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Network Coding in Relay-based Device-to-Device Communications

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Abstract

Device-to-Device (D2D) communications has been realized as an effective means to improve network throughput, reduce transmission latency, and extend cellular coverage in 5G systems. Network coding is a well-established technique known for its capability to reduce the number of retransmissions. In this article, we review state-of-the-art network coding in relay-based D2D communications, in terms of application scenarios and network coding techniques. We then apply two representative network coding techniques to dual-hop D2D communications and present an efficient relay node selecting mechanism as a case study. We also outline potential future research directions, according to the current research challenges. Our intention is to provide researchers and practitioners with a comprehensive overview of the current research status in this area and hope that this article may motivate more researchers to participate in developing network coding techniques for different relay-based D2D communications scenarios.

Index Terms

Device-to-Device; network coding; relay-based; random linear network coding

I. Introduction

As one of the key technologies in 5G systems, Device-to-Device (D2D) communications has been realized as an effective means to improve network capacity, reduce transmission latency, and extend cellular coverage. It allows two devices in close proximity to send/receive data directly by reusing cellular resources without causing harmful interferences. With the ever-growing service demands for an extended coverage, however, the traditional single-hop D2D communications paradigm is no longer able to deal with such demands, as the allowable communication range between two devices in such a paradigm is quite limited.

Therefore, multi-hop D2D (also referred to as relay-based D2D) communications mechanism plays a crucial role in addressing the aforementioned service demand, extending network coverage, and further enhancing system performance [1], [2].

Network Coding is a well-investigated technique and can reduce the number of retransmissions as well as improve network throughput by allowing network nodes to compute and then forward the received packets. Compared with the traditional "store-and-forward" communication model, the "compute-and-forward" scheme in network coding transmits data on the basis of cost-effective computations to eliminate the redundant packets (transmissions) and increase the system's efficiency. The advantage of applying network coding to D2D communications is briefly illustrated by Fig. 1, in which three devices A, B, and C all need to download a video frame from the server via the eNodeB (base station). We assume that the video frame is made of four packets $\{p_1, p_2, p_3, p_4\}$ and we use H to denote the set of packets that a device has successfully acquired and W to denote the set of packets that a device has lost and will need to reacquire. For example, $H_A = \{p_2, p_3, p_4\}$ and $W_A = \{p_1\}$ signify that device A has successfully obtained packets p_2, p_3, p_4 but missed packet p_1. Without network coding, a total of three packets transmissions will be needed for these devices to get the packet that they have missed. However, only two packet transmissions will be needed with network coding – device A sends the encoded packet $p_2 \oplus p_3 \oplus p_4$ to devices B and C; device C sends the encoded packet $p_1 \oplus p_3 \oplus p_4$ to devices A and B. As decoding packets requires the number of received encoded packets be at least equal to the number of lost packets [3], in the above case, each device will be able to decode the encoded packets that they have received to get the packet that they seek. As such, the number of packet transmissions and overhead in the system will be substantially reduced.

In network coding, a node can not only encode the packets that are being buffered but also encode a newly arrived packet with those that are cached at the node already. This mechanism may reduce the encoding latency. For example, suppose a node needs to receive 40 packets during the first round, encode them, and then sends the encoded packet out. If each packet takes 25 ms to arrive at the node, then the node will need to wait for 1 s for all the (initial) 40 packets to arrive, and then start encoding them and sending the encoded packet out. But, starting with the second round, the node will not need to wait for 1 s for the entire set of 40 packets to arrive and start encoding them. As soon as the first packet in the second round arrives, the node may encode it with all the packets received in the first round (excluding the first packet in the first round) and then transmit the encoded packet. Additionally, network coding may enhance the security of the data being transmitted in the context of multi-hop D2D communications, as the information received at any node is an encoded message (as opposed to a bare and non-encoded message) [4].

Considering that network coding techniques can be exceedingly beneficial to relay-based D2D communications, in this article, we first review state-of-the-art in network coding for multi-hop D2D communications in terms of application scenarios and network coding approaches. Then we present a relay node selecting an algorithm that chooses relay nodes by taking into consideration the expected transmission count and system throughput, and compare two representative network coding techniques, namely instant decodable network coding and random linear network coding, through experiments as a case study. Also, we point out potential future research directions for this topic. We expect this article to provide researchers and practitioners with a comprehensive overview of the current research status in this area and hope that this may motivate more researchers to participate in developing network coding techniques for different relay-based D2D communications scenarios.

