Multicasting in Tactical Networks: Forwarding Versus Network Coding

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Abstract: Multicasting refers to the transmission of packets to a group of one or more destinations. It can be very useful in military applications, such as command and control, in which a commander needs to send instructions to a group of tanks, users, or planes. Broadcast is a unique case of multicast, where all the nodes in the network are intended receivers. The broadcast case has been studied quite extensively in the literature, showing that the use of Network Coding (NC) requires fewer data transmissions than Packet Forwarding (PF). That motivates us to explore whether the same result holds true when only a subset of nodes are receivers. In this paper, we developed two linear optimization models that determine lower bounds on the number of required data packet transmissions when sending data in a Mobile Ad-hoc Network (MANET) from a single source to multiple receivers. The first model determines the minimum number of required packet transmissions under the assumption that PF is used. The second model assumes that data is distributed using NC. We derive lower bounds for different scenarios while varying the network size, network density, and the number of receivers in the multicast group and compare them with each other. Results indicate that the lower bounds for both PF and NC are almost the same for smaller network sizes (30 nodes or less), small multicast group sizes (5 or lower), or dense networks. However, for larger network sizes, sparser networks, and larger multicast group sizes NC is more advantageous than PF.

1 INTRODUCTION

Tactical networks are MANETs that are temporarily formed using radios with relatively long range and very limited bandwidth. These networks are built from mobile nodes such as sensors, soldiers and vehicles that communicate through tactical radio links. Most of the communications over tactical networks are group-oriented, requiring the transmission of the same data to several destinations. One example would be transmitting instructions from military headquarters to a group of military units that are moving together such as a squad, platoons, or battalions (Refaei and Bush, 2014; Egbogah et al., 2008). In such an environment, using unicast transmission is not efficient, so multicasting can be a good solution.

Multicasting refers to the transmission of packets to a group of nodes identified by a single multicast group address. Several multicast routing protocols have been proposed to address the problem of data distribution in MANETs which require transmitting data from single or multiple sources to multiple destinations.(Royer and Perkins, 1999; Lee et al., 2002; Lucile Canourgues and Beylot, 2006). These multicast routing protocols assume that packets are forwarded on a per-packet basis as would be the case in the Internet. Ahlswede et al. (Ahlswede et al., 2000) introduced a new idea to enhance the multicast traffic throughput called Network Coding (NC). NC enables the nodes to combine or encode a certain number of incoming packets together instead of simply forwarding them. One of the popular coding schemes is called Random Linear Network Coding (RLNC). RLNC allows a node to linearly combine a number of packets into one or more coded packets. A coding vector that contains the coding coefficient of the constituent packets is then appended to each coded packet. The receiving node must receive a certain number of linearly independent coded packets (at least equal to the number of original packets) to be able to decode the received packets.

In this paper, we are interested in comparing the lower bounds obtained from applying PF and NC to a multicast scenario. Our key metric is the required number of data packet transmissions at the MAC layer. Unlike most of the previous work, which explored the use of NC for increasing the multicast throughput, we are interested in exploring ways to distribute a given amount of data most efficiently to

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a group of receivers. The fewer packet transmissions a given approach requires, the fewer radio resources and (finite) battery energy are required. To that end, we develop two linear optimization models that, given a network scenario, determine lower bounds on the required number of data packet transmissions when sending data in a MANET from a single source to multiple destinations. Both linear programs are optimistic in that they assume that packets are never lost, in addition to being forwarded over the optimal path.

The outline of this paper is as follows. Section 2 reviews related work. Section 3, describes the PF and NC linear programs and compare the results obtained from both models. Finally, conclusions and future work are provided in Section 4.

2 RELATED WORK

There exist several work that addressed the problem of data distribution in MANETS. Some methods applied multicast routing protocols which is based on PF to enhance bandwidth utilization. Gopinath and Nagarajan (Gopinath and Nagarajan, 2015) proposed the residual energy-based reliable multicast routing protocol (RERMR), which increases packet delivery ratio and network life time. This is achieved by integrating a stability model with a multicast backbone to improve node stability and link quality. The protocol estimates the reliability of each path, as well as the residual energy of its nodes. The path with higher reliability and residual energy is then chosen for forwarding data packets. The algorithm monitors the error rate on each path and if the error rate for a certain path increases, another path will be selected. Simulation results show that the proposed algorithm has better performance in terms of higher delivery ratio, network stability, and lower delay. However, the algorithm assumes a priori knowledge of nodes direction of motion.

