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Effect of the Number of Clusters on the Performance of Cooperative Network Coding

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***Abstract*— Cooperative Network Coding synergistically integrates cluster-based Cooperative Communications and Network Coding to provide high performance by decreasing the outage probability and increasing the network reliability. In this paper, we investigate the effect of the number of hops on the performance of Cooperative Network Coding and analyze different scenarios. Cooperative Network Coding provides a constant throughput when the connectivity (cooperation among the nodes) *r* is at least 8, and is not sensitive to the probability of transmission loss of a link. When the connectivity *r* is 4, Cooperative Network Coding maintains the same constant property for the throughput for a number of node per cluster greater or equal than 12 and 14 when the probability of transmission loss of a link 0.1 and 0.25, respectively. Generally, in contrast to multihop *ad-hoc* networks, where the probability of successful reception exponentially decreases with the number of hops, we demonstrate that Cooperative Network Coding is relatively insensitive to throughput degradation due to the increasing of number of hops.**

Keywords- Cooperative Network Coding; Cooperative Networks; Network Coding; Connectivity; Multihop; Clustering.

I. INTRODUCTION

Cooperative Network Coding [1] is a novel technology that by combining *Cooperative Communications* and *Network Coding* improves the network performance by decreasing the outage probability and increasing the network reliability.

Network Coding [2] achieves capacity gain through coding of the received packets from multiple links/nodes, at intermediate nodes (network elements). By performing these coding operations, *Network Coding* increases network capacity and improves network reliability related to packet losses and link failures. This was first demonstrated by Ayanoglu, I, Gitlin and Mazo in [3].

Cooperative Communications allows multiple single-antenna nodes to share their antennas and generate a virtual multiple-antenna transmitter to achieve macro transmission diversity and enhance network performance by reducing the probability of packet loss.

In *ad-hoc* multihop networks, there is a path selection to transmit the packets from the source node to the destination node and if any packet is lost during transmission (does not reach the destination), that specific packet has to be retransmitted from the source. Fig. 1 shows the multihop network model for a 4-hop communication network, where each of the relays receives a packet from the previous node and forwards it to the next node towards the destination.

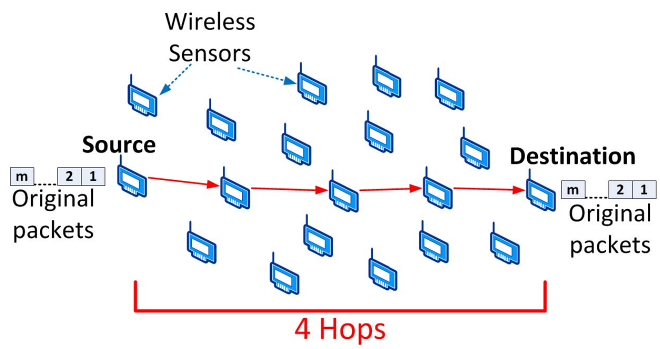


Figure 1. The Multihop Network model

Due to the lack of cooperation and/or path diversity, multihop networks are more susceptible to packet loss. That is, as the number of hops increases, the probability that a packet transmitted by the source is correctly received at the destination (Probability of Success) exponentially decreases and is given by the probability that a packet is correctly received at each hop $(1-p)$ to the number of hops h, where p is the probability of transmission loss of a link.

Thus, the probability of successfully receiving a packet in a multihop network is lower than the probability of successfully receiving a packet of a single hop network.

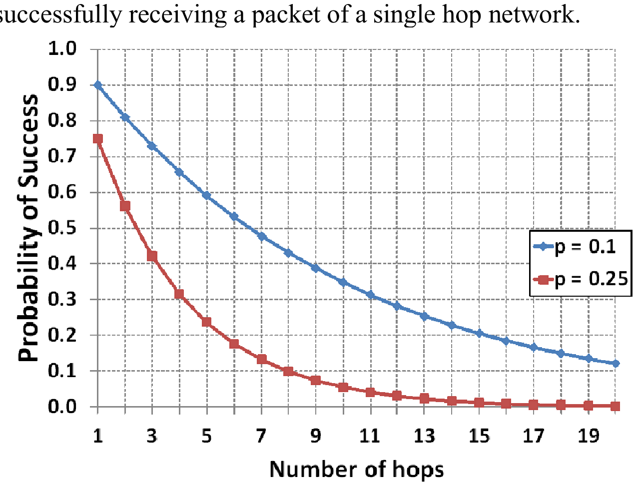


Figure 2. Probability of Successful reception of a packet vs. the number of hops

Figure 2 shows the probability of successful reception of a packet at the destination vs. the number of hops between the source and destination nodes for probabilities of transmission loss of a link of 0.1 and 0.25.