II. An Overview of Network Coding in Relay-based D2D Communications

A. Application Scenarios

Network coding assisted relay-based D2D communications can be applied to the following scenarios.

1) Hotspots Area—This scenario refers to convocations such as business association meetings, concerts, and online conferences, where people share common interests. In such a scenario, if a person/user misses some information, he may contact neighboring users for this information to be sent to him. A neighboring user, after receiving that request and reviewing the data sending/receiving status of its own neighbors, encodes the requested information appropriately and sends it back to the information requester. As such, the requesting user consolidates all encoded data that was sent to him from different neighboring users and chooses a proper way to decode the encoded data to obtain the needed information. This scheme eliminates the need for the requesting user to ask the system buffer for the information he needs, thereby alleviating the system traffic to a certain extent [5].

2) Delay-sensitive Networks—Real-time communications, such as audio and/or video conferences, are extremely sensitive to delays. An instantly decodable network coding (IDNC) technique can be applied to this scenario which allows a source user in D2D communications to perform XOR operations to packets with the cached data from its neighboring users. Thus, this mechanism can avoid massive matrix computations, improve packet decoding speed, and reduce delay.

3) Mobile Cloud—Although a mobile cloud can provide versatile services to support various mobile applications, one of the problems that it faces is bandwidth bottleneck [6]. For example, when multiple users are simultaneously in need of a video clip, narrow-band users can only request/use standard-quality resources, but broadband users may request/use high-quality or high-definition resources. Network coding can be used to encode the packets associated with a particular resource into two different types of packets: fundamental packets and enhanced packets of different levels. Once this is done, users with narrowband just need to download the fundamental packets to access the required resource; on the other hand, users with broadband need to receive the enhanced packets to complete the communication. Clearly, by doing so, the utilization efficiency of bandwidth can be improved [7].

4) Content-caching Networks—In content-caching networks typically, a user obtains the information he seeks either by sending a request to the server or by sending requests to neighboring users. The server will respond to the request by sending the requested content to the user, and the neighboring users would review the data cached on their sites and transmit appropriate packets to the user accordingly. Either way, in such a traditional data communication scheme, packets must arrive in a certain order to be considered valid. In network coding assisted data transmissions, however, packets may arrive in any order as long as they can be decoded successfully [8].

5) Public Network Security—It is vitally important to ensure data transmission security in public networks, especially considering the existence of malicious nodes that attempt to eavesdrop on such networks. Implementing network coding assisted D2D communications in such networks allows data to be encoded before they are transmitted. This data encoding process is equivalent to data encryption in the sense that even if the encoded data is intercepted by a malicious node, the malicious node would have no way of knowing how to decode the encoded data because of a lack of the knowledge of encoding scheme and encoding coefficients. As such, data transmission security is achieved.

6) Summary—It is worthwhile to point out that these scenarios are not exclusively separated from one another. There are some connections and, at the same time, some distinctions among them. Specifically, D2D communication in hot-spots, while being an instance of relay-assisted communications to a certain extent, regards all participating users as a collaborative group and concerns more about the holistic communication functionality and performance. Delay-sensitive networks are special in the sense that minor erroneous data transmissions are tolerable, but delayed data transmissions are not. While both mobile clouds and content-caching networks can work as a cache server providing services to local users, they differ fundamentally in that a mobile cloud primarily offers download services to its mobile customers by the means of a one-to-many broadcast, whereas a content-caching network may perform many-to-many communications by engaging multiple neighboring users. Public networks, on a different note, pri-oritize the information security and defense against malicious attacks. Therefore, different network coding techniques should be employed in different scenarios depending on the specifics of the scenarios.

B. Network Coding Techniques

Considered generally as a data transmission enhancement approach, network coding can be realized by different techniques.

1) Physic Layer Network Coding—Physical Layer Network Coding (PNC) [9] allows a user to simultaneously receive and encode data sent to it from two different users, which may improve the network resource utilization efficiency. To see this, consider traditional data transmission from user A to user B using a relay node. In this situation, the transmission paths (user A – relay node – user B) and (user B – relay node –user A) will be followed, and four time slots would be needed to complete the transmission. When PNC is used in this data transmission, the two users may simultaneously send their own data to the relay node in an one-time slot. At the relay node, the network-layer encoding of data is obtained by mapping the result of superimposing, modulating, and demodulating electromagnetic waves on the physical layer. In the next time slot, the relay node broadcasts the encoded data to user A and user B which then decodes the encoded data by using information stored on their sites to retrieve the data that they need, thereby completing the data transmission. It can be easily seen that only two time slots would be needed to accomplish the 4-time-slot data transmission using PNC. As such, a higher network throughput can be expected with the use of PNC. Nevertheless, there is a condition for PNC to work properly: the synchronization clock must be strictly followed to ensure the carrier wave synchronization and code synchronization.