The problem of finding the minimal set of forwarding nodes for broadcasting in the PF case is called the Minimum Connected Dominating Set (MCDS) problem and is known to be NP-hard (Čagalj et al., 2002). The best exact solution to find a Minimum Connected Dominating Set of an arbitrary graph of n nodes is described in (Fomin et al., 2008) and solves the problem in $O(1.9407^n)$, a slight improvement of the trivial (2^n) algorithm. If the complete topology is known, centralized heuristics such as the one in (Butenko et al., 2004) can be applied and provide in general a good approximation to the MCDS size. The work done in (Kunz et al., 2010) implemented this heuristic to derive the lower bound for broadcasting data from one source to all nodes in the network based on PF.

Other methods suggest the use of NC to reduce duplicate packet transmission and enhance the transmission efficiency of the network.The work done by Lun et al. (Lun et al., 2008), propose the use of Random Linear Network Coding (RLNC) to provide reliable communication in lossy multi-hop wireless networks. RLNC enables the node to linearly combine a number of incoming packets to produce a single encoded packet that conveys useful information about the whole data set. The encoded packets are then transmitted over the wireless channel in which packets can get lost. However, if the receiving node receives a certain number of linearly independent coded packets, it can reconstruct the original message. This ensures a reliable delivery of data.

Determining the lower bounds in the case of network coding was formulated as a linear optimization problem in (Kunz et al., 2010; Kunz et al., 2012). The program minimizes the total number of packet transmissions by all nodes, subject to the constraints that each receiver has to receive M coded data packets from each source. The underlying assumption is that, if a source generates M coded data packets, a receiver, upon receipt of all M coded data packets, will be able to decode them and regenerate the original data packets. A RLNC broadcast protocol called ARLNCCF was proposed in (Kunz et al., 2012). The protocol supports the use of cross source coding by allowing packets from different sources to be coded together. Results showed that the use of cross source coding can decrease the number of packet transmitted in the network by 8%-20%. Moreover,the PDR was improved and packet latency was decreased. However, the protocol complexity increased due to the need for managing packets from different sources.

Broadcast is a unique case of multicast, where all the nodes in the network are intended destinations. (Fragouli et al., 2008) studied in-depth the case for all-node broadcasting (all sources generate a data packet that then has to be shared with all other nodes in a wireless multi-hop network). The paper shows that for certain regular topologies (ring, square grid), NC can distribute the data at a competitive advantage over PF, which they refer to as coding gain. In the case of a ring topology, as the number of nodes grows, NC requires only half the number of packet transmissions compared to PF. In the grid topology, PF requires about 33% more packet transmissions. More generally, the theoretical analysis in the paper shows that network coding improves performance by a constant factor in fixed networks. In networks where the topology dynamically changes, for example due to mobility, and where operations are restricted to simple distributed algorithms, network coding can offer improvements of a factor of log n, where n is the number of nodes in the network.

3 OPTIMIZATION MODELS

The previous section showed that NC can have significant performance benefits over PF in various broadcasting scenarios, in particular as the network size increases. On the other hand, in the case of a single source and a single destination (unicasting), there is no difference between PF and NC: the minimum number of packet transmissions at the MAC layer is achieved by forwarding all data or coded packets over the shortest hop path connecting source and destination. In this section, we want to examine cases between these two extremes. Is NC beneficial in scenarios where a single source multicasts data to a (relatively small) number of receivers? To answer this question, we developed two linear optimization models using IBM ILOG CPLEX Optimization Studio. The programs determine lower bounds on the required number of data packet transmissions when sending data in a MANET from a single source to multiple destinations.

3.1 Problem Formulation

Consider a static wireless ad-hoc network with N nodes, that are randomly positioned in a square area, based on a uniform distribution. To compare the lower bounds in a meaningful way, we generated 25 network scenarios with the *setdest* utility in NS2, which places a certain number of nodes within a given area, using a uniform random distribution. We vary both the number of nodes in the network as well as the network density. We created networks with 10 to 100 nodes in steps of 10. The network size scales with the number of nodes to keep the nodal density approximately constant. To explore the impact of network density, three sets of network scenarios were created, which we refer to as Sparse Density, Medium Density, and High Density. In Sparse Density, the network area ranges from 470 m x 470 m for a 10 node network to an area of size 1500 m x 1500 m for a 100 node network. With an assumed transmission range of 250 m, nodes have, on average, slightly below 2 neighbors. All networks are connected. In Medium Density networks, the area size ranges from 346 m x 346 m to 1095 m x 1095 m, with nodes having, on average, slightly more than 4 neighbors. In High Density networks, the area size ranges from 255 m x 255 m to 806 m x 806 m, nodes have, on average, 8 to 9 neighbors.

