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Improving Broadcast Efficiency in Ad Hoc Networks Using Network Coding

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Abstract

Network coding is a new research area with potential to reduce the network resource usage. With network coding, intermediate nodes forward linear combinations of previously received packets.

The type of networks we consider are vehicle-mounted mobile tactical radio networks. Tactical communication may be required in areas where pre-deployed base stations are unavailable. Mobile ad hoc networks satisfy this requirement.

Since network resources are scarce in mobile networks without base stations, it is important to find efficient network algorithms. The focus in this thesis is on broadcast traffic in tactical ad hoc networks. Broadcast traffic is generated by important tactical applications, like voice group calls and sitation awareness, which disseminates information network-wide.

Multipoint relay flooding is a well-known technique for efficient distribution of broadcast traffic. We show that it is possible to further reduce the number of broadcast transmissions for multipoint relay flooding by using network coding. We also analyse how the transmission reduction depends on the network topology.

This report is based on Wanning Zhu's master thesis, "Multipoint Relay Flooding – Network Coding Improvements", KTH 2009.

Keywords: Ad hoc networks, Network coding, OLSR, MPR, Multipoint relay flooding

Sammanfattning

Nätkoding är en relativt ny teknik med potential att minska behovet av nätverksresuser. Med nätkodning kan mellanliggande noder vidarebefordra linjärkombinationer av tidigare mottagna paket.

Vi behandlar i denna rapport broadcast-trafik i taktiska ad hoc-nät med fordonsburna radionoder. Taktisk kommunikation kan vara nödvändig i områden utan tillgång till fasta eller transportabla basstationer, vilket medför att mobila ad hoc-nät måste användas. Utan upphöjda noder i ad hoc-nätet blir datatakten på länkarna låg och nätverksresurserna måste uttnyttjas effektivt. Broadcast-trafik (en-till-alla) är en viktig trafiktyp för mobil taktisk kommunikation. Multipoint relay flooding är en känd teknik för effektiv hantering av sådan trafik. Därför är det intressant att utvärdera om nätkodning ytterligare kan minska antalet sändningar som behövs för att nå alla noder i nätet med multipoint relay flooding. I den här rapporten visar vi att detta är möjligt. Vi undersöker också hur nätkodningen beror av topologin i nätet.

Rapporten baseras på Wanning Zhus Examensarbete, “Multipoint Relay Flooding – Network Coding Improvements”, KTH 2009.

Nyckelord: ad hoc-nät, nätkodning, OLSR, MPR, Multipoint relay flooding

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Chapter 1

Introduction

1.1 Background

The type of networks we consider are vehicle mounted tactical radio networks. Tactical communication may be required in areas where pre-deployed base stations are unavailable. Mobile ad hoc networks (MANETs) satisfy this requirement. Ad hoc networking is an important technology for military communications. It enables a group of nodes to form a communation network without requiring infrastructure components, such as base stations and fixed power sources [1].

Broadcasting is a common operation in tactical MANETs. Applications that generate broadcast traffic are expected to be executed frequently, such as group voice calls, status information exchange and orders. Therefore, efficient support for broadcasting is critical for these networks. The use of multipoint relay (MPR) flooding significantly reduces the number of retransmissions of broadcast messages compared to flooding. This thesis examine if broadcasts can be further improved via network coding.

1.2 Problem Definition

Network coding is a new research area that may have interesting applications in tactical networks. Network coding is based upon intermediate nodes combining messages before forwarding. Network coding has potential to enable better resource utilization and can achieve a theoretical upper bound on network resource utilization [14]. In this project, we study if it is possible to improve MPR flooding by using network coding. Specifically we determine the resulting reduction in the number of transmissions in the network.

1.3 Outline

This thesis starts with an overview of MANET technology in Chapter 2, of broadcast traffic in Chapter 3, and of network coding in Chapter 4. Chapter 5 presents the main ideas and models that will be explored in the rest of the thesis. Chapter 6 describes the simulations and the assumptions that were made to implement network coding for MPR flooding. The simulation results and special cases are presented in Chapter 7. Finally, in Chapter 8, conclusions are drawn and possible future work is presented.

Chapter 2

Mobile Ad Hoc Networks

Most wireless infrastructure-based networks utilize a single-hop radio connection between a node and the wired network. In such networks, performance analysis can be done in terms of this single radio link. Since we evaluate broadcast traffic in multihop wireless networks, this chapter gives a short introduction to MANETs.

2.1 Introduction to MANETs

A MANET is a decentralized network that utilizes self organization of multihop communication between potentially moving nodes (which do not necessarily move in a coordinated fashion). Hence the set of nodes participating in such a network and the network's topology may change over the course of time and space.

A MANET is composed of a group of nodes. All of the nodes in the network can transmit and receive data as well as relay data. Thus all nodes are both hosts and routers. It is the later property which enables multihop communication in the MANET. In addition, one or more nodes need to be listening for communications while at least one node attempts to transmit. For the remainder of this report we will assume that all nodes have a single kind of radio and that all can communicate directly if and only if they are within communication range. We also assume that nodes that are not transmitting are listening [2].

Figure 2.1 shows a simple MANET of three nodes *A*, *B* and *C*, where the middle node *B* acts as a router allowing communication between nodes A and C. Node B not only has to forward traffic between A and C, but node B must also deal with the problems that occur because nodes A and C cannot hear each other.

2.2 Ad hoc routing protocols

The technique of finding, maintaining, and utilizing multihop paths is called routing. A MANET requires a routing protocol that can deal with the changes in topology

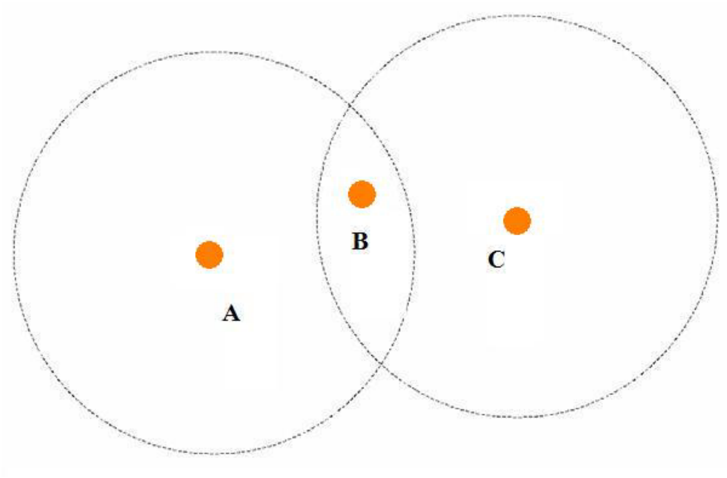


Figure 2.1: A simple MANET with 3 nodes, where the node B acts as a router

that node mobility may cause. The network should be self-organizing and the routing decisions should be made in a decentralized fashion. By adopting this self-organized and decentralized model, the network can adapt to both the arrival of new nodes and the departure (including departure due to failure) of nodes. To deal with the specific properties for MANET routing, a large number of routing protocols have been proposed. Protocols for ad hoc networks are often divided into the two groups reactive and pro-active.

