On Transmission Policies in Multihop Device-to-Device Communications with Network Coded Cooperation

Néstor J. Hernández Marcano*†, Janus Heide*, Daniel E. Lucani† and Frank H.P. Fitzek‡
*Steinwurf ApS, Aalborg, Denmark. Mail: {nestor|janus}@steinwurf.com
†Department of Electronic Systems. Aalborg University, Denmark. Mail: {nh|del}@es.aau.dk
‡Deutsche Telekom Chair of Communication Networks.
Technische Universität Dresden, Germany. Mail: frank.fitzek@tu-dresden.de

***Abstract*—Due to the expected amount of interconnected devices in the near future, a frequent communication setting will be the case where the end user is connected to the network through short range communication protocols to other mobile users. Therefore, there is an interest in introducing new mechanisms that provide reliable content distribution in these scenarios. Thus, in this work, we present ideal network coded transmission policies to reduce the number of transmissions in simple multihop networks. We propose two recoding schemes with a collision avoidance mechanism to reduce the number of transmission required to convey a batch of packets from a source to a destination through several non-interconnected relays. Our findings indicate benefits that when employing relays with a recoding scheme and different ideal medium access probabilities, reductions of at least 50% in the total number of transmissions might be attained.**

***Keywords*—Cooperation, network coding, multihop, device-to-device**

I. Introduction

In the following years, an exponential growth in data consumption for new services using telecommunication technologies is expected for future communication systems [1]. A standard assumption in former networks was that a single hop was sufficient to reach an end-user. However, due to this growth in the expected amount of connected devices and services, an end-user might not have connectivity directly from the source of information, but instead through other devices in the network that could aid in conveying information to it. Then, short range based mechanisms that can help to relay data in future network infrastructures have gathered significant interest from both academia and industry [2]–[4].

Thus, there is a major interest in finding decentralized schemes that extend connectivity and coverage in cellular systems while still providing high data rate and reliability to the end user. To achieve this, current alternatives are Device-to-Device (D2D) [5] or WiFi. For this purpose, multihop topologies with D2D communications might be formed to *cooperate* in conveying information to a receiver out of each of the cellular network [6], [7]. In this type of networks, different paths without inter-communication might be formed to reach the end receiver. These paths benefit from spatial diversity to forward the intended data to the final receiver since a loss in a path might be recovered from the correct reception in another. Hence, cooperative techniques result in increased reliability, coverage extension and throughput to end receivers. This potential has resulted in the inclusion of D2D communications in the 3rd Generation Partnership Project (3GPP) standardization efforts. To recover from packet erasures in the wireless medium, typically rateless codes are employed as a Forward Error Correction (FEC) technique. Nevertheless, although they provide benefits for single hop scenarios, they can not be deployed for cooperative communications without affecting their performance or decoding the data for each hop. Thus, rateless schemes seem an unsuitable coding choice against erasures in cooperative networks.

In this context, Network Coding (NC) [8], and particularly Random Linear Network Coding (RLNC) [9], provides not only an effective, faster and more efficient approach to relay data in multihop networks, but it simplifies the cooperation process since: (i) the information is not simply replicated, but distributed in a useful representation in the network and (ii) the final receiver only needs to get a number of linear combinations from any of the middle devices. This intuition has been exploited in previous works ranging from analysis to optimal policies and practical mechanisms, e.g., [10]–[14]. However, previous work has focused mostly in: topologies where all the cooperating devices inter-communicate with each other to coordinate the information, other scenarios like multicast or cooperation with fully connectivity in small clusters.

Thus, in this work, we present two simple decentralized transmission policies to reduce the total mean number of transmissions required to decode a batch of packets in a two-hop single source, single destination topology with various relays. To avoid collisions from the relays to the destination, we consider a collision avoidance mechanism at the Medium Access Control (MAC) layer that permits to allocate simultaneous transmissions from different nodes. Under this mechanism, we review the impact of a variable relay medium access probability in the number of transmissions to search for medium access probabilities that helps to minimize this metric in order to reduce the redundancy sent in this network. We present a set of ns-3 [15] simulations showing that at least a 30% reduction in the total transmissions, is possible for only enabling recoding at the relays. We also find that for our giving scenarios, an ideal medium access probability permits to reduce even more total packet transmissions. The paper is organized as follows: Section II defines the system model in this study. Section III gives a description of the transmission policies considered. Section IV shows ns-3 simulations to evaluate the policies. Final conclusions and future work are proposed in Section V.