2) Analog Network Coding—The essential idea of Analog Network Coding (ANC) [10] is the following: when two source nodes A and B would like to exchange some data via a relay node in an asynchronous way, the relay node will receive the superposition of three different signals – the signals sent by A and B, as well as an interfered signal (from either A or B) due to the asynchronous communications. Instead of decoding the signals, the relay node amplifies the signals and forwards them to A and B. A, after receiving the summed signal, then calculates the phase shift of B by using A's signal in the sum, thereby recovering the B signal destined to it; B can recover the signal that it expects from A in a similar manner. There is no need to avoid interference caused by non-synchronizations in using ANC. In fact, ANC can substantially improve the throughput of wireless networks where synchronizations cannot be ensured.

3) Space-Time Analog Network Coding—Space-Time Analog Network Coding (STANC) [10] is an extension of the ANC that combines ANC with the space-time coding technique. In STANC, two terminals simultaneously send signals to a set of relay nodes in time slot 1. In time slot 2, each of the relay nodes encodes the received data using the ANC technique and transmits the encoded data to both terminals. Each of the two terminals then decodes the received data to retrieve the information it seeks. Similar to ANC, STANC is notable for being able to overcome signal attenuations, use resources more efficiently, and increase system capacity.

4) Instant Decodable Network Coding—Instant Decodable Network Coding (IDNC) [11] uses the simple XOR operation to encode packets. In general, two time slots would be needed for IDNC to work effectively. In time slot 1, the sender transmits requested packets to all requesting users. In time slot 2, each receiver may ask the sender to resend the packets that it missed in time slot 1. By reviewing all the data-receiving status of neighboring nodes, the sender encodes the packets using XOR operations and resends them to the requesting users who then can decode the packets instantly to recover the data lost in time slot 1.

5) Random Linear Network Coding—In Random Linear Network Coding (RLNC), a relay node encodes the packets by randomly choosing some coefficients from a finite mathematical field, and then transmits the encoded packets and the encoding coefficients to receivers [12]. Typically, if a relay node needs to encode n packets, then it will choose an $N \times n$ (with $N > n$) coefficient matrix over a finite field, and multiply this matrix with the vector of the n packets to produce N encoded packets. A receiver, after receiving the N encoded packets, can recover the original n packets by finding the inverse of the matrix and then multiplying it with the N encoded packets. Note that RLNC fits networks with a dynamic topology well; all the senders and the relay nodes need to do is just to follow the planned strategy to transmit data. As such, RLNC is particularly suitable for multi-hop D2D communications. Note also that one of the problems with RLNC is that it requires a relatively large finite field to work with to ensure a satisfactory successful decoding rate.

6) Summary—Each network coding method has its own pros and cons that fits best with a particular scenario. Specifically, PNC, ANC, and STANC can be used in relay-assisted D2D communications to achieve gains in terms of space and/or time since the electromagnetic waves can be summed at the physical layers. Yet these techniques typically work at the physical layer; system gains in terms of space and/or time can be achieved by the fact that electromagnetic waves are aggregated at the physical layer. IDNC is another option, which works at the network layer, fitting quite well with delay-sensitive networks owing to its fast packet-decoding capability. RLNC, unlike the above network coding methods, also works at the network layer that can be used to improve the system throughput for content caching networks and mobile-cloud-based networks due to its ability to linearly combine packets and to encode packets independently. Also, the uniqueness of RLNC's encoding coefficients can naturally enhance data transmission security providing a secure data transmission foundation for public networks.

III. Network Coding in Dual-hop D2D communications: A Case Study

A. System Model

D2D communications between a pair of devices in a single cellular cell may be assisted by other idle devices in the same cell, which is particularly useful when the two devices cannot reach each other directly. As shown in Fig. 2, eNodeB manages the spectrum resources in the cell, CUE (cellular user equipment) is sending data to eNodeB, DUE1 (D2D user equipment 1) and DUE2 reuse the uplink resource of CUE and communicate via the assistance of some relay nodes.

