Energy Efficiency in Multi-source Network-coded Device-to-Device Cooperative Communications

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***Abstract*—Many researchers have recently proposed adopting relays to enhance performance in device-to-device (D2D) communication systems. With D2D technology, geographically closed terminals can be connected directly. By this means, information delivery in many practical application scenarios (e.g., in a shopping mall, a number of shops intend to distribute their vouchers/advertisements to potential customers in the vicinity) can be conducted more efficiently. In this paper we consider a wireless multi-source multi-destination D2D content distribution network and propose a network-coding based cooperative transmission scheme. Through system achievable energy efficiency analysis, we exhibit the potential benefits of applying network coding and user cooperation in future D2D communication systems.**

I. Introduction

With the rapid development of wireless communications and mobile Internet technologies, a huge amount of mobile applications providing proximity-based services have emerged recently [1]. Enabling such applications through the conventional centralized cellular technology solutions is known to be inefficient in utilizing wireless resources such as radio spectrum and device energy. Allowing direct *device-to-device (D2D)* connections is considered as an effective solution.

A typical D2D application scenario commonly expected is the local content distribution service, in which some content generators intend to distribute their messages to a number of end user devices in the vicinity. Practical examples of such scenarios include advertisement/voucher broadcast in a shopping mall, document distribution in a conference room, and photo/video sharing in a concert hall, etc. Since these services typically occur in indoor environments, operating the D2D communications in a *reuse-mode* [2], i.e., the transmissions reuse the uplink resource of a certain cellular user, can further improve the overall system spectral efficiency.

It is in general not easy to guarantee the communication performance in such reuse-mode D2D systems, due to the facts that D2D transmission power levels are usually constrained, the number of potential destinations is possible to be large, and the radio propagation environments can be quite complex, etc. Utilizing relays to realize cooperative communications has been commonly suggested as a potential solution to this issue.

Nevertheless, how to properly conduct the relaying operations should be carefully considered. In practical half-duplex systems, adopting the classic repetition coding at the relays would cause the available channel to be inefficiently utilized if the network contains multiple sources. The XOR-based network coding strategy can solve this issue, but is advantageous in only single-relay networks. A class of *maximum distance separable finite field network codes (MDS-FFNCs)* are hence proposed by [3]. Their coding principle lies in summation in higher order finite fields and the full-diversity achievability for uplink multi-source multi-relay transmissions is proved in [4].

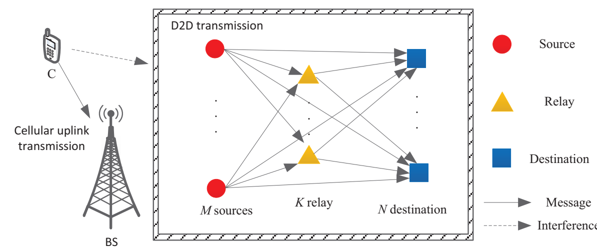

Fig. 1. System model.

In this paper, we propose applying the MDS-FFNC to reuse-mode D2D cooperative content distribution systems. These systems consider the broadcast of independent information from multiple sources to multiple destinations (i.e., all the destinations are interested in all the source messages), while being interfered by a cellular user. We analyze the system performance in terms of achievable energy efficiency, which exhibits the potential benefits of exploiting cooperative communications and network coding techniques in D2D systems.

II. System Model and Transmission Process

We consider a D2D communication network, shown in Fig. 1, with M information sources $S_1, \ldots, S_M$ intending to broadcast independent messages $I_{S_1}, \ldots, I_{S_M}$ respectively to N destination terminals $D_1, \ldots, D_N$. K idle terminals $R_1, \ldots, R_K$ in the vicinity can be chosen as relays, operating in the half-duplex decode-and-forward fashion, to assist in the transmissions. The information delivery process within the considered D2D system is carried out in the reuse-mode and coexists with the uplink transmissions of a cellular user C.

A frequency-flat slow fading environment is considered. The fading coefficient of the channel between any transmitter a and receiver b is denoted by $h_{a,b}$ and is modelled by a random variable drawn from a Rayleigh distribution, i.e., $h_{a,b} \sim \mathcal{CN}(0, \lambda_{a,b})$. For the whole transmission period, $h_{a,b}$ remains constant and is known only at the receiver. Since D2D

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communications are in general allowed for geographically-closed users, the typical transmission power levels are constrained. Further, if the D2D users are located in an indoor environment, an extra penetration loss induced by building walls would appear in the pathloss model between the D2D and cellular systems. Considering that cellular base stations have stronger interference cancellation capabilities, we neglect the interference from D2D users to the cellular system, but the uplink transmissions of C would interfere the D2D receivers.

