Performance Analysis of Relay-based Two-way D2D Communications with Network Coding

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***Abstract*—In this paper, we present an analytical approach to evaluate the performance of dual-hop, two-way, and asymmetric D2D communications with and without network coding. In our approach, we first establish a relationship between link outage probability (LOP) and packet loss probability (PLP), where PLP is defined as a function of LOP. By distinguishing between two types of probabilities, we then investigate the system throughput and end-to-end packet loss probability (E2EPLP). Our evaluation results reveal that when PLPs of all links along one-way D2D communications are greater or smaller than those of their corresponding links along the other direction, network coding can achieve higher throughput (about 25%), as well as an lower E2EPLP (approximately 10%). We believe that the proposed analytical approach can provide a useful insight into the application of network coding in relay-based D2D networks.**

***Index Terms*—Relay-based D2D communications, network coding, link outage probability, packet loss probability.**

I. Introduction

Device-to-Device (D2D) communication is one of the key technologies in 5G systems and is designed as an underlay in cellular networks to improve system performance. While D2D communications has been investigated in various scenarios, the single-hop D2D communications paradigm, however, is facing an enormous challenge in overcoming its limited coverage. This is mainly due to the fact that the power of D2D transmitter should be restrained to guarantee the signal-to-interference-plus-noise ratio (SINR) of cellular users. As a result, single-hop D2D communications may not be able to deal with long-distance services, such as social media and content sharing. Therefore, a multi-hop D2D (also referred to as relay-based D2D) communication can play a crucial role in expanding D2D coverage [1].

Network Coding (NC) is capable of improving the throughput performance by allowing relay nodes to compute and then forward the received packets. In addition, NC can enhance data secrecy compared with raw data (i.e., without NC) [2]. Applying NC to relay-based wireless communications has attracted tremendous interest from the research community [3]. For example, in the case of cooperative two-way relay networks, Yang et al. [4] proposed a truncated-ARQ aided adaptive network coding. In addition, for a two-way relay network, an analog network coding (ANC) with multiple-antenna sources and a single-antenna has also been investigated in [5]. Generally, we can classify network coding for D2D applications into four distinct categories: physical layer network coding (PNC) [6], space-time analog network coding (STANC) [7], instant decodable network coding (IDNC) [8], and random linear network coding (RLNC) [9]. Each is particular to a certain scenario. For instance, Jeon *et al*. [6] presented a physical layer network coding in a cellular-aided D2D communications scenario, where the base station encodes the inter-session messages for two independent D2D pairs. Wei *et al*. [7] investigated the dual-hop D2D communications with analog network coding and three pairs of D2D communications with space time analog network coding based on Alamouti scheme. In both cases, each device was assumed to be with multiple antenna. Due to the possibility of superposition in multiple electromagnetic waves at the physical layer, PNC and ANC, as well as STANC achieve space and/or time gains. On the other hand, IDNC and RLNC work at the network layer, would be more suitable for delay-sensitive services in relay-based D2D communications [10]. Keshtkarjahromi *et al*. [8] studies the IDNC in a content-aware D2D networks, in which a source broadcasts a common content to a group of cooperating mobile devices within proximity. In [9], a mean field game-theoretic incentivizing scheme was developed for real-time D2D networks using RLNC.

Although NC has been widely accepted as a viable approach for relay-based D2D communications, its impact on throughput and packet loss performances has not been thoroughly studied. In this paper, we investigate the performance of dual-hop, two-way, and asymmetric D2D communications in terms of throughput and end-to-end packet loss probability. Our main objective of this work is to develop an analytical approach for relay-based D2D communications by first establishing a function between link outage probability and packet loss probability, and then explore the end-to-end packet loss probability (E2EPLP). As an example of our developed analysis, the evaluation results reveal that when PLPs of all links along one-way D2D communications are greater or smaller than those of their corresponding links along the other direction, network coding can achieve not only a higher throughput gain, but also a better E2EPLP. This insight would shed light on the application of NC in relay-based D2D networks.