In stage 1 (see Fig. 2(a)), DUE1 broadcasts its packets $\{p_1^1, p_2^1, \ldots, p_m^1\}$ to the relay nodes in time slot 1, and DUE2 broadcasts its packets $\{p_1^2, p_2^2, \ldots, p_l^2\}$ to the relay nodes in time slot 2. The i-th relay node will encode the packets from DUE1 and DUE2 into a set of r_i encoded packets $\{p_1, p_2, \ldots, p_{r_i}\}$. Since DUE1 and DUE2 reuse the uplink spectrum of CUE, CUE will generate certain interference to the relay node (as shown by the red dotted line in the figure).

In stage 2 (see Fig. 2(b)), each relay node at a different time slot, broadcasts its own encoded packets together with the encoding coefficients to DUE1 and DUE2. After receiving the r_i encoded packets and the related encoding coefficients (placed in the packets header) from relay node i, DUE1 or DUE2 may obtain the desired data by decoding the encoded packets. During this stage, CUE may cause interference to the two D2D users DUE1 and DUE2.

B. A Relay Node Selection Algorithm

As an essential step for applying network coding to the above model, relay nodes should be selected according to certain criteria. For minimizing the number of needed data transmissions, we select relay node candidates by leveraging the metric of the expected transmission count [13]. The expected transmission count between two nodes is defined as the reciprocal of the probability of successfully transmitting a packet from one node to the other. For example, the expected transmission count of a one-hop route with a 50% delivery ratio is 2. All nodes that are idle and satisfy the node-selecting criteria will be added into a (preliminary) set, which will then be filtered by a condition of the number of decodable packets, to ensure that DUE1 and DUE2 have maximal throughput with a minimal number of needed relay nodes. Specifically, the following mechanism is proposed to select relay nodes.

1. The eNodeB chooses relay node candidates by their physical position. If a node is within the maximum allowed D2D communication range with respect to DUE1 and DUE2, then this node will be selected as a candidate.

2. If the expected numberss of transmissions from a candidate to DUE1 and to DUE2 are less than a preset threshold, then this candidate will be formally selected as a relay node. Evidently, a loose threshold would result in more relays being selected, which further leads to a better quality-of-service (QoS) of D2D communications. In contrast, a tight threshold setting would give rise to poor QoS for D2D links.

3. The size of the current set of relay nodes is further reduced by considering the amount of decodable packets with respect to DUE1 and DUE2 in the following way: if the number of decoded packets at DUE1 or DUE2 does not increase via decoding the encoded packets from a relay node, then this relay node would be removed from the current set of relay nodes.

4. If no relay node is selected, DUE1 and DUE2 would communicate with each other by way of regular cellular communications, i.e., via eNodeB.

C. Capacity, Interference, and Overhead Issues

In stage 1, as depicted in Fig. 2(a), the amount of packets to be encoded at a relay node is the number of packets that it receives from DUE1 and DUE2. Due to reuse of the cellular uplink resources by D2D links, DUE1 and DUE2 will cause interference to the cellular communications. As such, the transmitting power of DUE1 and DUE2 should be restricted so that it will not generate harmful interference to cellular communications.

In stage 2, the amount of decoded packets of DUE1, with respect to only one relay node, is the minimum between the data transmission rate of this relay node and the amount of encoded packets of this relay node in stage 1. The total amount of decoded packets of DUE1, with respect to multiple relay nodes, is the sum of the amounts of decoded packets of DUE1 with respect to individual relay nodes. The amount of decoded packets of DUE2 can be understood in a similar fashion. Since the relay nodes will also cause interference to the base station in this stage, the transmitting power of the relay nodes should be controlled within a certain range to ensure the quality of the cellular communications.

Given the number of time slots, both of DUE1 and DUE2 are able to receive more traffic with network coding than without network coding. However, employing NC to D2D communications would also incur overheads to the network - extra computations and communications. For the former, they are negligible to powerful smart devices. For the latter, the payload length in the packet plays a crucial role. According to the definition of communication overheads: $\frac{packet\ length - payload\ length}{packet\ length}$ [14], we know that if the payload length is large enough, the communication overheads are also negligible.

D. Performance Evaluation

Under the scenario depicted in Fig. 1, performance is evaluated to demonstrate the validity and effectiveness of network coding when it is applied to relay-based D2D communications. For comparison, all wireless links between DUE1 and relays and between relays and DUE2 are assumed to have an identical link loss probability in the simulations. Moreover, instead of comparing all network coding techniques, we only compare the performance between RLNC and IDNC since both work at the network layer. The detailed parameter settings for the simulations are shown in Table 1. All the simulation results are statistically collected by averaging the results of 1000 independent runs to guarantee that the obtained results are not affected by any stochastic factors.

