Energy Efficient Communications with Device-to-Device Links in Cellular Networks

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Abstract—Device-to-Device (D2D) communications in cellular networks allow devices to communicate directly without going through the base station. The D2D underlaying cellular networks method is aimed to increase network energy efficiency, as specified for Long-Term Evolution Advanced (LTE-A) and 5G systems. In this paper, we examine the performance of both cooperative and non-cooperative communications modes based on the energy models we establish, within a mobile network where both user equipment (UE) to base station and D2D transmission links co-exist. We show that the source-destination distance is an important factor to decide whether to use the cooperative or non-cooperative transmission scheme in order to achieve better energy efficiency. We have also investigated the effects of choosing different numbers of relaying branches and relays in each branch on the performance of the network. This investigation leads to identifying optimal transmission schemes for maximizing energy efficiency under varying environmental conditions.

Keywords-Energy efficiency; cooperative communications; D2D communications.

I. INTRODUCTION

Device-to-Device (D2D) communications, which enable direct data transmission between devices such as user equipment (UE) without help from existing infrastructures such as base stations (BSs) or access points (APs), has been investigated as a promising technique for future cellular networks [1]. It can reduce signaling overhead and save the limited resources of local cells and the network as a whole. The existing research in this area has been mainly focused on how D2D communications can run efficiently as an underlay to cellular networks to save energy consumption of UEs and BS and improve network performance such as spectral efficiency and throughput [2] [3].

D2D communications normally take place through a direct and reliable link between D2D devices to satisfy the quality-of-service (QoS) requirement for both D2D links and the cellular system simultaneously. However, meeting these requirements faces challenges from physical and resource limitations, including high loss rates due to changes in terrain, multipath fading, Doppler spread, interference and noise. This will not only reduce network performance but also waste the limited power of the devices involved.

Cooperative communications through applying relaying techniques including decode-and-forward (DF)

and amplify-and-forward (AF) are commonly used to overcome these problems, to enhance the transmission reliability by creating diversity [4][5]. These techniques can enable cellular user equipment (UE) to help each other through relaying other device's data and sharing their limited resources. However, involving more relay nodes will consume more energy, although this can be mitigated to some degree through proper power allocation schemes [6].

In this work, we examine the energy efficiency performance of a mobile cellular network that accommodates both D2D and UE assisted relaying communications. We also investigate the strengths and limitations of cooperative transmission schemes in this scenario, in comparison with non-cooperative schemes, under different conditions, such as transmission distance, relaying method, channel condition (path loss exponent) and interference. Through this investigation we can identify proper transmission schemes for optimizing the energy performance of the network in varied conditions. In addition, we derive the closed form outage probability that contributes to establishing the models of energy efficiency.

The remainder of this paper is organized as follows. Section II discusses the relevance of this research with other work. Energy efficiency models for both cooperative and non-cooperative transmission schemes in a cellular network are presented in Section III. Simulation results and discussions are provided in Section IV. Finally, the paper is concluded in Section V.

II. RELATED WORK

Most literature has been focused on the interference coordination issue between D2D and cellular communication links. The problem of maximizing cellular offloading with D2D communication was studied in [7], which is mainly focused on the communication aspects, including interference avoidance and energy efficiency. Multi-user multiple-input and multiple-output (MIMO) systems are also considered to obtain the maximal possible energy efficiency for cellular networks [8]. Currently, the cooperative D2D idea was exploited for enhancing social ties in human social networks [9] to promote efficient cooperation among devices.

In the energy efficiency aspect, work in [10] showed that the best position of devices can be found to minimize the total power used for the network, while in [11], multihop D2D communications where one UE may help other two UEs to exchange information has been

investigated in order to enhance energy efficiency. Most of the works reported have investigated energy efficiency and spectral efficiency over non-cooperative or cooperative communication links using only one relay branch. There is a lack of information regarding how to choose a specific transmission scheme and determine the number of relaying branches and the number of relays in each branch under different conditions such as the changing transmission distance between source and destination nodes, in order to find a solution for ensuring the best QoS within a network.