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II. Model

We consider the problem of reliably transmitting a batch of g packets in a time-slotted system from a source S to a destination D, through $R_1, \ldots, R_N$ relays in a 2-hop network as shown in Fig. 1. Each packet has a length of B bits. We model the channel between transmitter $X \in [S, R_i]$ and receiver $Y \in [R_i, D]$ as a packet erasure channel, e.g. packets are sent from X to rY a might be erased (lost) with an erasure probability of $\epsilon_{X \to Y}$. We consider there is not any inter-relay connectivity nor between the source and the destination, thus $\epsilon_{R_i \to R_j} = 1, \ \forall i, j \in [1, N]$ and $\epsilon_{S \to D} = 1$. We consider independent heterogeneous packet erasure rates for each of the connectivity links from the source to the relays, $\epsilon_{S \to R_i}, \ i \in [1, N]$ and from the relays to the destinations, $\epsilon_{R_i \to D}, \ i \in [1, N]$. Hence, the packet reception distribution of receiver Y from transmitter X is $Bernoulli(1 - \epsilon_{X \to Y})$ and is independent from all others.

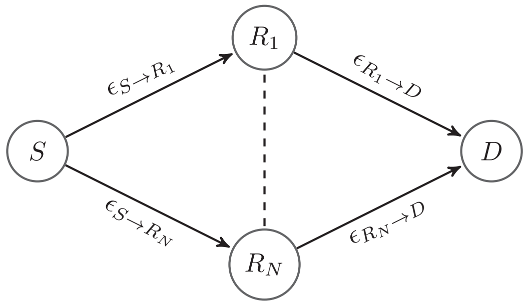

Fig. 1: 2-hop topology of a source (S), N relays ($R_1, \ldots, R_N$) and a destination (D) with a packet erasure rate in each respective link.

Tranmissions are performed through two hops. In the first hop, packets are transmitted from the source to the relays in a broadcast with RLNC fashion. The sender stops once each of the relays has g linearly independent (l.i.) coded packets. Through our study, we may refer to a l.i. coded packet as a degree of freedom. A newly received coded packet (or degree of freedom) will be called an innovative packet. Regarding the stopping condition, we may consider other stopping conditions to reduce the sender transmissions, but we consider this one since it is an upper bound for the transmissions in the first hop. Nevertheless, this condition permits to decode the data at the relays with inter-communication, if the content is also of their interest. For the second hop, the relays cooperate as a group to convey the information using either one of two possible recoding schemes, (i) recoding with RLNC or (ii) uncoded random forwarding which both will be detailed in Section III.

For any of these recoding schemes, it does not make sense for all the relays to transmit at the same time since there will be collisions at the receiver. Instead, each relay transmits with probability $p_i, \ i \in [1, N]$ only if it receives a packet from the sender in a given time slot. For simplicity, we consider $p_i = p, \ \forall i$. If two or more relays happen to transmit at the same time, we assume that a MAC layer mechanism allocates sequential non-colliding smaller time slots in a local network for the requesting relays. Therefore, in this case, we count the transmissions of the colliding relays as correctly received, regardless if the packets are innovative or not.

To take advantage of the information in the relays and not await for all to have the batch, once a packet is received from the source by the relays, they attempt to access the local medium with their respective probabilities. If several access the medium, they are scheduled by the MAC and make their transmissions. Thus, the destination benefits from receiving various packets in a single transmission. Finally, we assume that an ideal instantaneous feedback channel exists for any transmitter to know when its intended receivers are able to decode the data for stop sending packets.

III. Transmission Policies

In this Section, we give a description of the transmission policies employed to send the data. First, we provide a short description for RLNC as a coding scheme considered to broadcast the data from the source to the receivers. Later, we describe the recoding schemes employed at the relays and the MAC mechanism to avoid collisions of simultaneous transmitting relays.

