Network Coding Efficiency In The Presence Of An Intermittent Backhaul Network

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***Abstract*—In infrastructure-lacking environments, like military areas of operation, the intermittent availability of backhaul networks leads to greater reliance on peer to peer data exchange. In such settings, mobile nodes use Delay Tolerant Network (DTN) protocols for exchanging location specific data. High transmission delay, packet loss and intermittent connectivity increases the need for efficient data transmission in such scenarios. In this paper, we evaluate network coding for efficient data exchange between mobile wireless nodes under the presence of an intermittent backhaul network, like a satellite or cellular link. We analyze the upper bound of savings achievable with network coding for single-hop packet transmission, and introduce a network coding algorithm focused on reducing the required number of packet transmissions in such a setting. Evaluation of our proposed data exchange protocol shows how network coding can be applied to reduce transmission delay and minimize the dependency on an intermittent backhaul network in a communication scenario typical of a military environment.**

I. INTRODUCTION

In this paper we characterize the benefits of network coding for delivering a complete set of data packets to a group of receivers in a DTN environment with intermittent backhaul connectivity. It has been shown in previous publications ([1],[2],[3],[4]) that network coding can be applied to optimize data transmission in a pure DTN environment. In many situations where a DTN is used, there exists intermittent connectivity to a backhaul network through a cellular or satellite link. Access to the backhaul link is often expensive and is considered an extremely precious resource so its use is minimized.

We consider a case in which a group of nodes that are dispersed desires the same information, for example, current locations of animals in a national park or maps and conditions in a town after an emergency or in a military operation. The users require this information when they arrive at a fixed location, such as a meeting point. Backhaul connectivity to a server that has the complete data set is available at the meeting point, but it is expensive and limited, and therefore it is desirable to minimize its use (e.g. satellite). To this end, devices attempt to gather as much information as possible from peer nodes as they move towards the meeting point using DTN protocols. It has been shown in [5] that due to limited contact durations and limited meeting opportunities it is often difficult for nodes to obtain the full set of information. In our scenario, however, any information they do receive does not have to be retrieved over the precious backhaul link at the meeting point. Furthermore, because different nodes in the group may have acquired different portions of the information during their travels, the nodes may be able to augment each other's information at the meeting point using peer-to-peer methods further reducing the need to request information over the backhaul link.

The contributions of this paper are as follows:

- We present a network coding algorithm focusing on reducing the number of required transmissions via peer to peer and backhaul link data exchange.
- We analyze the savings achievable with network coding, and show how the minimal number of wireless nodes for exchanging a complete data set can be estimated.
- The proposed techniques are evaluated in the *OPNET 17.5* network simulator and we show a delay reduction for the exchange of data between mobile nodes by 33% on average compared to broadcast data exchange in a military network.

II. RELATED WORK AND BACKGROUND

In the literature, practical network coding was first introduced in [1] and has been successfully applied in different applications. In [6] network coding was used to improve the process of broadcasting packets in DTNs under the presence of adversaries. Random Linear Coding (RLC) was applied in [4] to provide the benefit of network coding in DTNs under epidemic routing. In [7], network coding was used to increase the energy efficiency of packet transmissions in wireless ad-hoc and sensor networks. The trade-off between number of packet transmissions and transmission delay for routing a batch of data packets in a DTN was discussed in [2]. These previously presented results show that applying network coding in a pure DTN environment improves efficiency and performance. In this paper we focus on the exchange of packets once the nodes arrive at a meeting point where peer to peer exchange opportunities with other nodes, and a limited backhaul connectivity exists.

In the following, we give a brief overview of the principle of network coding based on its introduction in [1] as it relates to this paper. The idea of network coding is to transmit the information content of several data packets with a single transmission. For wireless network coding, the overhearing of a packet broadcast by multiple receivers is utilized. A

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precondition for network coding is that different parts of the transmitted information are already present in the receivers.