In regard to relay-based D2D communications without network coding (relays forward the received packets directly), with IDNC, and with RLNC, Fig. 3 shows a comparison of these three cases in terms of end-to-end loss probability from DUE1 to DUE2 with respect to link loss probability when the number of packets is set to 1000. Clearly, we can see from this figure that with network coding the end-to-end loss probability can be significantly reduced, and that RLNC performs better than IDNC. This is because RLNC is a simple and powerful network coding scheme where the sender combines a set of packets using random coefficients from a finite field and broadcasts different combinations until all clients have received all linearly independent coded packets. In this case, RLNC achieves the best throughput among the three. The observation allows us to claim that RLNC is preferable to IDNC in being applied to relay-based D2D communications.

Fig. 4 and Fig. 5 demonstrate comparisons of encoding and decoding time and the number of decoded packets for RLNC and IDNC with respect to the number of packets, respectively. From these two figures we can see that, with the variation of the number of packets, RLNC needs a slightly longer time than IDNC to encode and decode the packets, but RLNC is capable of decoding more packets than IDNC in the same time span. This characteristic is of particular importance in ensuring signal-to-interference-plus-noise ratio (SINR) of D2D communications, especially when D2D links are interfered by the cellular communications. Therefore, we claim that RLNC can be more suitable for applications to relay-based D2D communications.

IV. Conclusion and Future Research Directions

In this article, we have encapsulated the application of network coding in D2D communications by addressing the applicative scenarios, and the pros and cons of different network coding approaches. We have explored network coding techniques in dual-hop D2D communication as a case study. Moreover, a relay selection algorithm based on the expected transmission count and the expected system capacity has been proposed, and the system capacity and interference issues have also been analyzed. Finally, impacts on the end-to-end loss probability, coding and decoding time, and number of decoded packets indexed by RLNC, IDNC, and no network coding have been investigated via simulations.

In viewing state-of-the-art of network coding in relay-based D2D communications, we suggest the following future research topics and directions.

- *Light-weight Network Coding*. Encoding rules of a network coding method should be as simple as possible. Complex coding calculations will burden CPU, increase encoding and decoding delays and compromise the low-delay feature of D2D communications. When there are a large number of data packets that need to be encoded, a large finite field would be required to ensure a sufficient decoding rate, which would result in huge computing overhead. In order to solve this problem, one can classify users according to their mobility pattern. While random linear network coding can be used for users with high mobility, some deterministic network coding method would be effective in reducing the size of the finite field and computing overhead for stationary network topologies with low mobility.
- *Efficient Resource Management*. In D2D broadcasting scenarios, for example, communications covering a hotspot area or concerning the safety of a public convocation, the link quality varies from one user to another. The data rate is limited by the worst link quality (e.g., bandwidth) among all links, so some link bandwidth would be wasted. One possible way to resolve this issue is to encode data hierarchically; that is, the data layer will be divided into the base layer and the enhancement layer. While the base layer packet contains full information with low-level QoS guarantee, the enhancement layer packet also contains full information but with high-level QoS guarantee. A receiver with poor link quality can just decode the packets at the base layer to complete the communication, and receivers with good link quality can decode the packets at both the base layer and enhancement layer for improved communication quality. On the other hand, when D2D devices in the relay group reuse the same spectrum resource [15], contention for spectrum resources among these devices will cause serious transmission collisions and enormous interference. In this case, a resource allocation and/or power control protocol with network coding could be designed to address this problem.
- *Security and Privacy*. Random network coding seems immune to eavesdroppers, as information is more scattered. However, in the case of relay-based D2D communications, a malicious relay may overhear all data packets from the transmitter and decode them, which gives rise to a serious security and privacy issue. In addition, jamming attacks from malicious relays would also cause notable trouble to the receiver, since corrupting a few packets will affect a larger set of data. Therefore, how to detect the malicious relays and removing them from the relay group with the assistance of eNodeB in this scenario, is of particular importance. In the previous section, communication among multiple relays is not considered, and a relay management mechanism can be established among relays to deal with this problem. In this case, a cluster head should be

elected by relays, which will be in charge of registering the removal of a relay, the addition of a new relay, and the status of cached packets at each relay. If multiple relays cache the same packet, the cluster head will send the corresponding signal to these relays informing them to use different coefficients to encode the packet. This not only can prevent encoded packets from being linearly related, but can enhance security and privacy (due to information being more spread out) as well.