In this paper, based on the initial work for wireless sensor networks [12], our investigation will identify the conditions for establishing appropriate transmission strategies among different commonly used transmission schemes in the context of a cellular network that includes both D2D and UE-to-BS links with cooperative as well as non-cooperative communications. This investigation is based on the development of analytical energy efficiency models for these transmission schemes, and involves performance analysis on, in particular, the trade-offs between cooperative and non-cooperative transmission schemes.

III. ENERGY EFFICIENCY MODEL

In this section, the analytical models of the required transmitting power, outage probability and energy efficiency in the context of a cellular network and D2D communication links are established for both cooperative and non-cooperative transmission schemes. Based on these models, an adaptive transmission strategy can be developed to optimize the energy performance.

Given a cellular network with a number of D2D pairs and cellular user equipment (CUE) and BS, the optimization of the system performance is achieved by maximizing the overall energy efficiency with an outage probability target:

$$Max \sum EE_{bi} \quad s.t.\{p_{outS\text{-}D}\} \qquad (1)$$

where EE_{bi} is the energy efficiency of the i-th transmission link either between CUE and BS or between D2D devices, and $p_{outS\text{-}D}$ is the fixed outage probability target.

Different transmission schemes involving D2D and CUE-to-BS links are shown in Fig. 1, including both non-cooperative and cooperative communications in CUE-BS links. In the cooperative communications scenario (Fig. 1 (b)), relaying with a varied numbers of branches and relays in each branch are illustrated and will be considered in analytical modeling in connection with D2D transmission in Subsections III.*A* & III.*B*.

We consider a cellular cell in which the transmission links are subject to narrowband Rayleigh fading with Additive White Gaussian Noise (AWGN) and propagation path-loss. The channel fades for different links are assumed to be statistically mutually independent.

A. Non-Cooperative Transmission Scheme

Consider the scenario shown in Fig. 1(a) where in addition to communication between cellular users through the base station, which forms CUE-BS links, cellular users
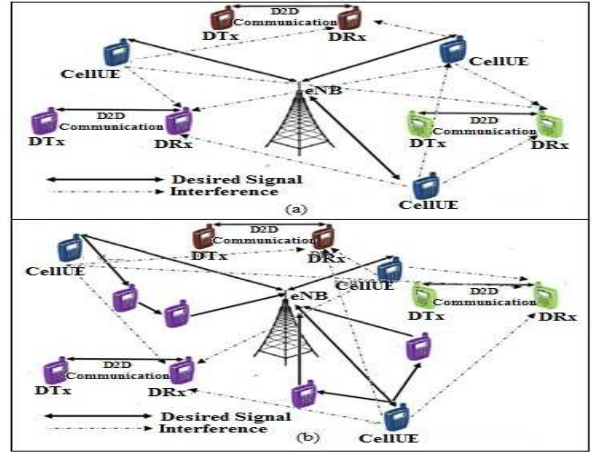

Figure 1. Transmission schemes in a cellular network: (a) CUE-BS using non-cooperative communications and direct D2D, and (b) CUE-BS using cooperative communications and direct D2D.

can also communicate with each other directly in the D2D mode. It is assumed that the distance between any D2D pair is shorter than that of the CUE-BS link in a cellular cell. When a D2D pair communicate by reusing the uplink (UL) resource of an active CUE that is transmitting data to the BS, the active CUE will interfere with to the D2D receiver (DRx) and at the same time the D2D transmitter (DTx) causes interference to the BS.