II. System Model

We consider a dual-hop, two-way, asymmetric D2D underlaying network, where two devices interact via several intermediate nodes, i.e., relays, as shown in Fig. 1. In this network, D_1 and D_2 are devices, $R_i, 1 \leq i \leq k$ are relays, and each wireless link between any two nodes, i.e., device-to-relay or relay-to-device has a different link quality. We assume

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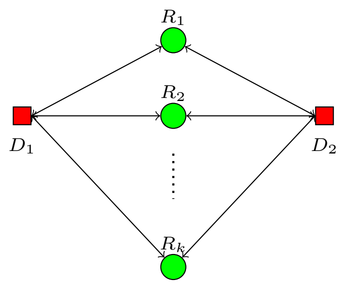


Fig. 1: System Model.

that the relays are selected by the eNodeB (base station), which coordinates the spectrum reuse in the cell, so that D2D and cellular communications are not mutually affected. We also assume that all participating nodes use the same channel. We emphasize that four time slots are needed in the absence of network coding (NC). Furthermore, this network model is applicable to scenarios where two far away devices are interested in establishing a link via relay nodes in coordination with the eNodeB [11].

On the basis of NC, two stages are involved. In the first stage, D_1 broadcasts its packets to the relays in time slot 1, D_2 broadcasts its packets to the relays in time slot 2, and then R_i encodes the packets from D_1 and D_2 into a set of encoded packets. In the second stage, each relay node, at a different time slot, broadcasts its own encoded packets (together with the encoding coefficients to D_1 and D_2, if any). After receiving the encoded packets (and the related encoding coefficients placed in the encoded packets header) from R_i, D_1 or D_2 may obtain the desired data by decoding the encoded packets.

Assume that the wireless channels involved in the above scenario follow the *Rician* Model, then the instantaneous power received from the transmitter, p_{tx}, has the following probability density function (PDF):

$$f(p_{tx}) = \frac{(1+K)}{\bar{p}_{tx}} \exp\left(-K - \frac{1+K}{\bar{p}_{tx}}\right) I_0\left(\sqrt{4K(1+K)\frac{p_{tx}}{\bar{p}_{tx}}}\right) \quad (1)$$

where K is the *Rician* factor, $K \in [1, 10]$, $I_0(\cdot)$ is the modified *Bessel* function of the first kind and order zero, and $\bar{p}_{tx}$ is the the local mean power in dominant and scattered signals.

Note that $\bar{p}_{tx}$ is able to characterize the near-far and shadowing effects, p_{tx} can capture the fading feature of a wireless channel [12]. The slow-varying local mean power $\bar{p}_{tx}$ is given by a log-normal PDF:

$$f(\bar{p}_{tx}) = \frac{1}{\sqrt{2\pi}\sigma\bar{p}_{tx}} \exp\left\{-\frac{1}{2\sigma^2}\ln^2\left(\frac{p_{tx}}{\hat{p}}\right)\right\},$$

where $\hat{p}$ follows the general path loss model $\hat{p} = d^{-\alpha}$, d is the distance between transmitter and receiver, and $2 \leq \alpha \leq 5$.

III. Performance Analysis

Packet loss probability (PLP) is generally correlated with link outage probability (LOP). For instance, a larger LOP indicates a poorer link quality, resulting in a higher PLP [13], [14]. Nonetheless, in contrast to the assumption in [13], a higher PLP is not necessary because of a larger LOP. This is mainly because the PLP depends not only on the link quality, but also other factors such as traffic load. Therefore, a clear distinction between the two types of probability should be made,

$$\Pr^l = g(\Pr^o), \quad (2)$$

where $\Pr^l$ is the link PLP, $\Pr^o$ is the link outage probability, and $g(\cdot)$ is a monotonically increasing function of $\Pr^o$ such that $0 \leq g(\Pr^o) \leq 1$.