A reactive routing protocol only updates a route when it is necessary. An example of a reactive routing protocol is dynamic source routing (DSR). When a packet needs to be forwarded and no route is available at the node, then a search-process is started to find a suitable path [11].

In contrast, a pro-active routing protocol continuously tries to update the routes in the network. An example of such a pro-active routing protocol is the optimized link state routing protocol (OLSR), described in Section 2.3. Because a pro-active routing protocol always maintains a full set of routes, when a packet needs to be sent the route is already known and can be used at once.

We assume that pro-active routing is better for the type of networks that we consider, since some of the services will require continuously updated routes to all nodes. Broadcasting of status information among the nodes is one such example.

2.3 The OLSR Protocol

OLSR [8] is a routing protocol that is optimized for MANETs, but can also be used in other wireless ad hoc networks. OLSR makes use of HELLO-messages that each node to transmit periodically to find its one-hop neighbors and two-hop neighbors. The nodes can then select its multipoint relays (MPR) based on this information. OLSR also broadcast topology control (TC) messages with help of the MPRs to disseminate toppology information throughout the network.

2.4 Different Types of Traffic

There are several different ways of addressing and transmitting a message over a network. One way in which messages differ is in how many receivers the message is addressed to. Which method is used depends on the application, and also on whether or not the sender knows specifically whom it is trying to contact, or only generally knows whom the message is intended for. Note that in this report, we only consider traffic inside the MANET.

- **Broadcast traffic** occurs when a single node transmit messages to all other nodes in the network. The goal is that when a node transmits a broadcast message, all other nodes in the MANET will receive that message.
- **Unicast traffic** is when messages are sent from one sender to one receiver.
- **Multicast traffic** occurs when messages are sent from one sender to a group of receivers.

2.5 Medium Access Control

Medium access control (MAC) is a sublayer of the data link layer specified in the seven-layer ISO model [9]. It provides addressing and channel access control mechanisms that make it possible for several interfaces to communicate within a multipoint network. When more than one radio must share the same channel, we need a MAC protocol to manage the transmissions in order to avoid collisions and to efficiently utilize the available bandwidth. In this thesis project, we assume that our systems use time division multiple access (TDMA) communication.

TDMA is a collision-free MAC protocol where the channel sharing is done in the time domain. This means that the time is divided into slots and that each node is assigned one or more time slots when it is allowed to use the channel [10].

Chapter 3

Broadcast traffic

Broadcast traffic disseminate information to all nodes in the MANET. A common use of broadcast is to find unicast routes in ad hoc networks. Since broadcasting can require many transmissions, it is important to implement an algorithm that reduce the number of transmissions as much as possible. In this regard, MPR flooding is much more efficient than trivial flooding, and because of this, MPR flooding is used in OLSR for broadcasting the TC-messages. In this chapter, we describe MPR selection and MPR flooding.

3.1 Multipoint Relays

In MANETs, messages can be forwarded on the same interface that it arrived on. Instead of trivial flooding, where all nodes retransmit all messages, with MPR flooding a node's messages are forwarded only by the node's MPRs, in order to reduce the number of transmissions that are needed to successfully deliver the messages [4]. An MPR set is a subset of a node's one-hop neighbors, such that together the nodes in this subset are able to reach all the two-hop neighbors [6]. We now describe an MPR selection algorithm, as suggested in [8]. In order to calculate the MPR set, the node must have link state information about all one-hop and two-hop neighbors.

Let $N_1(u)$ denote the set of one-hop neighbors of u, and $N_2(u)$ denote the set of two-hop neighbors of u.

1. Start with an empty MPR set $MPR(u)$.

2. Select those one-hop neighbor nodes in $N_1(u)$ as multipoint relays which are the only neighbor of some node in $N_2(u)$, then add these one-hop neighbor nodes to the multipoint relay set $MPR(u)$.

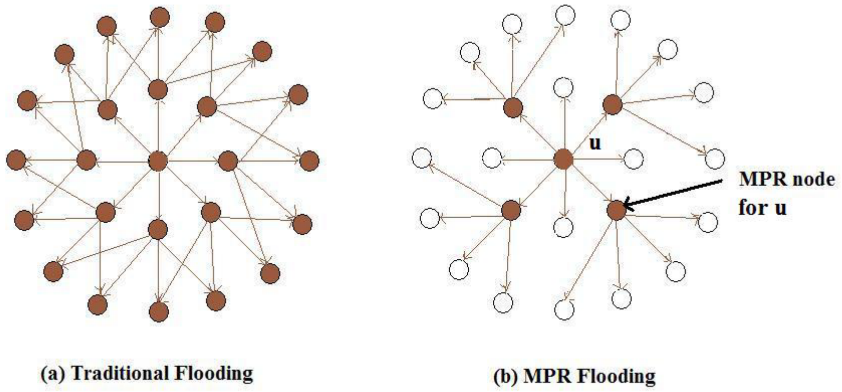
3. While there still exist some nodes in $N_2(u)$ which are not covered by the multipoint relay set $MPR(u)$:

- For each node in $N_1(u)$ not in $MPR(u)$, compute the number of nodes that it covers among the uncovered nodes in the set $N_2(u)$.
- Add the node to $MPR(u)$ for which this number is maximal.

In this work, we add the following modification to step 3: If there are more than one one-hop neighbor covering the same number of uncovered second neighbors, add the one with more neighbors (regardless of whether they are already covered or not). The reason for this modification is that this makes it more likely that several nodes choose the same node as MPR. This does not affect the performance of MPR flooding, but will improve the effect of network coding.

3.2 MPR Flooding

MPR flooding is a broadcast algorithm used in the ad hoc routing protocol OLSR. The principle is that each node has computed an MPR set, and only these neighbors will retransmit a message broadcasted by the node. Obviously, the smaller this set is, the more efficient the mechanism will be (i.e., the greater the optimization).



(a) Traditional Flooding

(b) MPR Flooding

Figure 3.1: Trivial flooding (a) and MPR flooding (b)

Figure 3.1 shows examples of both a trivial flooding algorithm and the MPR flooding algorithm. Here we see that there is a reduction in the number of transmissions by using MPR flooding.

