = \lambda_4 = 1$, $\lambda_2 = 0.1$, $R_{th} = 0.4$.

Figure 3 shows the outage probability of the D2D link when harvesting energy from the best BS link available at the time of the transmission under different I_p values. The parameters are set exactly as used in Fig. 2. We can see that the outage probability increased slightly in comparison to Fig. 2, and that is due to the fact that we are only harvesting energy from one BS link, where in Fig. 2 we harvest energy from multiple BS links. Figure 4 shows the theoretical and simulation results of the outage probability of the D2D link with the variation of α from 0 to 1 under different peak interference constraints I_p. As we can see, the outage probability of the D2D link decreases when higher peak interference is allowed.

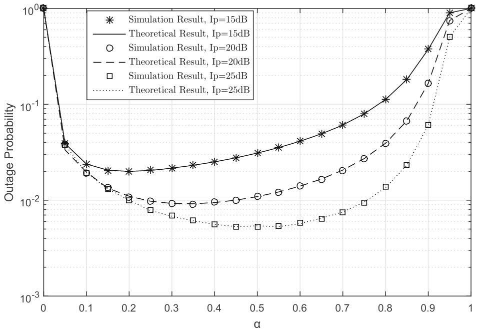

Fig. 4. Outage probability of the D2D link when α varies from 0 to 1. $\eta = 0.8$, $M = 10$, $K = 4$, $P_o = 15\,\text{dB}$, $P_I = 5\,\text{dB}$, $\lambda_1 = \lambda_3 = \lambda_4 = 1$, $\lambda_2 = 0.1$, $R_{th} = 0.4$.

5 Conclusion

In this paper, we investigated the performance of an underlying SCNs D2D link with the use of Time-switching EH techniques. We proposed two scenarios, in the first scenario we investigated the performance when the D2D transmitter harvests energy from all of the available BSs in the SCNs. In the second scenario, we investigated the performance of the system when the D2D transmitter harvests energy from the best available SCNs BS. From the obtained results, we can see clearly that the first scenario outperform the second scenario. We discovered that the performance of the system will decreases when increasing the number of interference links. Furthermore, the primary user peak interference constraint has a huge impact on the outage probability of the D2D link. Finally, for the best performance of the D2D link, the energy harvesting time fraction should be carefully set.

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