On Message Fragmentation, Coding and Social Networking in Intermittently Connected Networks

by

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BSc, King Saud University, 2006
MASc, University of Victoria, 2010

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ABSTRACT

An intermittently connected network (ICN) is defined as a mobile network that uses cooperation between nodes to facilitate communication. This cooperation consists of nodes carrying messages from other nodes to help deliver them to their destinations. An ICN does not require an infrastructure and routing information is not retained by the nodes. While this may be a useful environment for message dissemination, it creates routing challenges. In particular, providing satisfactory delivery performance while keeping the overhead low is difficult with no network infrastructure or routing information. This dissertation explores solutions that lead to a high delivery probability while maintaining a low overhead ratio. The efficiency of message fragmentation in ICNs is first examined. Next, the performance of the routing is investigated when erasure coding and network coding are employed in ICNs. Finally, the use of social networking in ICNs to achieve high routing performance is considered.

The aim of this work is to improve the better delivery probability while maintaining a low overhead ratio. Message fragmentation is shown to improve the CDF of the message delivery probability compared to existing methods. The use of erasure coding in an ICN further improve this CDF. Finally, the use of network coding was examined. The advantage of network coding over message replication is quantified in terms of the message delivery probability. Results are presented which show that network coding can improve the delivery probability compared to using just message replication.

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List of Abbreviations

CDF Cumulative Distribution Function

DTN Delay Tolerant Network

EC Erasure Coding

HCS Helsinki City Scenario

ICN Intermittently Connected Network

MSN Mobile Social Network

NCSF The Network Coding Success Factor

ODE Ordinary Differential Equations

ONE The Opportunistic Network Environment

PoI Points of Interest

RLNC Random Linear Network Coding

RWPM The Random Waypoint Model

SNW Spray and Wait

List of Symbols

a Time units needed for a node in the source community to meet a node in the intermediate community

A Node A

b Time units needed for a node in the intermediate community to meet a node in the destination community

B Node B

β_i Time units for a node to meet all other nodes in the same community i

βij The mean of exponential distribution between two communities i and j

C Node C

C_d The destination community

C_i Community i

C_o Other community excluding source and destination communities

C_s The source community

D The destination node

D_n The delivery probability with network coding

D_r The delivery probability with replication

F_d The desired value for Cumulative Distribution Function (CDF)

$F_e(T)$ The Cumulative Distribution Function (CDF) of the probability of message delivery at time T when erasure coding is employed

$F_f(T)$ The Cumulative Distribution Function (CDF) of the probability of message delivery at time T when fragmentation is employed

f_i The i^{th} encoded message using network coding

$F_i(T)$ The Cumulative Distribution Function (CDF) for the probability of delivering the i^{th} message fragment (block)

F_M A vector of M encoded messages using network coding

$F(T)$ The Cumulative Distribution Function (CDF) of the probability of message delivery at time T

$\mathbb{F}_z$ The large finite field for coefficient of encoding using random linear network coding

γ The average probability of meeting the destination node

$G(T)$ The cumulative distribution function of the message delivery probability as a function of N and T

K Number of a message pieces that is divided to before it is encoded

L A large set of a message pieces after it is encoded

l Number of encountered nodes that receive a copy of a message before it discarded

λ The number of time units that have elapsed since the last time the predictablility was updated for PRoPHET routing protocol

L_{in} The number of message copies that is distributed to the nodes in source community

L_{mid} The number of message copies that is distributed to the nodes in intermediate community

L_{out} The number of message copies that is distributed to the nodes in destination community

M Number of encoded messages using network coding

m Number of communities

n Number of fragments

N Number of mobile nodes

N_c The average number of mobile nodes in each community

n_i The number of fragments given to the i^{th} encountered node that is not carrying the message

p the probability of an encountered node which is not the destination accepting to carry a message

$P_{(A,B)}$ The probability of node A successfully delivering a message to Node B

P_d The desired probability of message delivery

$Pf_i(T)$ The probability that node i has not encountered the destination at time T

ϕ A matrix of coefficient randomly selected from a large finite field

$P(i,j)$ The probability of being in state i at time j

P_{init} An initialization constant between 0 and 1

q Time units needed for a node in the source community to meet a node in the destination community

r Time units needed for a node in the source community to meet a node in the destination community via intermediate community

R The replication factor for the erasure coding

ρ A scaling constant between 0 and 1 that determines the impact transitivity has on the delivery predictability for PRoPHET routing protocol

σ The aging constant in the range between 0 and 1 for PRoPHET routing protocol

t The required time steps for a message carrier node to meet non-message carrier node

T The required time steps to deliver a message

φ_i A coefficient randomly selected from a large finite field

x_i The original message of i node before encoding

X_M A vector of M original messages

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In the name of God, the Most Gracious, the Most Merciful

Unlimited acknowledgement goes to God the creator as he provides the ability to read, think and write.

I would like to thank Prof. T. Aaron Gulliver who has provided a great learning experience. It has been a great source of joy to work with him over the past few years. One never leaves his office without having learned a lot from the discussions and feedback, and also with a smile on ones face. He has the ability to discuss scientific matters in a friendly manner. I feel honoured to have worked with Prof. Gulliver, and it has been one of the best experiences in my life. He deserves a very big hug.

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Finally, the University of Hail (the institution that supported this work), deserves great thanks for the financial support during this program.

DEDICATION

To
Sarah and Bader (my wonderful parents),
Amal (my lovely wife),
and
Sarah (my sweet daughter).

Chapter 1

Introduction

1.1 Background

Wireless networks allow mobile users to communicate ubiquitously, and have become widespread in recent years. A wireless network can be organized in three ways. First, a fixed network infrastructure with access points can be employed. With this approach, mobile nodes communicate solely via these points. A drawback of this approach is that when a node moves from one access point to another, delay and packet loss may occur. Further, a node may move outside the range of the access points. The second approach is to form an ad hoc network to allow nodes to communicate. In an ad hoc network, each node has the ability to route a message to the destination without the existence of a fixed infrastructure. Nodes track each other by sending control messages when they move. This allows nodes to forward a message to its destination. However, maintaining node positions and routes can consume significant resources, particularly in dense environments. In addition, an ad hoc network is limited in size by the transmission ranges of the nodes. This size is typically much smaller than with a network based on access points. To overcome the limitation given above, an intermittently connected network (ICN) can be employed. In this case, nodes are able to route a message to the destination without keeping track of the movements of other nodes. Note that ICNs and Delay Tolerant Networks (DTN) are exchangeable terms in literature. Both assume a network that may incur delay can be large and unpredictable [1–9] due to the lack of the existence of a complete path between source and destination most of the time.

Intermittently connected networks (ICNs) have been the subject of much research activity because they allow node mobility without permanent connections between nodes. Although this offers great flexibility, it creates routing challenges. In fact, existing routing protocols for ad hoc networks are not applicable in this case because a route to other nodes may not exist. Thus, approaches to routing have been proposed for ICNs which assume that there is no path between a source and destination. These methods can be classified based on their choice of the next carrier of a message as opportunistic forwarding, prediction based, or social relationship based. With opportunistic forwarding, messages are forwarded to any encountered node. In predication based methods, an algorithm is used to predict which nodes have a higher probability of delivering a message to a destination. This is typically based on their contact history. Finally, social relationship based methods forward a message to encountered nodes that share a social relationship with the destination, for example, if both the destination and an encountered node attend the same school or college. The proposed ICN protocols include those in [1] and [2] for opportunistic forwarding, [3] for predication based forwarding, and [4–8] for social relationship based forwarding.

ICNs routing protocols aim to maximize the delivery probability, minimize the overhead ratio and computational complexity. The delivery probability (DP) is defined as the ratio of number of message received by destination nodes to the number of message sent by source nodes

$$\mathrm{DP} = \frac{\text{messages received}}{\text{messages sent}}. \tag{1.1}$$

The overhead ratio (OR) is defined as the ratio of messages relayed to messages delivered in the networks

$$\mathrm{OR} = \frac{\text{messages relayed}}{\text{messages received}}. \tag{1.2}$$

For example, in Figure 1.1, S wants to send a message to D. With a low OR protocol, only two copies of the message have been sent in the network, whereas, many more copies of the message are sent in the network with a protocol that has a high OR. Finally, the computational complexity (CC) of a protocol is estimated as the number of calculations that a node has to perform in order to select the next carrier for a message. For example, the CC for PRoPHET [3], which is described below, is the calculation of the probability of meeting a node again (1.3), the aging (1.4), and the transitive property (1.5). Note that these calculations may be done multiple times to

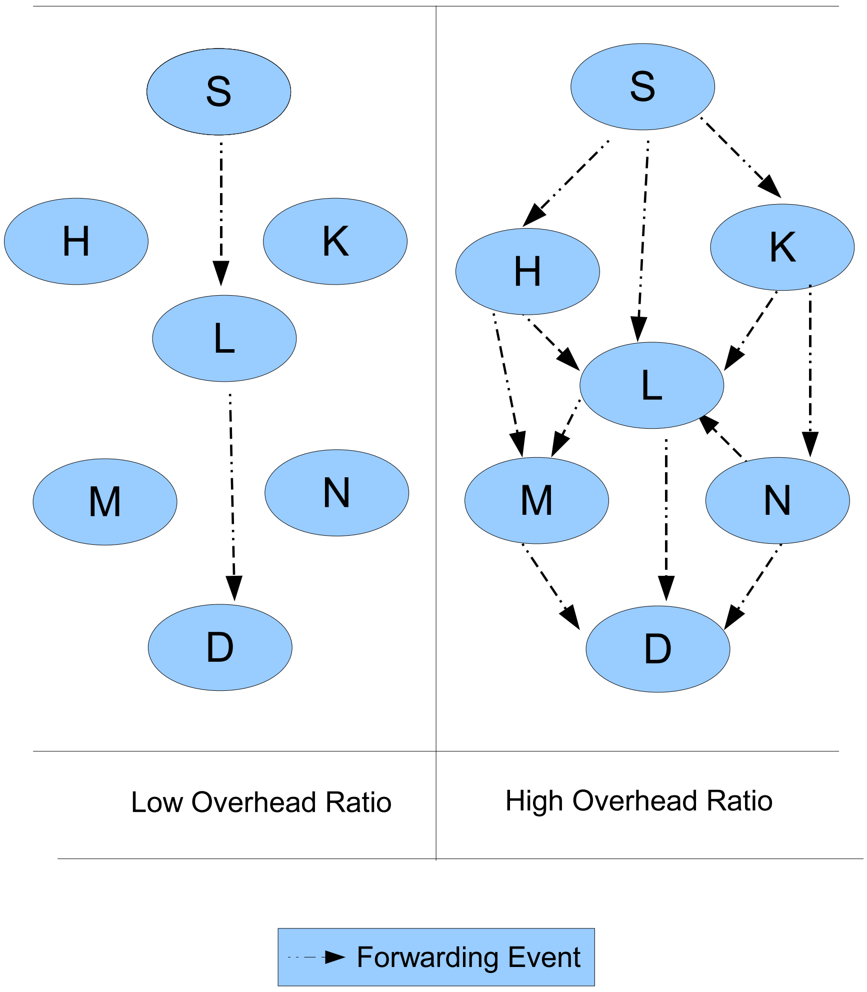


Figure 1.1: Comparison between high and low overhead ratios.

determine the next carrier for a message.

To examine the DP, OR and CC that occur in the opportunistically forwarding, prediction-based and social relationship-based methods, three ICN protocols are explored. These protocols are Epidemic [1], PRoPHET [3] and Status [4]. Epidemic is an opportunistically forwarding protocol, PRoPHET is a prediction-based protocol and Status is a social relationship based protocol.

Epidemic is a routing protocol that uses opportunistic forwarding to send messages. Epidemic is simple since the messages are flooded. Flooding is defined as forwarding messages to every encountered node that may deliver the messages to the destination. When node A comes into contact with node B, a session is initiated. This session consists of three steps as shown in Figure 1.2. First, A transits its summary vector (SV), which is indicates which messages are carried and initiated in this node, to B. Second, B transmits a vector requesting the messages that are in A but not in B from A. Finally, A sends the requested messages to B. The delivery probability with Epidemic is high [1]. However, significant resources including node memory and energy are consumed.

In order to solve the resource consumption problem with Epidemic, the probabilistic routing protocol (PRoPHET), a predication-based routing protocol, has been proposed [3]. As described in [3], the history of encountered nodes is buffered. To make a forwarding decision, the saved history is used to calculate the probability of meeting a node again. Nodes that are encountered frequently have a higher probability to meet again and older contacts are discarded over time. Messages are only forwarded when the delivery probability of an encountered node is higher than the current node which is the carrier of the message. The calculation of the probability of meeting a node has three parts: First, whenever a node is encountered, the probability of meeting it again is updated according to

$$P_{(A,B)} = P_{(A,B)old} + (1 - P_{(A,B)old}) \times P_{init} \tag{1.3}$$

where $P_{(A,B)}$ is the probability of node A successfully delivering a message to node B and P_{init} is an initialization constant between [0,1]. Equation 1.3 is based on the fact that nodes that often meet have a high delivery predictability. Second, if a pair of nodes do not encounter each other in a while, they are less likely to be good forwarders of messages to each other. Thus, the delivery predictability values should be reduced

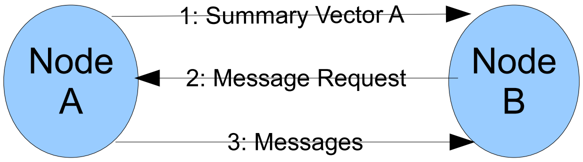


Figure 1.2: The forwarding process in Epidemic.

or aged. The aging equation is

$$P_{(A,B)} = P_{(A,B)old} \times \sigma^{\lambda} \tag{1.4}$$

where σ is the aging constant in the range [0,1), and λ is the number of time units (the time unit here can be defined based on the application and the expected delay of the network), that have elapsed since the last time the predictablility was updated. Finally, the transitive property in PRoPHET states that if node A frequently encounters node B, and node B frequently encounters node D, then node A probably is a good node to forward messages destined for node D. This is given by

$$P_{(A,D)} = P_{(A,D)old} + (1 - P_{(A,D)old}) \times P_{(A,B)} \times P_{(B,D)} \times \rho \tag{1.5}$$

where ρ is a scaling constant between [0,1] that determines the impact transitivity has on the delivery predictability. Node A uses $P_{(B,D)}$ and $P_{(A,B)}$ that received from encountered node B to update $P_{(A,D)}$ as in (1.3). The updated probability in (1.3) is used later to determine the suitability of node A in delivering a message to the destination node D.

Equations 1.3 and 1.4 are updated as follows. First, 1.3 is updated whenever A and B meet. Equation 1.4 is updated after every λ time units. Assuming A and B are the nodes that encounter each other, and D is the destination node, a message in A is forwarded to B if $P_{(B,D)} > P_{(A,D)}$.

According to [3], the consumption of network resources in PRoPHET is lower compared to Epidemic, but it still employs multi-copy flooding. Thus, resource consumption can be further reduced. In addition, PRoPHET suffers from computational complexity at the node level since each node has to compute the probability of an encountered node to deliver a message to a destination node.

Epidemic and PRoPHET show that opportunistic forwarding and prediction-based protocols suffer from high resource consumption and computational complexity, respectively. Thus, the use of social relationships in MSNs to solve these problems is proposed in [4]. Status [4] is a social relationship-based routing protocol. With this protocol, when a node is encountered a message is forwarded based on two factors. First, if the encountered node has a status, it may receive a copy of the message. Having a status means that the encountered node is going to a point of interest (PoI). A PoI is expected to have many nodes located there, such as a shopping mall or a park. Second, a message is forwarded to an encountered node if this node lives in the neighbourhood of the destination node. Status removes the computational complexity that exists in PRoPHET. It also reduce the resource consumption that occurs in Epidemic. However, with no limited resource, epidemic has a higher delivery probability.

The description of three protocols representing each method show that the protocols have a trade off between the DP, OR and CC. Many other protocols [1–9] have also proposed in literature to improve routing protocols in terms of DP, OR and CC.

The delivery probability can be improved by disseminating more message copies in the network [1]. However, nodes in an ICN are rarely connected, and typically only for short durations. Further, they have limited buffer space and battery life. Thus, transferring an entire message to an encountered node may not be possible, and many copies may later be discarded due to resource constraints. In such cases, a message fragment can be transferred. This allows for very short contact times, small buffer space availability, and low battery levels. In addition, the use of fragments can improve cooperation since an encountered node should be more willing to carry a portion of a message rather than the entire message. However, message fragmentation may reduce the delivery probability and increase delay. Thus, fragmentation in an ICN must be designed carefully to ensure that a message is properly divided to achieve good performance.

This dissertation first studies the effectiveness of dividing a message into two or more fragments. Next, the use of erasure coding and network coding in an ICN is examined. Finally, the impact of social network in ICNs is investigated. Thus the main focus of this work is on how to effectively disseminate a message. In particular, the efficiency of sending a complete message, breaking a message into pieces (fragmentation), or using redundancy (erasure coding or network coding), is examined.

1.2 Motivation

An intermittently connected network (ICN) is an attractive environment as it does not require an infrastructure and does not need to keep track of node routing information. However, this attractive environment is always challenging when it comes to how to route messages while maintaining a high delivery probability with a low overhead ratio. Thus, some approaches have been proposed in the literature for ICN routing [1–4]. The goal is to achieve a good message delivery probability. Many solutions focus on the routing itself, not on message dissemination strategies to improve the delivery probability. Message dissemination can be done using fragmentation and/or coding.

Thus, message delivery performance using fragmentation and coding is examined in this dissertation. Further, the social relationships between nodes are used to enhance message dissemination.

1.3 Problem Statement

Message dissemination that achieves a good delivery probability and maintains a fixed overhead ratio in ICNs is the main objective of this work. Many protocols proposed for ICNs only focus on how to route a complete message. However, sending a complete message in a network, such as an ICN may not achieve a good delivery probability because of the size of the message. This can be costly in terms of network resources including buffer size and battery life. It may also not achieve a satisfactory delivery probability because some messages may not be spread sufficiently in the network due to time or resource limitations. This problems is mitigated in this dissertation by using message fragmentation and coding.

1.4 Contributions of the Dissertation

Message dissemination in an ICN is the main focus of this work. Routing performance in an ICN is first examined when message fragmentation is employed. The performance with multiple fragments is examined, and both analytic and simulation results are presented. The contributions of this part are as follows:

- A Markov model is presented for an intermittently connected network (ICN).
- The cumulative distribution function (CDF) of the message delivery probability is derived.
- The message delivery probability with fragmentation is evaluated based on this CDF.
- A technique for message distribution to achieve a good delivery rate is proposed based on this CDF.
- The performance of routing protocols with message fragmentation in a realistic ICN environment is presented.

Another solution examined to achieve good message delivery performance is the use of coding. Erasure coding and network coding are both investigated to improve the delivery probability and maintain a low overhead ratio. This investigation also considers when it is the best to use coding in an ICN. The contributions of this part when erasure coding is considered are as follows:

- A Markov model is presented for message dissemination in an intermittently connected network (ICN).
- The cumulative distribution function (CDF) of the message delivery probability is derived.
- The performance with erasure coding is evaluated based on this CDF.
- A method is presented to choose the replication factor, $R = L/K$, based on minimizing the number time steps,T, needed to achieve a given value of the cumulative distribution function (CDF).
- The performance of routing protocols with erasure coding in a realistic ICN environment is presented.

The contributions of this part when network coding is considered are as follows:

- A model is presented for message dissemination in the intermittently connected network (ICN).
- The network coding success factor (NCSF) is derived. The NCSF provides a measure of the improvement in the delivery probability when network coding is employed versus using message replication.
- A mathematical proof is provided that the probability of message delivery when network coding is employed can be better that the probability when replication is employed. This is true when the number of encountered nodes (L) that receive a copy of a message before a message is discarded is greater than the number of combined messages (M).
- The performance of routing protocols with network coding in a realistic ICN environment is presented.