To transmit a certain number of packets with network coding, two different operations have to be executed: On the sending side, packets are encoded by performing a binary XOR between n selected data packets. On the receiving side encoded packets are decoded by performing an XOR operation with $n-1$ un-encoded packets already present at the receiver. This procedure enables all overhearing receivers to retrieve one new packet. To guarantee that each receiver is able to decode the received encoded packet, the following rule is defined in [1]:

RULE 1: To transmit n packets, $p_1, ..., p_n$ to n receivers, a sending node can encode the n packets if each receiver r_i has all $n-1$ packets.

III. Network Model

As discussed in the introduction, we consider a case in which users are interested in accessing location specific data like maps or weather information. Users move as individuals to the location where they need the data, for example a meeting point or stop on a tour. The users gather as much data as they can while moving using DTN protocols, and then complete their data set at the meeting point by either retrieving the data from peers or over a precious backhaul link.

More specifically, our network model consists of a wireless DTN of multiple mobile wireless nodes, as shown in Figure 1. The goal of every node is to collect all packets of a specific data set. Various data exchange opportunities occur with peers as the nodes move towards the meeting point. This results in a distribution of packets in each node with some overlap, so that certain packets are known by multiple nodes at a time.

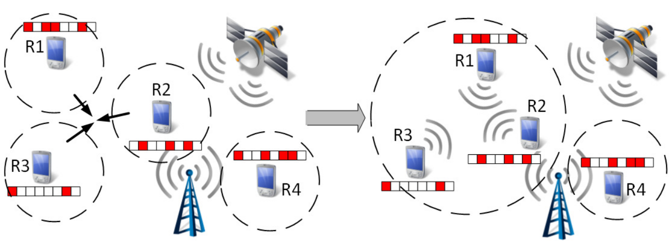

Fig. 1: Network model

In our experiments, we address the exchange of data when nodes get together as a group. We assume that through the DTN exchanges an initial distribution of data packets between nodes exists that is close to random.

When in the group, besides peer to peer connections for exchanging packets, nodes also have the opportunity to request data packets over a backhaul link with a high cost of energy and delay. Requesting packets over the backhaul link may become necessary if certain packets cannot be acquired over peer to peer connections. The direct communication between nodes is characterized by high loss rates but has a lower transmission delay and energy consumption than requesting packets from the backhaul network. Therefore we want to minimize the usage of the backhaul link as much as possible. The minimal number of nodes that have to meet for exchanging a complete data set, without requiring the backhaul link, can be estimated with a special case of the *Coupon Collectors Problem* as we discuss in Section V-B.

IV. Network coding protocol

In this section we introduce a 3-step protocol for single-hop peer to peer data exchange with network coding.

S	1	2	3	4	5	6	7	8
R1	1	x	x	x	5	x	7	8
R2	x	2	x	x	5	6	7	x
R3	1	x	x	4	x	6	x	8

Fig. 2: Coding opportunity matrix example

A. Step 1: Determine coding opportunity matrix

When nodes are within radio range, each node broadcasts a sequence number list of its current packets so that each receiving node is able to create a *map* of packets currently known by other nodes. We refer to this *map* of packets as the *coding opportunity matrix* as shown in an example in Figure 2. Based on the *coding opportunity matrix*, nodes are able to determine a combination of packets to reduce the number of required broadcasts as we will explain in detail in Section IV-B. After every node successfully determines the coding opportunity matrix, the node with the most packets continues with step 2 of the protocol since it is able to broadcast the most packets to the receiving nodes within radio range.

B. Step 2: Encoding of packets

Based on the *coding opportunity matrix*, the goal of our network coding algorithm is to find an optimal combination of packets so that the number of required transmissions can be reduced. An optimal combination of packets refers to the maximum number of un-encoded packets that can be XORed together considering *RULE 1* as discussed in Section II. In the example of a coding opportunity matrix shown in Figure 2, an 'x' states the node is missing this packet, e.g. node $R1$ is missing packets 2, 3, 4 and 6. Here, packets 6, 7 and 8 can be encoded, since 6 is missing by node $R1$, 7 by $R3$ and 8 by $R2$. We assume that sender S knows all packets. By encoding this set of packets it is ensured that every node is able to decode the received packet and retrieve it's missing packet. In this case, delivering three packets with one transmission is also the theoretical upper bound of savings in a scenario with three receivers. We discuss the theoretical upper bound of encoding packets in detail in Section V. Furthermore, packets 1 and 2 as well as packets 4 and 5 can be XORed together. Packet 3 has to be transmitted as a single packet since none of the receivers currently knows packet 3 and therefore no coding opportunities exist.