1. Using trivial flooding:
    - A source node u broadcasts message M.

- Each node v that receives the message forwards M unless it has been previously forwarded.

2. Using MPRs for flooding leads to a more restricted flooding. In this case:

   - A source node u broadcasts its message M.
   - A node v that receives M from x forwards it only if:
     (a) v is a multipoint relay of x;
     (b) the message was not previously recieved by v.

Chapter 4

Network Coding

The main idea behind network coding is that instead of simply forwarding data messages, each intermediate node form a linear combination of previously received messages and forwards these linear combinations [3]. In this chapter, we will introduce what network coding does and how it operates, by studying an example in the following sections.

4.1 Linear Network Coding

In our example network, each node combines a number of incoming data messages into one or more outgoing packets.

This example (shown in Figure 4.1) gives a more formal introduction to linear network coding:

- $M_1, M_2, ..., M_i, ..., M_n$, are incoming decoded data messages that have arrived at node N.
- $g^j = g_1^j, g_2^j, ..., g_i^j, ...g_n^j$, are the corresponding local encoding coefficients used by node N.
- Y_j is a linear combination of the recieved data messages, which will be transmitted by node N [4]:

$$Y_j = \begin{pmatrix} g_1^j & g_2^j & \cdots & g_i^j & \cdots & g_n^j \end{pmatrix} \begin{pmatrix} M_1 \\ M_2 \\ \vdots \\ M_i \\ \vdots \\ M_n \end{pmatrix} = \sum_{i=1}^{n} g_i^j \cdot M_i \qquad (4.1)$$

This summation is performed using a unary xor.

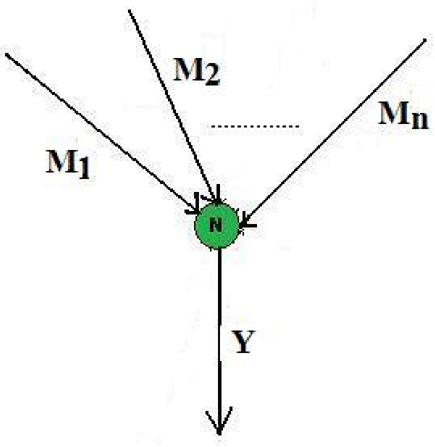


Figure 4.1: Linear network coding at a relay node

The example in Figure 4.2 show us the difference between the trivial method of just forwarding messages and network coding. Here, trivial flooding requires 6 transmissions while network coding requires 4 transmissions.

- Figure 4.2 (a): Assume that we wish to multicast two messages M_1 and M_2 to both node E and node F from the sources S_1 and S_2. As the figure shows, between node C and node D, either two channels or two transmissions are needed. Additionally, we are able to send M_1 from node A to node E and M_2 from node B to node F [5].

- Figure 4.2 (b): If we do the same transmission using network coding, node C receives and adds the two messages M_1 and M_2, then sends the result to node D. Node E receives the combined result from node D and the original M_1 from node A . Therefore it is able to decode the message M_2. Similarly node F receives the combined result from node D and the original M_2 from node B and can decode message M_1. Due to the synchronization of all the links each of the 7 channels sends only a single message during each time interval - in order to transmit the message once [5].

In this example, node C performs a linear encoding of the messages that it receives. Encoding can also be performed recursively on previously encoded packets [4], but we do not use this technique here. Instead each node always transmit linear combinations of messages that already has been decoded from received packets.

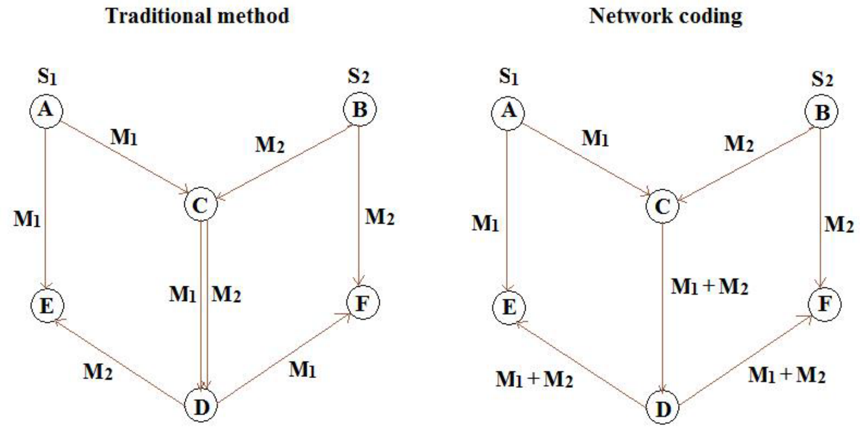


Figure 4.2: Trivial method (a) and network coding (b)

4.2 Decoding

Let $Y = (Y_1, Y_2, ..., Y_j, ..., Y_n)^T$ be a vector of received packets in a node. Let $G = (g^1, g^2, ..., g^n)$ be a matrix where row j is the coefficients g^j corresponding to the packet Y_j. If a node has received (G) and (Y), then the node needs to solve the equation system for each j: $Y_j = \sum_{i=1}^{n} g_i^j \cdot M_i$ in order to retrieve the original messages [4]. The decoding is performed by solving a set of linear equations. Since linear dependencies may occur, Gaussian elimination is used to remove these from the matrix to achieve full rank. The node recovers the source messages $M = (M_1, M_2, ..., M_n)$, by computing $M = G^{-1} \cdot Y$ [4].

Figure 4.3 shows an example of decoding. Node 1 receives data from its neighbors, node 2, 3, and 4 (these are messages M1, M2, and M3):

$$G \cdot M = Y \tag{4.2}$$

$$\begin{pmatrix} 1 & 0 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 0 \end{pmatrix} \begin{pmatrix} M_1 \\ M_2 \\ M_3 \end{pmatrix} = \begin{pmatrix} Y_1 \\ Y_2 \\ Y_3 \end{pmatrix} \tag{4.3}$$

In this example G is the matrix with ones and zeros, M is the set of source messages M_1, M_2, and M_3, and Y is the set of encoded packets Y_1, Y_2, and Y_3. If this system of equations is linearly independent (and hence the inverse of the matrix exists), and the number of unknown messages and the number of equations are equal, then the system of equations can be solved by $M = G^{-1} \cdot Y$

$$\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 0 \\ 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} Y_1 \\ Y_2 \\ Y_3 \end{pmatrix} = \begin{pmatrix} M_1 \\ M_2 \\ M_3 \end{pmatrix} . \tag{4.4}$$

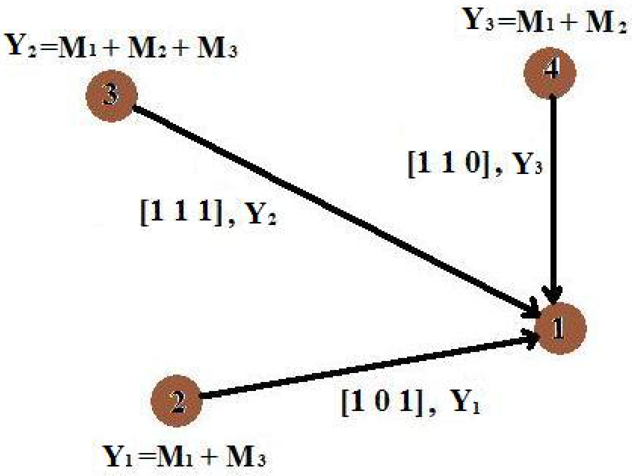


Figure 4.3: Example of decoding

4.3 Advantages and disadvantages

1. **Advantages**

   Network coding has potential to reduce the number of transmissions, because more than one message can be sent in one transmission [13].