The energy efficiency (EE) in this scheme is given by:

$$EE_1 = EE_{CB} + EE_{D2D} = \frac{R_{CB}}{P_{CB}} + \frac{R_{D2D}}{P_{D2D}} \qquad (2)$$

where EE_{CB}, R_{CB} and P_{CB} are the energy efficiency, achievable rate and power consumption of the CUE-BS link, respectively. EE_{D2D}, R_{D2D} and P_{D2D} are the energy efficiency, data rate and power consumption of the D2D link, respectively. Let B be the system bandwidth. The achievable rates R_{CB} and R_{D2D} in bits/s are expressed as:

$$R_{CB} = B \log_2 \left(1 + SINR_{CB}\right) \qquad (3)$$

$$R_{D2D} = B \log_2 \left(1 + SINR_{D2D}\right) \qquad (4)$$

and the signal-to-interference-and-noise ratios of the CUE-BS link, $SINR_{CB}$, and the D2D links, $SINR_{D2D}$ are given by:

$$SINR_{CB} = \frac{P_C |h_{CB}|^2 \gamma_{CB}}{P_D |h_{DB}|^2 \gamma_{DB} + N} \qquad (5)$$

$$SINR_{D2D} = \frac{P_D |h_{DD}|^2 \gamma_{DD}}{P_C |h_{CD}|^2 \gamma_{CD} + N} \qquad (6)$$

where P_C and P_D are the transmitting power of the CUE transmitter and D2D transmitter, respectively, N is the thermal noise power at any receiver, $|h_{ij}|^2$ is the channel fading coefficient between transmitter i ($i= \{C$ (CUE),D (DTx)$\}$) and receiver j ($j = \{B$ (BS),D (DRx) $\}$) where h_{ij} follows a complex normal distribution $CN(0, 1)$, and γ_{ij} is path loss between transmitter i and receiver j with the same index sets used for $|h_{ij}|^2$, which is given by [13]:

$$\gamma_{ij} = \frac{G\lambda^2}{(4\pi)^2 d_{ij}^\alpha M_l N_f} \qquad (7)$$

where d_{ij} is the distance between transmitter i and receiver j with the same index sets for i and j as described above, G is the total gain of the transmit and receive antennas, α is the path loss exponent, λ is the wavelength, M_l is the link margin and N_f is the noise figure at the receiver.

An outage occurs when *SINR* at the receiver falls below a threshold β in the CUE-BS link or η in the D2D link, which allows error free decoding. The outage probability of the single-hop transmission is given by [14]:

$$p_{outCB} = p(SINR_{CB} \leq \beta)$$
$$= 1 - \frac{P_C |h_{CB}|^2 \gamma_{CB}}{\beta P_D |h_{DB}|^2 \gamma_{DB} + P_C |h_{CB}|^2 \gamma_{CB}} \exp\left(\frac{\beta N}{P_C |h_{CB}|^2 \gamma_{CB}}\right) \qquad (8)$$

$$p_{outD2D} = p(SINR_{D2D} \leq \eta)$$
$$= 1 - \frac{P_D |h_{DD}|^2 \gamma_{DD}}{\eta P_C |h_{CD}|^2 \gamma_{CD} + P_D |h_{DD}|^2 \gamma_{DD}} \exp\left(\frac{\eta N}{P_D |h_{DD}|^2 \gamma_{DD}}\right) \qquad (9)$$

Due to the short distance between any D2D pairs, which means that the power of DTx is so low that the interference caused by DTx can be neglected. In addition, assume $\eta N \ll P_D |h_{DD}|^2 \gamma_{DD}$, so (8) and (9) can be rewritten as:

$$p_{outCB} = 1 - \exp\left(\frac{\beta N}{P_C |h_{CB}|^2 \gamma_{CB}}\right) \qquad (10)$$

$$p_{outD2D} = 1 - \frac{P_D |h_{DD}|^2 \gamma_{DD}}{\eta P_C |h_{CD}|^2 \gamma_{CD} + P_D |h_{DD}|^2 \gamma_{DD}} \qquad (11)$$