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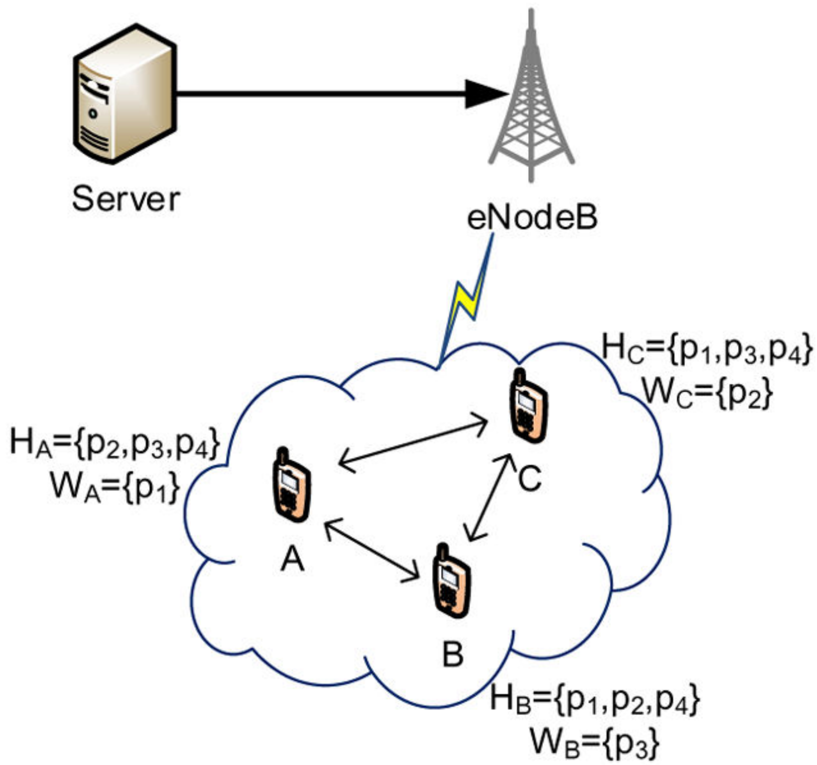
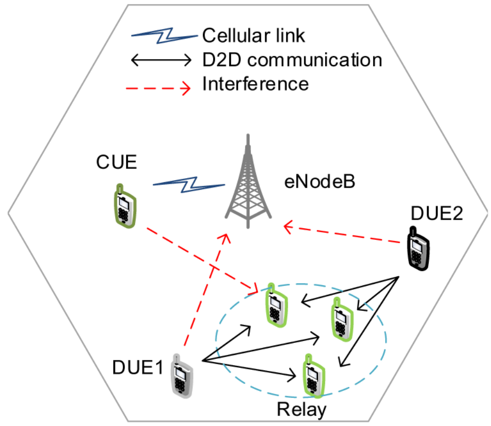
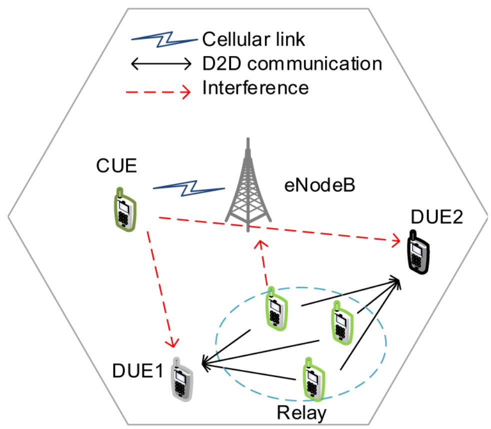


Fig. 1.
An illustrative example of network coding in D2D communications.



(a) Stage 1



(b) Stage 2

Fig. 2.
System model.