Finding an optimal combination of packets to encode is not a trivial task since multiple combinations are possible. Figure 3 shows a coding opportunity matrix with two possible combinations to encode packets. Encoding packets 1, 2 and 3 is a valid combination, but will not leave additional coding opportunities for packets 4, 5 and 6. In this case four transmissions have to be made for delivering six packets. Another possibility would be to XOR packets 1 and 6, 2 and 4 and packets 3 and 5. In this case only three transmissions are required to deliver six packets.

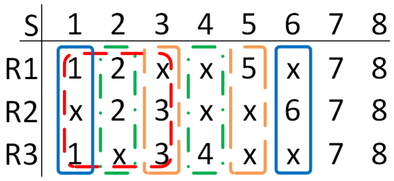

Fig. 3: Coding opportunity matrix example

In general, there is a higher probability a coding opportunity can be found if a packet is already known by multiple receivers. Our network coding algorithm follows a greedy approach to reduce the number of required transmissions, by selecting packets required by many receivers first and trying to find possible coding combinations. This ensures that packets with a higher probability for encoding are not transmitted first, leaving no coding opportunities for packets harder to combine.

Algorithm 1 Encode($COMatrix$, R)

Comment: First step, send all packets required by all receivers and remove them from the coding opportunity matrix, no coding opportunities exist for these packets

for all Pkt in $COMatrix$ **do**
  if Pkt is required by R **then**
    Send Pkt
    Remove Pkt from $COMatrix$
  end if
end for

Comment: Second step, determine coding opportunities, select initial packet required by $NumRecv$ receivers and encode with other packets considering RULE 1 from Section II

Define $NumRecv$ = $R - 1$

while $COMatrix$ not empty **do**
  Select Pkt required by $NumRecv$
  if Pkt found **then**
    $Pkts[]$ = coding opportunity packets in $COMatrix$
    if $Pkts[]$ is not empty **then**
      XOR Pkt with $Pkts[]$
    end if
    Add Pkt to transmission queue
    Remove encoded packets from $COMatrix$
  else
    $NumRecv - -$
  end if
end while

As input parameters, Algorithm 1 requires the number of receivers currently within radio range (R) and the coding opportunity matrix ($COMatrix$). The first step of the algorithm is to find packets in the coding opportunity matrix required by all receivers. For these packets no coding opportunities exist, so they have to be transmitted un-encoded and can be removed from the coding opportunity matrix.

In the second step of the algorithm, the actual coding opportunities are determined. The algorithm starts by searching in the coding opportunity matrix for a packet (Pkt) which is required by all receivers except one ($NumRecv$). If an initial packet is found, the algorithm selects coding opportunities from the $COMatrix$ considering *RULE 1* as defined in Section II. If coding opportunities are found, a binary XOR operation is executed between the initial packet and the selected coding opportunities $Pkts[]$. Otherwise the initial packet has to be transferred as a single packet. The selected packets are removed from the coding opportunity matrix and the resulting encoded packet is added to the transmission queue. If no initial packet Pkt, can be found, the threshold $NumRecv$ is decreased by one and the algorithm starts the same procedure again until all packets in the coding opportunity matrix are processed.

C. Step 3: Broadcasting encoded packets

After all packets in the coding opportunity matrix are processed and added to the transmission queue, packets are broadcast on the wireless channel. Upon receiving encoded packets, a node performs an XOR operation with $n - 1$ un-encoded packets and the received encoded packet. This enables every node to retrieve one new packet from every broadcast of an encoded packet.