In all scenarios, we assume that we have a single source which is node zero that needs to transmit data to a number of destinations *(d)*. The number of receivers in the multicast group can vary from 2 to 5 and 9 which is the maximum number of destinations that can exist in a 10 nodes network (the smallest network size we consider). The linear programs assume that the nodes with the highest ID are multicast receivers. As an example, if the user specifies that d nodes (out of N) are to be receivers, the model uses nodes *N-d* to *N-1* as the receiving nodes. With random node placements, these receivers could be close or far away from the source node (always node 0). The number of packet transmissions will be very sensitive to the relative location of source and destinations, particularly for smaller multicast group sizes and sparser networks. To allow for coding opportunities, the source node has to send more than a single data packet, so the two linear programs assume that the source sends 1000 data packets. We will use these scenarios to evaluate/compare PF and NC lower bounds.

Table 1 summarizes all experimental parameters we varied in this paper.

Table 1: Experimental Parameters.

Parameter	Possible Values
Number of Nodes	10, 20, 30, 40, 50, 60, 70, 80, 90, 100
Network Density	Sparse, Medium, High
Multicast Group Size	2, 5, 9

3.2 Packet Forwarding Model

The lower bound for PF is derived using a linear program which is illustrated as follow. Let s represent the source node, P represent the number of packets transmitted by the source node, *N(i)* is the set of one hop neighbours of node i, X_i is the number of packets transmitted by node i, $F_{i,j}(d)$ is the data flow from source node s over link *(i,j)* to destination d. The objective of the optimization model is to minimize the total number of packets transmitted by all the nodes in the network.

$$\min \sum \quad X_i$$

Subject to:

Constraint 1: the flow over any link *(i,j)* to destination d should be greater than or equal to zero.

$$F_{i,j}(d) >= 0 \quad (i, j \in N) \tag{1}$$

Constraint 2: flow balance constraints which indicates that, if i is the source node, it has to transmit P packets. If i is the destination node, it has to receive P packets. For any other intermediate node, the sum of outgoing flows minus the sum of incoming flows should be zero.

$$\sum_{j\in N(i)} F_{i,j}(d) - \sum_{l\in N(i)} F_{l,i}(d) = \begin{cases} P & for\ i=s \\ -P & for\ i=d \\ 0 & otherwise \end{cases} \quad (2)$$

Constraint 3: the flow over existing link *(i,j)* should not exceed the number of packets transmitted by the head of the link.

$$X_i \geq F_{i,j}(d) \quad (i,j \in N) \quad (3)$$

Constraint 4: the flow over any link is either all the packets or none.

$$F_{i,j}(d) = P \quad || \quad F_{i,j}(d) = 0 \quad (i,j \in N) \quad (4)$$

Figures 1 to 3 plot the lower bounds when using PF to implement multicasting for various multicast group sizes. The X axis plots the number of nodes in the network, the Y axis shows the number of packet transmissions to send a single packet to all destinations in the multicast group, averaged over all 25 scenarios. The results presented also include the 95% confidence interval.

The results illustrate that we need more packet transmissions per data packet for larger networks, assuming the network density remains constant. We also require more packet transmissions as the multicast group size increases. Finally, as network density increases, fewer packet transmissions are necessary to reach all multicast group members.