A. Source to Relays: Broadcast with RLNC

In this type of network coding, the original data $P_j, j \in [1, g]$, each of B bits, is used to create coded packets. In the following subsections, we describe the basic functionalities of RLNC [9], namely encoding and recoding.

1) Encoding: With RLNC, each coded packet is a random linear combination of the original set of g packets. Each original packet is considered as a concatenation of elements from a Galois Field (GF) of a given size q, which we denote $GF(q)$. To create a coded packet, a coding coefficient $v_{i,j}$, is chosen at random from $GF(q)$ for every packet P_j and multiplied and added following the respective GF arithmetics. In this way, a coded packet is:

$$C_i = \bigoplus_{j=1}^{g} v_{i,j} \otimes P_j, \ \forall i \in [1, g] \tag{1}$$

To indicate which packets were used to generate a coded packet, one form is to append its coding coefficients. In this case, the overhead included for $C_i, \ \forall i \in [1, g]$ by the coding coefficients is given by:

$$|v_i| = \sum_{j=1}^{g} |v_{i,j}| = g \times \lceil \log_2(q) \rceil \ \text{[bits]} \tag{2}$$

2) Decoding: To perform decoding, at each relay we define $\mathbf{C} = [C_1 \ldots C_g]^T$ and $\mathbf{P} = [P_1 \ldots P_g]^T$. Then, decoding reduces to solve the linear system $\mathbf{C} = \mathbf{V} \cdot \mathbf{P}$ using Gaussian elimination [16]. Here, the coding matrix $\mathbf{V}$ contains any set of g linearly independent packets C_i as rows as follows:

$$\mathbf{V} = \begin{bmatrix} \underline{\quad v_1 \quad} \\ \vdots \\ \overline{\quad v_g \quad} \end{bmatrix} = \begin{bmatrix} v_{1,1} & \ldots & v_{1,g} \\ \vdots & \ddots & \vdots \\ v_{g,1} & \ldots & v_{g,g} \end{bmatrix} \tag{3}$$

The decoder begins to compute and remove the contributions from each of the pivot elements, e.g. leftmost elements in the main diagonal of (3), to reduce $\mathbf{V}$ to reduced echelon form. In this way, it is possible to recover the original set of packets. When a packet successfully arrives at a receiver, it checks if

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the packet is l.i. from all its previous. If not, it discards it. In case of being l.i., the receivers adds it to its coding matrix as mentioned before. This repeats until all receivers have collected their required combinations. An Acknowledgment (ACK) is sent through the feedback channel from the last relay after it gets its final combination and the source stops sending packets.

B. Relays to Destination I: Recoding Schemes

If a packet arrives at a relay, it will proceed to send the data to the destination according to a given recoding scheme. In our study, we consider two recoding schemes which we describe subsequently.

1) RLNC Recoding Scheme: Network coding allows intermediate nodes in a network to recombine (or recode) packets obtained from their sources whether they are coded or not. Thus, we define a recoded packet as R_i and its corresponding encoding vector as w_i with coding coefficients $[w_{i,1} \dots w_{i,g}]$, as follows:

$$R_i = \bigoplus_{j=1}^{g} w_{i,j} \otimes C_j,\ \forall i \in [1, g] \tag{4}$$

In (4), $w_{i,j}$ is the coding coefficient that multiplies C_j, uniformly and randomly chosen from $GF(q)$. Notice that C_j is a packet received previously which might be coded already. However, this does not affect the original encoding since a recoded packet is again a (new) linear combination of the previous ones. Any destination that collects $R_i, i \in [1, g]$ linearly independent coded packets from all the relays, appended with their respective w_i similarly as in (2), will be able to decode the data as mentioned before. In this scheme, a relay sends recoded packet only if the rank of its coding matrix is greater than zero. Otherwise, it will always generate linearly dependent packets which may introduce overhead in the network. Still, some redudant packets might be sent given that, particularly at the beginning of the transmission process, a relay might have few coded packets to combine. However, as more l.i. coded packets are received, this redundancy tends to diminish.