V. Coding Opportunity Analysis

This section provides a mathematical analysis of the theoretical upper bound of transmission savings achievable with network coding. Furthermore we also discuss a special case of the *Coupon Collector's Problem* which can be used to estimate the required number of nodes within radio range to exchange all packets of a data set.

A. Upper bound of transmission savings

As explained in Section IV, the number of transmissions required to broadcast a certain amount of data packets with network coding depends on which packets are already known by the receiving nodes. In Section IV-B we show that multiple ways to encode packets exist and the number of required transmissions can vary. An optimal case of coding opportunities is present when every receiver in a group of nodes is missing a different packet. If the optimal case of coding opportunities is present, the required number of transmissions compared to the case without network coding decreases as the number of receivers increases as discussed in [1]. For our analysis of the theoretical upper bound of savings achievable with network coding, we assume an optimal distribution of packets so that the maximum number of coding opportunities exist.

In the equations shown, R refers to the number of receiving nodes and n represents the number of packets of an overall data set. As we explain in Section IV-C, every receiver of an encoded packet is able to retrieve one new data packet. Therefore the maximum number of packets that can be encoded for one transmission, equals the number of receivers R. In the ideal case, the number of required transmissions T of n packets to R receivers can be calculated with Equation 1.

$$T = \frac{n}{R} \tag{1}$$

Equation 1 assumes that the number of packets n is divisible by the number of receivers R. If we assume an ideal case of coding opportunities as shown in Figure 4 and n is not divisible by R, there will be one encoded packet containing less than R packets. The general form of calculating the required number of transmissions T for broadcasting n packets to R receivers, if the optimal case of coding opportunities is assumed, is shown in Equation 2.

$$T = \frac{n - (n \bmod R)}{R} + min(1, n \bmod R) \qquad (2)$$

Figure 4 shows an example of a packet distribution with optimal coding opportunities. Here, the information content of 8 packets can be transmitted with only 3 packets, saving 62.5% of the required transmissions.

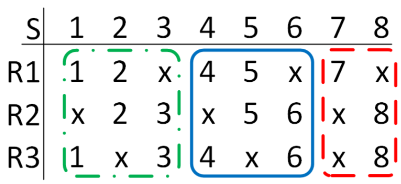

Fig. 4: Optimal packet distribution

If we set the number of packets n in relation to the required number of transmissions with network coding, we are able to calculate the relative value of required transmissions when optimal coding opportunities exist. By subtracting the relative value of required transmissions from 1, we can determine the upper bound of savings S with network coding in comparison to a standard packet by packet broadcast as shown in Equation 3.

$$S = 1 - \frac{\frac{n-(n \bmod R)}{R} + min(1, n \bmod R)}{n} \qquad (3)$$

If the number of packets n is divisible by the number of receivers R, we can reduce 3 to Equation 4. This shows, if an optimal distribution of packets is given, the theoretical upper bound of savings S with network coding in a single-hop scenario only depends on the number of concurrent receivers.

$$S = 1 - \frac{1}{R} \qquad (4)$$

B. Application of Coupon Collector's Problem

In our scenario as presented in Section III, several nodes with different subsets of packets exchange their data if radio connectivity is present. Depending on the size of the subset in every node and the number of nodes within radio range, there is a certain probability the combination of these subsets will cover all data packets. In [8], the probability of retrieving all parts of a collection from multiple random subsets is analyzed.

If we assume a random distribution of packets, the expected number of nodes R, with a subset of p packets, necessary to cover all data consisting of n packets can be calculated with Equation 5 as stated in [8].

$$R = \binom{n}{p} \sum_{j=1}^{n} (-1)^{j+1} \frac{\binom{n}{j}}{\binom{n}{p} - \binom{n-j}{p}} \qquad (5)$$

Table I shows the estimated number of nodes required to cover all data for specific sizes of random subsets of an overall collection of 100 packets. For example, if we assume every node has a random set of 70 packets, on average 5 nodes are required to be within radio range so that all packets of a specific set of data can be retrieved. This analysis helps to estimate the number of nodes required to meet so that all packets of a complete collection can be retrieved without connecting to a cellular network or a communication satellite. In our evaluations presented in Section VI we show the retrieved percentage of a certain data set when different numbers of nodes with various initial packet subsets are within radio range. The observed results meet our expectations as presented in Table I.