We use the standard signal-to-interference-plus-noise ratio (SINR) model to calculate the link outage probability where a transmission is successful if the SINR exceeds a certain threshold ϵ [12]. Therefore, we can show

$$\Pr(p_0 > \epsilon p_N) = \int_0^\infty f_{p_N}(x) \int_{\epsilon x}^\infty f_{p_0}(y) dy dx. \quad (3)$$

Using series expansion

$$I_0(\epsilon) = \sum_{n=0}^\infty \frac{1}{(n!)^2}\left(\frac{\epsilon^2}{4}\right)^n$$

we can rewrite Eq. (3) according to Eq. (1) as

$$\Pr(p_0 > \epsilon p_N) = \sum_{n=0}^\infty \frac{K^n}{n!} e^{-K} \sum_{m=0}^n \frac{s^m}{m!} \int_0^\infty x^m s^{-sx} f_{p_N}(x) dx,$$

where $s = \frac{\epsilon}{\bar{p}_0}$.

Applying *Laplace* transform to the above equation yields

$$\Pr(p_0 > \epsilon p_N) = e^{-K} \sum_{n=0}^\infty \sum_{m=0}^n (-1)^m \frac{K^n}{n!} \frac{s^m}{m!} \frac{d^m \mathcal{L}(f_{p_N}(x), s)}{ds^m},$$

so we can obtain the link outage probability as

$$\Pr^o = 1 - \Pr(p_0 > \epsilon p_N). \quad (4)$$

It is trivial to assume that the PLP of all links in Fig. 1 are independent of each other. Denoting RG as the relay group consisting of all relays, the packet loss probabilities between D_1 and RG, and between D_2 and RG are

$$\begin{cases} \Pr^l_{D_1,RG} = \bigcup_{i=1}^k \Pr^l_{D_1,R_i} \\ \Pr^l_{D_2,RG} = \bigcup_{i=1}^k \Pr^l_{D_2,R_i} \\ \Pr^l_{RG,D_1} = \bigcup_{i=1}^k \Pr^l_{R_i,D_1} \\ \Pr^l_{RG,D_2} = \bigcup_{i=1}^k \Pr^l_{R_i,D_2} \end{cases}. \quad (5)$$

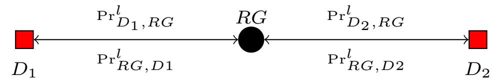
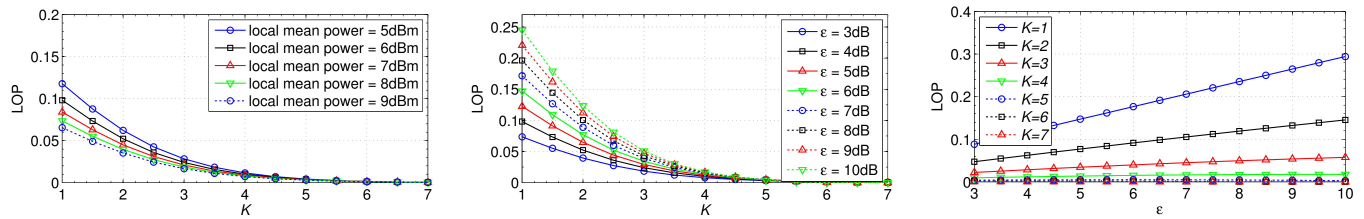


Fig. 2: Simplified system model.

With the above Eq. (5), the system model can be simplified as shown in Fig. 2. Note that the third and fourth equation of Eq. (5) are different from the first and second due to asymmetry of wireless links; that is, each wireless link between any two nodes has a different link quality.

Let $\Pr^s$ be the successful delivery probability, then we will have

$$\begin{cases} \Pr^s_{D_1,RG} = 1 - \bigcup_{i=1}^k \Pr^l_{D_1,R_i} \\ \Pr^s_{D_2,RG} = 1 - \bigcup_{i=1}^k \Pr^l_{D_2,R_i} \\ \Pr^s_{RG,D_1} = 1 - \bigcup_{i=1}^k \Pr^l_{R_i,D_1} \\ \Pr^s_{RG,D_2} = 1 - \bigcup_{i=1}^k \Pr^l_{R_i,D_2} \end{cases}. \quad (6)$$



(a) Link outage probability (LOP) vs. Rician factor K in SINR threshold $\epsilon = 4$ with different local mean power $\bar{p}_{tx}$.

(b) LOP vs. K in $\bar{p}_{tx} = 6$ dBm with different ϵ.

(c) LOP vs. ϵ in $\bar{p}_{tx} = 5$ dBm with different K.