The final part of this work is the use of social networking to improve the performance of messages routing in an ICN. A study of the role of social networking in ICN routing is conducted. In particular, the impact of social networking on the message delivery probability is investigated. In addition, message dissemination is proposed based on node connectivity (social relationships). The contributions of this part are as follows:

- A model is developed for an MSN when all communities participate in message delivery. This improves on the model in [9] where only the source and destination communities participate in message delivery.
- The probability of delivering a message is derived for the case when all communities participate.
- The number of message copies disseminated to the source, destination, and other communities that maximizes the message delivery probability is determined. This is done by ensuring the delivery of the message copies to the destination community in the shortest time possible.
- Compared to the method in [9], with the spray and wait routing protocol the proposed method is shown to provide a higher delivery probability in a real world environment.

1.5 Organization of the Dissertation

This dissertation is divided into six chapters including this chapter which introduces intermittently connected networks (ICNs). The challenges of routing in an ICN is presented. Some of the techniques proposed in the literature are discussed. The motivation and contributions of the dissertation are also presented.

The second chapter presents the first proposed solution for message dissemination. In particular, fragmentation is introduced to improve the delivery probability. This chapter starts by introducing a model to describe message flow in ICNs. Based on the model, the performance of fragmentation is compared with that when complete messages are disseminated. The chapter finishes by presenting simulation results using a real environment to illustrate the efficiency of fragmentation in ICNs.

The third chapter discuses the use of erasure coding to improve the message delivery probability. The corresponding ICN model is presented and the delivery probability is derived when erasure coding is employed. A comparison of the delivery probability with and without erasure coding is then given. The results are compared to when only fragmentation is employed. This chapter examines the performance when complete, fragmented, or erasure coded messages are disseminated. Results using a real simulation environment confirms the analysis in this chapter.

The fourth chapter examines the use of social networking in ICNs. This chapter provide a model for ICNs based on social networking. Based on social networking, a node may be part of one of three communities: source, destination or other. Using this classification, the delivery probability is analyzed and a technique for message distribution proposed. These results are confirmed using a real simulation environment.

The fifth chapter propose network coding to improve the delivery probability in ICNs. This approach is shown to improve the delivery probability and reduce the overhead ratio. A quantitative analysis for the performance with network coding is presented. Simulation results are also given to illustrate the achievable performance improvements.

The final chapter concludes the dissertation. A summary of the contributions are given, followed by ideas for future work to extended the concepts presented.

Chapter 2

On Message Fragmentation in Intermittently Connected Networks

This chapter introduces fragmentation as a technique for message dissemination. This chapter is organized as follows. First section discusses the related work to the employed ICN Markov model and fragmentation in ICN. Next, the ICN Markov model is presented. Based on this model, the cumulative distribution function (CDF) of the message delivery probability is derived. The message delivery probability with fragmentation is evaluated in Section 2.3. In addition, a technique for message distribution to achieve a good delivery rate is proposed based on the analysis in Section 2.2. Finally, some conclusions are given in Section 2.4.

2.1 Related Work

In the mathematical epidemiology field, numerous models have been developed for the spread of infectious diseases [10]. These techniques have been applied to computer networking problems such as the the spread of worms and viruses [11]. Haas and Small [12] modelled sensor networks using a epidemiological model. They considered the probability of a node with a message encountering a node not carrying the message, and the probability of delivering a message in a given time was estimated. Epidemic [1] is a well-known ICN data dissemination technique which is similar in concept to the spread of infection diseases. Robin et al. [13] modelled epidemic routing in an ICN using a Markov model. Unlike the approach in [12], this model only considers the probability of meeting nodes, and ignores the time to encounter a node not carrying a message. The message delay was examined in [13] using a Laplace-Stieltjes transform. Zhang et al. [14] used ordinary differential equations (ODE) to model epidemic routing and estimate the message delivery time. However, an ODE solution only provide moments of the performance metrics of interests, while a solution using a Markov model can provide complete distributions. Therefore, a Markov model for message dissemination in an ICN is employed here.

Message fragmentation has been considered in [15] and [16]. However, in [15] only the relationship between fragment size and node contact duration was examined. Thus, the effectiveness of message fragmentation in an ICN environment remains unknown. Message fragmentation in an ICN was evaluated via simulation in [16], and the effectiveness of proactive and reactive fragmentation was illustrated. With proactive fragmentation, a message is divided into multiple fragments at the source node. Reactive fragmentation is only employed between nodes when their contact duration is insufficient to transfer an entire message. It was assumed that the probability of a node accepting a fragments is the same regardless of the fragment size, which is not realistic. The objective here is to analyze the effect of message fragmentation considering that the probability of accepting a fragment is a function of its size.

2.2 The Intermittently Connected Network Model

Consider a network with $N{+}1$ identical mobile nodes and a single message to be delivered by a source node to a destination node. Intermediate nodes can be used as relay nodes. The goal is to determine the time steps required and the number of copies that should be disseminated to obtain a given delivery probability.

Let t_i be the number of time steps for the ith message carrier to meet a non carrier. At this point in time, the number of message copies may increase from i to $i+1$. Let γ be the average probability of meeting the destination node. This can be determined based on the inter-meeting times t_{iD} between the message carriers and the destination node D. Finally, let p be the probability of an encountered node which is not the destination agreeing to carry a message. This probability is a function of the size of the message, where a larger size is assumed to have a lower probability of acceptance.

Figure 2.1 shows the ICN Markov model where state i, $i = 1, \ldots, N$, denotes the number of nodes that have copies of the message, i.e., $i = 1$ denotes that the source has all of the message copies, and state D denotes that the destination has been encountered. This model shows that there are three possibilities for a node with a message to deliver. First, the message is delivered to the destination with probability γ. Second, a copy of the message is given to an encountered node with probability $p(1/t_i)(1-\gamma)$. Finally, the message remains with the node with probability $1-p(1/t_i)(1-\gamma)-\gamma$. A similar model was introduced in [12], but without considering the probability of accepting a message. This probability is introduced here to evaluate the impact of message fragmentation in an ICN.

2.2.1 ICN Model Analysis

The model in Fig. 2.1 is used here to determine the number of time steps required for a message to be delivered to the destination with a given probability. Let the probability of being in state i at time 0 be $P(i, 0)$ so that

$$P(1,0) = 1, P(2,0) = P(3,0) = \cdots = P(N,0) = P(D,0) = 0.$$

Further, let the probability of being in state i at time step $j > 0$ be $P(i,j)$, which is given by [12]

$$\begin{aligned}
P(1,j) &= P(1,j-1)(1-d_1-\gamma)^j, && (2.1)\\
P(2,j) &= P(2,j-1)(1-d_2-2\gamma) + d_1P(1,j-1), && (2.2)\\
P(i,j) &= P(i,j-1)(1-d_i-i\gamma) + d_{i-1}P(i-1,j-1), && (2.3)\\
\vdots \quad & \quad \vdots && \\
P(N,j) &= P(N,j-1)(1-N\gamma) + d_{N-1}P(N-1,j-1), && (2.4)\\
& && (2.5)
\end{aligned}$$

where $d_i = \frac{p}{t_i}(1-i\gamma)$ and $\sum\limits_{k=1}^{N} a_k + a_D = 1$. This gives that

$$P(D,j) = P(D,j-1) + \sum_{i=1}^{N}(i\gamma)P(i,j-1). \tag{2.6}$$

The probability of message delivery depends on three factors: the probability of meeting the destination γ, the number of time steps between node encounters t_i, and

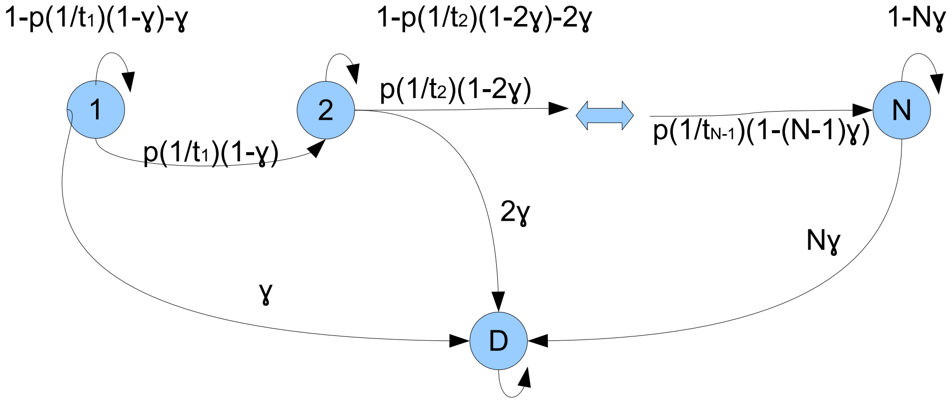


Figure 2.1: The intermittently connected network (ICN) Markov model.

the probability of an encountered node accepting a message p. The parameters γ and t_i are based on node movement, whereas p is determined by the encountered nodes. For example, nodes may accept messages over 5 MB in size with probability 0.5, and messages less than 5 MB with probability 1. Thus, p can have a significant effect on message dissemination.

The above probabilities can be simplified as

$$\begin{aligned}
P(2,2) &= d_1 \\
P(2,3) &= d_1(g_1 + g_2) \\
P(2,4) &= d_1(g_1^2 + g_1g_2 + g_2^2) \\
P(2,5) &= d_1(g_1^3 + g_1^2g_2 + g_1g_2^2 + g_2^3) \\
\vdots\quad &\quad \vdots \\
P(3,3) &= d_1d_2 \\
P(3,4) &= d_1d_2(g_1 + g_2 + g_3) \\
P(3,5) &= d_1d_2(g_1^2 + g_1g_2 + g_1g_3 + g_2^2 + g_2g_3 + g_3^2) \\
P(3,6) &= d_1d_2(g_1^3 + g_1^2g_2 + g_1^2g_3^2 + g_1g_2^2 + g_1g_2g_3 + g_1g_3^2 + g_2^3 + g_2^2g_3 + g_2g_3^2 + g_3^3) \\
\vdots\quad &\quad \vdots \\
P(4,4) &= d_1d_2d_3 \\
P(4,5) &= d_1d_2d_3(g_1 + g_2 + g_3 + g_4) \\
P(4,6) &= d_1d_2d_3(g_1^2 + g_1g_2 + g_1g_3 + g_1g_4 + g_2^2 + g_2g_3 + g_2g_4 + g_3^2 + g_3g_4 + g_4^2) \\
P(4,7) &= d_1d_2d_3(g_1^3 + g_1^2g_2 + g_1^2g_3 + g_1^2g_4 + g_1g_2^2 + g_1g_3^2 + g_1g_4^2 + g_1g_2g_3 + g_1g_2g_4 + g_1g_3g_4 \\
&\quad +g_2^3 + g_2^2g_3 + g_2^2g_4 + g_2g_3^2 + g_2g_4^2 + g_2g_3g_4 + g_3^3 + g_3^2g_4 + g_3g_4^2 + g_4^3) \\
\vdots\quad &\quad \vdots
\end{aligned} \tag{2.7}$$

which gives

$$P(i,j) = \left(\prod_{k=1}^{i-1} d_k\right)\left(\sum_{|\alpha|=j-i} g^{\alpha}\right), \tag{2.8}$$

where $d_k = (1/t_k)(1-k\gamma)$, $g_k = (1-d_k-k\gamma)$, $\alpha = \{\alpha_1, \alpha_2, \ldots, \alpha_i\}$, $g^{\alpha} = (g_1^{\alpha_1} g_2^{\alpha_2} \cdots g_i^{\alpha_i})$, i is the number of encountered nodes since the message was created, and N is the total number of encountered nodes. When $i = N$

$$\left(\prod_{k=1}^{N-1} d_k\right) = \frac{\left(1-\gamma\left(\frac{N-1}{2}\right)\right)^N}{t^N}, \tag{2.9}$$

and

$$\left(\sum_{|\alpha|=j-i} g^{\alpha}\right) = \left(\frac{2j}{N-1} - 1\right)^{N-1} \left(1-\gamma\left(\frac{N-1}{2}\right) - t^{-N}\left(1-\gamma\left(\frac{N-1}{2}\right)\right)^{N}\right), \tag{2.10}$$

where $t_k = t$ is assumed for simplicity, and t can be set to the average number of time steps to encounter a node not carrying the message.

The Cumulative Distribution Function (CDF) of the probability of message delivery after T time steps is given by [12]

$$F(T) = 1 - (Pf_1(T) \times Pf_2(T) \times \cdots \times Pf_N(T)) \tag{2.11}$$

where $Pf_i(T)$ is the probability that node i has not encountered the destination after T time steps. $Pf_i(T)$ is a function of the message dissemination process for the protocol employed. For example, with the epidemic routing protocol [1], the ith node will receive a copy of the message at time step $t\left(\left\lceil \sum_{k=1}^{i-1} \frac{N-1}{N-k} \right\rceil\right)$ so that

$$Pf_i(T) = 1 - P\left(D, \left[T - t\left(\left\lceil \sum_{k=1}^{i-1} \frac{N-1}{N-k} \right\rceil\right)\right]\right). \tag{2.12}$$

This is illustrated in Figure 2.2. With the binary spray and wait routing protocol [2], the ith node will receive a message at time step $t\left(\left\lceil \sum_{k=1}^{\log_2 i} \frac{N-1}{N-2^k-1} \right\rceil\right)$ so that

$$Pf_i(T) = 1 - P\left(D, \left[T - t\left(\left\lceil \sum_{k=1}^{\log_2 i} \frac{N-1}{N-2^k-1} \right\rceil\right)\right]\right). \tag{2.13}$$

This is illustrated in Figure 2.3. It was shown in [12] that the performance of these two protocols is similar.

The number of time steps required to achieve a desired probability of message delivery P_d is given by

$$T = \left\lceil F^{-1}(P_d) \right\rceil. \tag{2.14}$$

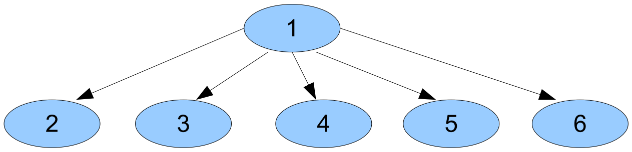


Figure 2.2: Message dissemination with the epidemic routing protocol.

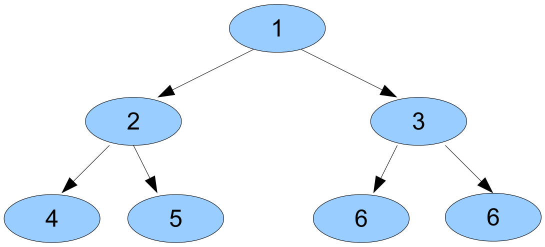


Figure 2.3: Message dissemination with the spray and wait routing protocol.

For example, if $P_d = 0.85$ and $\lceil F^{-1}(0.85) = 300 \rceil$, then a node will take 300 time steps to deliver a message with this probability. After this time, the message can be discarded by the nodes carrying it. The relationship between T and $F(T)$ is examined in Section 2.3.

2.2.2 The Effect of N and T on the Message Delivery Probability CDF

In this section, the CDF of the message delivery probability is derived as a function of N and T. This will be used later to determine a strategy for dissemination of message fragments. The probability of a node meeting the destination, γ, is a complex function which is typically not known a priori. It can vary significantly between nodes, therefore we consider a uniform distribution for γ. Using (2.6), we then obtain

$$\begin{aligned} G(T) &= \int_0^1 (P(D,j)\,\mathrm{d}\gamma = \int_0^1 \left(P(D,j-1) + \sum_{i=1}^{N} (i\gamma) P(i,j-1) \right) \mathrm{d}\gamma \\ &= \int_0^1 P(D,j-1)\,\mathrm{d}\gamma + \int_0^1 \sum_{i=1}^{N} (i\gamma) P(i,j-1)\,\mathrm{d}\gamma \\ &= \int_0^1 \left(\sum_{j=0}^{T-1} \sum_{i=1}^{N} (i\gamma) P(i,j) \right) \mathrm{d}\gamma \qquad (2.15) \end{aligned}$$

From (2.8), (2.9), (2.10) and (2.15), we have

$$G(T) = \frac{\left(-\frac{1}{2} + \frac{T}{N-1}\right)^N N\,(1+N)\,t^{-2N}\,(X - Y + Z)}{4\,(1+2T-N)\,(N-1)} \qquad (2.16)$$

where

$$X = \frac{2^{-N}\left(4^{1+N} - 3\,(3-N)^{2N} + 4\,(3-N)^{2N} N - 7\,(3-N)^{2N} N^2 + 2\,(3-N)^{2N} N^3\right)}{1 + 3N + 2N^2}, \qquad (2.17)$$

$$Y = \frac{2\left(2^{2+N} + (-1)^N\,(-3+N)^{1+N}\,(1+N^2)\right) t^N}{(1+N)\,(2+N)}, \qquad (2.18)$$

and

$$Z = \frac{\left(2^{4+N} + (-1)^{N} (-3+N)^{1+N} (6 - N + N^2 + N^3 + N^4)\right) t^N}{(1+N)(2+N)(3+N)}. \tag{2.19}$$

Equation (2.15) is a closed form expression for the CDF. It will be used later to determine the number of message fragments that should be given to an encountered node that is not carrying the message.

2.3 Messages Fragmentation in an ICN

Message fragmentation results in a message being divided into two or more blocks (fragments). The goal of fragmentation is to increase the message delivery probability. In this section, the effect of message fragmentation in an ICN is investigated. We first consider only two fragments and then generalize the results to an arbitrary number of fragments.

2.3.1 Two Message Fragments

Figure 2.4 shows the ICN model for two fragments. It is assumed that the fragments travel along independent paths so that the probabilities for the fragments are independent. The cumulative distribution function of a message is then given by

$$F_f(T) = F_1(T) \times F_2(T), \tag{2.20}$$

where $F_i(T)$ is the CDF for the probability of delivering the ith message fragment.

The probability of an encountered node accepting a fragment should be higher than the probability of accepting the entire message, thus improving node cooperation. Because the required contact time is reduced, less energy will be consumed per transfer, and the number of successful transfers should be increased [15].

As an example, consider $N = 5, 10$ and 20. To obtain values for t_i and γ, node mobility was simulated using the approach in [12]. For $N = 5$, $t_i = 40, 33, 30$ and 6, for $N = 10$, $t_i = 40, 33, 30, 6, 10, 20, 7, 5$ and 5, and for $N = 20$, $t_i = 40, 33, 30, 6, 10, 20, 7, 5, 5, 4, 4, 3, 6, 6, 31, 9, 6, 6$ and 4. Only values of t_i for $i = 1$ to $N - 1$ are given since after these time steps the Nth state has been reached. The approach employed in [13] was used to determine that $\gamma = .003, .007$ and $.013$ for

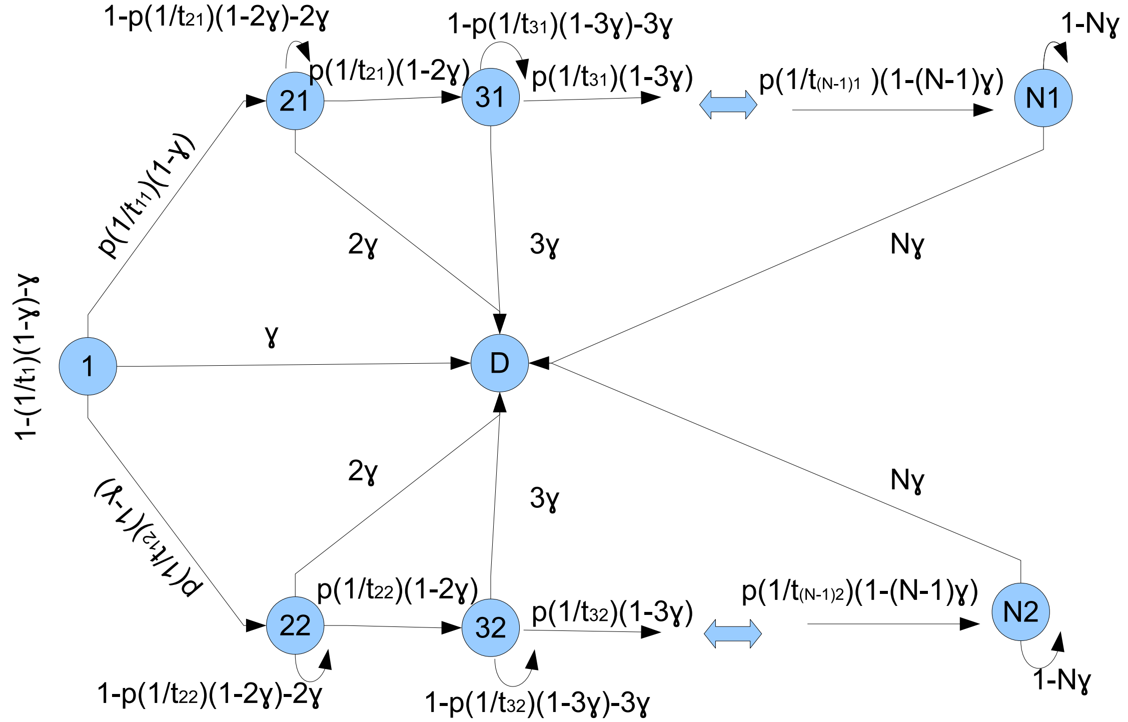


Figure 2.4: The ICN Markov model for two message fragments.