TABLE I: Random subset size corresponding to the expected number of nodes to cover all data packets

Random Subset	Nodes		Random Subset	Nodes
10	49.94		60	6.20
20	23.85		70	4.84
30	15.11		80	3.75
40	10.71		90	2.78
50	8.03		100	1.00

VI. Evaluation

We implemented our network coding algorithm in the *OPNET 17.5 Modeler* and show the practical usage of our protocol when applied in a specific scenario as we will introduce in Section VI-A. In Section VI-B and VI-C we present our results.

A. Communication Scenario

To evaluate network coding in a DTN environment with limited backhaul connectivity, we consider a specific communication scenario of multiple mobile wireless nodes typical of a military environment. For peer to peer communication a radio with a transmission rate of $200Kbps$, a packet size of $4096bits$ and a range of $100m$ is used. Direct node to node communication faces a high loss rate of 25-35% and a transmission delay of several seconds depending on the number of transmitted packets.

The satellite link has a negligible loss rate but is only available intermittently and has a much higher delay and energy consumption than exchanging packets between nodes. Therefore our goal is to minimize the usage of the satellite link. The satellite connection has a rate of $122Kbps$ and a propagation delay of $240ms$ which can be calculated as stated in [9]. The satellite link also uses a packet size of $4096bits$. We assume that a server reachable by the satellite link has the complete data set.

Transmission delay during a military operation is crucial, since soldiers have to be informed about the current operation status to adjust their behavior. Reducing delay for data exchange in such a setting is a critical task for operation success, so that soldiers can react as quickly as possible to unforeseen events in the battlefield.

We also considered peer to peer links with higher bandwidth: While this setting reduces the delay for direct packet exchange, it had no influence on the transmission savings achievable with our network coding protocol.

We consider three different communication options for our evaluation scenario:

- Only peer to peer packet exchange
- Peer to peer and satellite packet exchange
- Only satellite packet exchange

If only peer to peer packet exchange is used, depending on the distribution and number of packets in a group of nodes within radio range, the intersection set of packets will result in a certain percentage of the overall data set. In Section V-B we showed how the number of nodes required to be within radio range for covering a complete data set can be estimated with a special case of the Coupon Collector's Problem.

In the second case, we also consider an intermittent satellite link, in addition to peer to peer communication, for requesting packets not present in any of the nodes within radio range. Packets missing by all nodes within radio range are first requested over the satellite link before other packets are exchanged between nodes through peer to peer transmissions. Retrieving packets from the satellite first enables our nodes to recover lost packets during peer to peer exchange if at least one node receives the packet. This reduces the need to retransmit packets on the satellite link.

The third option assumes that all missing packets are requested over a satellite link. This option has the highest delay and is only available intermittently, but can be applied in case all nodes are out of radio range but concurrently request packets from the backhaul network.