2. **Disadvantages**

   - The loss of one packet can affect many messages.
   - The delay will be increased, as there is an increased need for buffering, and more computations are required compared to simple forwarding of messages.

Chapter 5

Local Network Coding Improvement for MPR Flooding

5.1 Main idea

This thesis project focus on determining if we can significantly reduce the number of transmissions required by MPR flooding, by allowing the MPR nodes to use network coding.

We take advantage of the fact that in MPR flooding each MPR node has information about the links between its neighbors, which means that an MPR node knows exactly which of its neighbors that recieve the same packets as it receives itself. By using this stored information, the node can use network coding to further reduce the number of transmissions needed to forward messages to its neighbors.

5.2 Transmission reduction

For MPR flooding without network coding, let Λ_i be the number of messages that node i transmits during a time interval Δ. Of these Λ_i messages, Γ_i messages originates from the node i itself, while the rest are retransmited. Let Λ_{li} be the number of known messages from node l that node i must retransmit to its neighbors.

$$\Lambda_i = \sum_{l, l \neq i} \Lambda_{li} + \Gamma_i \tag{5.1}$$

Note that if node i is not selected as an MPR node, then Λ_{li} is zero for all nodes l, which means that $\Lambda_i = \Gamma_i$. For simplicity, in the rest of the report we assume that all nodes transmit one message each as source nodes. This means that $\Gamma_i = 1$ for all nodes i.

Assume that MPR node *i* uses network coding to encode messages into a number of linear combinations of messages, such that all its neighbors can decode the received packets and find the messages. Of the Λ_i messages that are encoded, some are already known by the neighbors, and some messages are unknown. Let U_i be the maximum number of unknown messages (of those messages that node i must retransmit) at any of node i's neighbors. We assume that it is always possible to encode the Λ_i messages into U_i packets such that all neighbors can solve the corresponding equation system. With network coding, the number of transmissions from node i is now reduced from Λ_i to U_i. In order to calculate U_i we need to know the number of known messages at each neighbor.

Therefore, let $X_i(l)$ be the number of known messages (of those messages that node i must retransmit) at node i's neighbor l.

$$X_i(l) = \Lambda_{li} + \sum_{m \in N(i), m \neq l} \Lambda_{mi} \cdot A_{ml} \tag{5.2}$$

Note that X_i is zero if the node i is not an MPR node. In expression (5.2) we have that:

1. $N(i)$ is the set of neighbors of node i.
2. A is an adjacency matrix for the network. $A_{ml} = 1$ when there is a link between node m and l, which means that node l and node m are neighbors.
3. $\Lambda_{mi} \cdot A_{ml}$ is the number of messages which both node l and node i has received from node m, and that must be retransmitted by node i.
4. Summing over all neighbors of node i, expression $\sum_{m \in N(i), m \neq l} \Lambda_{mi} \cdot A_{ml}$ give the number of messages which both node l and node i receive from the neighbors of node l when they transmit their messages to node i.

Now we can express U_i as:

$$U_i = \Lambda_i - min_{l \in N(i)} X_i(l) \tag{5.3}$$

Let R be the relative traffic reduction with network coding for the network. Without network coding, MPR flooding generates $\sum_{i=1}^{n} \Lambda_i$ transmissions in the network. With network coding, each node i will save $\Lambda_i - U_i$ transmissions. Thus we can express R as:

$$R = \frac{\sum_{i=1}^{n} \Lambda_i - U_i}{\sum_{i=1}^{n} \Lambda_i} = \frac{\sum_{i=1}^{n} min_{l \in N(i)}(X_i(l))}{\sum_{i=1}^{n} \Lambda_i} \tag{5.4}$$

5.3 Example

Consider the number of transmissions in MPR flooding when the MPR nodes shown in Figure 5.1 use network coding.

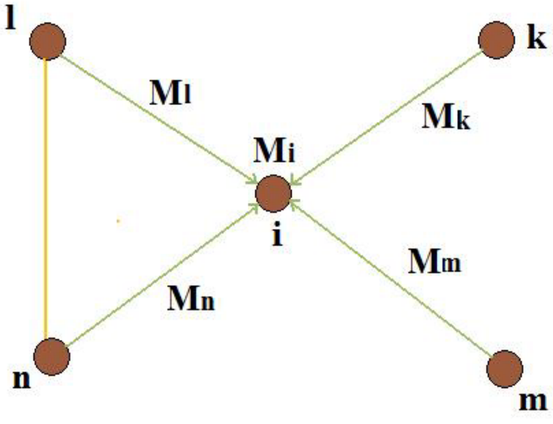


Figure 5.1: Transmissions in MPR flooding when the MPR nodes use network coding

- Nodes $l, m, n,$ and k have selected node i as their MPR node. Node i receives messages from all of these nodes and re-broadcast a coded packet to its neighbors if they have not received the corresponding messages from their own neighbors previously.
- the links with arrows, such as $k \rightarrow i$, means that node i is one of the MPR nodes of node k.
- the link without arrows, means that the two nodes are neighbors but not MPR nodes to each other.
- M_i, M_k, M_l, M_m, M_n are the messages from nodes i, k, l, m and n.

In this example, node l receives one message from node n, and it has one message from itself before it sends a packet to node i; node n receives one message from node l and one message from itself; node m and node k receives only their own. In order for all nodes to be able to decode all the packets they have received, when the node i receives all the packets from nodes k, l, m, n, it will re-combine and re-broadcast all messages (including the message from node i) to its neighbors.

By studying the example above, when network coding is used, it is enough for node i to transmit message sums $(M_i, M_m + M_n, M_k + M_n, M_l + M_k)$ so that the other nodes can regain all the messages ($U_i = 4$, see the calculations blow). We see that there are four transmissions at node i by using network coding. Without using network coding there would be one more transmission.