In [1] and [4], the authors demonstrated that Cooperative Network Coding outperforms multihop networks because of the combination of cooperation and network coding. In both [1] and [4], the metrics to evaluate the performance of Cooperative Network Coding are the probability of successful reception and the throughput. In this paper, we extend the work done in [1] and [4] by investigating the effect of the number of clusters / hops on the performance of Cooperative Network Coding and Cooperative Network Coding with link-level retransmissions.

The paper is organized as follows. In section II, we briefly summarize the work done in [1], [4] and [5]. Section III presents the effect of the number of hops on the performance of Cooperative Network Coding and the simulation results. Finally, Section IV concludes our work.

II. Related Work

Cooperative Network Coding was proposed by Haas and Chen in [1] where they investigated the performance of this technology compared to networks that implement only *Cooperative Communications* and networks that do not implement either *Network Coding* or *Cooperative Communications*.

In Cooperative Network Coding, nodes on a path (from a source to a destination) are replaced by clusters of nodes, which are in geographically close proximity to each other. When the source node has a block of information, i.e. m original packets, to transmit to the destination node, the source creates linear combination of the m original packets ("combination packets") and transmits those towards the nodes in the first cluster (Cluster 1). The number of combination packets received by each node in the first cluster depends on the connectivity r_s between the source and the nodes in the first cluster, which represents the amount of cooperation to transmit the block of information to the nodes in the first cluster. Then, nodes in a cluster create new combination packets, using random linear network coding, from the received combination packets and transmit those towards the next cluster. Each node in a cluster (2 through K) acts as MISO (Multiple Input, Single Output) by receiving multiple combination packets and transmitting one new combination packet. The number of received packets by each node in a cluster depends on the connectivity r_{ij} between nodes in cluster $i+1$ and the node (i,j). The number of clusters between the source and destination nodes is represented by K and is also related to the number of hops $K+1$ that the packets have to go through, from the source node, to reach the destination node. At the destination node, the received combination packets from cluster K are decoded and the original message is recovered. Therefore, the destination must receive at least m packets to recover the m original packets. Fig. 3 shows the Cooperative Network Coding model that was described above.

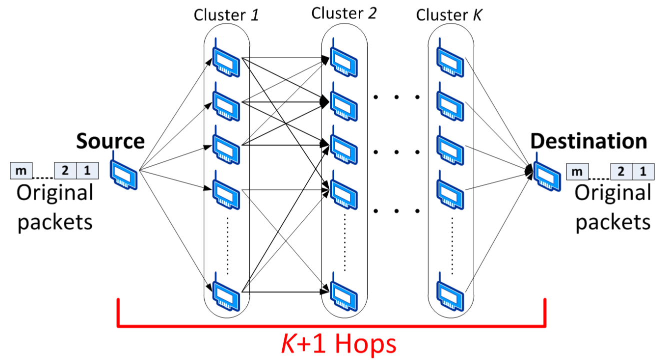


Figure 3. The Cooperative Network Coding model

The information redundancy in *Cooperative Network Coding* improves reliability, when some combination packets are in error, since it is very likely that other network paths have provided the sufficient number of combinations for the destination node to recover the original packets.

In [1], the authors analyzed the effect of number of clusters K when the number of nodes per cluster n is 13 for probabilities of transmission loss of a link of 0.05 and 0.1 and found that the performance of Cooperative Network Coding is essentially constant as a function of the number of clusters. Also, the authors conclude their paper by suggesting that to achieve an optimal performance of Cooperative Network Coding the connectivity r_s and r_{ij} should be set to 8, the number of nodes per cluster n should be at least 15 for probabilities of transmission loss of a link p less or equal to 0.1 and 3 clusters between the source and destination nodes.