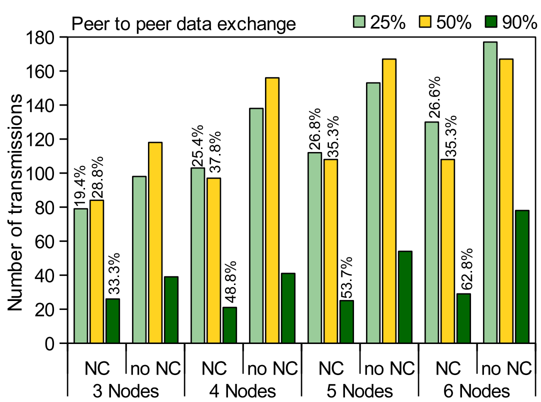

Fig. 5: Transmissions savings with network coding (NC) for option 1

B. Transmission savings

To evaluate the performance of our algorithm, we compare the number of transmissions required to exchange data packets with and without network coding. We ran simulations of data exchange in the introduced scenario for numbers of 3 to 6 nodes within radio range. Each node is assigned an initial random subset of packets, of a collection of 100 data packets, that represent the data they have received using DTN protocols while traveling to the meeting site. We present results for approximate initial subset sizes of ∼25%, ∼50% and ∼90% of packets, randomly assigned to each node. As stated in Section VI-A, direct communication between nodes is faster than a satellite connection, but very unreliable with a loss rate of 25-35%. Connecting to the intermittent satellite link is very expensive in terms of delay, but is reliable with negligible loss rate.

In Figure 5 we show simulation results for communication option 1: The savings with network coding are displayed in percent on top of the columns representing the number of packet transmissions. As shown, nodes with a higher fraction of packets are able to achieve better savings with network coding. Nodes with random 90% of packets save between 33-62% of transmissions or 13-49 packets, for exchanging a file consisting of 100 data packets on a link with around 30% loss. In comparison, nodes with 25% of packets only achieve savings of 20-27% which accounts for 19-47 transmissions depending on the number of receivers.

As stated in Section V, coding opportunities, and therefore savings, depend on the distribution of packets in different nodes as well as on the number of receiving nodes. Since only peer to peer communication is used in this communication option, nodes may only retrieve a subset of the overall data set. For example, 3-6 nodes with an initial subset size of 25% of packets, are able to cover 62-86% of the complete data set. We present detailed results for retrievable data set fractions in Section VI-C.

The number of transmissions in Figure 5 varies depending on the initial packet subset and coding opportunities. When 6 nodes are within radio range, we observe that nodes with initial packet sizes of 25% make more transmissions than nodes with 50% of packets initially. This is because the intersection set of 6 nodes with initial 25% of packets covers about 86% of the overall data set, while every node is missing approximately 75% of the packets. Therefore nodes request more packets from their peers compared to nodes that already have 50% of the overall data set.

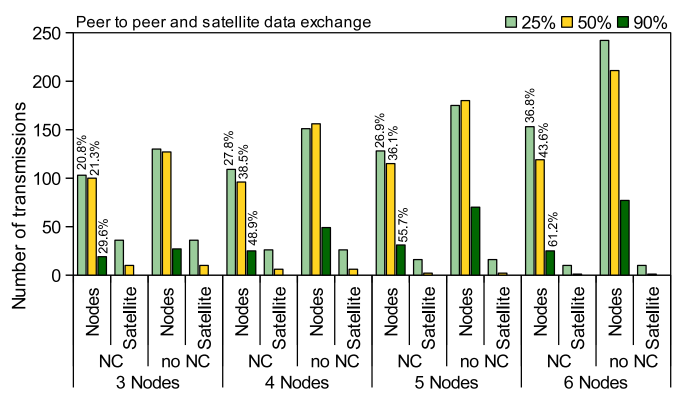

Fig. 6: Transmissions savings with network coding (NC) for option 2

Figure 6 shows the simulation results for exchanging packets with option 2. Here, in addition to sending data between nodes, packets that none of the nodes within radio range have are requested from the backhaul network over the intermittent satellite link. As shown, in case each node has random 25 or 50% of packets, a certain number of packets has to be requested over the satellite. As expected, the results show that a higher number of nodes within radio range covers a higher percentage of the overall data set and therefore fewer packets have to be requested from the backhaul network. For the presented results, we assume a satellite link with negligible loss rate. In our experiments we also tested satellite links with different loss rates. Our evaluation results showed that communication option 2 is able to recover lost packets requested over the satellite link if at least one node received the requested packet. Communication option 3 achieves transmission savings of 30-35% on average depending on the initial packet set and the number of nodes concurrently receiving packets from the satellite.