Fig. 3: Link outage probability with various parameters.

Evidently, the Pr^s in the above equations are independent of each other due to Eq. (5).

With the above equations, we now analyze the performance of D2D with and without network coding (NC). We assume that the total amount of packets sent from D_1 to D_2 is $\mathcal{N}_1$, those from D_2 to D_1 is $\mathcal{N}_2$, and four time slots are needed to accomplish two-way communications [2]. In the former case, i.e., without NC, the PLP from D_1 to D_2 is

$$\begin{aligned}\text{Pr}^{l,0}_{D_1,D2} &= \frac{\mathcal{N}_1 - \mathcal{N}_1 \cdot \text{Pr}^s_{D_1,RG} \cdot \text{Pr}^s_{RG,D_2}}{\mathcal{N}_1} \\ &= 1 - \text{Pr}^s_{D_1,RG} \cdot \text{Pr}^s_{RG,D_2},\end{aligned} \tag{7}$$

and similarly, we have the PLP from D_2 to D_1:

$$\text{Pr}^{l,0}_{D_2,D1} = 1 - \text{Pr}^s_{D_2,RG} \cdot \text{Pr}^s_{RG,D_1}. \tag{8}$$

Where "0" in the superscript of probability represents "without NC."

We define the end-to-end packet loss probability (E2EPLP) as the packet loss ratio of two-way traffic, so the E2EPLP of the system without network coding in the first stage is

$$\text{Pr}^{l,0}_{E2E} = 1 - \frac{\mathcal{N}_1 \cdot \text{Pr}^{s,0}_{D_1,D_2} + \mathcal{N}_2 \cdot \text{Pr}^{s,0}_{D_2,D_1}}{\mathcal{N}_1 + \mathcal{N}_2}. \tag{9}$$

In the latter case, i.e., with NC, only three time slots are needed. The probability of RG that can successfully encode the packets is

$$\text{Pr}^s_{stg1} = \frac{\mathcal{N}_1 \cdot \text{Pr}^s_{D_1,RG} + \mathcal{N}_2 \cdot \text{Pr}^s_{D_2,RG}}{\mathcal{N}_1 + \mathcal{N}_2}, \tag{10}$$

In the second stage, the probability of D_2 successfully receiving the packets from D_1 is

$$\text{Pr}^{s,1}_{D_1,D_2} = \text{Pr}^s_{stg1} \cdot \text{Pr}^s_{RG,D_2} \tag{11}$$

where "1" in the superscript of probability indicates "with NC."

Therefore, the PLP from D_1 to D_2 is

$$\text{Pr}^{l,1}_{D_1,D_2} = 1 - \text{Pr}^s_{stg1} \cdot \text{Pr}^s_{RG,D_2}. \tag{12}$$

Likewise, the probability of D_1 successfully receiving the packets from D_2 is

$$\text{Pr}^{s,1}_{D_2,D_1} = \text{Pr}^s_{stg1} \cdot \text{Pr}^s_{RG,D_1} \tag{13}$$

and the PLP from D_2 to D_1 is

$$\text{Pr}^{l,1}_{D_2,D_1} = 1 - \text{Pr}^s_{stg1} \cdot \text{Pr}^s_{RG,D_1}. \tag{14}$$

Thus, the E2EPLP for the case with network coding is

$$\text{Pr}^{l,1}_{E2E} = 1 - \frac{\mathcal{N}_1 \cdot \text{Pr}^{l,1}_{D_1,D_2} + \mathcal{N}_2 \cdot \text{Pr}^{l,1}_{D_2,D_1}}{\mathcal{N}_1 + \mathcal{N}_2}. \tag{15}$$