3.3 Network Coding Model

Determining the lower bounds in the case of NC is derived using the linear program we introduced in (Kunz et al., 2010), but here we are interested in multicast scenarios where only a subset of the nodes are intendent destinations. The main difference between the PF and NC linear programs is in Constraint 4 which indicates that the flow over any link is either all the packets or none. This constraint can not be used in the case of NC as it will force the node to forward all the packets it received and the idea of NC is to allow the node to combine multiple incoming packets into one or more outgoing coded packets. Removing that constraint will raise another problem which will be illustrated using the following example. Consider a ring network consisting of six nodes, and assume that the source node (node 1) wants to transmit two packets (a and b) to destination nodes 3, 4, and 5. If we use PF, the minimum number of required packet transmission to deliver the two packets to all the three destinations is 8 packets as shown in Figure 4. Node 1 will transmit the two packets to its one hop neighbours node 2 and 6, then node 2 will transmit the two packets to node 3. Meanwhile node 6 will transmit the two packets to node 5. Finally either node 3 or node 5 will transmit the two packets to node 4. However, if we remove Constraint 4, the result from the optimization program indicate that we need only 6 packet transmissions to deliver the two packets to all the destinations. Figure 5 illustrates how packets are transmitted in the case of NC. The source node will transmit packet a to node 2 and packet b to node 6, node 2 will transmit packet a to node 3, while node 6 will transmit packet b to node 5. After that node 3 will transmit packet a to node 4. Meanwhile node 5 will transmit packet b to node 4. In this case, node 4 received the two packets a and b, but each of node 3 and 5 received only one packet, so node 4 will encode packet a and packet b and transmit one encoded packet (a $\oplus$ b) which will be received by nodes 3 and 5. Nodes 3 and 5 will decode the received encoded packet to obtain the missing packet (either a or b). The problem that arises here is that although the source node transmitted two packets when it sent packets a and b, and each transmission occupies the transmission media, the minimum number of packet transmission should be 7 not 6. However, if we account for physical packet transmissons the way we do in the PF case, these two transmissons would only be counted as one packet transmission sent by the source node. In order to fix this problem we introduce the notion of dummy nodes. In the above scenario, the two packets transmitted by node 1 will first be sent to node 1's dummy node, and count as two physical packet transmissions, before the dummy node forwards the two packets to different intended receivers.

We assume that any real node i has to transmit the packets to its dummy node $\bar{i}$, which in turn will forward the packets to the direct neighbours of i. Assume that we are again transmitting P packets, which now may be coded (i.e., combinations of native data packets). The objective of the program is to minimize the total number of packets transmitted by all nodes in the network.

$$\min \sum \ X_i$$

Subject to:

Const. 1: the flow from node i to its dummy node $\bar{i}$ should be less than or equal to the number of physical packets transmitted by that node.

$$X_i >= F_{i,\bar{i}}(d) \quad \forall\ i,j \in N \quad (5)$$

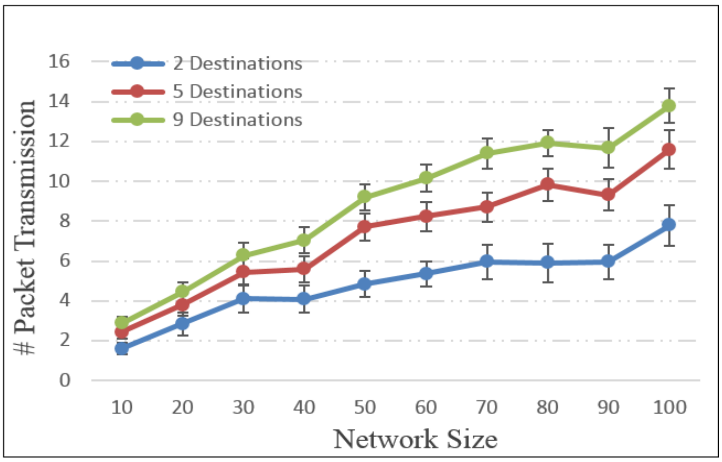

Figure 1: Lower Bounds for PF in Networks of Sparse Density.

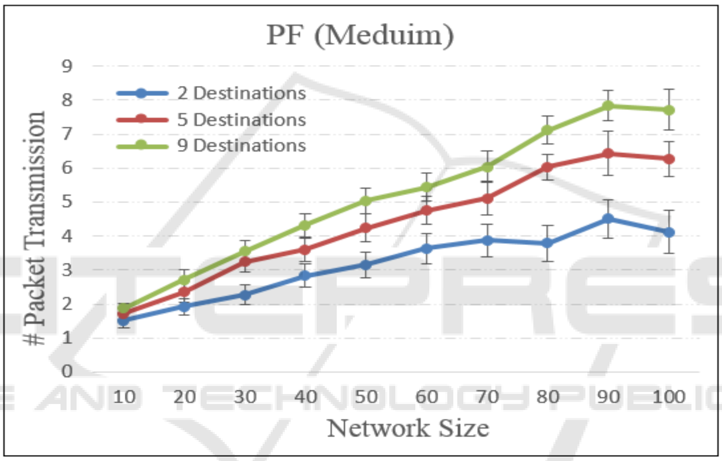

Figure 2: Lower Bounds for PF in Networks of Medium Density.