Energy consumption is largely proportional to the requirement of maintaining a certain level of transmission reliability or the successful transmission rate. In order to maintain a required level of the reliability of a transmission link, denoted by $U(0 \leq U \leq 1)$, the maximum outage probability is bounded by:

$$p_{out} \leq 1 - U \qquad (12)$$

Replacing p_{out} by p_{outCB} in (10) and p_{outD2D} in (11), respectively, and taking the nature logarithm on the both sides of the expression in (12) when replacing p_{out} by p_{outCB}, we then have:

$$\frac{\beta N}{P_C |h_{CB}|^2 \gamma_{CB}} \leq \ln(U^{-1}) \qquad (13)$$

$$\frac{P_D |h_{DD}|^2 \gamma_{DD}}{\eta P_C |h_{CD}|^2 \gamma_{CD} + P_D |h_{DD}|^2 \gamma_{DD}} \geq U \qquad (14)$$

The main objective for performance optimization is to maximize the overall energy efficiency under different environmental conditions. Thus, the transmit power required to satisfy the reliability requirement or be constrained by the outage probability for the direct transmission must be:

$$P_C \geq \frac{\beta N}{|h_{CB}|^2 \gamma_{CB}} (\ln(U^{-1}))^{-1} \qquad (15)$$

$$P_D \geq \frac{U \eta P_C |h_{CD}|^2 \gamma_{CD}}{(1-U)|h_{DD}|^2 \gamma_{DD}} \qquad (16)$$

Therefore, the overall energy efficiency in *bits/J* of both CUE-BS and D2D links using direct transmission are expressed as:

$$EE_1 = \frac{R_{CB}}{P_C + P_0} + \frac{R_{D2D}}{P_D + P_0} \qquad (17)$$

where P_0 (J/s) is the internal circuitry power consumption of user devices.

B. Cooperative Transmission Scheme

In cooperative transmission, CUEs communicate with the BS through relay devices in addition to the direct CUE-BS link. D2D communications involve direct transmission between any two UE devices including CUE-Relay and Relay-Relay links, as shown in Fig.1(b). Relays receive the noisy version of the transmitted symbol and transmit the received symbol after some processing to the next relay or the BS. In this case, the active CUE and the transmitting relays will interfere with the D2D receiver (DRx) and at the same time the D2D transmitter (DTx) causes interference to the receiving relays and BS.

The energy efficiency in this scenario is given by:

$$EE_2 = EE_{Coop} + EE_{D2D} = \frac{R_{Coop}}{P_{coop}} + \frac{R_{D2D}}{P_{D2D}} \qquad (18)$$

where EE_{Coop}, R_{Coop} and P_{Coop} are the energy efficiency, achievable rate and overall power consumption of the cooperative CUE-BS link, respectively. The achievable rate R_{Coop} in bits/s is expressed as:

$$R_{Coop} = B \log_2\left(1 + SINR_{CB} + \sum_{j=1}^{K} SINR_{rjB}\right) \qquad (19)$$

where K is the number of relaying branches. The signal-to-interference-and-noise ratios of the j-th Relay-BS (R-BS) link, $SINR_{rjB}$ is given by:

$$SINR_{rjB} = \frac{P_{CC}|h_{rjB}|^2 \gamma_{rjB}}{P_D |h_{DB}|^2 \gamma_{DB} + N} \qquad (20)$$

where P_{CC} is the transmitting power of cooperative relays, h_{rjB} is the channel coefficient of the cooperative R-BS link. In this paper, we present two types of cooperative transmission schemes: 1) using multiple (K) relaying branches with one relay in each branch, and 2) using multiple relaying branches and with multiple (n) relays in each branch. The selective decode and forward (SDF) relaying protocol is used in these two schemes and relays perform cooperation when the information from the CUE is correctly received by them. We assume that the selection combining technique is used at the destination on the received packets. For the transmission scheme shown in

Fig. 1(b), the outage probability is given by jointly considering the outages in CUE-BS, CUE-R and R-BS links, i.e.

$$p_{outcoop} = p(SNR_{CB} \leq \beta) \cap p(SNR_{Cr} \leq \beta)$$
$$+ p(SNR_{CB} \leq \beta) \cap p(SNR_{Cr} > \beta) \cap p(SNR_{rB} \leq \beta) \quad (21)$$