- $\Lambda_{li} = 1, \Lambda_{ni} = i, \Lambda_{ki} = 1, \Lambda_{mi} = 1$ We assume that i has one own message to transmitt: $\Gamma_i = 1$.

- $\Lambda_i = \sum_{l \in \mathbf{k},\mathbf{l},\mathbf{m},\mathbf{n}} \Lambda_{li} + \Gamma_i = 5$
- $X_i(l) = 2, X_i(n) = 2, X_i(k) = 1, X_i(m) = 1$
- $U_i = \Lambda_i - min_{l \in N(i)} X_i(l) = 5 - 1 = 4$
- $R = \frac{\Lambda_i - U_i}{\Lambda_i} = \frac{5-4}{5} = 20\%$

Chapter 6

Simulations

6.1 The Simulator

A Matlab based simulator is used to evaluate the reduction in messages for a number of different network topologies and with a number of different total numbers of nodes. The simulator is divided into functions . The functions for generating a network, were developed by Jacob Löfvenberg (senior scientist at FOI). The other functions have been developed as part of the thesis work. This includes: a function for selection of MPR nodes, a function for MPR flooding, and a function for decoding known packets.

6.2 Assumptions for the Simulations

Earlier we stated some of our assumptions. In order to simplify the simulation, network coding will be the single factor which we consider. Therefore we have made the following choices and assumptions for our simulations:

1. We create a random network with nodes distributed in two dimensions. We study the propagation of traffic streams through this network. Each node in the network broadcasts a message.

2. In order to simplify the simulation, we assume that all the nodes in the network are perfectly synchronized.

3. We assume that all nodes in the network can decode all the incoming packets from its neighbors' previous transmissions.

4. We assume that there are no bit errors over the link, hence there is no packet loss and no erroneous packets are transmited.

5. Finally, we assume that MPR nodes always have correct and current knowledge about their one-hop and two-hop neighbors.

6.3 Simulation Setup

1. We generated networks with random node positions on a flat surface. The networks had two forms: 5 networks within a rectangle of dimensions 10×1 unit lenghts, and 5 networks within a square of dimensions 10×10 unit lenghts. The size of the networks was 10, 20, 40 ,80 and 160 nodes. We simulated 5000 networks for each combination of size and form of network. For each combination, the transmission range varied from a high frequency of disconnected networks (no possible route between two nodes) to a high frequency of fully connected networks (all nodes are neighbors). Disconnected networks was discarded and not evaluated.
2. Then we used the MPR selection algorithm in Section 3.1 to compute the selected MPR nodes for each network.
3. Finally, we calculated the total number of transmissions for all MPR nodes by simulating the MPR flooding technique in Section 3.2. We then estimated the reduced traffic ratio using expression 5.4.

Chapter 7

Results

7.1 Graphical Results

In Figures 7.1 to 7.10, dark blue lines represent the average traffic reduction. Cyan stars represent the traffic reduction R for the networks where only one of the nodes in the network has been selected as MPR. Magenta squares represent the networks with two MPR nodes. Red crosses are for the networks with 3 MPR nodes. Black circles are for networks with four MPR nodes. Green dots represent networks with more than four MPR nodes. Black diamonds represent networks without MPR nodes.

7.2 Comparing the Simulation Results

Generally, the largest average traffic reduction R in these simulations, is between 25% and 30% and occurs when a network has only one MPR node, and the average number of neighbors is approximately 70% of the total number of nodes. The worst average traffic reduction is 0% when a network is fully connected.

In small networks with 10 nodes (shown in Figure 7.1 and Figure 7.2), we see that the average traffic reduction R is scattered, but we can see that the tendency is that the average value of R decreases from around 25% (for rectangle networks) and 20 % (for square networks) when the average number of neighbors increase. Especially, when the networks are fully connected the value of R is zero. In the next section we will discuss this behavior.

When we increase the number of nodes to 20 nodes (as shown in Figure 7.3 and Figure 7.4), R decreases to around 10% for rectangle networks and 12% for square networks until the average number of neighbors increases to around 12 nodes. After that, there is only one MPR node in each network, and the networks are almost fully connected, hence R increases and then decreases.

Figure 7.5 and Figure 7.6 show the results for networks with 40 nodes. It can be seen that the traffic reduction for the networks with only one MPR node has a different behavior as the number of neighbors increases, compared to the other

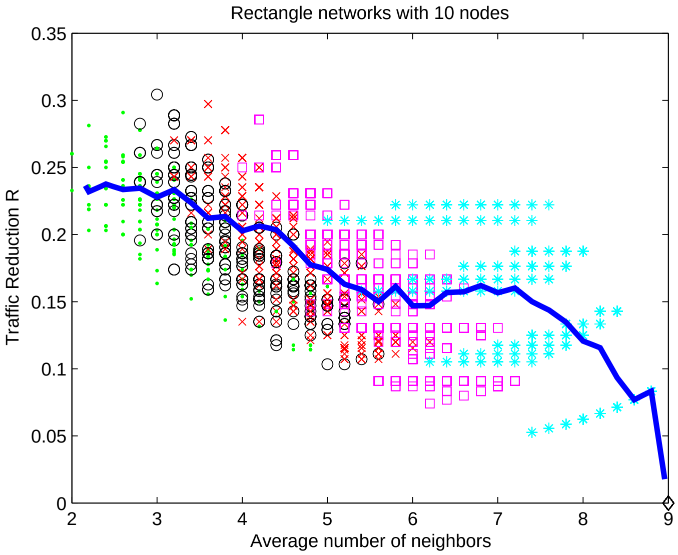


Figure 7.1: Traffic reduction, network coding used in a rectangle network with 10 nodes

networks. For these networks, the traffic reduction increases with a higher average number of neighbors, up to a maximum, and then decreases again down to zero. As the average number of neighbors decreases, the number of MPR nodes increases, and the estimated value of the average R where the value of average number of neighbors is between 30 and 35, is better than in most of our simulations. Note that in Figure 7.9, there is a bump when the average number of neighbors is between 20 and 80, see section 7.3 item 3. For the largest networks, see Figure 7.7, Figure 7.9, and Figure 7.10, we can clearly see a large increase in the traffic reduction as the networks goes from two MPRs to only one MPR in the network.

7.3 Discussion

1. For a fully connected network, no retransmissions are needed and no MPR nodes are selected. Since in this case, no nodes has information of its neighbors messages, network coding will not be used at all in the network. Therefore, the traffic reduction will be zero. This can be seen in the simulation results, see Figure 7.1 to Figure 7.2. With n nodes in a fully conncted network, the average number of neighbors is $n - 1$, and there is a black diamond (networks without MPRs) in all figures at the coordinates $(n - 1, 0)$.