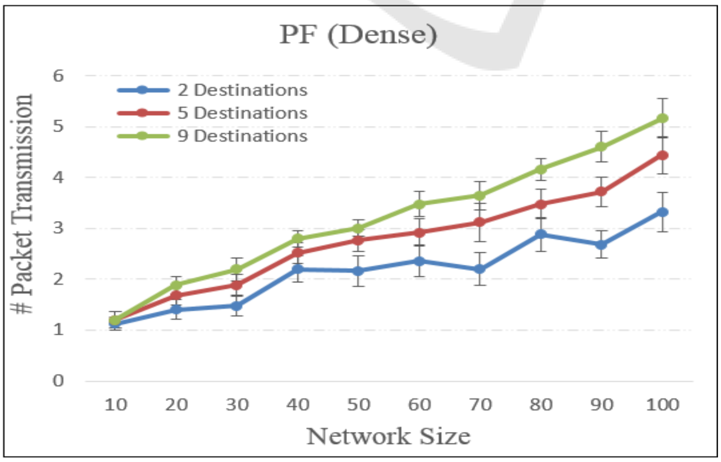

Figure 3: Lower Bounds for PF in Networks of High Density.

Const. 2: flow balance constraints which indicate that the source node has to generate P packets and the destination node should receive P coded data packets. Otherwise, the node should forward all the data

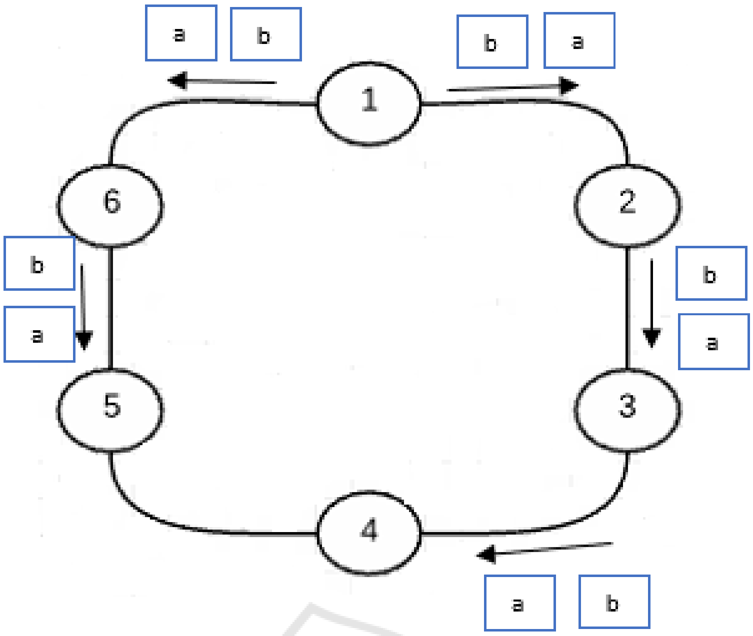

Figure 4: Packet Transmission using PF.

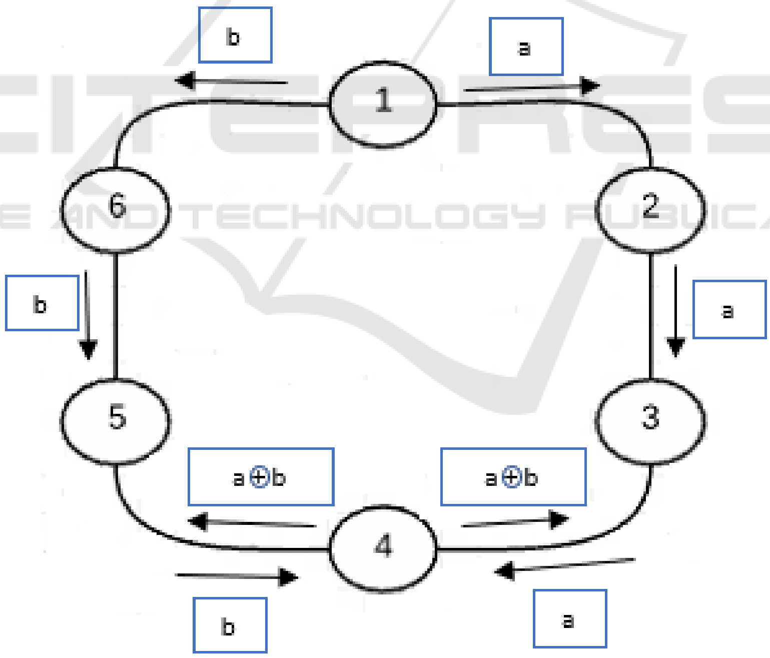

Figure 5: Packet Transmission using NC.

packets it received to its dummy node.