Cooperative Network Coding with link-level retransmission was investigated by Arrobo, Gitlin and Haas in [4] and the authors found that when the number of clusters K is 3, cluster sizes are smaller and link-level retransmission is implemented only between the nodes in the last cluster and the destination node, Cooperative Network Coding with link-level retransmission achieves optimal performance and outperforms Cooperative Network Coding without link-level retransmission.

In [5], the authors analyzed the effect of connectivity on the performance of Cooperative Network Coding without link-level retransmission and concluded that with a connectivity value of 4, Cooperative Network Coding achieves optimal performance, and the increase of the connectivity only provides marginal gain compared to the number of network coding operations that each node has to perform.

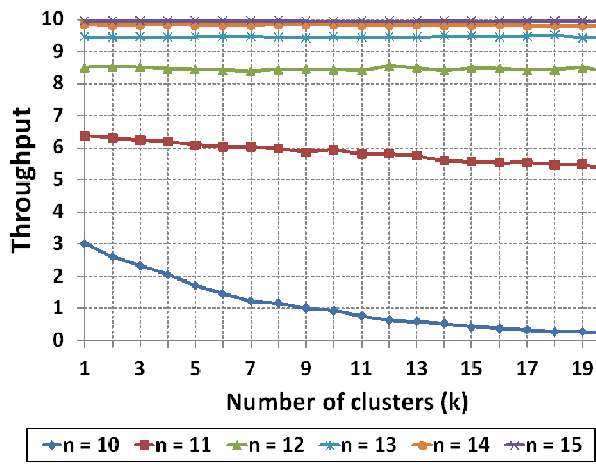
III. Effect of the Number of Clusters on The Performance of Cooperative Network Coding

In this section, we present a number of scenarios to analyze the effect of the number of clusters / hops K on the performance of Cooperative Network Coding. The different scenarios indicate whether the network's throughput is decreasing as the number of cluster increases or there is no throughput degradation at all.

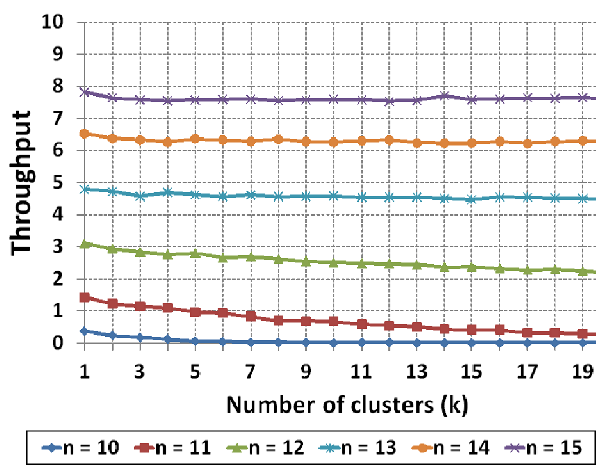
The results were obtained through simulations by running 10000 experiments and averaging the results. Additionally, similar to [1] and [4], we assumed that:

- 10 original packets are transmitted, $m = 10$;
- The number of nodes per cluster is the same for all the clusters, $n = n_i$;
- All the nodes, including the source node, have the same connectivity value, $r = r_s = r_{ij}$;
- All the links have the same probability of transmission loss, $p = p_{(i,j)(i+1,l)}$.

As it was recommended in [1] and [5], by setting the connectivity to 8 and 4, respectively, it is possible to achieve the highest performance of Cooperative Network Coding. Thus, we consider the level of cooperation (connectivity) to 4 and 8 to find out the effect of the number of clusters between the source and destination nodes.