2) Random Forwarding Scheme: For this case, all the packets received by a relay before acknowledging decoding are stored by it. Then, once a packet arrives at a relay, it simply forwards uniformly at random one of the currently stored packets. Although storage resource consuming, forwarding any of the previous packets nulls the possibility that any pair of relay always send two inter-dependent coded packets. Still, in this scheme, a relay is constrained to send distingueshable packets, reducing the total amount combinations that could possibly be sent. Any destination that collects g l.i. coded packets from all the relays will be able to decode the data. Same as before, a relay tries to forward a previously received packet if its rank is greater than zero.

C. Relays to Destination II: Collision Avoidance Mechanism

Once a packet is generated with any of the previous recoding schemes, a relay senses the wireless local medium and access with probability p. If two or more relaying devices coincide in a packet transmission, we assume (without loss of generality) a MAC mechanism that allocates non-colliding time slots for each coinciding relay in order to avoid collisions. The detection time of a possible collision is considered to be ideal. Thus, coinciding relay nodes do not abort the current transmission and incur in retransmissions. Hence, a single transmission is accounted for each of the coinciding nodes.

IV. Simulation Results

To analyze the performance of our proposed transmission policies, we execute a set of ns-3 [15] simulations to observe the effect of the recoding scheme, code parameters and number of relays under a given combination of packet erasure rates in the links.

We consider the number of transmissions as a metric since other metrics such as the energy or throughput, which affect performance of cellular and wireless networks, depend directly on the number of transmissions for data decoding. We evaluate this metric at the source, the relays and the total amount of transmissions required to get the content at the destination. For evaluation purposes, we make this computations under homogeneous source-relays and relays-destination packet erasure probabilities for all the relays, e.g. $\epsilon_{S\to R_i} = \epsilon_{S\to R}\ \forall i \in [1, N]$ and $\epsilon_{R_i \to D} = \epsilon_{R\to D}\ \forall i \in [1, N]$.

To accomplish this, we employ the Kodo C++11 network coding library [17] with ns-3 through a project stored in a Git repository [18] that contains a set of examples using a set of Kodo C++ bindings with ns-3. A descriptive tutorial for this project can be found in [19]. From the repository, we run the `kodo-wired-broadcast` example and get the number of transmissions required to decode the data in 10^3 runs. To get independent runs, the pseudo-random number generator is set to use the default seed and the `RngRun` parameter is set equal to the run number in the `ns3::RngSeedManager` class. With the previous data, we compute the distribution for the number of transmissions in each of the nodes and later extract the mean of it.

For the simulations, we use the following parameters: $N = [1,\ 2,\ 3]$, $g = [8,\ 16,\ 32,\ 64]$, $q = [2,\ 2^8]$, $\epsilon_{S\to R} = [0.1,\ 0.3]$, $\epsilon_{R\to D} = [0.1,\ 0.3]$, $p = [0.01,\ 0.05,\ 0.1,\ 0.2,\ 0.3,\ 0.4,\ 0.5,\ 0.6,\ 0.7,\ 0.8,\ 0.9,\ 1]$ for the medium access probability and the recoding schemes considered in Section III.

A. The effect of the Number of Relays (N)

Fig. 2 shows the effects of the number of users in the total amount of transmissions from both the sender and the relays. We show it for the case of the random forwarding scheme, packet erasure probabilities $\epsilon_{S\to R} = 0.3$, $\epsilon_{R\to D} = 0.1$ and code parameters $g = 32$, $q = 2^8$. In this scheme, we observe that for more than one relay, there is a reduction in the total amount of transmissions required for decoding. Including more relays permits to have more sources of possible l.i. coded packets for the destination. However, in this case, always increasing the number of relays is not the optimal strategy because they may share various degrees of freedom. The ideal number of relays depends on the medium access probability. For a low access probability in the random forwarding scheme, the relays transmission attempts are reduced helping them collect different sets of degrees of freedom. For a high medium

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access probability, more transmissions at the relays of non-innovative packets tend to occur, given that they forward similar set of packets at the beginning. Hence, fewer relays are useful in this scenario. Notice that in this case, new coded packets are only introduced by the source.