$$F_{i,\bar{i}}(d) - \sum_{j \in N(i)} F_{\bar{j},i}(d) = \begin{cases} P & for\ i = s \\ -P & for\ i = d \\ 0 & otherwise \end{cases} \quad (6)$$

Const. 3: the flow balance constraints on the dummy node is zero.

$$\sum_{j \in N(i)} F_{\bar{i},j}(d) - F_{i,\bar{i}}(d) = 0 \quad (7)$$

Const. 4: the number of packets transmitted by any node i should be greater than or equal to zero.

$$X_i >= 0 \quad \forall\, i \in N \quad (8)$$

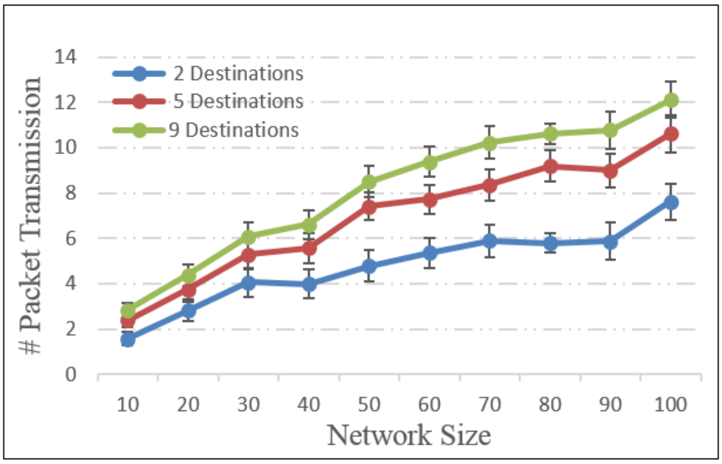

Figure 6: Lower Bounds for NC in Networks of Sparse Density.

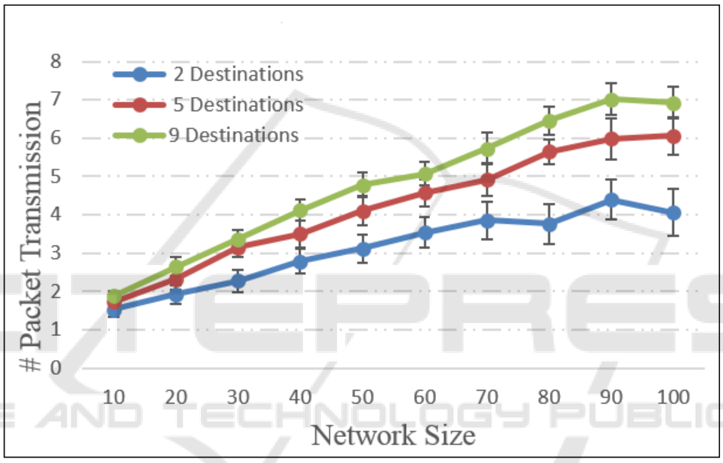

Figure 7: Lower Bounds for NC in Networks of Medium Density.

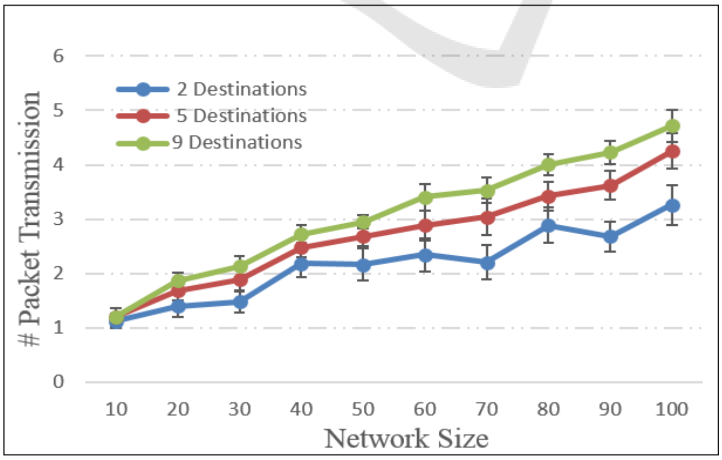

Figure 8: Lower Bounds for NC in Networks of High Density.

Figures 4 to 6 plot the lower bounds when using NC to implement multicasting for various multicast group sizes. The 95% confidence intervals are quite tight, giving us assurance that the results averaged over 25 scenarios are meaningful enough to draw some conclusions/observations from our data.