(a)

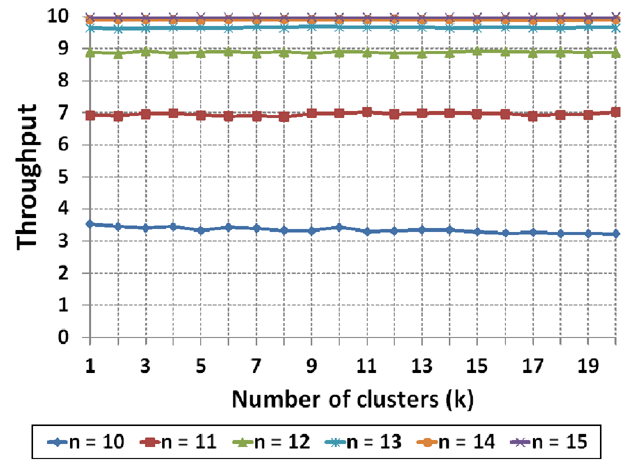


(b)

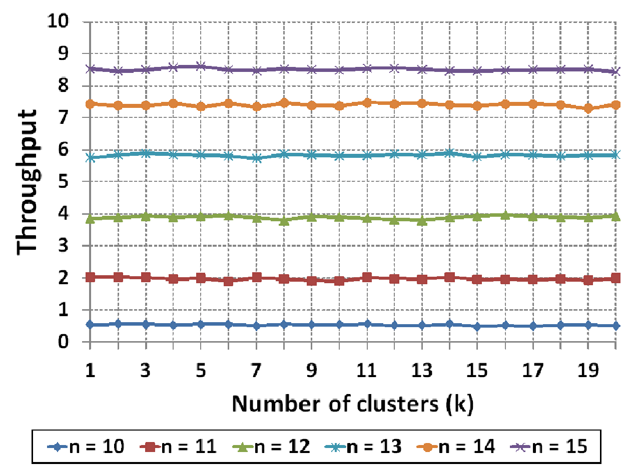
Figure 4. Throughput vs. number of clusters for connectivity r=4 and probability of transmission loss of a link of (a) p=0.1, (b) p=0.25

In Fig. 4, we can see that the throughput in Cooperative Network Coding does not vary significantly for cluster size, n, greater or equal than 13 nodes, regardless the probability of transmission loss of a link. For cluster size smaller than 13 nodes, we can see that the throughput decreases when the number of clusters increases. However, this decrease of the performance is not that significant as in a multihop network, which does not take advantage of cooperation among the nodes.

In Fig. 4 (a), we can see that to achieve the optimal throughput ($m = 10$), the cluster size should be at least 14 nodes per cluster when the probability of transmission loss of a link is 0.1. Also, from Fig. 4 (b), we can see that because the probability of transmission loss of a link is relatively high, the cluster size should be increased to values beyond 15 nodes per cluster to obtain a throughput equal to the number of original packets.



(a)



(b)

Figure 5. Throughput vs. number of clusters for connectivity r=8 and probability of transmission loss of a link of (a) p=0.1, (b) p=0.25

Figure 5 (a) and (b) show that because of the degree of cooperation among the nodes (connectivity r), the Cooperative Network Coding performance is not sensitive to the number of hops, regardless the probability of transmission loss of a link. Similarly, when the connectivity is 4, for small probabilities of transmission loss of a link, the appropriate cluster size is at least 14 nodes per cluster and for higher probabilities of transmission loss of a link, the cluster size be beyond 15 nodes per cluster.

As we can see in Fig. 4 (b) and Fig. 5 (b), the network's throughput does not significantly vary with the number clusters/hops. However, the network's throughput is not optimal since the source node is transmitting 10 original packets and, in average, less than 9 packets are being received (decoded) at the destination node. Thus, we should increase the number of nodes per cluster n to increase the throughput and combat the high probability of transmission loss $p = 0.25$.

Additionally, this characteristic of lack of sensitivity to the number of clusters K is seeing in Cooperative Communications with link-level retransmission, where the link-level retransmission is implemented between the nodes in the last cluster and the destination node.

IV. CONCLUSIONS

In this paper, our study concentrated on analyzing the effect of the number of clusters between the source and destination nodes on the performance of Cooperative Network Coding for a different range of parameters.

As opposed to multihop *ad-hoc* networks, where the outage probability exponentially increases with the number of hops, Cooperative Network Coding provides a very low outage probability that is not very sensitive to the number of hops when the system parameters are properly set. We can observe this characteristic of invariability in the throughput when the cluster size is at least 14 nodes per cluster for any number of hops K.

Generally, the throughput of Cooperative Network Coding is almost invariant to the number of hops between the source and the destination nodes independently of the probability of transmission loss for connectivity values greater or equal to 4.

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