When we have multiple (K) branches and multiple relay (n) in each branch:

$$p_{outcoop} \approx (\beta)^{(K+1)} N^{(K+1)} \left(\left(1 \middle/ P_C \gamma_{CB} |h_{CB}|^2 \left(1 \middle/ P_C \gamma_{C_{\bar{1}}} |h_{C_{\bar{1}}}|^2 + \right. \right. \right.$$
$$\left. \left. \left. \sum_{i=2}^{n} \left(d_{\eta\bar{\eta}}^{\alpha} \middle/ P_{CC_i} \gamma_{\eta\bar{\eta}} |h_{\eta\bar{\eta}}|^2 \right) + d_{r_nB} \middle/ P_{CCn} \gamma_{r_nB} |h_{r_nB}|^2 \right)^K \right) \right) \quad (22)$$

where P_C and P_{CC} are the transmit power at the CUE and relays, respectively. We set the transmit power to be proportional to the distance between two communicating nodes. For broadcast transmission, e.g., when the CUE transmits, the longest distance, i.e., the distance between the CUE and the BS, d_{CB}, is considered. So, the power between the two communicating nodes is given by:

$$P_{ij} = \Lambda_{ij}{}^{\alpha} P_C \quad (23)$$

where Λ_{ij} denotes the power coefficient between node i and node j. In our model, we assume that the value of Λ_{ij} depends on the distance of the CUE-BS, relay-relay or relay-destination link. For example, the transmit power for the relay-destination link is:

$$P_{rB} = \Lambda_{rB}{}^{\alpha} P_C = \left(\frac{d_{rB}}{d_{CB}} \right)^{\alpha} P_C \quad (24)$$

As Equation (22) can be rewritten as:

$$p_{outcoop} \approx (\beta)^{(K+1)} N^{(K+1)} \middle/ P_C{}^{(K+1)} \left(1 \middle/ \gamma_{CB} |h_{CB}|^2 \left(1 \middle/ \gamma_{C_{\bar{1}}} |h_{C_{\bar{1}}}|^2 + \right. \right.$$
$$\left. \left. \sum_{i=2}^{n} \left(1 \middle/ \gamma_{\eta\bar{\eta}} \Lambda_{\eta\bar{\eta}}^{\alpha} |h_{\eta\bar{\eta}}|^2 \right) + 1 \middle/ \gamma_{r_nB} \Lambda_{r_nB}^{\alpha} |h_{r_nB}|^2 \right)^K \right) \quad (25)$$

We can formulate the power minimization problem by specifying a required reliability level, in a similar way to the method used in Subsection III. *A*. The optimization problem can be stated as follows: Optimize P_C or P_{CC} so that

$$Max \sum EE_2 \, s.t. \{p_{outcoop} \leq 1 - U\} \quad (26)$$

Both P_C and P_{CC} (contained in $p_{outcoop}$) are involved in the optimization process for the cooperative transmission mode. And the transmitted power used in the selective decode–and-forward scheme with multiple relays, P_T, is bounded by:

$$P_T \geq \beta N_0 \left(1 \middle/ \gamma_{CB} |h_{CB}|^2 \left(1 \middle/ \gamma_{C_{\bar{1}}} |h_{C_{\bar{1}}}|^2 + \sum_{i=2}^{n} \left(1 \middle/ \gamma_{\eta\bar{\eta}} \Lambda_{\eta\bar{\eta}}^{\alpha} |h_{\eta\bar{\eta}}|^2 \right) \right.\right.$$
$$\left.\left. + 1 \middle/ \gamma_{r_nB} \Lambda_{r_nB}^{\alpha} |h_{r_nB}|^2 \right)^K \right)^{(1/(K+1))} \left(\ln(Q_s^{-1}) \right)^{-(1/(K+1))} \quad (27)$$

Therefore, the overall consumed power can be expressed as:

$$P_{coop} = (p_{outCr})(P_C + P_0) + (1 - p_{outCr}) \left(((K * n) * \Lambda_{rB}{}^{\alpha} + 1)P_C + (K * n + 1)P_0 \right) \quad (28)$$

The first term on the right-hand side corresponds to the consumed energy when the relay is not able to correctly decode the message from the CUE, which means that this link is in outage. In this case, only the CUE consumes transmit power and the destination node and K relays consume receive power. The second term counts for the event that the CUE-Relay link is not in outage, hence transmit and processing power at relays and receive power at the destination are consumed.