$N = 5, 10$ and 20, respectively. It is assumed that $p = 1/2$ if a message is sent without fragmentation, whereas $p = 1$ if a message is divided into two fragments. This is reasonable since a node may easily find a node to carry a 5 MB message whereas it will take longer to meet a node that agrees to carry a 10 MB message. Results for other values of p can easily be determined. The desired delivery probability is set to $p_d = 0.85$. We now determine the number of time steps T required to achieve this delivery probability with and without fragmentation.

Figure 2.5, 2.6 and 2.7 presents the CDF $F(T)$ without message fragmentation for $N = 5$ when $p = 1, .5, .25$, respectively. The figures shows that $130, 150$ and 180 time steps are required to achieve $P_d = .85$ when $p = 1, .5, .25$, respectively. Thus the time steps required to achieve the desired probability delivery increase as the probability of accepting a message decreases.

Figure 2.8 shows the CDF with $N = 5$ when the probability of accepting a message without fragmentation is only $p = 1/4$ and $p = 1/2$ compared to $p = 1$ when fragmentation is employed. In this case, message fragmentation provides better performance when $F(T) \geq 0.6$ and $F(T) \geq 0.9$ when $p = 1/4$ and $p = 1/2$, respectively. Thus the benefits of using messages fragmentation increase as the probability of accepting a message decreases compared to the corresponding probability for a message fragment.

Figure 2.9 presents the CDF $F(T)$ with and without message fragmentation for $N = 5, 10$ and 20. This shows that more encountered nodes (more distributed copies of a message), leads to a higher CDF for a given T, as expected, but the performance with message fragmentation improves as N is increased. For example, with $N = 5$ fragmentation is better for $F(T) \geq 0.9$. However, when $N = 20$ fragmentation is better when $F(T) \geq 0.7$. Note that the number of time steps needed to achieve $F(T) \geq 0.85$ with fragmentation is lower when $N = 10$ and 20. However, for a smaller value ($N = 5$), fragmentation needs more time steps to achieve this value.

2.3.2 Multiple Message Fragments

In this section, the use of n messages fragments in an ICN is considered. Figure 2.10 presents the ICN model for n message fragments. The CDF of a message is then given by

$$F_f(T) = F_1(T) \times F_2(T) \times \cdots \times F_n(T), \tag{2.21}$$

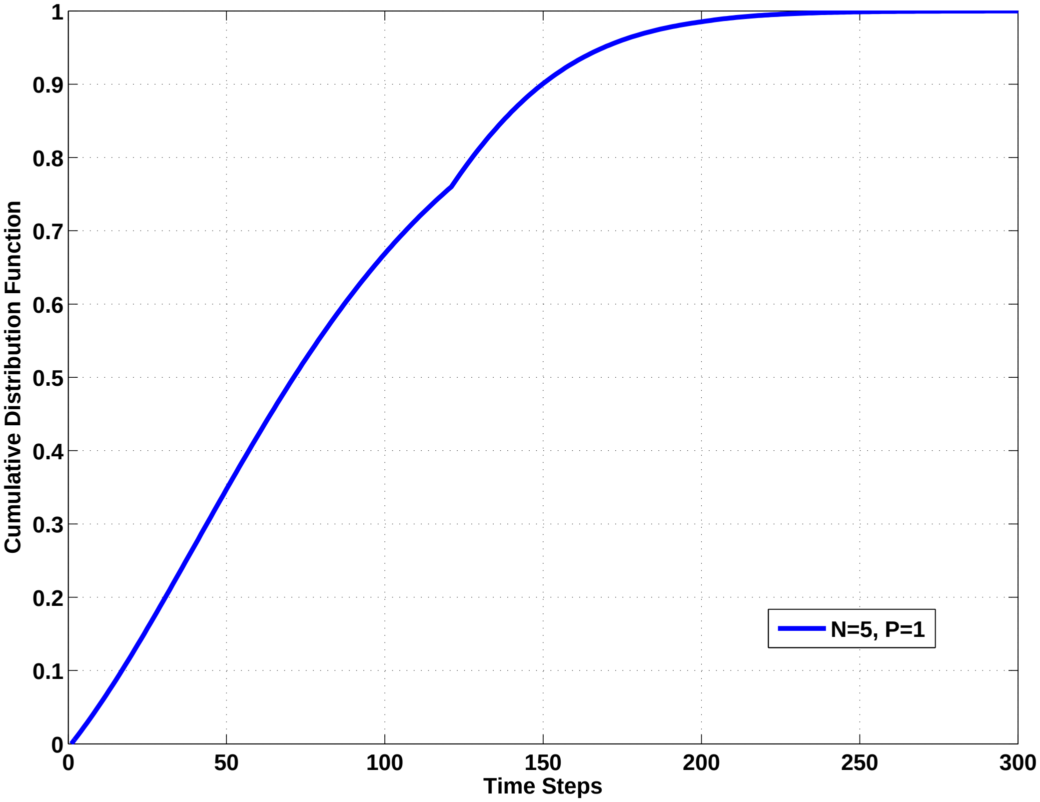


Figure 2.5: The CDF of the message delivery probability without fragmentation and with $p = 1$.

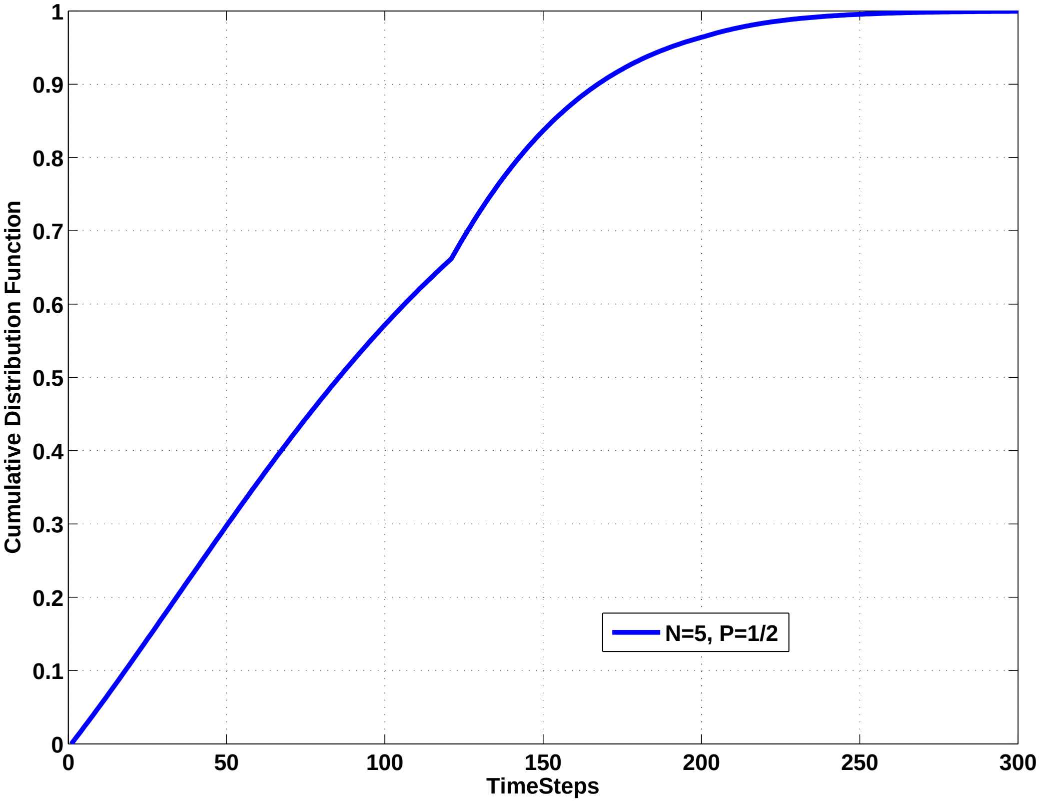


Figure 2.6: The CDF of the message delivery probability without fragmentation and with $p = .5$.

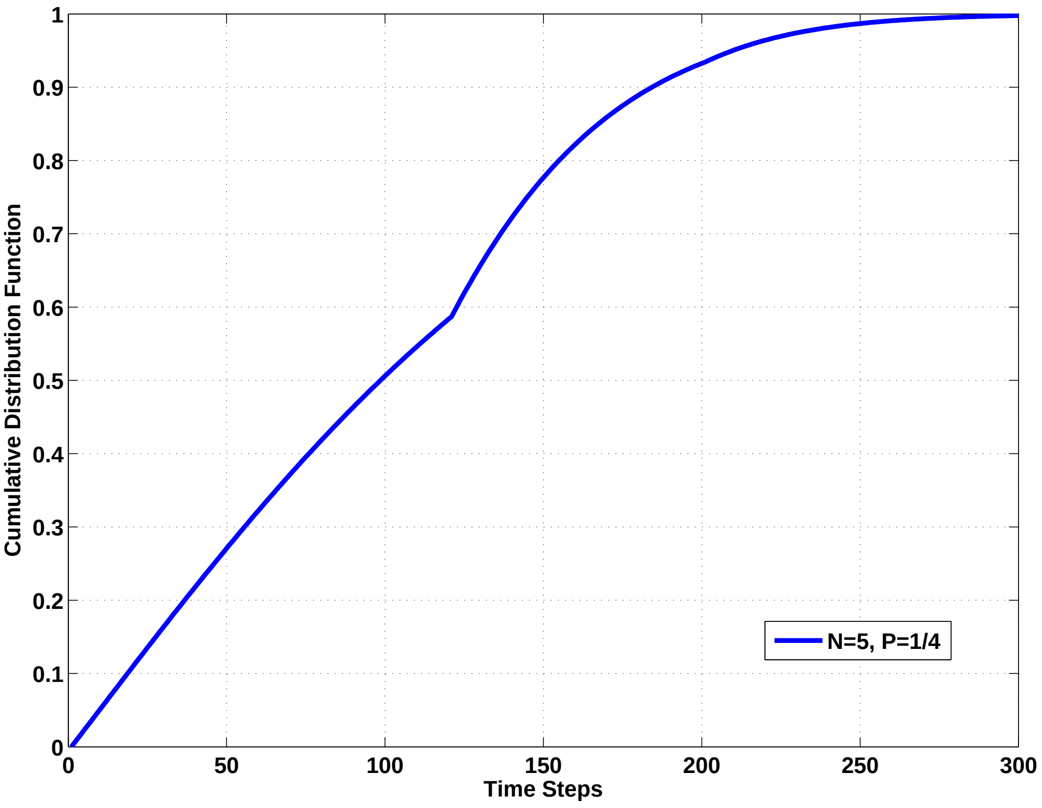


Figure 2.7: The CDF of the message delivery probability without fragmentation and with $p = .25$.

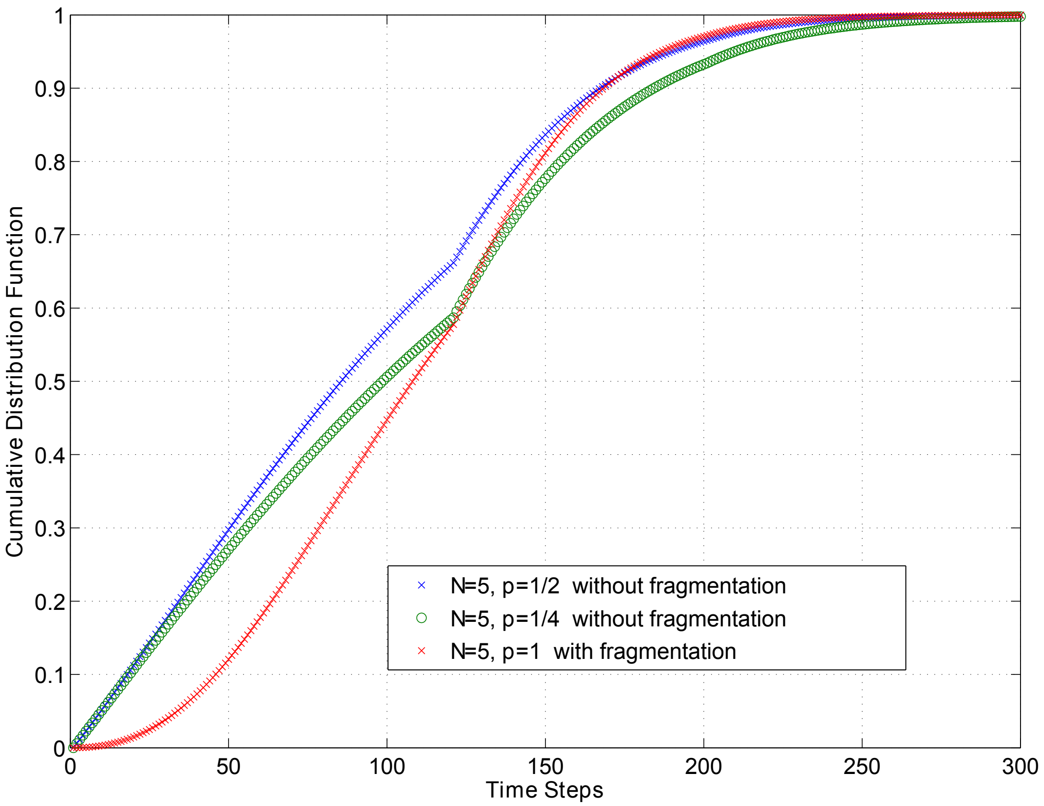


Figure 2.8: The CDF of the message delivery probability with $n = 2$ fragments and $p = 1$ versus no fragmentation and $p = 1/2$ and $1/4$.

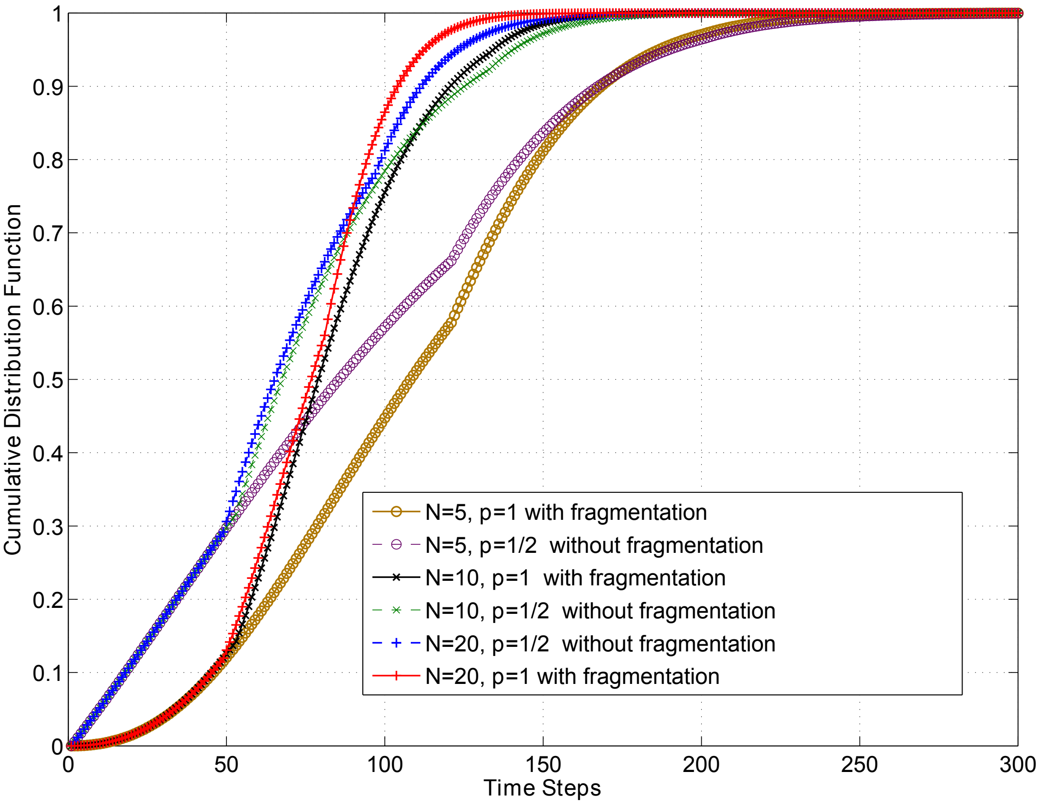


Figure 2.9: The CDF of the message delivery probability with $n = 2$ fragments and $p = 1$ versus no fragmentation and $p = 1/2$.

where $F_i(T)$ is the CDF for the probability of delivering the ith message fragment. For illustration purposes, it is assumed that when n fragments are used, $p = 1/n$ without fragmentation. The largest value of n is determined for which message fragmentation performs better when $F(T) > .85$.

The best number of fragments to use will vary depending on the number of encountered nodes. For example, with $N = 5$ nodes, there may be no advantage in breaking a message into a large number of fragments. However, with $N = 20$, a large value n may be beneficial. Figure 2.11 shows that using $n = 3$ fragments when $N = 5$ will not achieve $F(T) \geq 0.85$ faster than not using fragmentation (fragmentation is only better when $F(T) \leq 0.90$). However, Figure 2.12 shows that fragmentation with $n = 3$ can achieve $F(T) \geq 0.75$ faster when $N = 20$. In fact, $F(T) \geq 0.85$ is achieved faster for up to $n = 8$ fragments.

2.3.3 Improving Message Delivery via Variable Fragmentation

In this section, the improvement in ICN message delivery is examined in terms of the CDF $F(T)$. With fragmentation, each message is divided into n blocks (fragments). The problem is then how many fragments to give to an encountered node. Let n_i be the number of fragments given to the ith encountered node that is not carrying the message. Giving too few fragments to these encountered nodes may result in an insufficient number of message fragments in the network before the message expires. Thus, a complete message may not be delivered to its destination. Further, giving many fragments (e.g. $n_i \approx n$), to these encountered nodes when T is small may waste resources as better candidates for message delivery may be encountered later. The goal is to spread the fragments such that the CDF $F(T)$ is large while conserving resources.