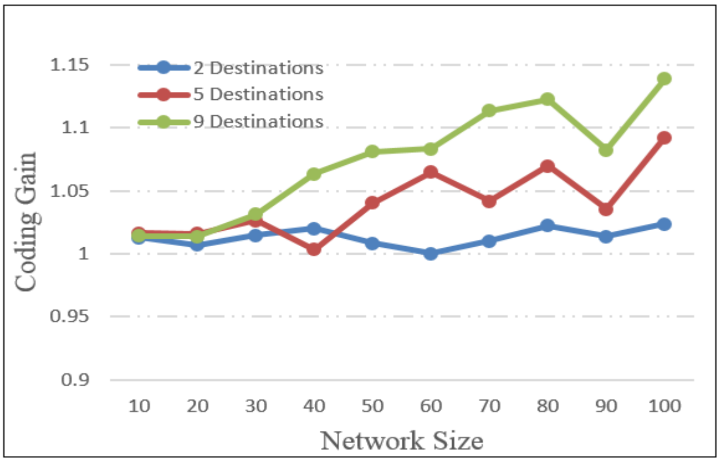

Figure 9: Coding Gain in Networks of Sparse Density.

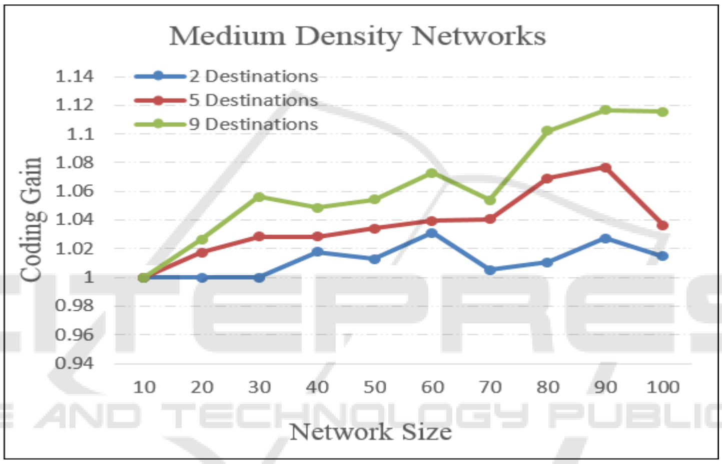

Figure 10: Coding Gain in Networks of Medium Density.

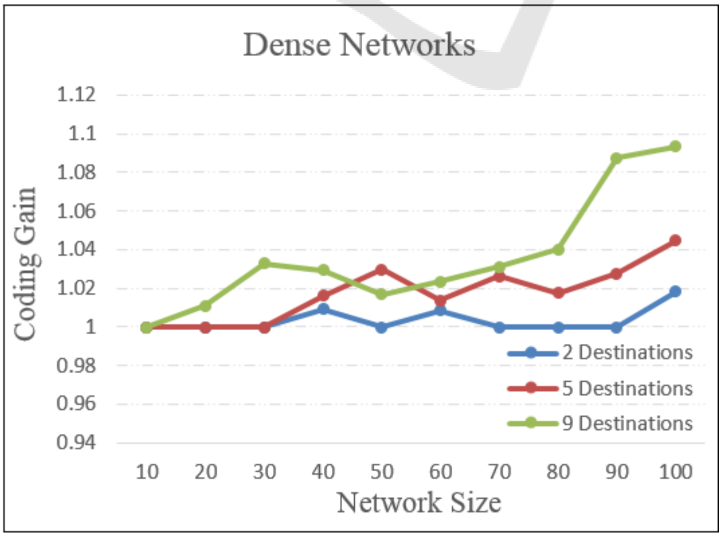

Figure 11: Coding Gain in Networks of High Density.

Similar to the PF results, NC results show that as the multicast group size increases, more packet transmissions are required to reach all group members. For a given network density, as the number of nodes increases, again more packet transmissions are required, as destinations are (potentially) further away from the multicast source. Finally, as network density increases, the network diameter shrinks, resulting in fewer packet transmissions to reach a given number of multicast receivers.

3.4 Comparing NC and PF Results

Based on the results obtained from PF and NC in the previous sections, the question that arises is whether NC has a clear advantage over PF. To answer this question, we calculated the coding gain and plotted it in Figures 7, 8, and 9 as a function of network size, network density, and multicast group size.