The optimization problem with one constraint variable and its Lagrangian is given by:

$$\frac{\partial P_{coop}}{\partial P_T} + \zeta \frac{\partial p_{outcoop}}{\partial P_T} = 0 \quad (29)$$

Where ζ denotes the Lagrangian factor. The derivatives of the overall power consumption P_{coop} and the outage probability $p_{outcoop}$ with respect to the transmit power P_T lead to:

$$\left(K \left(\sum_{i=1}^{n} X_i \right) + 1 \right) \xi / \mu + b_{Cr} \middle/ P_{coop}^2 \left(nKP_{Tx} + (K(n-1)+1)P_{Rx} \right) -$$
$$\zeta \left[b_{CB}(K+1) \left(b_{Cr1} + \sum_{i=2}^{n} b_{r1ri} + b_{rB} \right)^K \right] \middle/ P_{coop}^{K+2} = 0 \quad (30)$$

Based on P_{coop} resulting from the above optimization process, the energy efficiency can then be obtained through (18).

IV. NUMERICAL RESULTS AND DISCUSSION

In this section, we examine the energy efficiency of different transmission schemes under various channel and transmission conditions in a cellular network shown in Fig. 1 using computer simulation. We then show how the transmission scheme can be chosen in an adaptive way to optimize the energy performance. The network settings used for simulation are listed in TABLE 1. Given a certain network topology, we randomly choose a CUE-BS pair and apply different transmission schemes for comparison purposes. Assume the achievable rate R in this scenario to be 1 Mbit/s, and the required system reliability level (U) to be 0.999.

Fig. 2 shows the energy efficiency performance of both cooperative and non-cooperative schemes. As we can observe, cooperative transmission outperforms the non-cooperative transmission when the transmission range is beyond 17 meters for the CUE-BS link (Fig. 2(a)) and 2 meters for the D2D link (Fig. 2(b)), respectively. We can see from Fig. 2(a) that the non-cooperative direct transmission has considerably higher energy efficiency than cooperative schemes for short-range transmission, i.e., $d_{CB}<17$m in the case of cooperative transmission using $K=2$ branches with $n=1$ relay per branch, and $d_{CB}<44$m in the

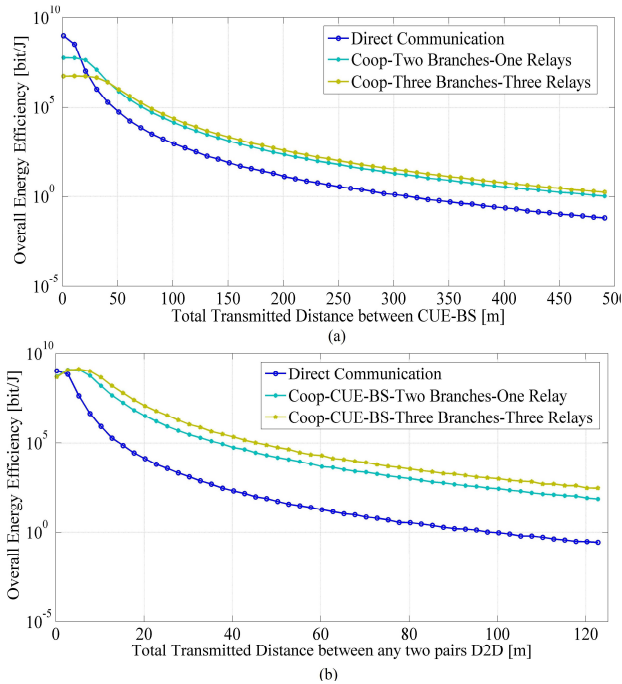Figure 2. Energy efficiency vs Total transmitted distance (β = η =0 dB).