Epidemic is the most widely employed technique for routing messages [1], and thus it is used here for comparison purposes. In this case, entire messages are given to all encountered nodes so that

$$n_i = n. \tag{2.22}$$

With the spray and wait routing protocol, message fragments are spread to the first

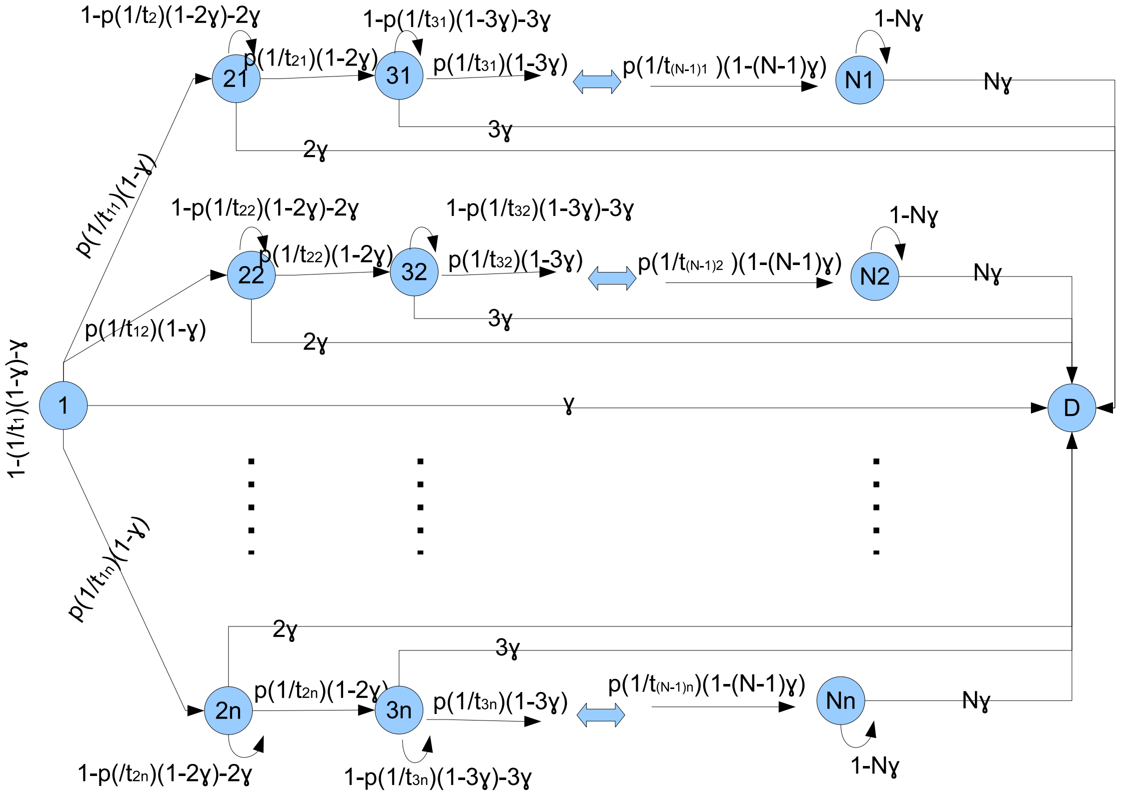


Figure 2.10: The ICN Markov model for n message fragments.

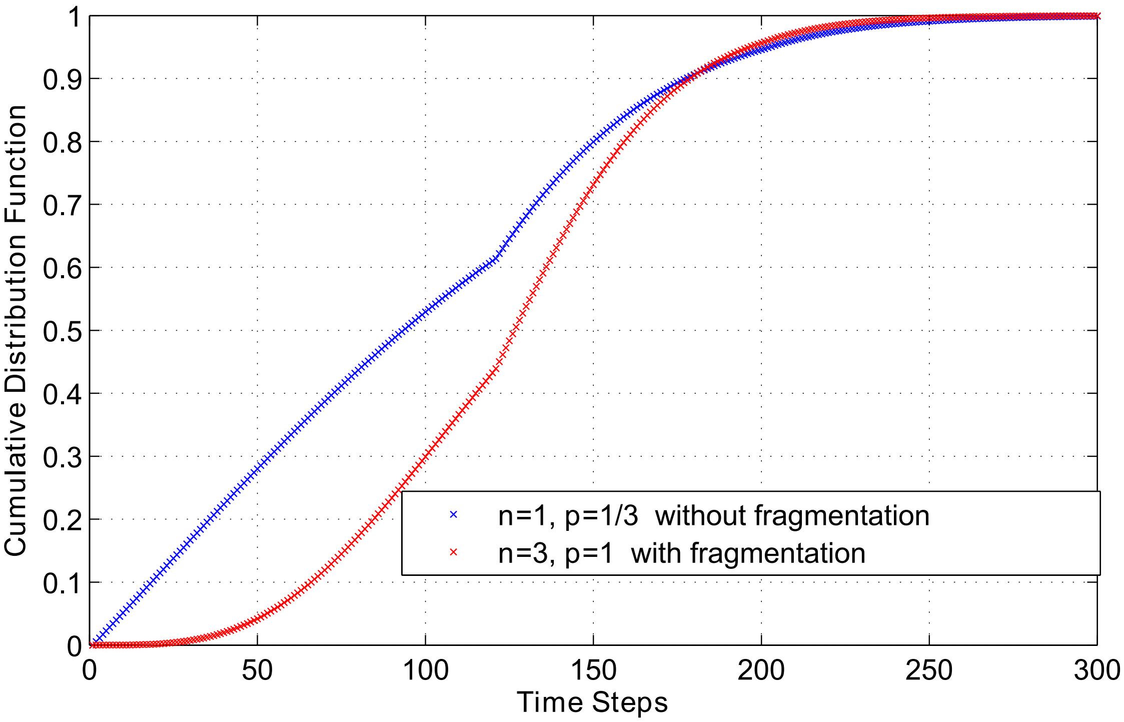


Figure 2.11: The CDF of the message delivery probability with and without fragmentation when $N = 5$.

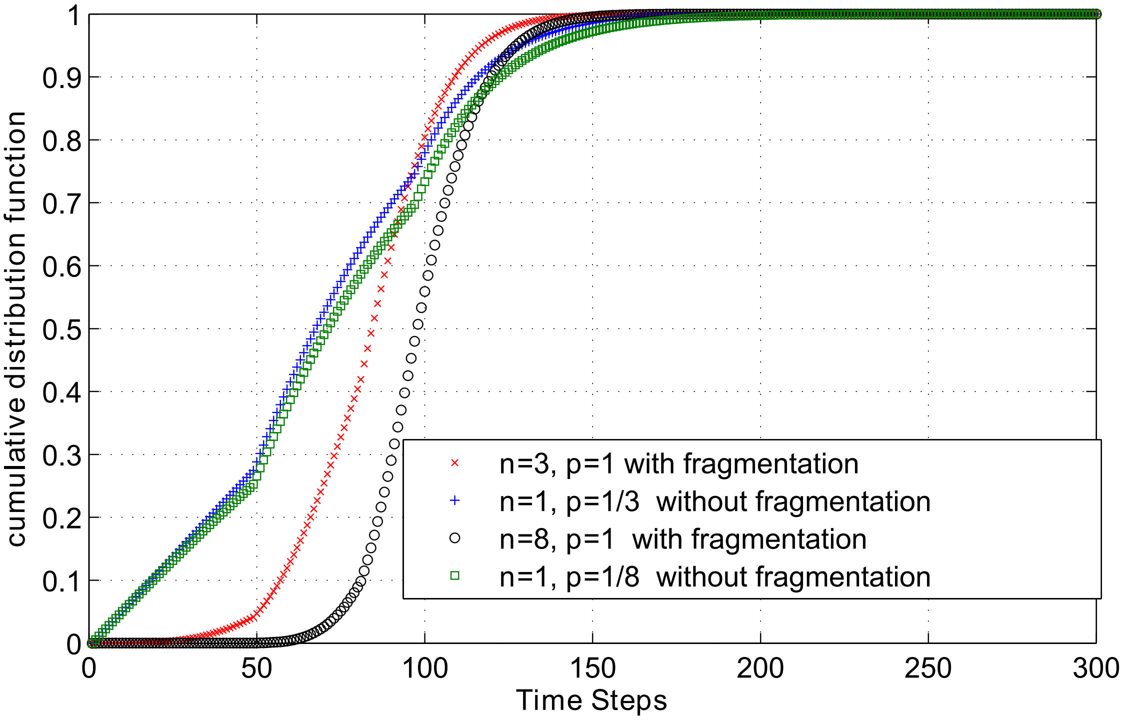


Figure 2.12: The CDF of the message delivery probability with and without fragmentation when $N = 20$.

l encountered nodes according to [2]

$$n_i = \begin{cases} n/2^{\log_2 i}, & \text{for the first } l \text{ encountered nodes;} \\ 0, & \text{otherwise.} \end{cases} \tag{2.23}$$

These protocols do not consider the time remaining for the message to expire when passing it to an encountered node. Thus, a new approach is presented here which considers this time to determine how much of a message to transfer. It is shown that this can lead to a better probability of message delivery, and thus a better delivery ratio.

The Proposed Routing Protocol

The proposed routing protocol considers the time remaining before a message expires in determining how many fragments to give to an encountered node. The number of fragments is determined according to

$$n_i = n \times (1 - G(T)) \tag{2.24}$$

When a message is created, $G(T)$ will be small, but will increase over time. Thus n_i will decrease as time increases, and a node will stops distributing fragments when $G(T)$ reaches 1.

Performance Evaluation

The behaviour of $G(T)$ is first examined for γ uniformly distributed between 0 and 1. As before, $N = 5, 10$ and 20 encountered nodes are considered during the life of a message. Figure 2.13 shows how $G(T)$ increases over time, and thus how the delivery ratio increases with time. Further, as N increases, $G(T)$ also increases.

To evaluate the performance of the protocols, the number of messages exchanged and the number of messages delivered with the epidemic, spray and wait, and proposed techniques. The number of messages exchanged provides a measure of the network resources consumed. The number of delivered messages is a function of the delivery probability. Messages exchanged or delivered are examined against the network load. The network load is defined as the number of messages generated in the network.

Figure 2.14 shows the number of messages exchanged versus the network load. A message can be exchanged between nodes many times before it is delivered to the destination or discarded. This figure shows that the number of messages exchanged in the network is highest with epidemic routing. The proposed technique uses has the lowest number of exchanges and so uses the fewest network resource. However, this should not be at the expense of the messages delivery probability. For example, the spray and wait protocol exchanges more messages than the proposed technique when $N = 20$, but fewer when $N = 5$. The best protocol exchanges a low number of messages but has a high number of delivered messages.

To evaluate the message delivery probability, two cases are considered, $\gamma \in [0, .5]$ and $\gamma \in [.5, 1]$, which indicate that the encountered nodes have a low or high probability of encountering the destination, respectively. These probabilities are generated randomly using a uniform distribution. Figure 2.15 shows the number of delivered messages versus the network load. The number of delivered messages can be higher than the number of messages generated (network load) if multiple nodes deliver a message to the destination. Figure 2.15 shows that the number of delivered messages is highest with epidemic routing when $\gamma \in [0, .5]$. However, the number of messages delivered is always equal to or greater than the network load (which means that redundant copies of messages often reach the destination). The proposed technique has fewer message exchanges for the same number of delivered messages. Further, the spray and wait protocol delivers only 75% of the messages when $N = 5$, whereas the proposed technique achieves a 95% messages delivery. These percentages are the ratio of delivered messages to messages generated. Similar results occur when $\gamma \in [.5, 1]$, as shown in Figure 2.16. The only difference is that the spray and wait protocol has performance almost identical to that of the proposed technique when $N = 5$. These results indicate that the proposed approach will perform better as N increases. It always delivers more than 95% of the messages generated and exchanges fewer messages except for $N = 5$ with the spray and wait protocol. However, in this case spray and wait only has a 75% probability of message delivery.

2.3.4 Performance Evaluation

ONE [21] is a discrete event simulator that combines movement modeling, routing simulation, visualization and reporting. Mobility models such as the random waypoint model (RWPM) and Helsinki City Scenario (HCS) are implemented in ONE. RWPM

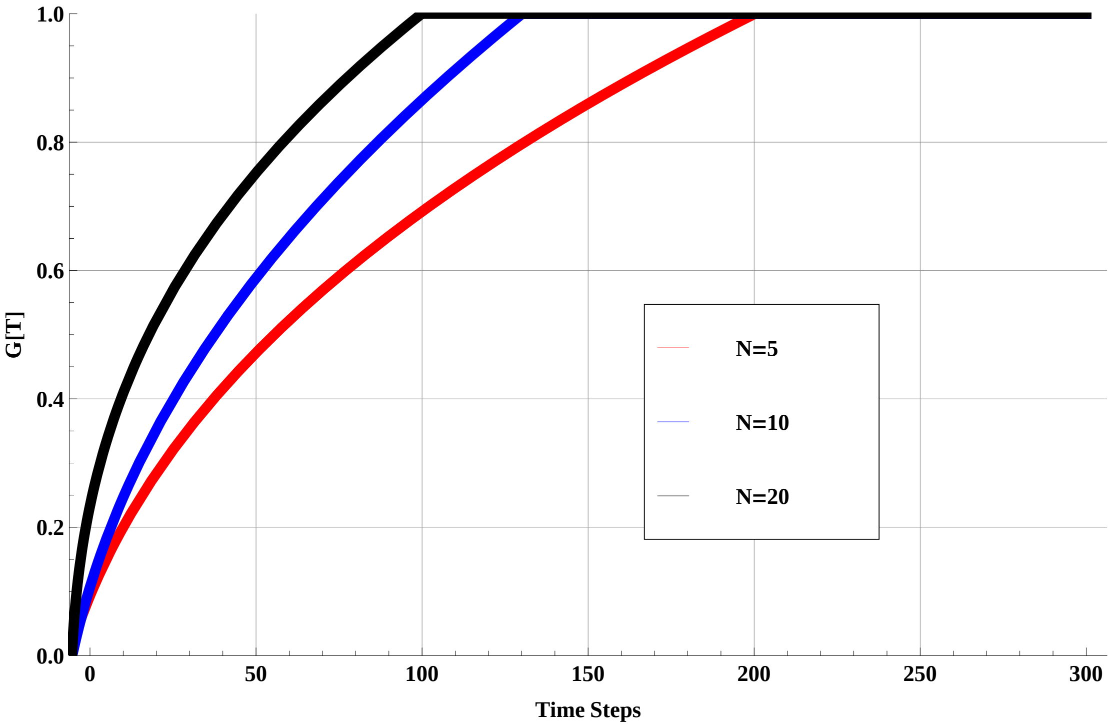


Figure 2.13: The behaviour of $G(T)$ versus N and T.

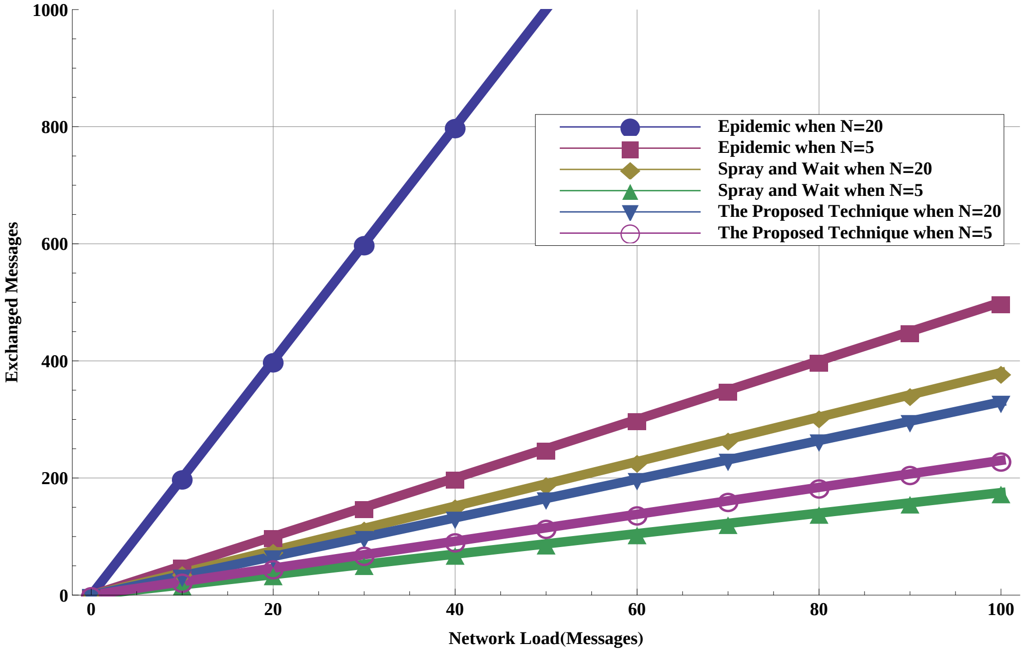


Figure 2.14: The number of exchanged messages versus the network load (number of messages in the network).

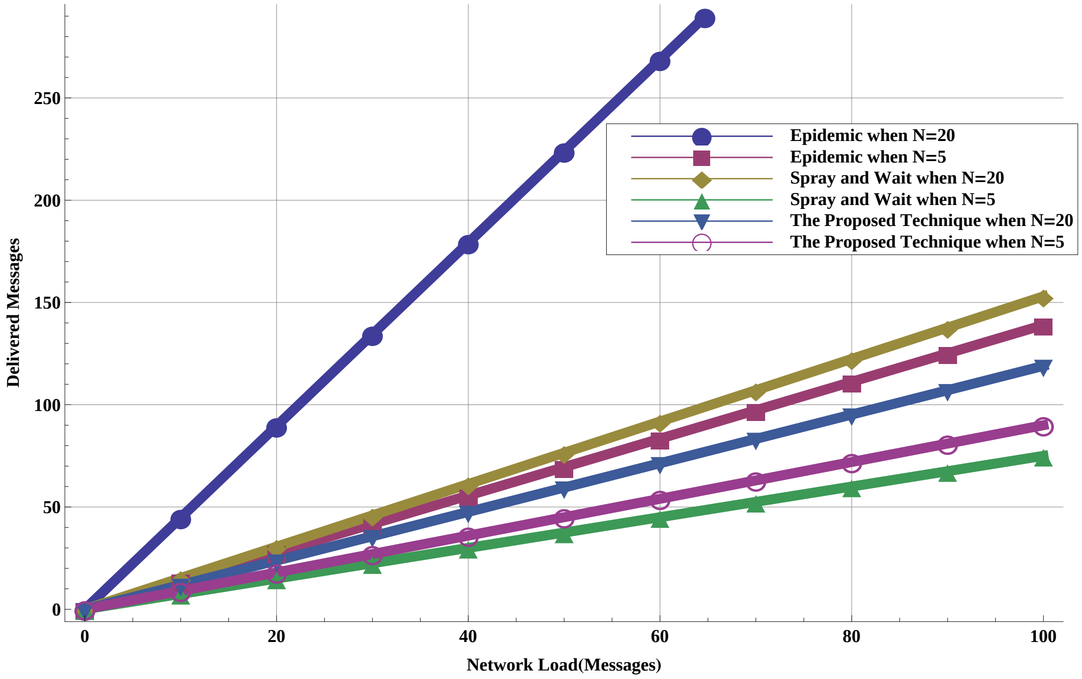


Figure 2.15: The number of delivered messages versus the network load when $\gamma \in [0, .5]$.