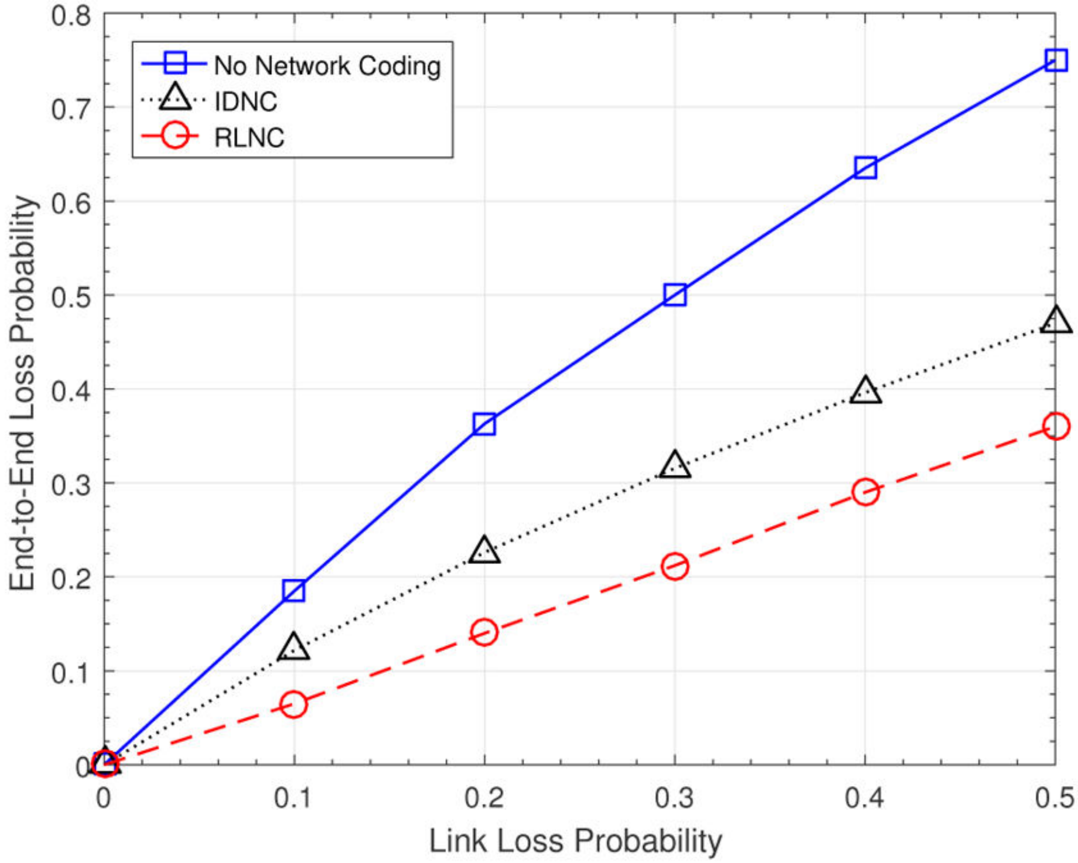


Fig. 3.
Comparison of end-to-end loss probability.