Next, we focus on the difference of E2EPLPs in both cases. Denote

$$\Delta = \text{Pr}^{l,1}_{E2E} - \text{Pr}^{l,0}_{E2E}, \tag{16}$$

and for simplicity, let $\mathcal{X}_1 = \text{Pr}^s_{D_1,RG}, \mathcal{X}_2 = \text{Pr}^s_{D_2,RG}, \mathcal{X}_3 = \text{Pr}^s_{RG,D_1}, \mathcal{X}_4 = \text{Pr}^s_{RG,D_2}$, then we can formulate Eq. (9) and (15) as

$$\text{Pr}^{l,0}_{E2E} = 1 - \frac{\mathcal{N}_1\mathcal{X}_1\mathcal{X}_4 + \mathcal{N}_2\mathcal{X}_2\mathcal{X}_3}{\mathcal{N}_1 + \mathcal{N}_2} \tag{17}$$

and

$$\text{Pr}^{l,1}_{E2E} = 1 - \frac{\mathcal{N}_1^2\mathcal{X}_1\mathcal{X}_4 + \mathcal{N}_1\mathcal{N}_2\mathcal{X}_2\mathcal{X}_4 + \mathcal{N}_1\mathcal{N}_2\mathcal{X}_1\mathcal{X}_3 + \mathcal{N}_2^2\mathcal{X}_2\mathcal{X}_3}{(\mathcal{N}_1 + \mathcal{N}_2)^2}. \tag{18}$$

$$\Delta = \frac{\mathcal{N}_1\mathcal{N}_2}{(\mathcal{N}_1 + \mathcal{N}_2)^2}(\text{Pr}^l_{D_2,RG} - \text{Pr}^l_{D_1,RG})(\text{Pr}^l_{RG,D_1} - \text{Pr}^l_{RG,D_2}). \tag{19}$$

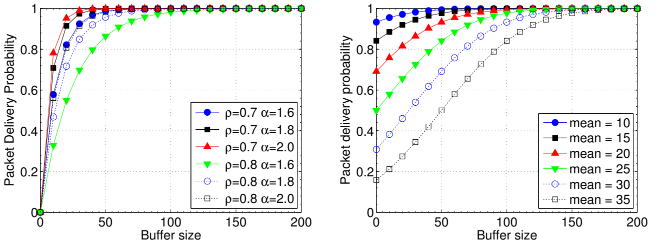
The above equation implies that when PLPs of all links along one-way D2D communications are greater or smaller than those of their corresponding links along the other direction, network coding can achieve not only a higher throughput gain, but more importantly, a better performance in terms of E2EPLP as well.

IV. Evaluation

In this section, we compare the throughput and end-to-end packet loss probability (E2EPLP) of relay-based D2D with network coding (NC) against those without NC. Two scenarios based on Fig. 1 are used for performance comparison: three-relays-based ($k = 3$) and four-relays-based ($k = 4$) two-way D2D communications. The experimental parameters are shown in Table I. All the data is statistically collected by averaging the results from 10,000 independent runs.

TABLE I: Parameters Settings

Parameter	Value
Rician factor K	[1, 7]
SINR threshold ϵ	[3, 10]
Local mean power $\bar{p}_{tx}$	[5, 9]
Path loss exponent α	[2, 5]
$\mathcal{N}_1, \mathcal{N}_2$	1000
Packet size	1024 bytes



(a) *Pareto* traffic model (b) *Gaussian* traffic model

Fig. 4: Packet delivery probability vs. buffer size with different traffic model.

Fig. 3 shows the link outage probability (LOP) with the variation of different parameters. To compare the performance of D2D with and without NC, we assume that

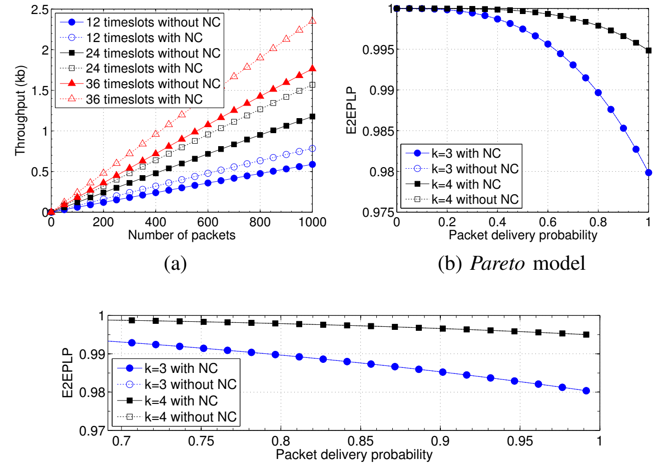
$$\mathrm{Pr}^l = g(\mathrm{Pr}^o) = \mathrm{Pr}^o \cdot \hat{\mathrm{Pr}}, \tag{20}$$

where parameter $\hat{\mathrm{Pr}}$ is the packet delivery probability defined to reflect traffic conditions over this link.