For presentation simplicity, we assume that all links within the D2D system experience a similar level of propagation loss and set $\lambda_{a,b} = \lambda_d$, for all $a \in \{S_1, \cdots, S_M, R_1, \cdots, R_K\}$ and $b \in \{R_1, \cdots, R_K, D_1, \cdots, D_N\}$. The variances of fading coefficients between C and all D2D receivers are also set as the same value $\lambda_{C,b} = \lambda_c$, $\forall b \in \{R_1, \cdots, R_K, D_1, \cdots, D_N\}$. A *symmetric* D2D system is considered. All the D2D users transmit with identical power P. Each message contains the same information rate R (in bits) and its transmission spans one unit-bandwidth TDMA time slot. The analysis presented later can also be extended to general cases.

The considered system studies the situation that all the N destinations are interested in all the M source messages. Hence if *every* destination is capable of recovering $I_{S_1}, \ldots, I_{S_M}$ without any error, the communication is successful. Otherwise, if at least one of the destinations cannot obtain any message, the communication is declared to be *failed*. In addition, the channel codes employed on the physical layer are assumed to be sufficiently strong. The error probability at each receiver is therefore dominated by the *outage probability*.

The delivery of $I_{S_1}, \ldots, I_{S_M}$ from the sources to the destinations consumes a total of $M+K$ time slots. At the mth ($1 \le m \le M$) slot, S_m broadcasts I_{S_m} to all the relays and destinations. The remaining K time slots are assigned to the K relays respectively. If R_k ($1 \le k \le K$) correctly recovers all the M source messages using its received signals from $S_1, \cdots, S_M, R_1, \cdots, R_{k-1}$, it combines $I_{S_1}, \cdots, I_{S_M}$ to a new codeword I_{R_k} and broadcasts I_{R_k} to all the remaining relays and the destinations, at the $(M+k)$th time slot. Otherwise, R_k remains silent to avoid error propagation.

The construction of $I_{R_1}, \cdots, I_{R_K}$ follows the MDS-FFNC structure [3]. Specifically, I_{R_k} is a summation of source messages in a certain *finite field*, i.e., $I_{R_k} = \sum_{i=1}^{M} \gamma_{R_k,S_i} I_{S_i}$ where γ_{R_k,S_i} are coding coefficients. The matrix form of the coding procedure is expressed as (1). The MDS-FFNC coding coefficients are designed to guarantee the global encoding kernels (GEK) [5] to be linearly independent, so that a submatrix constituted by any M rows of the transfer matrix in (1) is non-singular. Hence having any M messages within $I_{S_1}, \cdots, I_{S_M}, I_{R_1}, \cdots, I_{R_K}$ suffices to recover $I_{S_1}, \cdots, I_{S_M}$.

$$\begin{bmatrix} I_{S_1} \\ \vdots \\ I_{S_M} \\ I_{R_1} \\ \vdots \\ I_{R_K} \end{bmatrix} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \\ \gamma_{R_1,S_1} & \gamma_{R_1,S_2} & \cdots & \gamma_{R_1,S_M} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{R_K,S_1} & \gamma_{R_K,S_2} & \cdots & \gamma_{R_K,S_M} \end{bmatrix} \begin{bmatrix} I_{S_1} \\ I_{S_2} \\ \vdots \\ I_{S_M} \end{bmatrix}. \quad (1)$$

In what follows, we analyze the achievable energy efficiency of this network-coding based cooperation scheme.

III. Energy Efficiency Analysis

The achievable *energy efficiency*, denoted by ξ_{EE}, is defined as the average successful transmission data rate between the sources and the destinations, in bits per unit of bandwidth by using one joule energy. To calculate ξ_{EE}, we use $\mathcal{P}_{out}$ to denote the system outage probability, i.e., the probability that the communication fails or at least one destination cannot successfully obtain all the source messages. Then the system achievable *spectral efficiency* η_{SE} is defined as $\eta_{SE} \triangleq (1 - \mathcal{P}_{out})\,\bar{R}$, in which $\bar{R} = \frac{MR}{M+K}$ is the average transmission rate of the M-source D2D network ($M+K$ is the number of time slots consumed to complete transmission).