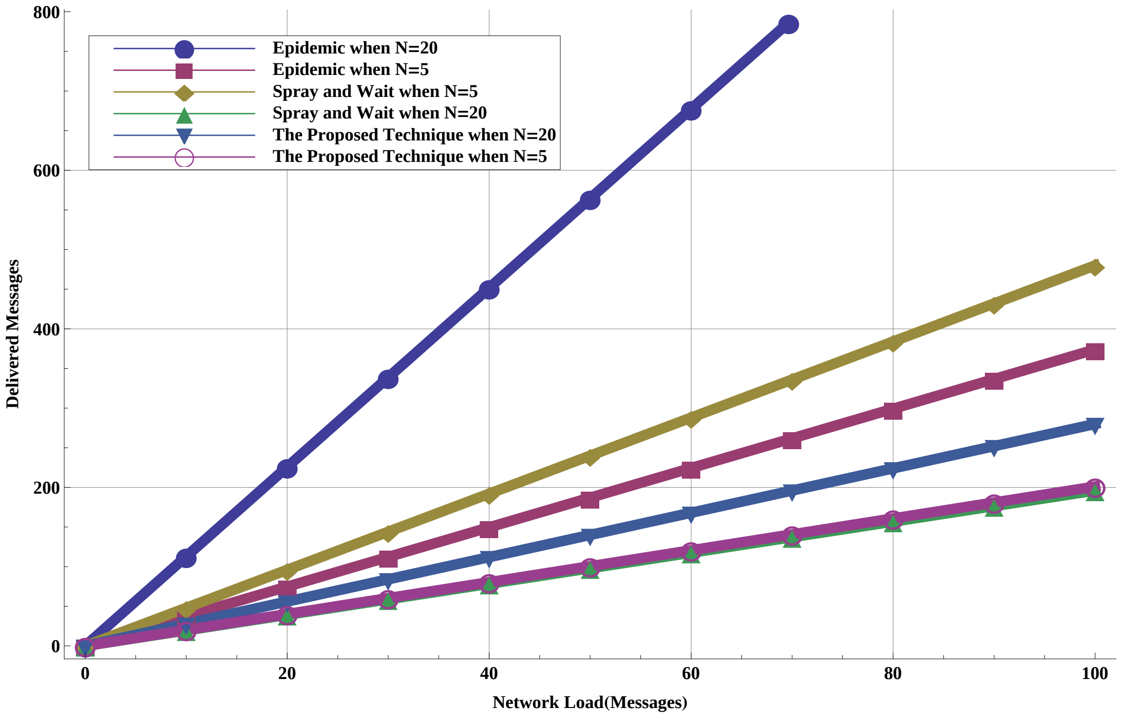


Figure 2.16: The number of delivered messages versus the network load when $\gamma \in [.5, 1]$.

is a simple mobility model based on random directions and speeds. This model assumes completely random node movement which is unrealistic. Mobile devices are usually carried by humans, thus it is more realistic to assume that nodes move towards a specific destination, then towards another destination, and so on. These destinations could be a mall or a restaurant, thus they can be called points of interest (PoI) in the network. The realistic map-based model Helsinki City Scenario (HCS) has nodes moving in downtown Helsinki and is used here.

The parameter settings are based on a realistic environment as in [16]. The simulation parameters are summarized in Table 1. Each node represents a user moving at a realistic speed along the shortest paths between PoIs and random locations. The nodes are divided into four groups having different PoIs and different, pre-determined probabilities of choosing the next group-specific PoI or random place to visit. The trams follow real tram routes in Helsinki. The simulation area is $4500 \times 3400m^2$ size.

The epidemic routing protocol was the first proposed for ICNs [1]. Thus it the first considered here to investigate the use of fragmentation in a realistic environment. For $N = 5$, there are 126 nodes divided based on their movement speeds into 40 fast nodes that move by car, 6 medium speed nodes that move by tram, and 80 slow nodes that move by foot. For $N = 10$, 160 nodes are moving by foot, 80 by car, and 12 by tram, and for $N = 20$, 320 nodes are moving by foot, 160 by car, and 24 by tram.

Figure 2.17 shows the cumulative distribution function when epidemic routing is employed. The black, red and brown lines show $F(T)$ when each message is divided into two fragments with $p = 1$ and $N = 5, 10$ and 20, respectively. The green, blue and purple lines show $F(T)$ when entire message are disseminated with $p = 1/2$ and $N = 5, 10$ and 20, respectively. These results indicate that for $F(T) > .35$, fragmentation provides better performance. In all cases, there is a crossover point where message fragmentation is better regardless of the value of N. However, the advantage of using fragmentation increases as N increases. For example, fragmentation improves $F(T)$ by $3\%, 10\%$ and 15% when $N = 5, 10$ and 20, respectively, at the end of the simulation period (300 time steps). This confirms the analytic results.

Next, fragmentation is examined with the spray and wait (SNW) routing protocol [2]. Figure 2.18 shows the results using this protocol with and without fragmentation. As before, $p = 1$ with fragmentation, and $p = 1/2$ without fragmentation. The performance without fragmentation is better at the start, but fragmentation is better when $F(T) > .2$. Message fragmentation provides superior performance regardless of the value of N, however the gain with $N = 10$ is approximately twice that with

Table 2.1: The Simulation Parameters

Parameter	Value
Transmit Speed	250 KBps
Transmit Range	50 m
Speed of Nodes-Foot	.5 - 1.5 m/s
Speed of Nodes-Tram	7 - 10 m/s
Speed of Nodes-Car	2.7 - 13.9 m/s
Message Size	0.5 - 4 MB
Buffer Size	2000 MB

$N = 5$ at the end of the simulation period. Further, the gain with $N = 20$ is 20% better than with $N = 10$.

2.4 Conclusion

The use of message fragmentation in an intermittently connected network (ICN) was considered. It was shown that fragmentation can lead to a better message delivery probability, particularly when the number of encountered nodes is high. To further improve this probability, the number of fragments given to an encountered node was determined adaptively. Compared to the previously proposed message dissemination techniques for ICNs, epidemic and spray and wait, this approach provides a better delivery probability. Further, fewer messages exchanges are required to achieve a given probability of message delivery. These results were confirmed using simulation in a realistic ICN environment. It was shown that fragmentation can improve the delivery probability up to 30% when the number of encountered nodes is $N = 20$. This gain will increase as N increases.

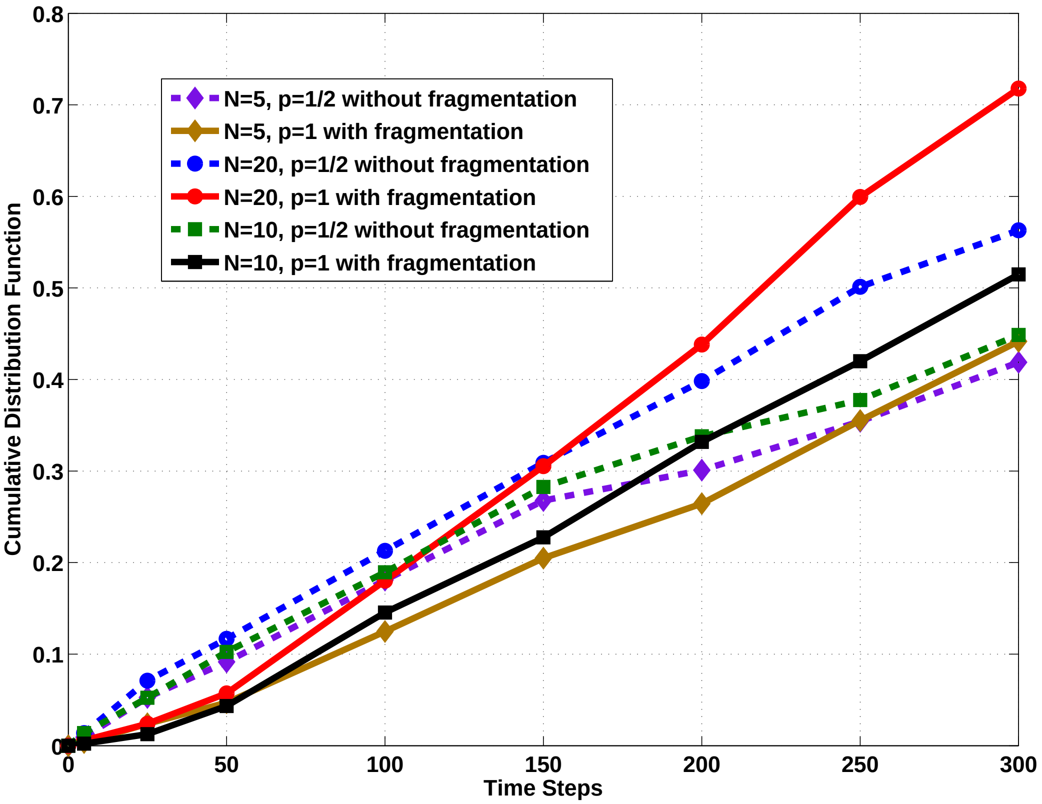


Figure 2.17: The CDF for the epidemic protocol with fragmentation and $p = 1$ versus no fragmentation and $p = 1/2$.

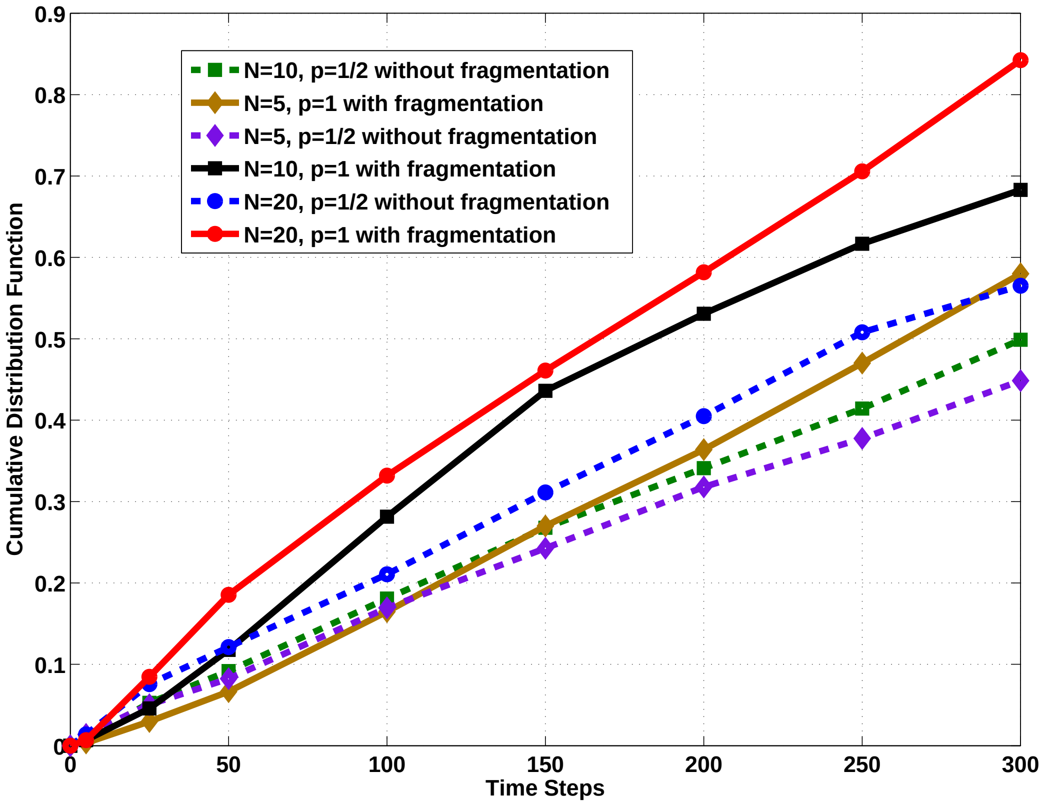


Figure 2.18: The CDF for the spray and wait protocol with fragmentation and $p = 1$ versus no fragmentation and $p = 1/2$.

Chapter 3

Erasure Coding in Intermittently Connected Networks

The previous chapter examined the use of fragmentation in intermittently connected networks (ICNs). Fragmentation allows for shorter contact times, small buffer space availability, and low battery levels. The use of fragments can also improve cooperation since an encountered node will likely be more willing to carry part of a message rather than the entire message. However, this fragmentation can reduce the delivery probability and increase delay. A solution to this problem is to also employ erasure coding. With erasure coding (EC), messages are divided into K data blocks and then encoded into a larger set of L blocks such that the original message can be reconstructed from a subset of K of these L blocks. This is very useful in an ICN where blocks transferred to encountered nodes may be discarded or not delivered to the destination. The focus here is not on developing a new ICN routing protocol, but rather to improve the performance with a given protocol. Note that fragmented messages are defined here as messages that employ fragmentation ($K = L$) without coding.

A Markov model is employed here to model message dissemination in an ICN. This allows for the analysis of the delivery ratio based on the number of message copies in the network to determine when erasure coding is advantageous.

The remainder of this paper is organized as follows. Section 3.2 presents the Markov model for message dissemination. The cumulative distribution function (CDF) of the message delivery probability is also derived. The performance with erasure coding is evaluated in Section 3.3, and a method is presented to choose the replication factor, $R = L/K$, based on minimizing the number time steps, T, needed to achieve a given value of the cumulative distribution function (CDF). The performance of routing protocol with erasure coding in a realistic ICN environment is presented in Section 3.4. Finally, some conclusions are given in Section 3.5.

3.1 Related Work

Erasure coding first divides a message into K data blocks and then converts these blocks into a larger set of L blocks (encoded blocks) such that the original message can be constructed from a subset of K of these L blocks. The replication factor for erasure coding is defined as $R = L/K$.

Erasure coding is used in ICN to increase reliability, improve the delivery rate and lower the delay in message delivery. This coding can improve the probability of messages delivery to the destination, regardless of the communication failure rate [18]. Several results on erasure coding for ICNs have appeared in the literature including [**?**,20] and [18]. In [**?**], it was shown that erasure coding can improve the delivery rate while maintaining a fixed delivery delay. Similar results were presented in [20] for erasure coding with heterogeneous nodes. The cost of erasure coding, defined as the number of message bytes transferred between nodes in the network, was discussed in [18]. However, no analysis was given to show that erasure coding improves the delivery rate. In this work, analytic results are presented to evaluate the performance improvement with erasure coding in an ICN in terms of the delivery rate and delay. The performance of erasure coding in an ICN is compared to the performance when only fragmentation ($R = 1$) is employed. Further, a method to choose a replication factor to achieve a given message delivery in an ICN is proposed based on minimizing the delay.

3.2 Intermittently Connected Network (ICN) Model

Consider a network with $N + 1$ identical mobile nodes and a single message to be delivered by a source node to a destination node. Intermediate nodes can be used as relay nodes. The goal is to determine the time steps required and the number of copies that should be disseminated to obtain a given delivery probability. Further, how to distribute these copies must be determined.

Let t_i be the number of time steps for the ith message carrier to meet a non carrier. At this point in time, the number of message copies may increase from i to $i+1$. Let γ be the average probability of meeting the destination node. This can be determined based on the inter-meeting times t_{iD} between the message carriers and the destination node D. Recall that the original message is divided into K blocks, and these are encoded into L blocks where $L \geq K$. Thus $L = K$ denotes message fragmentation without coding. Let p be the probability of an encountered node which is not the destination accepting to carry a block. This probability is a function of the size of the block and the replication factor (R), where a larger size of a block or/and larger R is assumed to have a lower probability of acceptance.

Figure 3.1 shows the ICN Markov model for a message block where state i, $i = 1, \ldots, N$, denotes the number of nodes that have copies of the block, i.e., $i = 1$ denotes that the source has all the copies, and state D denotes that the destination has been encountered. This model shows that there are three possibilities for a node with a message block to deliver. First, the block is delivered to the destination with probability γ. Second, a copy of the block is given to an encountered node with probability $p(1/t_i)(1-\gamma)$. Finally, the block remains with the node and no new node is encountered which will take the block with probability $1 - p(1/t_i)(1-\gamma) - \gamma$. A similar Markov model was introduced in [12], but without considering the probability of accepting a block. Further, message fragmentation and coding were not considered. The probability of accepting a block is introduced here to evaluate the impact of message fragmentation and coding in an ICN.

3.2.1 ICN Model Analysis

The model in Fig. 3.1 is used here to determine the number of time steps required for a message block to be delivered to the destination with a given probability. Let the probability of being in state i at time 0 be $P(i,0)$ so that

$$P(1,0) = 1, P(2,0) = P(3,0) = \cdots = P(N,0) = P(D,0) = 0.$$

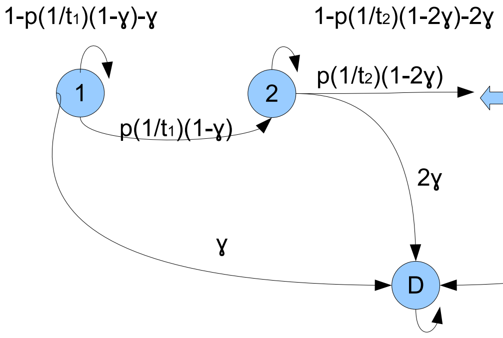


Figure 3.1: The intermittently connected network (ICN) Markov model.

Further, let the probability of being in state i at time step $j > 0$ be $P(i, j)$, which is given by [12]

$$\begin{aligned}
P(1,j) &= P(1,j-1)(1-d_1-\gamma)^j, && (3.1)\\
P(2,j) &= P(2,j-1)(1-d_2-2\gamma)+d_1P(1,j-1), && (3.2)\\
P(i,j) &= P(i,j-1)(1-d_i-i\gamma)+d_{i-1}P(i-1,j-1), && (3.3)\\
\vdots \quad & \quad \vdots && \\
P(N,j) &= P(N,j-1)(1-N\gamma)+d_{N-1}P(N-1,j-1), && (3.4)\\
& && (3.5)
\end{aligned}$$

where $d_i = \frac{p}{t_i}(1 - i\gamma)$ and $\sum_{k=1}^{N} a_k + a_D = 1$. Thus the probability of delivering the message block after j time steps is

$$P(D,j) = P(D,j-1) + \sum_{i=1}^{N} (i\gamma)P(i,j-1). \tag{3.6}$$

This probability of delivery depends on three factors: the probability of meeting the destination γ, the number of time steps between node encounters t_i, and the probability of an encountered node accepting a message block p. The parameters γ and t_i are based on node movement, whereas p is determined by the encountered nodes. For example, nodes may accept a block of size less than 5 MB with probability 1, but a block less than 5 MB with probability 0.5. Thus, p can have a significant effect on message dissemination.

The above probabilities can be simplified as

$$\begin{aligned}
P(2,2) &= d_1 \\
P(2,3) &= d_1(g_1+g_2) \\
P(2,4) &= d_1(g_1^2+g_1g_2+g_2^2) \\
P(2,5) &= d_1(g_1^3+g_1^2g_2+g_1g_2^2+g_2^3) \\
\vdots &\quad \vdots \\
P(3,3) &= d_1d_2 \\
P(3,4) &= d_1d_2(g_1+g_2+g_3) \\
P(3,5) &= d_1d_2(g_1^2+g_1g_2+g_1g_3+g_2^2+g_2g_3+g_3^2) \\
P(3,6) &= d_1d_2(g_1^3+g_1^2g_2+g_1^2g_3^2+g_1g_2^2+g_1g_2g_3+g_1g_3^2+g_2^3+g_2^2g_3+g_2g_3^2+g_3^3) \\
\vdots &\quad \vdots \\
P(4,4) &= d_1d_2d_3 \\
P(4,5) &= d_1d_2d_3(g_1+g_2+g_3+g_4) \\
P(4,6) &= d_1d_2d_3(g_1^2+g_1g_2+g_1g_3+g_1g_4+g_2^2+g_2g_3+g_2g_4+g_3^2+g_3g_4+g_4^2) \\
P(4,7) &= d_1d_2d_3(g_1^3+g_1^2g_2+g_1^2g_3+g_1^2g_4+g_1g_2^2+g_1g_3^2+g_1g_4^2+g_1g_2g_3+g_1g_2g_4+g_1g_3g_4 \\
&\quad +g_2^3+g_2^2g_3+g_2^2g_4+g_2g_3^2+g_2g_4^2+g_2g_3g_4+g_3^3+g_3^2g_4+g_3g_4^2+g_4^3) \\
\vdots &\quad \vdots
\end{aligned} \tag{3.7}$$

which gives

$$P(i,j) = \left(\prod_{k=1}^{i-1} d_k\right)\left(\sum_{|\alpha|=j-i} g^{\alpha}\right) \tag{3.8}$$

where $d_k = (p/t_k)(1-k\gamma)$, $g_k = (1-d_k-k\gamma)$, $\alpha = \{\alpha_1, \alpha_2, \ldots, \alpha_i\}$, $g^{\alpha} = (g_1^{\alpha_1}g_2^{\alpha_2}\cdots g_i^{\alpha_i})$, i is the number of encountered nodes since the message was created, and N is the total number of encountered nodes. When $i = N$

$$\left(\prod_{k=1}^{N-1} d_k\right) = \frac{\left(p\left(1-\gamma\left(\frac{N-1}{2}\right)\right)\right)^N}{t^N}, \tag{3.9}$$

and

$$\left(\sum_{|\alpha|=j-i} g^{\alpha}\right) = \left(\frac{2j}{N-1} - 1\right)^{N-1} \left(1 - \gamma\left(\frac{N-1}{2}\right) - \left(\frac{p}{t}\right)^{N} \left(1 - \gamma\left(\frac{N-1}{2}\right)\right)^{N}\right), \tag{3.10}$$

where $t_k = t$ is assumed for simplicity, and t can be set to the average number of time steps to encounter a node not carrying the message block. From (3.6), (3.8), (3.9) and (3.10), we obtain

$$P(D,T) = \frac{1}{2}\left(\frac{2T}{N-1} - 1\right)^{1-N} N(N+1)\gamma\left(\frac{pX}{t}\right)^{N}\left(X - \left(\frac{pX}{t}\right)^{N}\right), \tag{3.11}$$

where

$$X = \left(1 - \left(\frac{N-1}{2}\right)\gamma\right). \tag{3.12}$$

The Cumulative Distribution Function (CDF) of the probability of delivery after T time steps is given by

$$F(T) = 1 - (Pf_1(T) \times Pf_2(T) \times \cdots \times Pf_N(T)) \tag{3.13}$$

where $Pf_i(T)$ is the probability that node i has not encountered the destination after T time steps. $Pf_i(T)$ is a function of the message dissemination process for the protocol employed. For example, with the epidemic routing protocol [1], the ith node will receive a copy of the message at time $t_1\left(\sum_{k=1}^{i-1} \frac{N-1}{N-k}\right)$ so that

$$Pf_i(T) = 1 - P\left(D, \left\lfloor T - t_1\left(\sum_{k=1}^{i-1} \frac{N-1}{N-k}\right)\right\rfloor\right). \tag{3.14}$$

When the binary spray and wait routing protocol [2] is employed, the ith node will receive a block at time step $t\left(\left\lceil\sum_{k=1}^{\log_2 i} \frac{N-1}{N-2^k-1}\right\rceil\right)$ so that from (3.11) we obtain

$$Pf_i(T) = 1 - P\left(D, \left\lfloor T - t\left(\left\lceil\sum_{k=1}^{\log_2 i} \frac{N-1}{N-2^k-1}\right\rceil\right)\right\rfloor\right). \tag{3.15}$$

The number of time steps required to achieve a desired probability of message delivery P_d is given by

$$T = \left\lceil F^{-1}(P_d)\right\rceil. \tag{3.16}$$

For example, if $P_d = 0.85$ and $\lceil F^{-1}(0.85) = 300 \rceil$, then a node will take 300 time steps to deliver a message block with this probability. After this time, the block can be discarded by the nodes carrying it as the desired delivery probability has been achieved. The relationship between T and $F(T)$ is examined in Section 3.3.