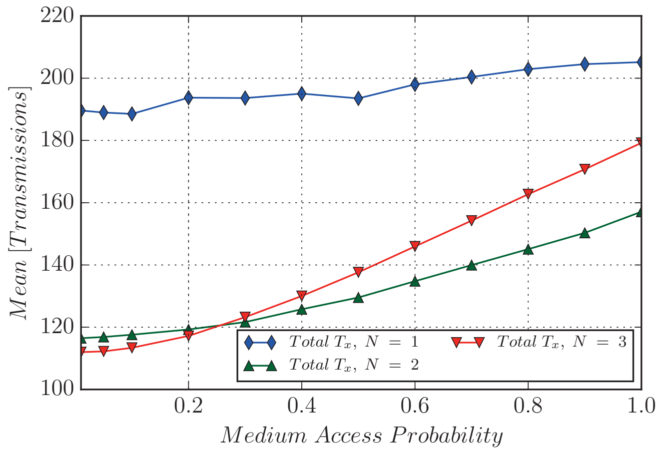

Fig. 2: Mean total number of transmissions, $Total\ T_x$, for decoding at the destination with a different amount of relays using a Random Forwarding Scheme. Scenario: $\epsilon_{S\to R} = 0.3,\ \epsilon_{R\to D} = 0.1$. Parameters: $g = 32,\ q = 2^8$

B. The effect of the Recoding Scheme and Field Size (q)

Fig. 3 shows the effects in the total number of transmissions by using a RLNC Recoding Scheme with different field sizes. We show it for the case of $g = 32$ packets, packet erasure probabilities $\epsilon_{S\to R} = 0.3,\ \epsilon_{R\to D} = 0.1$ and field sizes $q = 2,\ 2^8$. Allowing the relays to recode packets from their received degrees of freedom, reduces the total amount of transmissions for decoding by at least 30%, when comparing the results for $GF(2^8)$ in Fig. 2 and Fig. 3. The inherent recoding capability of RLNC makes each recoded packet indistingueshable from others, removing the restriction of receiving specific packets as in the forwarding scheme. Also, in Fig. 3, it can be observed the effect of the field size. Here, using a high field provides the advantage of requiring less transmissions than using a lower one, regardless of the number of relays. The reason is that, in the high field case, innovative packets are generated with very high probability.

We also observe there is an optimal medium access probability that minimizes the total number of transmissions for a given number of relays. From Fig. 3, a low medium access probability increments the number of transmissions required in the first hop as we consider more relays. The lower the access probability, the higher amount of time slots that a relay needs to wait for attempting a transmission and the higher amount of transmissions that the source makes since it stops transmitting once all the relays have all the degrees of freedom. For a high access probability, the relays access more frenquently the medium to transmit data, reducing the amount of transmissions from the source. However, if the access probability is too high, various redudant transmissions are made near the end.

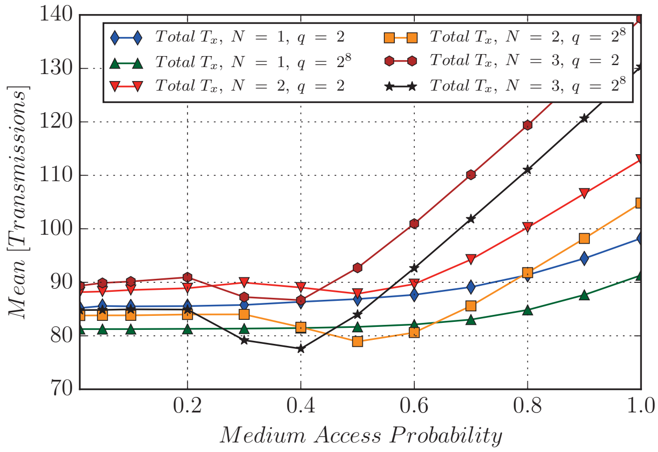

Fig. 3: Mean total number of transmissions, $Total\ T_x$, for decoding at the destination with different field sizes using a RLNC Recoding Scheme. Scenario: $\epsilon_{S\to R} = 0.3,\ \epsilon_{R\to D} = 0.1$. Parameters: $g = 32,\ q = 2,\ 2^8$.

C. Source and Relay Transmissions, Generation Size Effect (g)

Fig. 4 and Fig. 5 show the number of sender, relay and total transmissions employing a RLNC Recoding Scheme with two generation sizes. Fig. 4 shows the case of two relays, while Fig. 5 the case of three relays.