TABLE 1.   SIMULATION PARAMETERS

Parameters	Value
N	-100dBm
B	10 MHz
U	0.999
Max P_C or P_D	250 mW
P_0	100 mW
f_c	2 GHz
Ml	4 dB
Nf	1 dB
G	5 dBi
α	4

case of cooperative transmission using $K=3$ branches with $n=3$ relays per branch.

When the distance of the CUE-BS link is short the transmit power of CUE is proportionally low according to (23), so the interference of CUE to the D2D receiver DRx is low as well. This reduces the overall required transmit power from DTx and then increases energy efficiency for short distance transmission, as shown in Fig. 2(b).

Fig. 3depicts energy efficiency against the numbers of CUEs and D2D pairs which uniformly distributed in a cellular cell. Substantial performance gaps in energy efficiency can be observed from Fig.3(a) and Fig. 3(b) between the direct transmission scheme in CUE-BS or D2D links and the optimal transmission schemes using cooperative relaying.

Results in Fig. 4 show how energy efficiency varies with the threshold of SINR (β) for both cooperative and non-cooperative schemes with different distances in CUE-BS links (d_{CB}). When distance is 10m (Fig. 4(a)) using direct transmission is most energy efficient and significantly better than cooperative transmission for β<9dB. This is because within a short distance direct
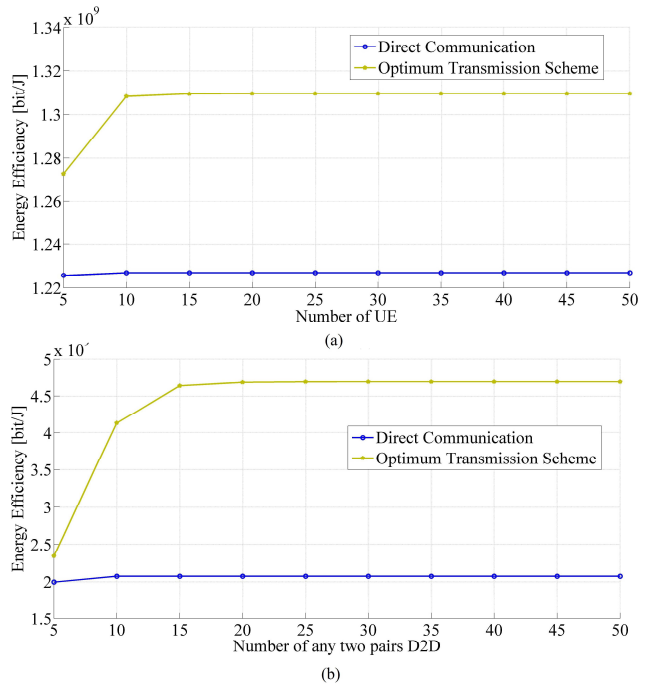

Figure 3. Energy efficiency vs numbers of CUEs and D2D (β = η =0 dB).

transmission is good enough to meet the reliability requirement while having a less number of transmitters than the cooperative transmission scheme. When the SINR threshold becomes higher, the scheme with one relay and one branch ($n=1$, $K=1$) performs better than others, but schemes with more branches and relays for this short distance leads to the increase of the transmit power and then the decrease of energy efficiency.

When the transmission range increases (d_{CB}=35m), the energy efficiency of direct transmission decreases as shown in Fig. 4(b). It can be seen that transmission with two relaying branches(with one relay each) in addition to the direct link is most energy efficient for the relatively good channel conditions (β<5dB). When the SINR threshold becomes higher, other schemes with more relays and branches (n>1, K>1) perform better than others. For β>5dB, transmission with three branches and three relays per branch are the best in terms of energy efficiency, with a trend that more relays are needed to maintain the highest possible efficiency when the channel condition gets worse. This is because using more than one relay in each branch will lead to the transmit power of relays being significantly reduced due to shortened distance between devices.