3.3 Erasure Coding in an ICN

With erasure coding, a message is divided into K blocks and then encoded into L blocks where $L > K$. A subset of K of these L encoded blocks is required to reconstruct the original message. The goal of erasure coding is to increase the message delivery probability and/or lower the delay in delivering a message. This section examines the performance of erasure coding in an ICN. A method to choose the replication factor R is also proposed based on T and $F(T)$.

3.3.1 Erasure Coding Performance

Although techniques for message delivery in an ICN exist [1], it is desirable to increase the delivery ratio and decrease the messages delivery time. This can be achieved by employing message fragmentation and/or coding [?, 16, 17, 20]. In this section, the CDF of the message delivery probability is considered for routing of complete messages, fragmented messages and encoded messages (using erasure coding). Note that fragmented messages are defined here as messages that employ fragmentation without coding.

Figure 3.2 shows the Markov models for message routing in an ICN when a complete message, fragmented message ($L = K = 2$), and coded message (using erasure coding with $L = 4$ and $K = 2$), are routed through the network. When a complete message is routed, only the original message is transferred between intermediate nodes until it reaches the destination. With fragmentation, the message is divided into two fragments, and both are needed to reconstruct the message at the destination. The CDF of a message is then given by

$$F_f(T) = F_1(T) \times F_2(T), \tag{3.17}$$

where $F_i(T)$ is the CDF for the probability of delivering the ith message fragment (block). For simplicity, we assume that $F_i(T)$ is the same for all i so that $F_i(T) =$

$F(T)$. The delivery probability CDF for a message fragmented into K blocks is then

$$F_f(T) = F_i^K(T). \tag{3.18}$$

When erasure coding is employed with $L = 4$ and $K = 2$, only two blocks out of the four encoded blocks are needed to reconstruct a message at the destination. The message delivery probability CDF is then given by

$$F_e(T) = \binom{4}{2}F^2(T) + \binom{4}{3}F^3(T) + \binom{4}{4}F^4(T), \tag{3.19}$$

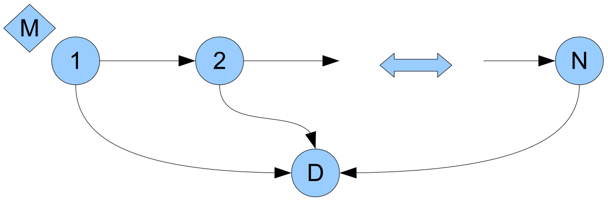
In general, the message delivery probability CDF for an encoded message is

$$F_e(T) = \sum_{i=K}^{L} \binom{L}{i} F^i(T). \tag{3.20}$$

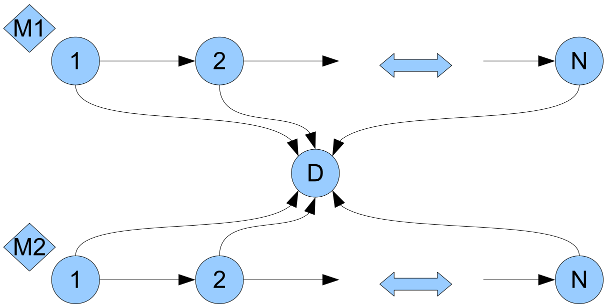
The performance when routing complete, fragmented, and coded messages in an ICN is now examined. Consider an example with $N = 10$. In this case, there are 9 time steps to reach state N. Node mobility was simulated using the approach in [12] to obtain the values $t_i = 40, 33, 30, 6, 10, 20, 7, 5$ and 5 for $i = 1, \ldots, N-1$. The technique employed in [13] was used to determine that $\gamma = .007$. It is assumed that $p = 1/2$ if a message is sent without fragmentation, whereas p can be larger if a message is divided into fragments. This is reasonable since it should be easier find a node to carry a 5 MB message than a 10 MB message. The value p is not only a function of the block size, but also R, N, K and the number of users in the area, X. Larger values of R, N and K result in more message blocks in the network. Fragmentation with or without coding is assumed to have the same message block size, so in this case p is given by

$$p = 1 - \frac{RNK}{2X}, \tag{3.21}$$

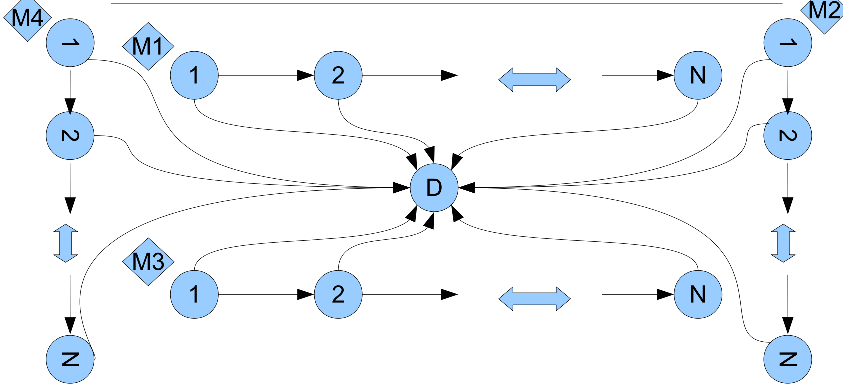
where the factor of 2 is included to obtain the average number of users in the area which have a message block. Thus p decreases as R, N and K increases since an encountered node will be more likely to have a block of a message. In addition, p increases as X increases since more nodes in the network means a greater chance of meeting a node that has not received a block of a message. Thus with no coding



(a) M: The original message



(b) M1: The first fragment of M M2: The second fragment of M n=2



(c) M1: The first encoded block M2: The second encoded block
M3: The third encoded block M4: The fourth encoded block

Figure 3.2: ICN Markov models for (a) no coding or fragmentation, (b) fragmentation only, and (c) coding and fragmentation.

and $N = 10$, $K = 2$, and $X = 250$, $p = 0.96$, whereas for the same parameters and coding with $R = 2$, $p = 0.92$. Note that $X = 250$ was obtained from the simulation environment employed in Section 3.4.

Figure 3.3 presents the message delivery probability CDF with and without message fragmentation and erasure coding for $N = 10$ based on (3.13), (3.18), and (3.20). This shows that fragmentation is better for CDF ≥ 0.9 when $R = 1$. However, erasure coding with $R = 2$ is better than routing without fragmentation when CDF ≥ 0.5. Note that the number of time steps needed to achieve CDF ≥ 0.90 with erasure coding is lower than with fragmentation.

A denser environment is now considered with $N = 20$. In this case, there are 19 time steps to reach state N. Using the approach in [12], $t_i = 40, 33, 30, 6, 10, 20, 7, 5, 5, 4, 4, 3, 6, 6, 31, 9, 6, 6$, and 4 were obtained for $i = 1, \ldots, N-1$. Further, it was determined that $\gamma = .013$ based on the technique in [13]. From the simulation environment in Section 3.4, $X = 500$, $N = 20$. Since the environment is dense and more nodes are expected to be encountered, $K = 4$ is now used. With no coding and $N = 20$, $K = 4$, and $X = 500$, $p = 0.92$, whereas for the same parameters and coding with $R = 2$, $p = 0.84$.

Figure 3.4 presents the message delivery probability CDF with and without fragmentation and erasure coding for the $N = 20$ based on (3.13), (3.18), and (3.20). This shows that fragmentation is better for CDF ≥ 0.95 when $R = 1$. However, erasure coding with $R = 2$ is better than routing without fragmentation when CDF ≥ 0.5 is desired. This figure shows that when K increases, the benefits of only fragmentation ($R = 1$) decreases, especially when N is low. However, erasure coding with $R = 2$ maintains a high CDF even with an increased K.

3.3.2 Choosing the Replication Factor R

With erasure coding, the replication factor $R = L/K$ has a significant effect on performance. Randomly choosing R may lead to a poor CDF $F_e(T)$ resulting in a long delivery delay T, which is not desirable. This will result in many undelivered messages in the network and excessive resource consumption, e.g. battery energy and node storage space. Thus R should be carefully chosen to minimize T and maintain a good $F_e(T)$. To achieve these goals, consider the following optimization problem

$$\text{Minimize } T \tag{3.22}$$

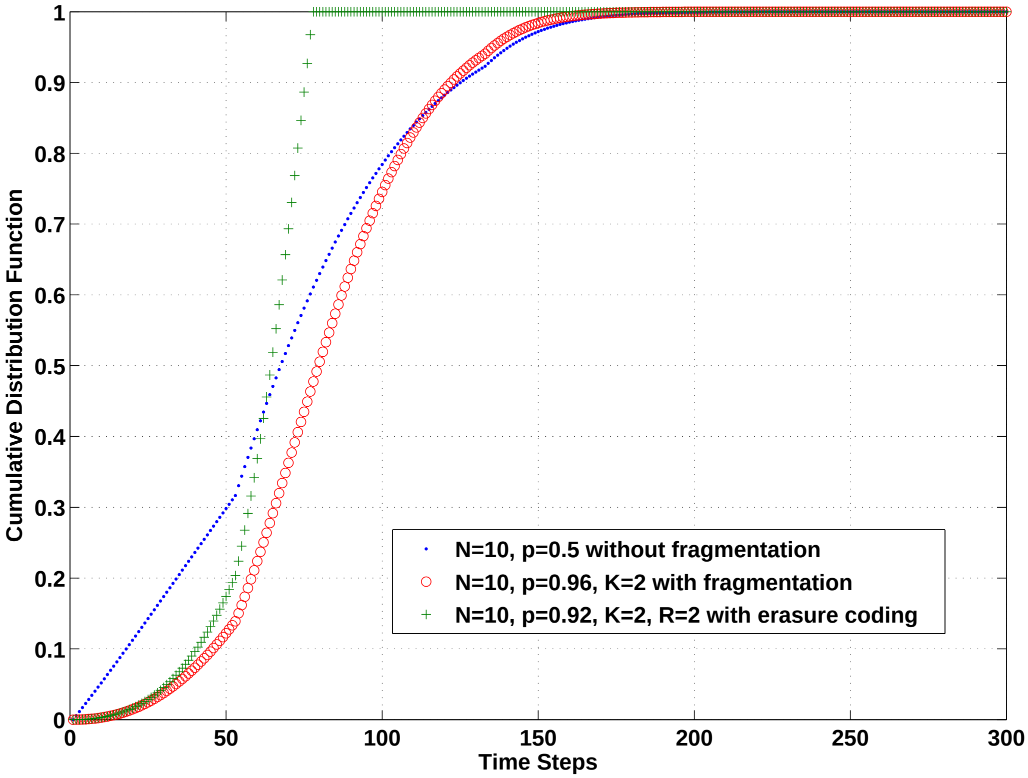


Figure 3.3: The message delivery probability CDF in an ICN with $N = 10$.

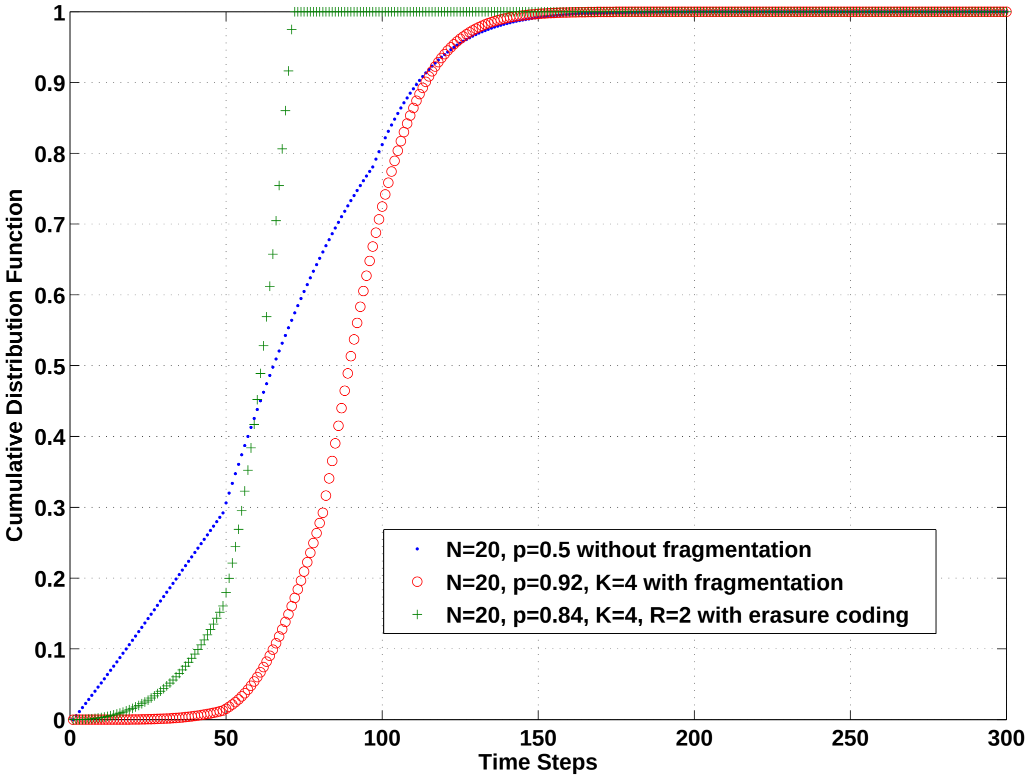


Figure 3.4: The message delivery probability CDF in an ICN with $N = 20$.

subject to

$$F_e(T) \geq F_d \tag{3.23}$$

and

$$R \geq 1 \tag{3.24}$$

where $F_e(T)$ is given in (3.20) and F_d is the desired value for the CDF. Note that $F_e(T)$ is a function of the CDF $F_i(T)$. For simplicity, we assume that $F_i(T)$ is the same for all i so that $F_i(T) = F(T)$, where $F(T)$ is given in (3.13). The CDF $F(T)$ can be simplified by substituting $t = T/N$ since it is reasonable that the average time to encounter a node is the number of time steps required to deliver a message divided by the expected number of encountered nodes. Therefore, $F(T)$ can be written as

$$F(T) = \frac{1}{2}N(N+1)\left(\frac{pN}{T}\right)^N\left(-1+\frac{2T}{N-1}\right)^{N-1}\gamma X^N\left(X-\left(\frac{pN}{T}\right)^N X^N\right), \tag{3.25}$$

where

$$X = \left(1-\left(\frac{N-1}{2}\right)\gamma\right). \tag{3.26}$$

From (3.20) and (3.25), $F_e(T)$ for $K = 2$ is

$$\begin{aligned} &F_e(T) = \\ &4^{-L}\left(4+\frac{4^{-N}N(N^2-1)\frac{N}{T}^{2N}\left(\frac{2T}{N-1}-1\right)^N\gamma(pY)^N\left(2^N\frac{T}{N}^N((N-1)\gamma-2)+2(pY)^N\right)}{N-2T-1}\right)^L \\ &-1-\left(\frac{4^{-1-N}LN(N^2-1)\frac{N}{T}^{2N}\left(\frac{2T}{N-1}-1\right)^N\gamma(pY)^N\left(2^N\frac{T}{N}^N((N-1)\gamma-2)+2(pY)^N\right)}{N-2T-1}\right)^L, \end{aligned} \tag{3.27}$$

where

$$Y = 2+\gamma-N\gamma, \tag{3.28}$$

Note that $F_e(T)$ can be easily found for other values of K.

To illustrate the above optimization problem, consider the following example. As in Section 3.3.1, assume $N = 10$, $\gamma = .007$ and $K = 2$. The relationship between the replication factor R and the number of time steps T to deliver a message with $F_d = 0.9$ is given in Table 3.1. This shows that increasing R reduces T until $R = 3$. Then a further increase in R increases T due to the lower value of p caused by the increase in the number of blocks. These results indicate that in an ICN environment, the choice of R has a significant impact on T.

The relationship between the replication factor R and the number of time steps T to deliver a message with $F_d = 0.9$ is given in Table 3.2 for $K = 4$, $\gamma = .013$ and $N = 20$. This shows that increasing R reduces T until $R = 5$. Then a further increase in R increases T. The results of tables 3.1 and 3.2 indicate that a larger value of R is needed when K is increased to achieve the desired CDF value $(F_e(T)) \geq .90$.

3.4 Performance Evaluation

ONE [21] is a discrete event simulator that combines movement modeling, routing simulation, visualization and reporting. Mobility models such as the random waypoint model (RWPM) and Helsinki City Scenario (HCS) are implemented in ONE. RWPM is a simple mobility model based on random directions and speeds. This model assumes completely random node movement which is unrealistic. Mobile devices are usually carried by humans, thus it is more realistic to assume that nodes move towards a specific destination, then towards another destination, and so on. These destinations could be a mall or a restaurant, thus they can be called points of interest (PoI) in the network. The realistic map-based model Helsinki City Scenario (HCS) has nodes moving in downtown Helsinki and is used here.

The settings employed are based on a realistic environment as in [16]. The simulation parameters are summarized in Table 3.3. Each node represents a user moving at a realistic speed along the shortest paths between PoIs and random locations. The nodes are divided into four groups having different PoIs and different, pre-determined probabilities of choosing the next group-specific PoI or random place to visit. The trams follow real tram routes in Helsinki. The simulation area is 4500×3400 m^2 in size.

Table 3.1: The Relationship Between R and T for $N = 10$, $K = 2$, and $X = 250$

Replication Factor (R)	Time Steps (T)
1	150
2	90
3	77
4	105
5	170

Table 3.2: The Relationship Between R and T for $N = 20$, $K = 4$, and $X = 500$

Replication Factor (R)	Time Steps (T)
1	140
2	80
3	70
4	65
5	63
6	110
7	190

The epidemic routing protocol was the first proposed for ICNs [1]. Thus it the first considered here to investigate the use of fragmentation and erasure coding in a realistic environment. For $N = 10$, there are 252 nodes divided based on their movement speeds into 80 fast nodes that move by car, 12 medium speed nodes that move by tram, and 160 slow nodes that move by foot. For $N = 20$, there are 504 nodes divided based on their movement speeds into 160 fast nodes that move by car, 24 medium speed nodes that move by tram, and 320 slow nodes that move by foot. Note that fragmented messages are defined as messages that employ fragmentation without coding.