2. For a network with only one MPR node, the nodes in this network are almost

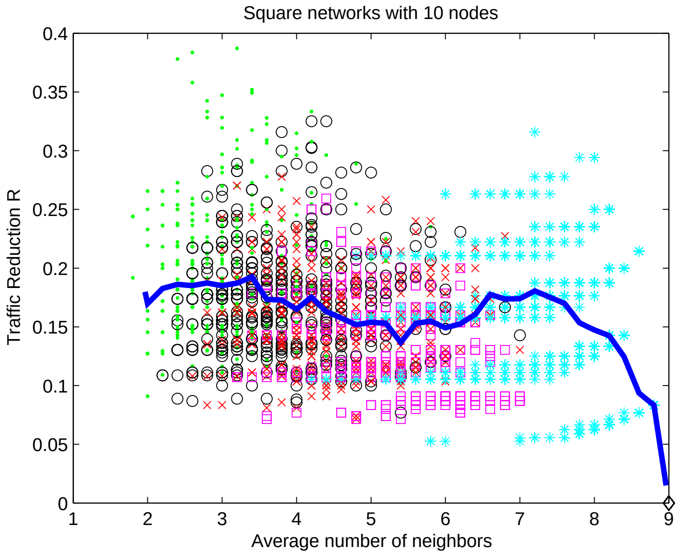


Figure 7.2: Traffic reduction, network coding used in a square network with 10 nodes

fully connected. In the figures, the networks with one MPR node (blue stars) the relative traffic reductions is quite large (near 30% for the larger networks), but goes to zero as the average number of neighbors increases. The reason is that the network becomes more like a fully connected network in this case.

- In Figure 7.11, there is an example network with only one MPR node which connects two fully connected subnets. If there are the same number of nodes in each subnet, this leads to the best transmission reduction for this type of network. In this case, the MPR flooding traffic through the MPR node *i* is symmetric, which is good for the transmission reduction in the network coding case. The network size is n. When each node in this network broadcast one message with MPR flooding, we get n source transmissions and then $n-1$ retransmissions in the MPR node i. This gives a total of $2n-1$ transmissions with ordinary MPR flooding. The two subnets in this example has size $(n-1)/2)$, and no of their nodes can hear a transmission from the other subnet. So U_i, the maximum number of unknown messages at the neighbors to i, is equal to $(n-1)/2$. This means that with network coding, the MPR node i only need to transmit $U_i = (n-1)/2$ packets. Without network coding, node i transmit $\Lambda_i = n$ times, so the traffic reduction in node i is $\Lambda_i - U_i = (n+1)/2)$. The traffic reduction in non-MPR nodes is zero. Thus from expression 5.4, we have that the relative traffic reduction is:

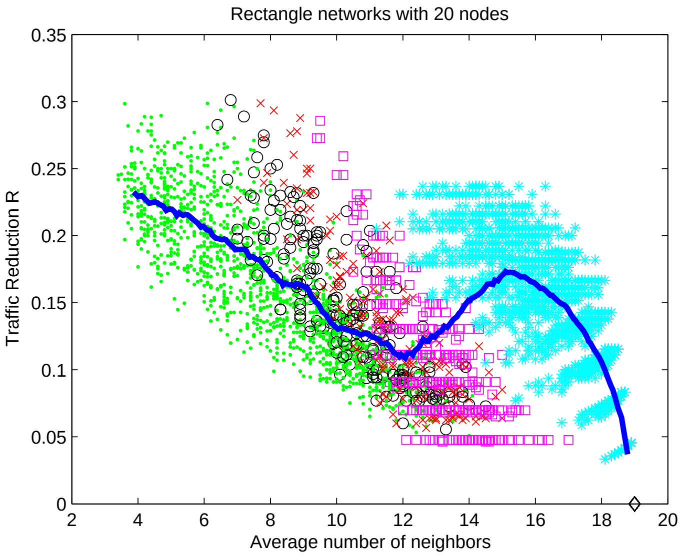


Figure 7.3: Traffic reduction, network coding used in a rectangle network with 20 nodes

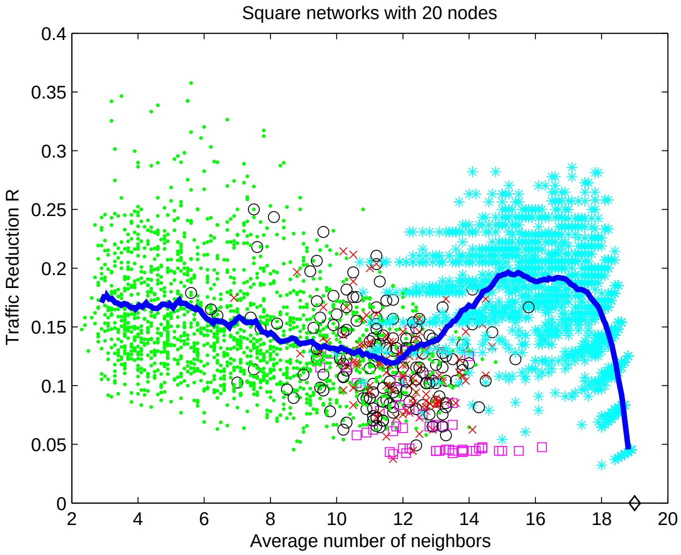


Figure 7.4: Traffic reduction, network coding used in a square network with 20 nodes

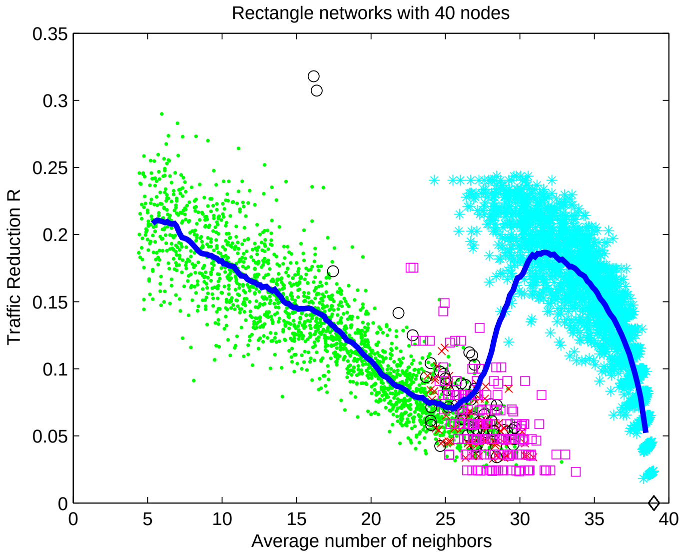


Figure 7.5: Traffic reduction, network coding used in a rectangle network with 40 nodes

$$R = \frac{\frac{n+1}{2}}{2n-1} \approx \frac{n}{4n} = 0.25 \text{ for large } n. \tag{7.1}$$

It is easy to see from variations of this example, that symmetric MPR-flooding traffic is good for traffic reduction with network coding, and assymmetric traffic is bad.