NC has an advantage over PF if it requires fewer packet transmissions, so we divide the number of packet transmissions under PF by the number of packet transmissions under NC. A value of 1 indicates that both approaches require the same number of packet transmissions to deliver a data packet to all multicast receivers. A value of 1.2, for example, would indicate that PF requires 20% more packet transmissions than NC under the same scenario. Consider for example that we want to calculate the coding gain in a sparse network of size 90 nodes and 9 destinations. The number of required packet transmissions in case of PF is 11.68 which can be obtained from Figure 1. The corresponding number of required packet transmissions in case of NC is 10.79 which is obtained from Figure 6. Dividing the number of required packet transmissions in case of PF by that of NC we get 1.08 which is the value plotted in Figure 9. This value indicates that PF requires transmitting 8% more packets than NC.

Figures 7, 8, and 9 illustrate that NC is never worse than PF, no matter the network density, number of nodes, or multicast group size. Using NC will often result in a coding gain, and the gain is more pronounced for larger networks, sparser networks, and larger multicast group sizes. For multicasting to 2 destinations, NC has at best a marginal improvement over PF (often less than 1%, with a maximum gain of 3%). For multicasting to 9 destinations, NC starts to show a non-trivial gain for networks as small as 30 nodes. However, given the width of the confidence intervals for the individual data points, we should not over-analyze these differences. It turns out that, for all network sizes, multicast group sizes, and network densities, the differences in the lower bounds are NOT statistically significant.

4 CONCLUSIONS

Based on our models and the results collected, it would seem that NC is potentially advantageous, unless we limit ourselves to small networks (30 nodes or less) and small multicast group sizes (5 or lower). However, any coding scheme also introduces overheads: packets have to be encoded at the source, decoded at the receiver, and potentially recoded at intermediate nodes. Depending on the coding scheme used, network coding may also increase end-to-end latency, as a number of coded packets may have to be received at a node before the original data packets can be reconstructed. Finally, in a network coding scheme, losing a single coded packet may result in a receiver being unable to recover a number of original data packets. In deciding whether to apply PF or NC, these factors also should be considered.

In the future work, we plan to build on these models to model/include the impact of lossy links.

REFERENCES

Ahlswede, R., Cai, N., Li, S.-Y. R., and Yeung, R. W. (2000). Network information flow. *IEEE Transactions on information theory*, 46(4):1204–1216.

Butenko, S., Cheng, X., Oliveira, C. A., and Pardalos, P. M. (2004). A new heuristic for the minimum connected dominating set problem on ad hoc wireless networks. In *Recent developments in cooperative control and optimization*, pages 61–73. Springer.

Čagalj, M., Hubaux, J.-P., and Enz, C. (2002). Minimum-energy broadcast in all-wireless networks: Np-completeness and distribution issues. In *Proceedings of the 8th annual international conference on Mobile computing and networking*, pages 172–182. ACM.

Egbogah, E. E., Fapojuwo, A. O., and Chan, N. (2008). Scalable team oriented reliable multicast routing protocol for tactical mobile ad hoc networks. In *IEEE, Military Communications Conference (MILCOM)*.

Fomin, F. V., Grandoni, F., and Kratsch, D. (2008). Solving connected dominating set faster than 2 n. *Algorithmica*, 52(2):153–166.

Fragouli, C., Widmer, J., and Boudec, J.-Y. L. (2008). Efficient broadcasting using network coding. *IEEE/ACM transactions on Networking*, 16(2):450–463.

Gopinath, S. and Nagarajan, N. (2015). Energy based reliable multicast routing protocol for packet forwarding in manet. *Journal of applied research and technology*, 13(3):374–381.

Kunz, T., Mahmood, K., and Li, L. (2012). Broadcasting in multihop wireless networks: The case for multi-source network coding. In *IEEE, International Communications Conference (ICC)*.

Kunz, T., Paul, S., and Li, L. (2010). Efficient broadcasting in tactical networks: Forwarding vs. network coding.

In *IEEE, Military Communications Conference (MILCOM)*.

Lee, S.-J., Su, W., and Gerla, M. (2002). On-demand multicast routing protocol in multihop wireless mobile networks. *Mobile networks and applications*, 7(6):441–453.

Lucile Canourgues, Jerome Lephay, L. S. and Beylot, A.-L. (2006). Stamp: Shared-tree adhoc multicast protocol. In *IEEE, Military Communications Conference (MILCOM)*.

Lun, D. S., Médard, M., Koetter, R., and Effros, M. (2008). On coding for reliable communication over packet networks. *Physical Communication*, 1(1):3–20.

Refaei, M. T. and Bush, J. (2014). Secure reliable group communication for tactical networks. In *IEEE, Military Communications Conference (MILCOM)*.

Royer, E. M. and Perkins, C. E. (1999). Multicast operation of the ad-hoc on-demand distance vector routing protocol. In *The 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking*.