In addition, we denote the total power consumption of the system by P_{total}. Clearly, P_{total} consists of two parts: the sources' power consumption and relays'. The former can be expressed by $M(P + P_c)$, where P is transmit power of each D2D device and P_c represents circuit power that may include power consumed by radio-frequency (RF) circuits and baseband processing. To derive the relays' power consumption (in the average sense), we use $\mathcal{P}_{out,k}$ to denote the probability that R_k is not activated at its scheduled time slot, since it cannot recover the source messages from its received signals. The relays' average power consumption is $\sum_{k=1}^{K} \left((1 - \mathcal{P}_{out,k})(P + P_c) + \mathcal{P}_{out,k} P_{idle}\right)$, where P_{idle} is the power consumption of a silent node [6]. Consequently,

$$P_{total} = M(P+P_c) + \sum_{k=1}^{K} \Big((1-\mathcal{P}_{out,k})(P+P_c) + \mathcal{P}_{out,k} P_{idle} \Big).$$

Now the system energy efficiency can be expressed by [7]

$$\xi_{EE} = \frac{\eta_{SE}}{P_{total}}. \quad (2)$$

In order to calculate ξ_{EE}, we need to find the expressions of $\mathcal{P}_{out,k}$ and $\mathcal{P}_{out}$ as follows. Note that at each time slot, only one transmitter is scheduled to broadcast signals. Hence the received signal at a D2D receiver b can be expressed as

$$y_b = \sqrt{P} h_{a,b} x_a + \sqrt{P'} h_{C,b} x_C + n_b, \quad (3)$$

where x_a is the transmit signal of the scheduled transmitter a (if activated), x_C is the interference signal from C with power P', and n_b is the additive white Gaussian noise (AWGN) with power N_0. Following [8], the probability that b can correctly recover the message contained in x_a is expressed as:

$$\begin{aligned} p &= P_r \left\{ \log\left(1 + \frac{P|h_{a,b}|^2}{P'|h_{C,b}|^2 + N_0}\right) \ge R \right\} \\ &= \frac{\lambda_d P}{\lambda_c P'(2^R - 1) + \lambda_d P} e^{-\frac{(2^R-1)N_0}{\lambda_d P}}. \end{aligned} \quad (4)$$

Use u_s to denote the status of the sth relay: $u_s = 0$ means that R_s cannot recover the M source messages from its received signals and $u_s = 1$ means it can. Then $\sum_{s=1}^{k-1} u_s$ is the number of relays within $R_1, \cdots, R_{k-1}$ that are activated before the $(M+k)$th time slot. If R_k is able to correctly decode at least M signals from the M sources and the $\sum_{s=1}^{k-1} u_s$ activated relays, the probability of which is $Q(u_1, \cdots, u_{k-1}) \triangleq \sum_{j=M}^{M+\sum_{s=1}^{k-1} u_s} \binom{M+\sum_{s=1}^{k-1} u_s}{j} p^j (1-p)^{M+\sum_{s=1}^{k-1} u_s - j}$, then R_k can recover $I_{S_1}, \cdots, I_{S_M}$ and hence is activated to broadcast I_{R_k} constructed using the MDS-FFNC coefficients. Otherwise, it remains silent. Use $\sum_{\mathbf{u}_{k-1}}$ to denote summation for all possible $u_1, \cdots, u_{k-1} \in \{0, 1\}$. $\mathcal{P}_{out,k}$ can be expressed as

$$\mathcal{P}_{out,k} = 1 - \sum_{\mathbf{u}_{k-1}} \left(\prod_{i=1}^{k-1} (\mathcal{P}_{out,i})^{1-u_i} (1-\mathcal{P}_{out,i})^{u_i} \right) Q(u_1, \cdots, u_{k-1}). \tag{5}$$

Starting from $\mathcal{P}_{out,1}$, the expressions of $\mathcal{P}_{out,k}$ for all $k \in \{2, \cdots, K\}$ can be obtained.