Eq. (20) is reasonable. Due to the fact that Pr^o and $\hat{\mathrm{Pr}}$ are based on two different metrics in the physical and network layer, respectively as the signal quality of a link is usually independent of traffic conditions over that link.

In characterizing traffic conditions, two representative models, i.e., *Pareto* and *Gaussian* models, are introduced to obtain $\hat{\mathrm{Pr}}$. Figs. 4(a) and (b) show the packet delivery probability with different parameter configurations, where x-axis denotes the buffer size/queue length at the D2D receiver. Moreover, ρ and α in Figs. 4(a) are server utilization and shape parameter of *Pareto* distribution, respectively. Parameter $mean$ in Figs. 4(b) is the mean value of *Gaussian* distribution. More information about these parameters and their settings for each model can be found in [15] and [16]. From this figure, we can see that $\hat{\mathrm{Pr}} \in [0, 1]$ with the *Pareto* model and $\hat{\mathrm{Pr}} \in [0.1587, 1]$ with the *Gaussian* model. In particular, when the mean value equals 20 in the *Gaussian* model, $\hat{\mathrm{Pr}}$ ranges from 0.6915 to 1. Based on these observations, the performance for D2D with and without NC are compared.

Fig. 5 presents the comparison results of end-to-end packet loss probability (E2EPLP) with various $g(\cdot)$. In the simulations, we assume that the link outage probabilities (LOPs) from D_2 to relay nodes, between relay nodes to D_1 and D_2 are the same, and are equal to the corresponding value when $\bar{p}_{tx} = 5$ dBm, $\epsilon = 4$, and $K = 1$, as shown in Fig. 3. Moreover, we assume that the LOPs from D_1 to relay nodes vary with the increase of ϵ from 4 to 7. It can be seen from Fig. 5 that the E2EPLP with more relays is lower than that with less ones. This is obvious because more relays indicate more reliable transmissions, which, in turn, means a lower E2EPLP. Also, we observe from Figs. 5(b) and (c) that the E2EPLP with NC and that without NC in the same testing scenario are almost the same. This observation reveals an extremely useful insight into the application of network coding in relay-based D2D networks – the system throughput can be significantly enhanced by network coding without compromising the E2EPLP.



(a) (b) *Pareto* model

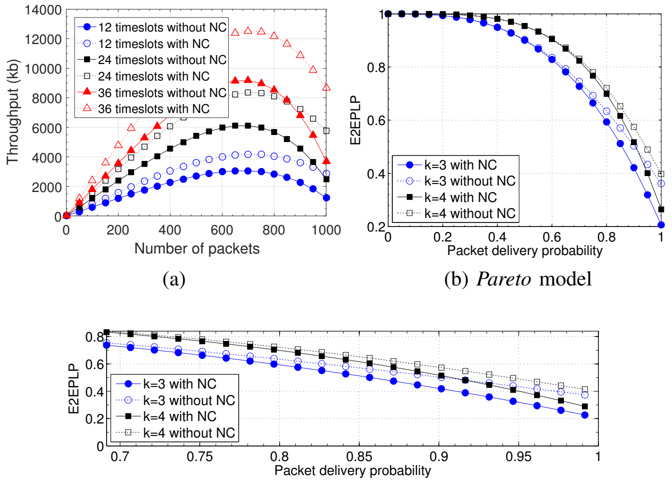
(c) *Gaussian* model

Fig. 5: Performance comparison for D2D with NC vs. without NC in Case I.