In Fig.4(c), the energy performance of the same set of transmission schemes is displayed but the distance is 100m. In this scenario, transmission with multiple branches (K= 3) and three relays (n=3) per branch is more efficient than direct transmission, and schemes with two branches (K=2) with one relay (n=1) each in all channel conditions. This indicates that the diversity created through cooperation has an impact on the increment of energy efficiency. In addition, it reveals that when channel conditions get worse, having additional relays in a branch is a simple and effective way to prevent transmission failure events while keeping energy consumption as low as possible.

There are a number of factors that can affect energy consumption in a cellular networks. Cooperative transmission involves additional paths and devices (relays) compared to direct transmission, which costs more energy.
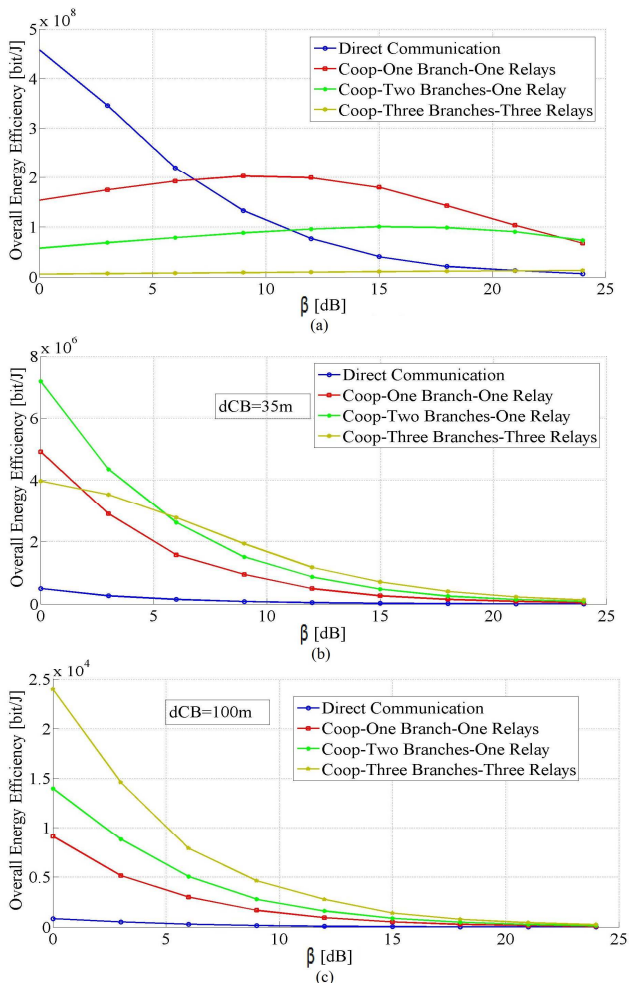
Figure 4. Energy efficiency vs β.

But the diversity it creates can save energy by reducing the number of retransmissions due to the reduced packet loss rate. In addition, increasing the number of relays in each branch reduces the distance of each transmission hop, resulting in lower transmit power needed for relays. But when the number of relays increases, the total circuitry power will accumulate as it depends on the number of transmitting devices and is independent from the transmission distance. As a result, the total energy consumption will increase if too many branches and relays are used.

Therefore, to achieve the best energy performance proper transmission schemes including in both CUE-BS and D2D links should be selected given the transmission conditions, such as the source-destination distance and channel quality. The results of this work provide an effective guidance for deciding when and how the cooperative or direct transmission scheme should be employed. Based on our investigation, an energy-efficient transmission strategy can be formed in cellular networks by adaptively choosing cooperative or non-cooperative trans-mission schemes for varied network and transmission conditions.

V. CONCLUSION

We have investigated the energy performance of a cellular network supporting both D2Dcommunications and CUE-BS links in either cooperative or non-cooperative transmission modes. Based on the outage probability and energy efficiency models derived, we have shown that cooperative and non-cooperative transmission schemes can be used collectively alongside D2D communications to achieve the highest possible energy efficiency depending on environmental conditions such as the channel quality and transmission range. Adaptive transmission strategies based on the results presented in this paper can therefore be derived to optimize the energy performance in such a network.

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