Now we focus on the destinations. Given that after the $(M+K)$th time slot, the K relays' statuses are $u_1, \cdots, u_K$, then a total of $\sum_{s=1}^{K} u_s$ relays are activated. If a destination can correctly decode the signals transmitted from at least M nodes among the sources and the activated relays, it is able to recover all source messages. Clearly the probability of this situation is $Q(u_1, \cdots, u_K)$. The probability that all the N destinations can obtain all source messages is hence $Q(u_1, \cdots, u_K)^N$. Consequently, the system outage probability, i.e., the probability that at least one destination cannot attain all source messages, can be derived using

$$\mathcal{P}_{out} = 1 - \sum_{\mathbf{u}_K} \left(\prod_{i=1}^{K} (\mathcal{P}_{out,i})^{1-u_i} (1-\mathcal{P}_{out,i})^{u_i} \right) Q(u_1, \cdots, u_K)^N. \tag{6}$$

All the elements that are necessary to calculate the energy efficiency are attained. Next, we use numerical results to illustrate the performance of the proposed scheme.

IV. Numerical Results

We evaluate and compare the performance of the MDS-FFNC cooperative transmission scheme with the conventional direct transmission scheme without relaying. The outage probability, spectral efficiency, and energy efficiency of the latter scheme can be derived following the analysis provided in the above section, by setting $K = 0$. We use networks with 3 sources, 2 relays, and N destinations, as example systems. The value of N will be chosen as $N = 20$ and $N = 40$ respectively. In the numerical evaluations, the system and channel parameters are set following [9], and are shown in Table I. In addition, the transmit power of C is assumed to be 3 times of P, the transmit power of D2D devices.

TABLE I
System and Channel Parameters

Parameter	Value
Pathloss model for D2D users	$38.46 + 20\log_{10}(d_d)$ dB
Pathloss model from C to D2D receivers	$15.3 + 37.6\log_{10}(d_c)$ dB
Distance between D2D users (d_d)	20 m
Distance between C and D2D receivers (d_c)	200 m
Circuit power (P_c)	100 mW
Idle power (P_{idle})	100 mW
Wall penetration loss between C and D2D receivers	20 dB
System Bandwidth (B)	15 kHz
Noise power spectrum density (N_0/B)	-174 dBm/Hz

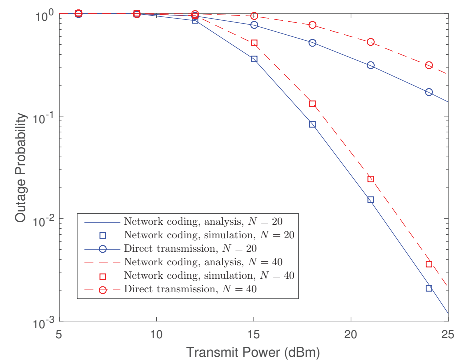

Fig. 2. Outage probability comparison, with $\bar{R} = 3$ bits/Hz/s.

We first illustrate the system outage probability in Fig. 2, when the average system transmission data rate $\bar{R}$ is chosen to be 3 bits/Hz/s. For the proposed scheme, both the analytical results derived using the approach presented in Section III and Monte Carlo simulation results are shown. It is seen that the analytical and simulation results coincide with each other, which proves the accuracy of the analytical method. We can also clearly observe the diversity gain provided by the proposed scheme over direct transmission from the slopes of the error probability curves. The advantages of the network-coding based cooperative transmission strategy becomes more notable when the network contains more destinations. Hence we can conjecture that in future D2D content distribution systems, if information sources intend to deliver their messages to potentially a large number of end users, applying the proposed scheme will serve as a much better solution than simply setting up connections directly between D2D sources and destinations.

Now we start looking at the achievable energy efficiency performance. By changing P, Fig. 3 displays ξ_{EE} versus $\mathcal{P}_{out}$, when $\bar{R} = 3$ bits/Hz/s. It is seen that when the network demands relatively high reliability in data transmission (i.e. $\mathcal{P}_{out}$ is small), the proposed scheme achieves considerably larger energy efficiency than the direct transmission scheme. In other words, information is delivered using less energy consumption. The reason behind this observation, which can be seen in Fig. 2, is that for a small value of $\mathcal{P}_{out}$ (e.g., $\mathcal{P}_{out} \leq 10^{-2}$), direct transmission requires much larger transmit power P to reach the outage probability target, compared with the network-coding cooperative scheme. Again, the performance gap becomes more significant when N increases. In addition, it is interesting to see that when $\mathcal{P}_{out}$ is large, direct transmission may outperform the proposed scheme. This is because for fair comparison, the average transmission data rates $\bar{R}$ of both schemes are set as the same value. Since utilizing relays demands more time slots to complete transmission, the information rate contained in each message needs to be larger in the proposed scheme ($R = T\bar{R}/M$ bits per source message, where T is the number of demanded time slots). The poor outage performance is actually the result of a very low signal-