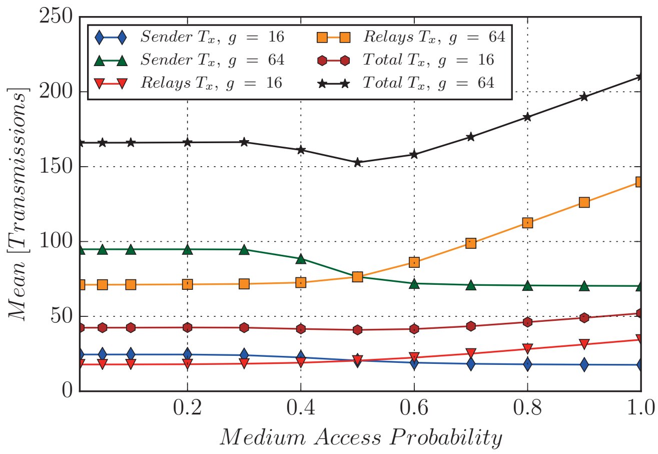

Fig. 4: Mean Sender (Source), Relays and Total number of transmissions, $Sender\ T_x$, $Relays\ T_x$, $Total\ T_x$ for 2 relays with different generation sizes using a RLNC Recoding Scheme. Scenario: $\epsilon_{S\to R} = 0.3,\ \epsilon_{R\to D} = 0.1$. Parameters: $N = 2,\ q = 2^8$

Using a higher generation size simply requires more transmissions given that more degrees of freedom are needed to be sent to the destination. It occurs independently of the number of relays to aid the source since it only varies with the generation size. By separating the sender and relays transmissions, we observe how the optimal medium access probability arises and where does it occur. As mentioned previously with Fig. 3, a low access probability increases the number of transmissions from the sender whereas a high access probability does the proper for the relays. We again observe these effects in both Fig. 4 and Fig. 5. Moreover, the total amount of transmissions is minimal particularly when the medium access probability

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approaches $p = 1/N$ approximately, e.g. a uniform medium access probability in all of the cases.

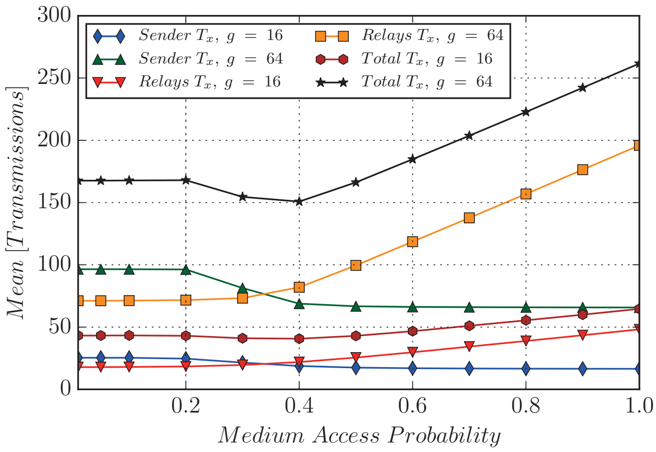

Fig. 5: Mean Sender (Source), Relays and Total number of transmissions f, $Sender\ T_x$, $Relays\ T_x$, $Total\ T_x$ for 3 relays with a different generation sizes using a RLNC Recoding Scheme. Scenario: $\epsilon_{S\to R} = 0.3,\ \epsilon_{R\to D} = 0.1$. Parameters: $N = 3,\ q = 2^8$

V. Conclusions

In this work, we propose different transmission policies to reduce the mean number of transmissions in network coded cooperative systems, since this a key metric that controls other relevant ones such as the energy consumption or the throughput. Through extensive system simulations, we could observe the benefits of a RLNC recoding scheme with a MAC collision avoidance mechanism to exploit the benefit of spatial diversity with a set of relays in multihop communications, observing a reduction in the number of transmission for various medium access transmission probabilities. Future work in this are should focus on evaluating ideal policies for minimum completing time as evaluated in [20] and [10] for similar topologies.

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