- Figure 7.12 shows an extreme example of another network of size n with only one MPR node in the network. There is exactly one unconnected node for each node except for the MPR node i. If each node broadcast one message with MPR flooding, the node i will transmit its own message and retransmit $n-1$ messages, a total of $\Lambda_i = n$ transmissions. The total number of transmissions in the network is $2n-1$. Now, with network coding, node i can save a lot of retransmissions. The number of known messages at any neighbour to node i is $n-2$, which should be the traffic reduction with network coding, according to Section 5.2. To see that this is correct, let all nodes transmit their source messages and then let node i transmit the sum of all received messages from its neighbors. Indeed, node i saves $n-2$ transmissions compared to ordinary MPR flooding. The total number of transmissions in the network without network coding is $2n-1$, so the relatice traffic reduction is

$$R = \frac{n-2}{2n-1} \approx 0.5 \text{ for large } n. \tag{7.2}$$

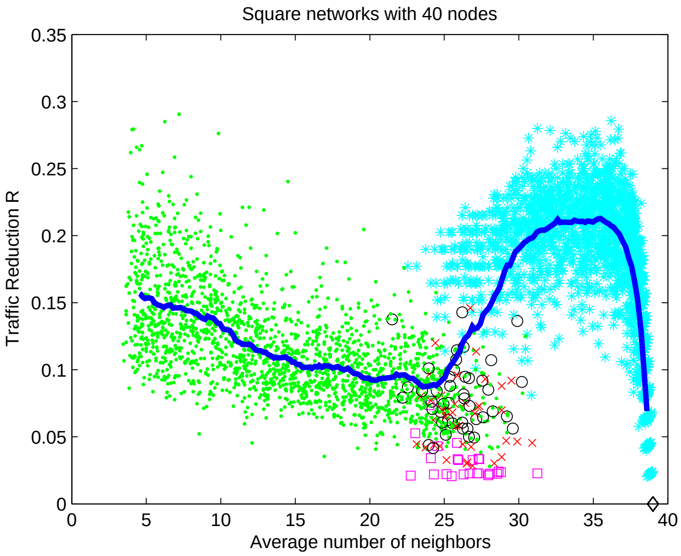


Figure 7.6: Traffic reduction, network coding used in a square network with 40 nodes

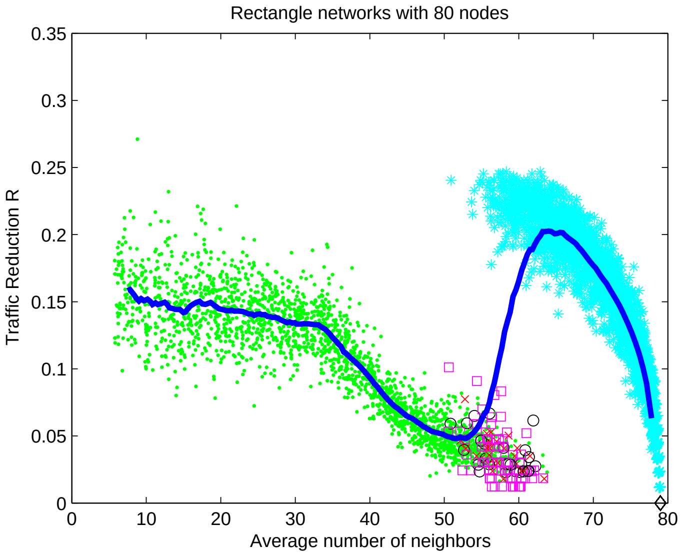


Figure 7.7: Traffic reduction, network coding used in a rectangle network with 80 nodes

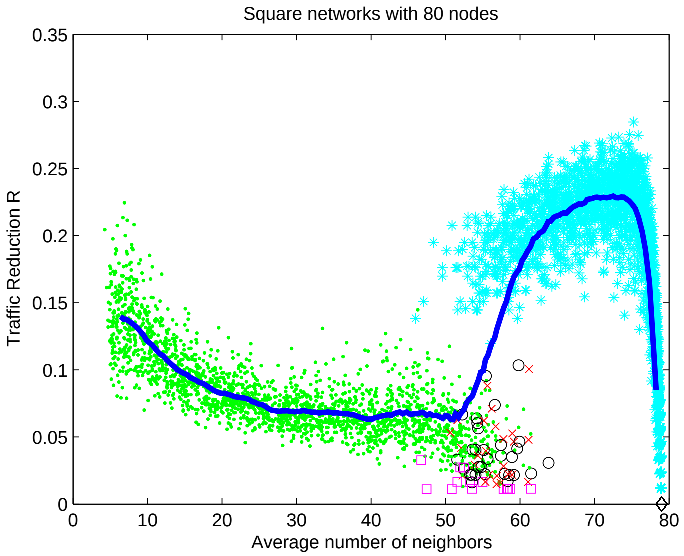


Figure 7.8: Traffic reduction, network coding used in a square network with 80 nodes

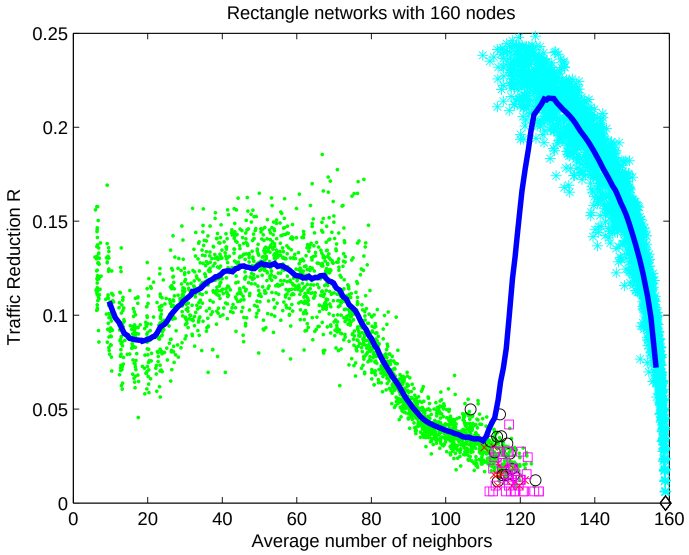


Figure 7.9: Traffic reduction, network coding used in a rectangle network with 160 nodes