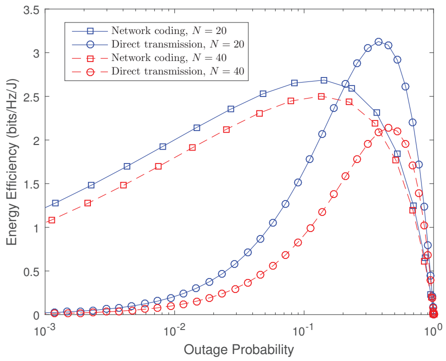

Fig. 3. Energy efficiency versus outage probability. $\bar{R} = 3$ bits/Hz/s.

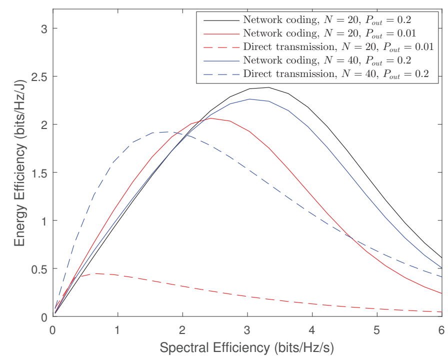

Fig. 4. Energy efficiency versus spectral efficiency.

to-noise ratio (SNR) at the receiver. In this condition, the decoding process is affected mainly by high message rates, rather than the small-scale fading phenomenon. Hence the proposed scheme would need larger total power to compensate such coding errors, which results in a low energy efficiency.

Finally, we consider the case that the system reliability requirement, i.e., $\mathcal{P}_{out}$, is predetermined, while the average data rate $\bar{R}$ can be adjusted to obtain better performance. Fig. 4 displays the relationship between ξ_{EE} and η_{SE}. It is seen when η_{SE} increases (i.e., $\bar{R}$ increases) from zero, ξ_{EE} first increases and then decreases. Hence for a fixed $\mathcal{P}_{out}$, there is a choice of $\bar{R}$ that maximizes the achievable energy efficiency. This is the point that, averagely, a certain amount of information is delivered from the sources to the destinations with the minimum energy consumption. Certainly, one can use larger P and $\bar{R}$ to attain higher spectral efficiency ($\mathcal{P}_{out}$ remains unchanged). But now larger energy is necessary to allow each bit of information to successfully reach the destinations. From the figure, we can again notice the advantages of the proposed scheme. Considering $N = 20$, when $\mathcal{P}_{out}$ needs to be small (e.g., $\mathcal{P}_{out} = 10^{-2}$), the highest achievable energy efficiency of the network-coding based scheme is significantly larger than that of direct transmission. When the reliability requirement is relatively low, as we explained above, due to that the high message data rate has more impact on the decoding process in the low SNR regime, the network-coding scheme's performance gain over direct transmission would be smaller. However, in the example network when $N = 40$ and $\mathcal{P}_{out}$ is as high as 20%, the highest achievable energy efficiency of the proposed scheme is still notably better than that of direct transmission. Finally, comparing the curves for $N = 20$ and $N = 40$ with $\mathcal{P}_{out} = 0.2$ shows that the highest achievable ξ_{EE} reduces when a network has more destinations. This is because outage event occurs more frequently if N is large. Hence higher power has to be consumed to guarantee the reliability level.

V. Conclusion

In this paper, we have studied the impact of applying a properly designed network-coded relaying strategy in a reuse-mode multi-source multi-destination D2D communication network. We have presented an analytical method to calculate the achievable energy efficiency of the proposed scheme. Our results have shown that, compared with conventional direct transmission, the considered network-coding based relaying scheme possesses the potential of significantly reducing the average energy consumption in delivering information. Note that in this paper we assume all the D2D channel coefficients to have the same variance. If practical environments with complex propagation characteristics are taken into consideration, the benefit of the network-coding based user cooperation strategy would be more notable.

Acknowledgements

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