Figure 3.5 shows the cumulative distribution function (CDF) of the message delivery probability when epidemic routing is employed for complete, fragmented and erasure coded messages. The network parameters are $K = 2$, $N = 10$, and $R = 2, 3, 4$ and 5 (these are the same parameters considered in the literature, e.g. [18]). Figure 3.5 shows that erasure coding improves the CDF compared to routing complete or fragmented messages by 15% and 25%, respectively. This is because when a complete message is routed, some do not reach their destination due to buffer overflow. When overflow occurs, a node discards some of its buffered messages. Fragmentation helps solve this problem by routing only parts of messages. This allows nodes to keep fragments longer than complete messages. However, all the message fragments must reach the destination in order to reconstruct the message, and this may cause long delays. With erasure coding, any K out of the L blocks is sufficient to reconstruct a message. However, when $R > 3$, the results in Figure 3.5 shows that no further improvement in the CDF will occur. This means that when 2 blocks out of 6 are needed, epidemic achieves its best performance in terms of the desired CDF value. Thus choosing R appropriately leads to a high message delivery probability and lower resource consumption [17].

The benefit of using erasure coding in ICN is further investigated in Figure 3.6, which shows the CDF when $N = 20$. In this case, a message is divided into 4 blocks so that 4 blocks are required to reconstruct the message at the destination. When erasure coding is employed, for $R = 2, 3, 4$ and 5 there are $8, 12, 16$ and 20 blocks, respectively, but only 4 are required to reconstruct the message at the destination. Figure 3.6 shows that erasure coding improves the CDF by up to 40% compared to routing complete or fragmented messages. However, with a larger number of fragments ($K = 4$ compared to $K = 2$) needed to reconstruct a message, epidemic performs poorly at the beginning of the simulation since not enough fragments reached

Table 3.3: The Simulation Parameters

Parameter	Value
Transmit Speed	250 KBps
Transmit Range	50 m
Speed of Nodes-Foot	.5 - 1.5 m/s
Speed of Nodes-Tram	7 - 10 m/s
Speed of Nodes-Car	2.7 - 13.9 m/s
Message Size	500K - 4M
Buffer Size	2000MB

their destination over a small period of time. Nonetheless, Figure 3.6 shows that with erasure coding, the performance is much better with $K = 4$ after sufficient time compared to with $K = 2$. Further, the best performance is achieved with $R = 4$. This is reasonable since when K increases, more blocks of an encoded message are needed for reconstruction at the destination,

Next, erasure coding is examined with the spray and wait routing protocol [2]. Figure 3.7 shows the cumulative distribution function of the message delivery probability when this protocol is employed with $N = 10$. This shows that erasure coding improves the CDF compared to routing complete or fragmented messages by 18% 16%, respectively, and $R = 3$ provides the best performance. Note that with the spray and wait protocol, a fixed cost is maintained for each message whether it is routed as a complete, fragmented, or coded messages. The cost is defined as the total number of transmitted bytes for a message. For example, when a complete message is routed with 10 copies, a fragment of a message is routed with $K \times 10$ copies due to the fact that a fragment of a message is smaller than a complete message by factor of K [**?**, 17]. For $N = 20$, Figure 3.8 shows that $R = 4$ is required to achieve the best performance, which is the same as with the epidemic routing protocol. Note that routing with fragmentation and erasure coding initially performs poorly due to the need to reconstruct a message from several blocks. However, the performance improves over time, and ultimately erasure coding provides the best results.

The results with both the epidemic and spray and wait routing protocols confirm the analytic results presented earlier. As R increases, less time is needed to achieve a given delivery probability. However, an optimal value of R is reached beyond which performance is degraded due the large number of blocks in the network.

3.5 Conclusion

The use of erasure coding in an intermittently connected network (ICN) was considered. It was shown that erasure coding can lead to a better message delivery probability cumulative distribution function (CDF), compared to routing a complete or fragmented messages. To further improve this probability, the choice for the replication factor R was examined. Performance results using a realistic ICN environment were used to confirm the analysis. It was shown that erasure coding can improve the delivery probability up to 40% with a proper choice of R.

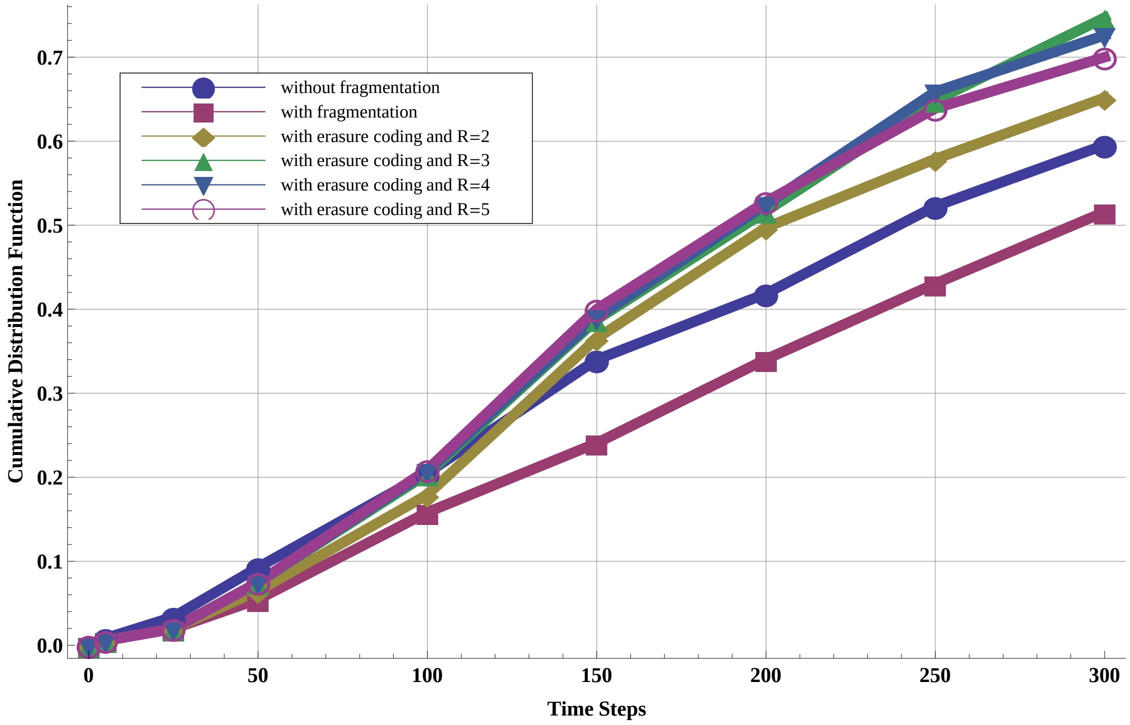


Figure 3.5: The message delivery probability CDF in an ICN with the Epidemic routing protocol and $N = 10$.

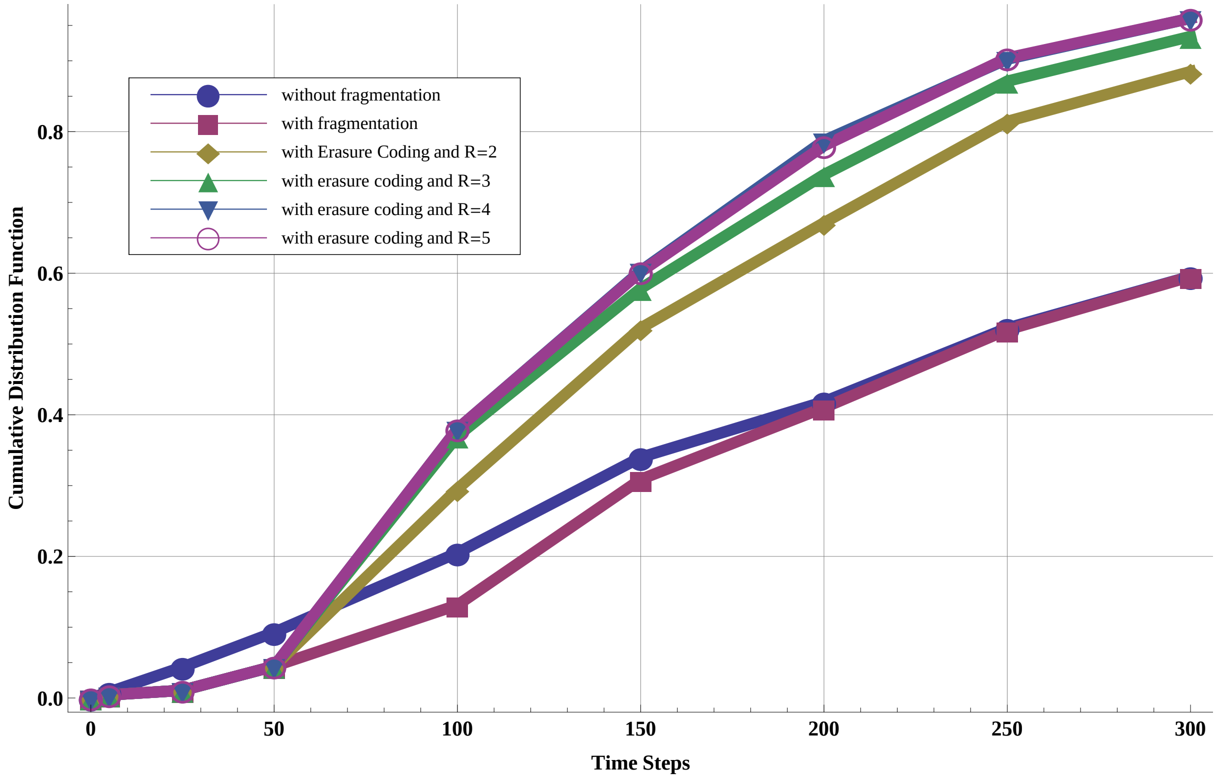


Figure 3.6: The message delivery probability CDF in an ICN with the Epidemic routing protocol and $N = 20$.

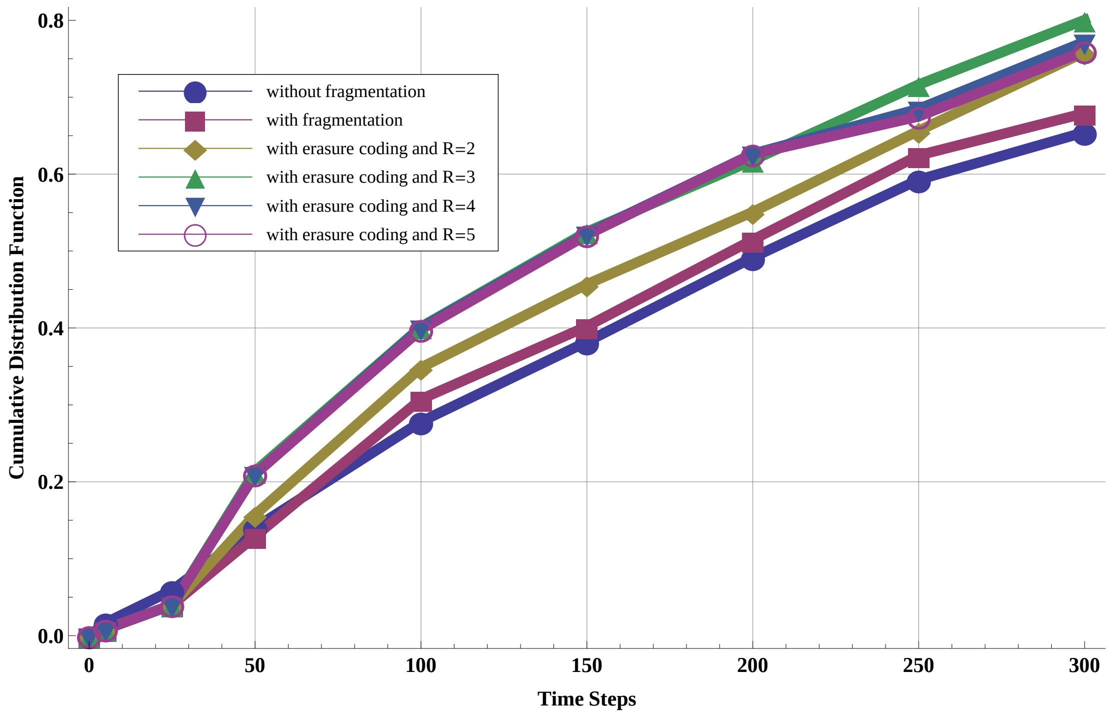


Figure 3.7: The message delivery probability CDF in an ICN with the Spray and Wait routing protocol and $N = 10$.

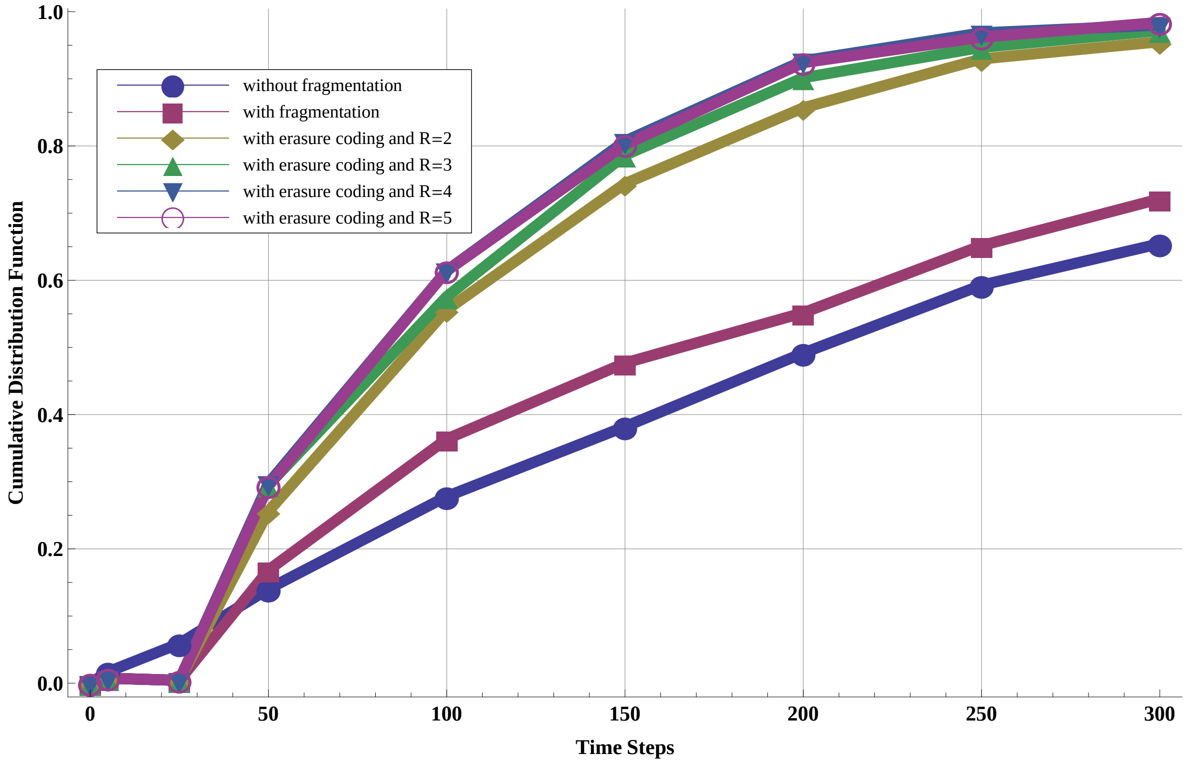


Figure 3.8: The message delivery probability CDF in an ICN with the Spray and Wait routing protocol and $N = 20$.

Chapter 4

Social Networking in Intermittentely Connected Networks

The previous two chapters examined messages delivery in ICNs when fragmentation or erasure coding is employed. Both fragmentation and erasure coding break a message into pieces, which can make routing to the destination easier. This is because routing message fragments compared to complete messages consumes less resources including the storage space of the encountered nodes, thus greater node cooperation can be expected. However, fragmentation and erasure coding have poor performance at the beginning of message routing. This is because a destination has to wait for a sufficient number of message fragments or blocks to reconstruct a message. Thus message routing should be investigated. Routing in ICNs can be classified based on the choice of the next carrier of a message as opportunistic forwarding, prediction based, or social relationship based. Routing messages based on social relationships is examined in this chapter. This is because of the high message delivery probability and low resource consumption with social relationships methods compared to the opportunistic and predication based routing [4]. Thus the nodes relationships are considered here to improve the message delivery probability and reduce resource consumption.

This chapter is organized as follows. It starts by discussing the related work on using social networks for routing in ICNs. Next, the mobile social network (MSN) model is presented. Based on this model, the message delivery probability is derived. In addition, a message distribution technique is proposed to achieve a good delivery rate based on the MSN model. Finally, some conclusions are given at the end of the chapter.

4.1 Related Work

A mobile social network (MSN) is defined as a mobile network that uses social relationships or activities to facilitate communication between nodes. Thus, routing in such an environment uses either similar social interests (activities) or similar social environments (number of neighbours), to distribute messages to encountered nodes. For example, LABEL [5], SocialCast [6], and Status [4] use the interest similarities between an encountered node and the destination to forward a message. Conversely, SimBet [7] uses the similarity of the surrounding environment of the encountered nodes to forward a message. In particular, a message is forwarded based on the number of the neighbours a node has. Finally, Bubble [8] employs both of the above techniques for routing. The aim of mobile social network routing protocols is to achieve a high delivery rate without adding extra complexity to the protocol. However, most results in the literature are based only on simulation. In this work, the delivery probability in ICNs using social relationships is derived theoretically.

A simple mobile social network (MSN) model was presented in [9]. This approach considers three different communities: the source node community, the destination node community, and all other nodes not in these communities. Only the source and destination node communities are considered in delivering messages, while the other community is ignored. However, some MSN routing protocols have shown that nodes not in the source or destination communities can be beneficial in delivering messages [4]. This is because destination community nodes may frequently encounter these other nodes. In addition, spraying (the process of disseminating copies of a message to encountered node), to only nodes in the source and destination communities might require a long time before meeting the message destination. This limits the message delivery probability, and might cause a long delay before delivery occurs. Therefore, the approach in [9] is improved here to include routing via all nodes, not just those in the source and destination communities. This allows more nodes to participate in message delivery.

4.2 The Mobile Social Network (MSN) Model

The mobile social network (MSN) model employed here is based on that given in [9]. It is assumed that there are m communities C_1 to C_m, and each community has on average N_c nodes. Further, the inter-meeting time between nodes in C_i and nodes in C_j has an exponential distribution with mean βij. The nodes within the same community are considered identical in terms of meeting behaviour, but nodes in different communities are considered having different behaviour. Based on this model, the delivery probability is derived.

Figure 4.1 presents the MSN model analyzed here. It contains three main communities, the source community (C_s), the destination community (C_d), and the other community (C_o). The other community contains all nodes not in the source and destination communities, and so can be a combination of several communities. Assume that a node in C_s has a message for a node in C_d. In [9], the source node in C_s distributes message copies only to nodes in C_s or C_d. Conversely, the method proposed here allows a node to distribute copies to a node in any community. This approach is based on the work in [4] where it was shown that an intermediate community can be useful in delivering a message to the destination. Therefore, giving a source node the freedom to distribute message copies to a node in any community should improve the delivery probability. Note that source spraying [2] is considered in this work analysis. Source spraying allow the source node only to distribute copies of the message, whereas other nodes keep their copies until meeting the destination node.