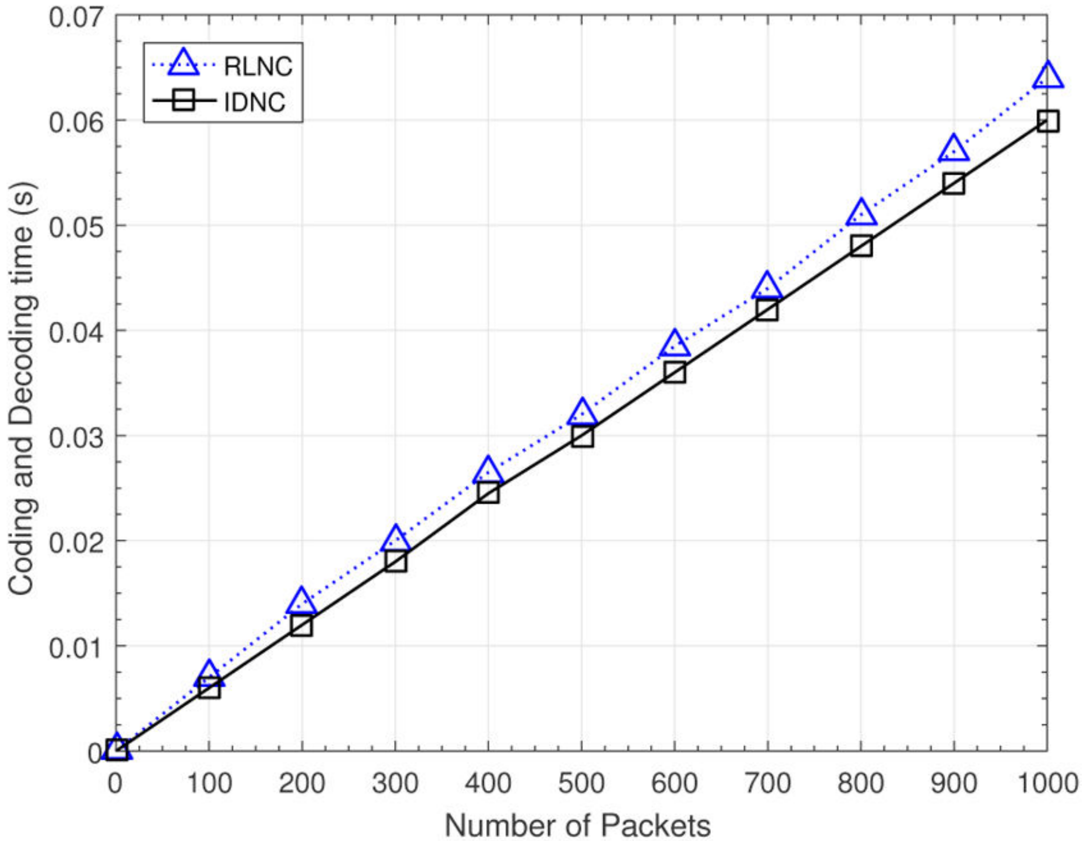


Fig. 4.

Comparison of coding and decoding time.

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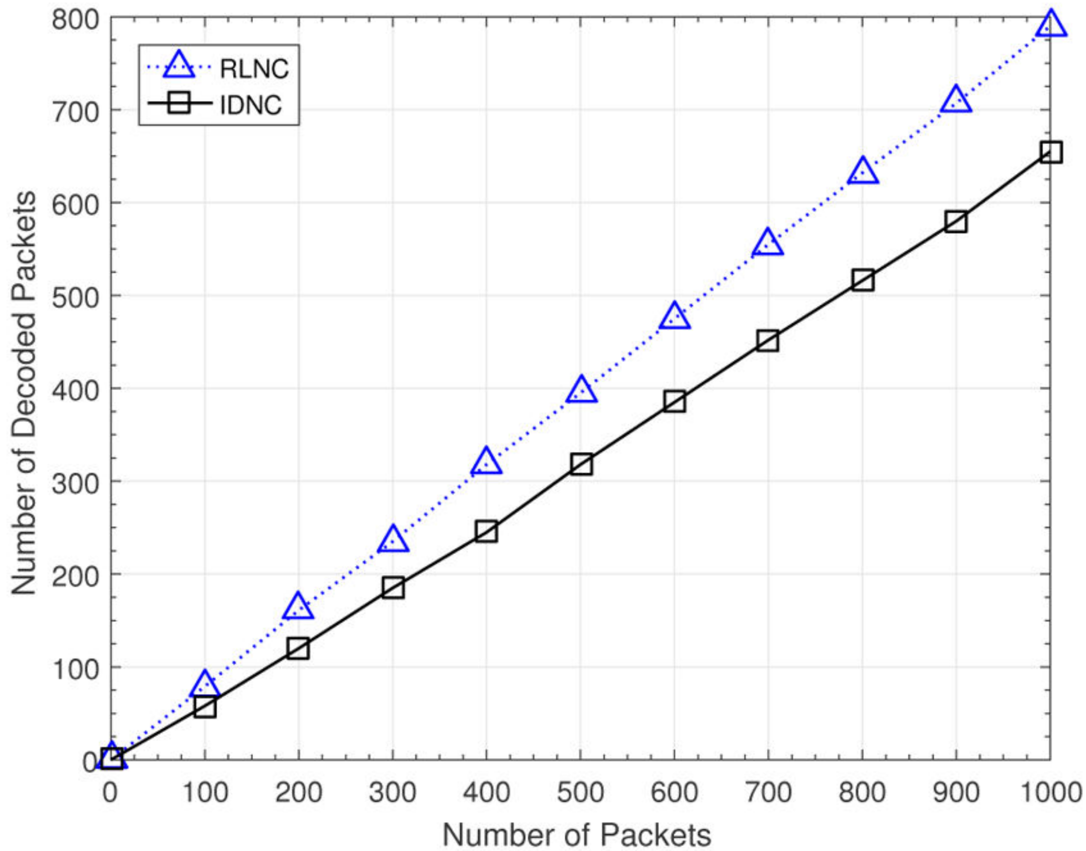

Fig. 5.
Comparison of the number of decoded packets.

TABLE I

Parameters Settings

Parameter	Value
Network coding field size	8
Number of generations	10
Link loss probability	[0.1, 0.5]
Number of packets	[100,1000]
Network coding technique	RLNC, IDNC