As mentioned previously, without NC D_1 and D_2 need four time slots to accomplish two-way communications, but with NC, they need only three. We explore throughput in 12, 24, and 36 time slots for comparison, that is, without network coding, D_1 and D_2 need to send each other $3\mathcal{N}_1$ and $3\mathcal{N}_2$ in 12 time slots, $6\mathcal{N}_1$ and $6\mathcal{N}_2$ in 24 time slots, and $9\mathcal{N}_1$ and $9\mathcal{N}_2$ in 36 time slots; but with network coding, $4\mathcal{N}_1$ and $4\mathcal{N}_2$ in 12 time slots, $8\mathcal{N}_1$ and $8\mathcal{N}_2$ in 24 time slots, and $12\mathcal{N}_1$ and $12\mathcal{N}_2$ in 36 time slots. While system throughput with NC is always higher as expected, the E2EPLP with NC is almost the same as that without NC. This observation indicates that the system throughput can be significantly enhanced by network coding without compromising E2EPLP, which exactly matches the implication of Eq. (19).

In Case II, we set LOPs from D_1 to relay nodes, from D_2 to relays, from relays to D_1, and from relays to D_2 are 0.1, 0.9, 0.15, and 0.95, while keeping the other simulation parameters fixed. The experimental results are shown in Fig. 6. Not surprisingly, Fig. 6 (a) delivers the same insight with Fig. 5(a), but E2EPLP, in both Fig. 6(b) and (c), with NC is smaller than that without NC which is in compliance with Eq. (19). In other words, when PLPs of all links along one-way D2D communications are greater or smaller than those of their corresponding links along the other direction, network coding can achieve not only a higher throughput (about 25%), but also a better E2EPLP (approximately 10%). Such an insight, to some extent, is aligned with the fact that NC utilizes the diversity of wireless link to achieve system gains. Since the link quality in a practical D2D network varies, the throughput and E2EPLP gains can be derived when a proper NC technique is designed and applied.

In addition to the numerical results, we also compare the performance of two schemes (scheme 1 denotes the case under the assumption of [13] in terms of PLP, i.e., $\mathrm{Pr}^l = \mathrm{Pr}^o$, and scheme 2 is the case under the assumption of Eq. (2)) with and without NC via simulations. In our simulations, all wireless



(a)

(b) *Pareto* model

(c) *Gaussian* model

Fig. 6: Performance comparison for D2D with NC vs. without NC in Case II.

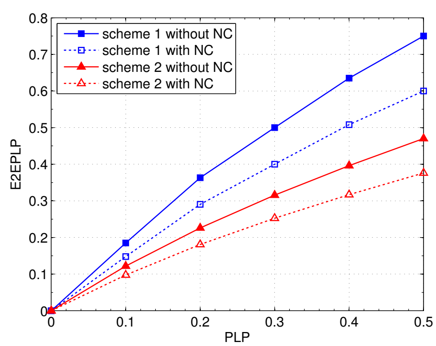


Fig. 7: E2EPLP with various PLP.

links between D_1 and relays and between relays and D_2 are assumed to have an identical PLP. The simulation parameter settings for the simulations are set as follows: network coding field size, number of generations, PLP, number of packets, and $\hat{\Pr}$ are set to 8, 10, [0.1, 0.5], 1000, and 0.6915, respectively. The simulation results are statistically collected.

Fig. 7 shows the comparison results, where $k = 3$ and the instant decodable network coding (IDNC) technique is leveraged. We can see from this figure that the E2EPLP can be reduced about 10% with NC, compared to the schemes without NC. This again confirms both of the analytical and numerical results.

Based on the above results, we claim that when PLPs of all links along one-way D2D communications are greater or smaller than those of their corresponding links along the other direction, network coding can achieve not only a higher throughput gain, but also a better E2EPLP. Such an insight, to some extent, is aligned with the fact that NC utilizes the diversity of wireless link to achieve system gains. Since the link quality in a practical D2D network varies, the throughput and E2EPLP gains can be derived when a proper NC technique is designed and applied.

V. Conclusion

In this paper, we have investigated the performance of dual-hop two-way D2D communications with and without network coding. The relationship between link outage probability (LOP) and packet loss probability (PLP) has been established, and the throughput and end-to-end packet loss probability (E2EPLP) have been explored. As an example of our developed analysis, we have found through experiment that when the PLPs of all links along one-way communications are greater than those of corresponding links along another one-way communications, we can obtain approximately 10% E2EPLP gain with network coding. This insight is expected to shed light on the application of network coding in relay-based D2D networks.

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