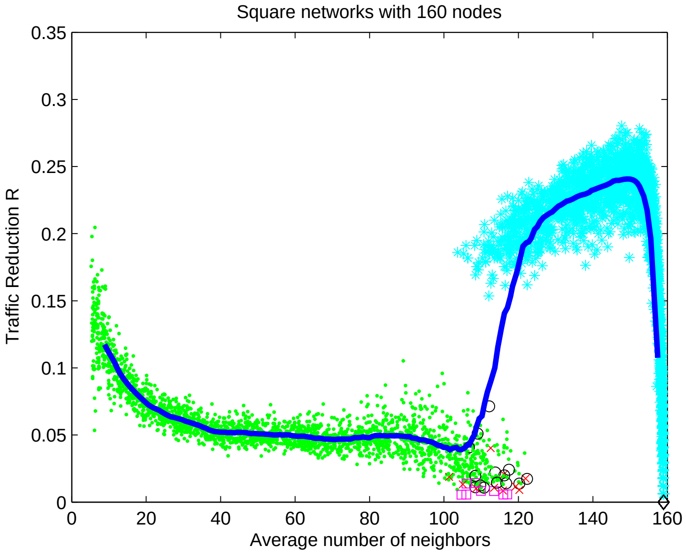


Figure 7.10: Traffic reduction, network coding used in a square network with 160 nodes

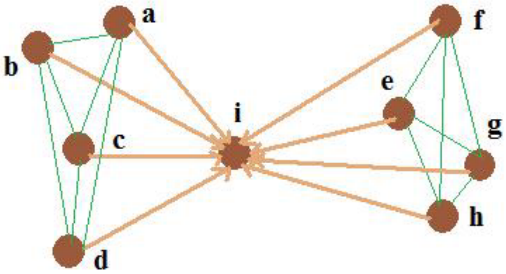


Figure 7.11: ’Bottleneck’ in a network with one MPR node

This kind of network will give the greatest reduction on R. However, the probability of having such a network randomly is very low.

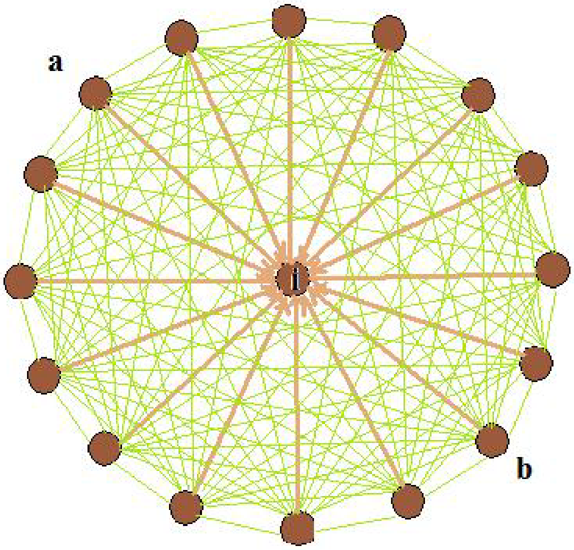


Figure 7.12: Example network which gives best result on 'G'

3. In our simulations, networks with only two MPR nodes, give a poor traffic reduction. The reason is that the MPR flooding traffic is very assymetric for these networks. Each of the two MPRs in the network relays messages mostly in one direction, and it is not possible to save many transmissions with network coding in this case.

   This effect can be seen clearly in Figure 7.7, Figure 7.8, Figure 7.9, and Figure 7.10. This type of network always happened when the average number of neighbors is between 60% and 70% of total number of nodes. For a small network, the total message sum is low, hence R is variable, but it could be higher.

   As the average number of neighbors decreases, the number of MPR nodes increases, and the traffic reduction R increases. However, in Figure 7.9, there is a bump when the average number of neighbors is between 20 and 80. This phenomenon may depend on how the MPR nodes are distributed in the networks.

4. Now consideer a network with all nodes lined up like a chain, see Figure 7.13. The total number of MPR nodes is $n - 2$. If all nodes broadcast one message, the total number of MPR-flooding transmissions is $n + (n - 1)(n - 2)$. The minimum number of known messages at a neighbor to a node i (of those that node i must retransmit) is equal to the minimum of the nodes to the right or to

the left of node i. Using equation (5.4), we get that the relative traffic reduction as follows.

For even n:

$$R = \frac{2(0+1+\cdots+(\frac{n}{2}-1))}{n+(n-1)(n-2)+1} \approx 0.25 \text{ for large } n \tag{7.3}$$

For odd n:

$$R = \frac{2(0+1+\cdots+(\frac{n-1}{2}-1))+\frac{n-1}{2}}{n+(n-1)(n-2)+1} \approx 0.25 \text{ for large } n \tag{7.4}$$

This means that for extremely sparse connected networks, the relative traffic reduction should be close to 0.25. This is also indicated by the simulation results.

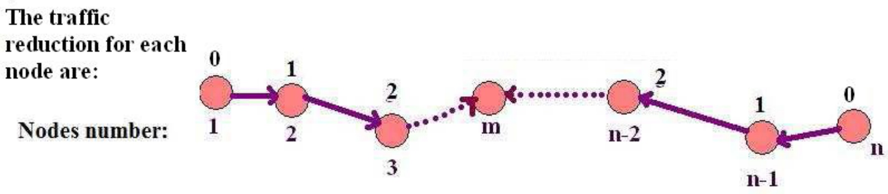


Figure 7.13: A chain network

Chapter 8

Conclusions and Future Work

8.1 Conclusions

We can first conclude that network coding always has a non-negative effect on the required number of transmissions for MPR flooding in a MANET. The results of our simulations are varying, with a traffic reduction up to 40%, although theoretically it could be up to 50% (see Section 7.3). The traffic reduction depends heavily on the network topology, how the MPR nodes are distributed, and how many MPR nodes there are in the network.

In a tactical MANET, the network topology will change over time. Using the MPR algorithm, the MPR nodes can use the updated information about one-hop and two-hop neighbors' connections, and it is possible to calculate the potential traffic reduction, thus allowing a decision to be made of whether it is advantageous to use network coding locally in each node.

In our simulations, the factors we considered were the number of nodes, form of networks, and connections between nodes which depends on the distance between nodes. However when network coding is used, factors such as delay, packet loss, coding overhead, and so on, must be considered in the network design.

8.2 Future Work

1. It would be intresting to further evaluate how different rectangle proportions affect the results.

2. How does the traffic reduction compare to the additional costs if we include the factors, such as delay, packet loss, channel errors and additional computation for mobile networks.

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