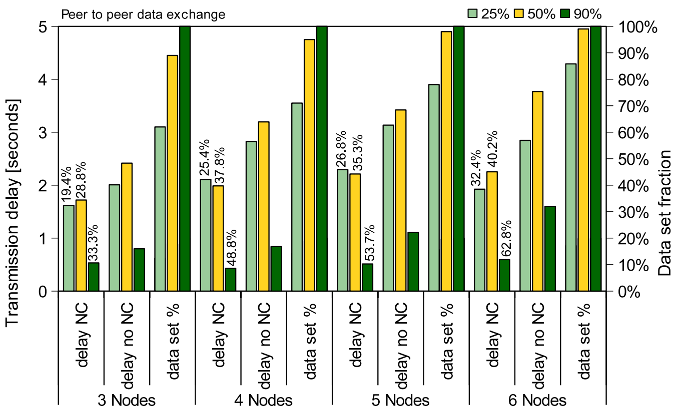

Fig. 7: Transmission delay and percentage of delivered data for option 1

C. Delay reduction

In our evaluation scenario as introduced in Section VI-A, each node wants to collect the information of other nodes as fast as possible. To reduce delay, requesting packets over the satellite link should be minimized if possible. Figure 7 shows the delay and delivered data set fraction for communication option 1. Network coding applied for this communication option shows significant reduction of delay by 37% on average. Since delay is a major issue for data exchange during a military operation as we discuss in Section VI-A, this is a significant improvement compared to the case without network coding.

Our proposed methods are able to reduce the delay by 29.9% for option 2 and 32.5% for option 3 on average. In case of option 3, our network coding protocol is able to increase the speed of the satellite link by up to 10 seconds. Figure 8 shows the communication delays to retrieve all required data packets over the satellite link. This communication option is only intermittently available, but guarantees the delivery of all requested packets also if nodes are out of radio range and peer to peer packet exchange is not an option.

D. Algorithm overhead analysis

We tested the overhead of our network coding algorithm by encoding 10,000 packets in a scenario of one sender with all packets and three receivers with random 50-90% of the overall packets. On a single-core processor we determined a runtime of $540ms$ for the encoding procedure. We also implemented a parallel version of the algorithm in OpenMP and measured a runtime of $320ms$ on a quad-core processor. As presented in our evaluations, applying the network coding algorithm is reducing communication delay by several seconds in most cases, which justifies the runtime overhead of our algorithm.

VII. Conclusion

In this paper we studied the efficiency of network coding for peer to peer packet exchange in a DTN with the presence of an intermittent backhaul network. We propose a data exchange protocol for single-hop wireless packet transmission with network coding and analyze the benefits of encoding packets,

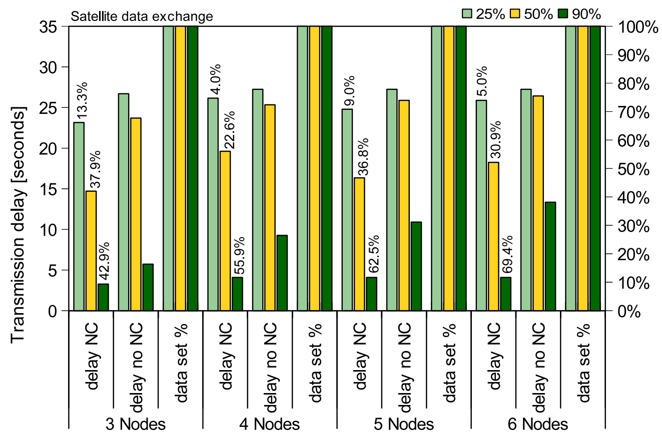

Fig. 8: Transmission delay and percentage of delivered data for option 3

theoretically and in a simulation environment. Our results show how the relation between packet distribution and nodes within radio range affect the transmission savings and percentage of delivered packets when our network coding protocol is applied. Our evaluations of the proposed techniques in an environment typical of a military operation show a delay reduction for data exchange between mobile nodes by 33% on average.

Acknowledgment

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