4.2.1 MSN Model Analysis

In this section, the MSN delivery probability is analyzed. Assume that each community has $N_c + 1$ nodes, and it takes on average β_i time units for a node to meet all other nodes in the same community i. If the average time to meet another node in the same community is a single time unit, then the average time for a node in the source community to meet all other nodes in C_s is $\beta s = N_c$. Moreover, it is assumed that $\beta_{sd} = q\beta_s$, $\beta_{so} = a\beta_s$, and $\beta_{od} = b\beta_o$ where q and a denote the increased time needed for a node in the source community to meet a node in the destination and other communities, respectively. If b is the corresponding time factor for a node in β_o to meet a node in the destination community, then $r = a \times b$ corresponds to the time needed for a message to be delivered to the destination via a node in the other (intermediate) community. This will improve the message delivery probability compared

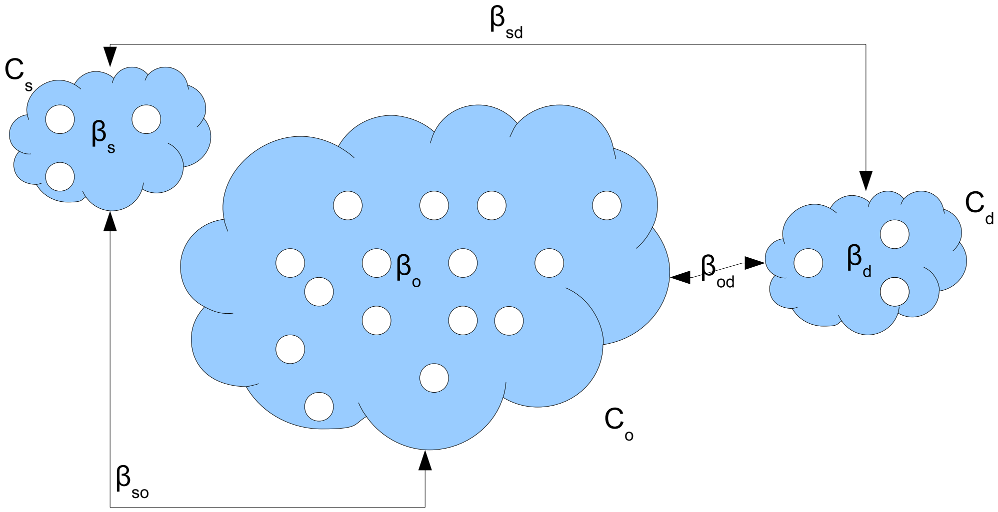


Figure 4.1: The mobile social network model.

to the results in [9] as this community was not considered. Thus for the proposed model, three components contribute to the delivery probability: source community spraying, other community spraying, and destination community spraying.

Source community spraying: The source distributes $L_{in}-1$ copies of the message to nodes in the same community C_s. Each of these nodes can deliver the message to the destination with probability $\frac{1}{qN_c}$. This is because a node in C_s requires q time units to meet a node in the destination community C_d. Once a message copy has reached the destination community, N_c time units are needed to meet all other nodes in C_d. This leads to a probability of delivery of $\frac{i}{qN_c}$ at time i.

Intermediate community spraying: The source gives L_{mid} copies of the message to nodes in the other (intermediate) community. Each of these nodes can deliver the message with probability $\frac{1}{rN_c}$. This is because a node in C_s requires r time units to meet a node in destination community C_d via an intermediate community node. Once a copy reaches the destination community, it needs N_c time units to meet all other nodes in C_d. Since a copy of a message requires at least 2 time units to reach C_d via an intermediate community node, the delivery probability in this case is $\frac{i-2}{rN_c}$ (i.e., the delivery probability via C_o nodes is zero until time 2).

Destination community spraying: The source gives L_{out} copies of the message to nodes in the destination community. Each of these nodes can deliver the message with probability $\frac{1}{qN_c}$. It takes q time units for a message to be transferred from the source to the destination community. Thus the delivery probability via a node in a destination community is $\frac{i-1}{qN_c}$ (i.e., the delivery probability via C_d nodes is zero until time 1).

The probability of message delivery and the expected delivery time are now derived. Based on the above components, there are four phases in the delivery process. First, in the All Spraying phase, nodes in the source, intermediate and destination communities receive copies of the message from the source node. Once the L_{in} copies are distributed in the source community, the Two Spraying phase begins. In this phase, only nodes in the intermediate and destination communities receive copies of the message from the source node since the source community nodes have received their share. Next, in the One Spraying phase, only destination community nodes receive copies of the message from the source node since the intermediate nodes have already received their share. This is because it is assumed that $q > r$. Finally, when the source node has distributed all copies of the message, the network enters the Waiting phase where the nodes that have received copies of the message attempt to deliver the message.

According to the above protocol, the delivery probability of a message in the All Spraying phase is

$$P_1 = \sum_{i=1}^{L_{in}-1} D_1(i)\left(\frac{2i-1}{qN_c} + \frac{i-2}{rN_c}\right) \tag{4.1}$$

where

$$D_1(i) = \prod_{j=1}^{i-1}\left(1 - \left(\frac{2j-1}{qN_c} + \frac{j-2}{rN_c}\right)\right) \tag{4.2}$$

where $\left(\frac{2i-1}{qN_c} + \frac{i-2}{rN_c}\right)$ is the probability of delivering the message to the destination at the i^{th} time unit, and 4.2 is the probability of nondelivery before the i^{th} time unit. In the second phase (Two Spraying), since distribution of copies to nodes in the source community has finished, the delivery probability becomes

$$P_2 = \sum_{i=Lin}^{r(L_{mid})-1} W_1 D_2(i)\left(\frac{L_{in}+i-1}{qN_c} + \frac{i-2}{rN_c}\right) \tag{4.3}$$

where

$$W_1 = \prod_{j=1}^{L_{in}-1}\left(1 - \left(\frac{2j-1}{qN_c} + \frac{j-2}{rN_c}\right)\right) \tag{4.4}$$

$$D_2(i) = \prod_{u=L_{in}}^{i-1}\left(1 - \left(\frac{L_{in}+u-1}{qN_c} + \frac{u-2}{rN_c}\right)\right). \tag{4.5}$$

In the third phase (One Spraying) message copies are still distributed by the source node to the destination community. Therefore, the delivery probability is given by

$$P_3 = \sum_{i=r(L_{mid})}^{q(L_{out})} W_1 W_2 D_3(i)\left(\frac{L_{in}+i-1}{qN_c} + \frac{r(L_{mid})}{rN_c}\right) \tag{4.6}$$

where

$$W_2 = \prod_{u=L_{in}}^{r(L_{mid})-1}\left(1 - \left(\frac{L_{in}-u-1}{qN_c} + \frac{u-2}{rN_c}\right)\right) \tag{4.7}$$

$$D_3(i) = \prod_{v=r(L_{mid})}^{i-1}\left(1 - \left(\frac{L_{in}+v-1}{qN_c} + \frac{r(L_{mid})}{rN_c}\right)\right). \tag{4.8}$$

In the Waiting phase, since the source has finished distributing copies of the message, the delivery probability is

$$P_4 = \sum_{i=q(L_{out})+1}^{\inf} W_1 W_2 W_3 D_4(i) \left(\frac{L_{in} + q(L_{out}))}{qN_c} + \frac{r(L_{mid})}{rN_c} \right) \tag{4.9}$$

where

$$W_3 = \prod_{v=r(L_{mid})}^{q(L_{out})} \left(1 - \left(\frac{L_{in} + v - 1}{qN_c} + \frac{r(L_{mid})}{rN_c} \right) \right) \tag{4.10}$$

$$D_4(i) = \left(1 - \frac{L_{in} + q(L_{out})}{qN_c} + \frac{r(L_{mid})}{rN_c} \right)^{i-q(L_{out})-1}. \tag{4.11}$$

Using the above analysis, the delivery probability can be computed for any value of l.

4.2.2 Choosing L_{in}, L_{mid} and L_{out}

Determining L_{in}, L_{mid} and L_{out} is now considered. The choice of these values has a significant on the delivery probability in the network. The goal here is to ensure that the l message copies reach the destination community C_d in the shortest time possible, as this will maximize the delivery probability. Figure 4.2 shows the time needed for the (L_{in}, L_{mid} and L_{out}) message copies to reach the destination community when $l = 11$, $q = 5$ and $r = 2$.

For copies given to nodes in the source community, $L_{in} + q$ time units are needed for them to reach C_d. This is based on the assumption that on average a node in the source community that has not received a copy of the message is encountered every time step. and q is the time needed for a node in C_s to meet a node in C_d. During this time, the source node will encounter nodes from C_d. Thus, the number of copies that are directly forwarded to nodes in the destination community is

$$L_{out} = \frac{L_{in} + q}{q}. \tag{4.12}$$

Furthermore, the source node forwards a message copy to a node in the other communities C_o if they meet during the $L_{in} + q - r$ time units. r time units are needed to deliver a message to C_d via a node in C_o. Thus, the number of copies that are

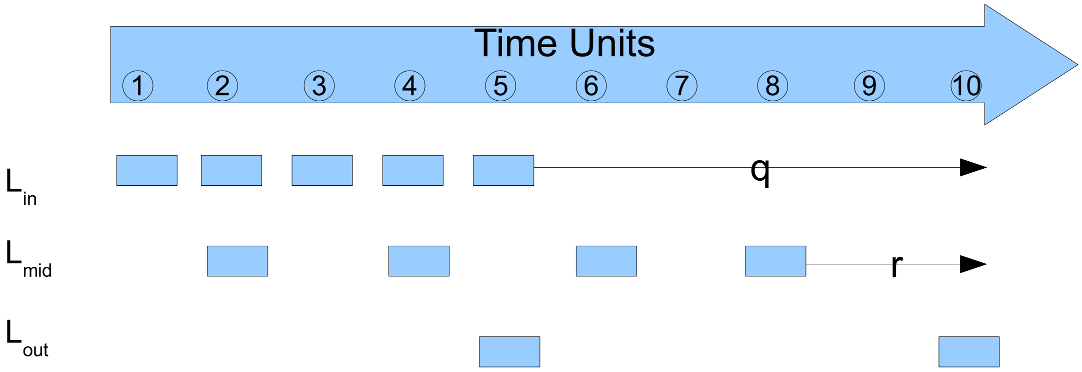


Figure 4.2: The distribution of message copies to encountered nodes.

forwarded to nodes in the other communities is

$$L_{mid} = \frac{L_{in} + q - r}{r}. \tag{4.13}$$

The total number of message copies is $l = L_{in} + L_{mid} + L_{out}$, which gives

$$l = L_{in} + \frac{L_{in} + q - r}{r} + \frac{L_{in} + q}{q}, \tag{4.14}$$

so that

$$L_{in} = \frac{rqL - q^2}{rq + r + q}. \tag{4.15}$$

4.2.3 Comparative Analysis

The delivery probability of the proposed method where all communities participate in delivering a message is compared to the corresponding probability when only the source and destination communities participate [9]. As an example, consider the delivery probability when $q = 3$, $r = 2$ and $l = 15$. Figure 4.3 shows the improvement in the delivery probability using the proposed method. These results exclude the final phase (Waiting phase). When only the source and destination communities participate in the delivery process, $L_{in} = 11$ and $L_{out} = 4$ [9]. The delivery probability when all communities participate is given for $L_{in} = L_{mid} = L_{out} = 5$, and the optimal distribution obtained using (4.15), which gives $L_{in} = 7$, $L_{mid} = 4$ and $L_{out} = 4$. The results for both of these distributions outperform the delivery probability when only the destination and source communities participate in message delivery. However, the optimal distribution provides the best performance, as expected, so that the messages reach the destination community in the shortest time possible.

The proposed technique will provide a greater performance improvement if q is increased. This indicates that a source node will take longer to meet a node in the destination community. Therefore, distributing message copies to nodes in an intermediate community will have a greater effect on the delivery probability. For example, when q is increased to 5 with the above parameters, the delivery probability with the proposed technique is improved by at least 30%, as shown in Figure 4.4. Conversely, the increase with the method in [9] is only 15%. In this figure, $L_{in} = 12$ and $L_{out} = 3$ when only source and destination communities participate, and the optimal distribution is $L_{in} = 7$, $L_{mid} = 5$ and $L_{out} = 3$. These results again confirm that the distribution obtained using (4.15) maximizes the delivery probability. Further, it can be concluded that when all communities participate in messages delivery, the delivery probability will be greater than when only the source and destination communities participate, if $q > r$.

4.3 Performance Evaluation

4.3.1 The ONE Simulator

ONE [21] is a discrete event simulator that combines movement modeling, routing simulation, visualization and reporting. Mobility models determine node movement in the simulator. Several mobility models including the random waypoint model (RWPM) are implemented in ONE. RWPM is a simple mobility model based on random directions and speeds. This model assumes a completely random movement for nodes, and is employed here for comparison purposes.

The parameters in [16] are used to provide a realistic environment. There are three node communities, each consisting of 40 nodes. Nodes spend 70% of the time in their own communities. The remaining time they travel through other communities. The simulation parameters are summarized in Table 4.1.

4.3.2 Simulation Results

The spray and wait routing protocol [2] is employed as it has been shown to be efficient in terms of the overhead ratio [2]. The number of message copies disseminated in the network is $l = 10$. Figure 4.5 shows that when all communities participate in message delivery, the delivery probability is increased by 20%. This validates the results in the previous section that more communities participating will lead to a better delivery probability. In a more realistic environment, the intermediate communities should contain more nodes than the source or destination communities. Therefore, the number nodes in these communities is now doubled to 80, and the results are presented in Figure 4.6. The delivery probability when all communities participate in message delivery is again better than when only the source and destination communities participate. In addition, the improvement in delivery probability is greater when the other communities are larger.

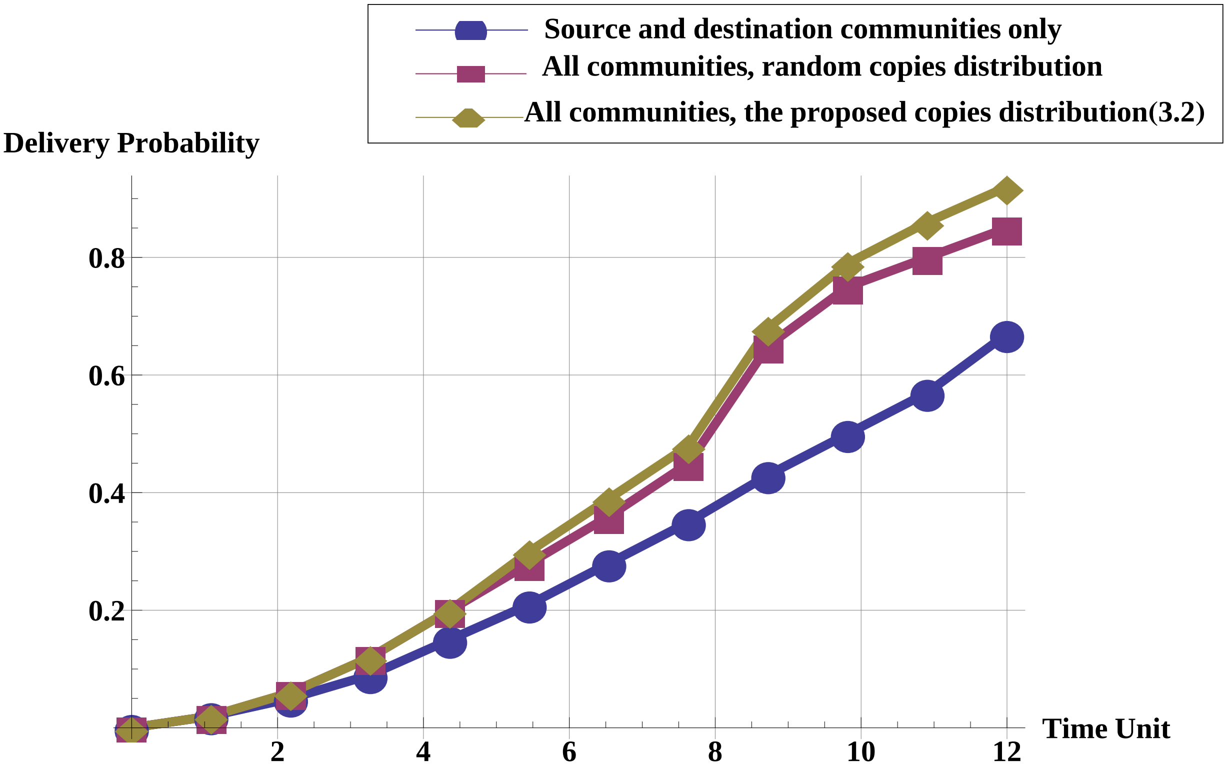


Figure 4.3: The delivery probability with $q = 3$, $r = 2$ and $L = 15$.

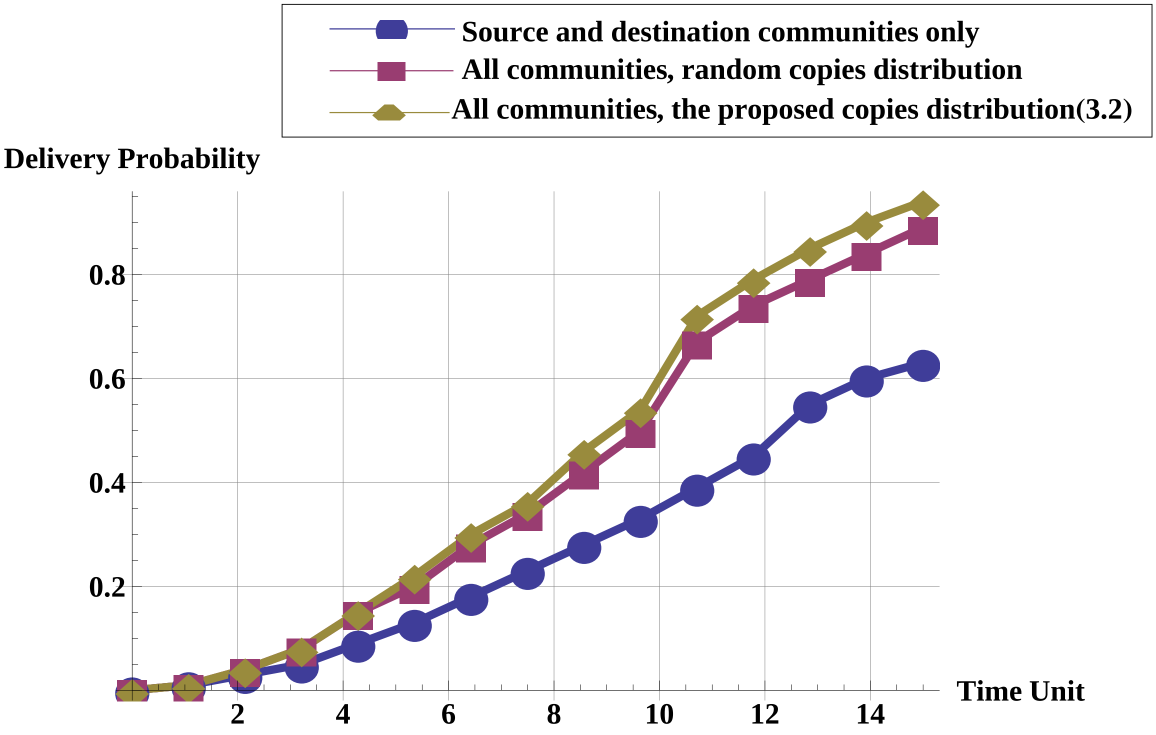


Figure 4.4: The delivery probability with $q = 5$, $r = 2$ and $L = 15$.

Table 4.1: The Simulation Parameters

Parameter	Value
Transmit Speed	250 KBps
Transmit Range	50 m
Speed of Nodes	.5 - 1.5 m/s
Message Size	.5 - 1 MB
Buffer Size	2000 MB

4.4 Conclusion

The efficiency of using social relationships for message delivery in an intermittently connected network (ICN) was considered. In particular, two approaches to node dissemination were considered, exchange messages with the source and destination communities only, or exchange messages with all communities. Analytic and simulation results were presented which show that exchanging messages with communities other than the source and destination communities can significantly improve the delivery probability.

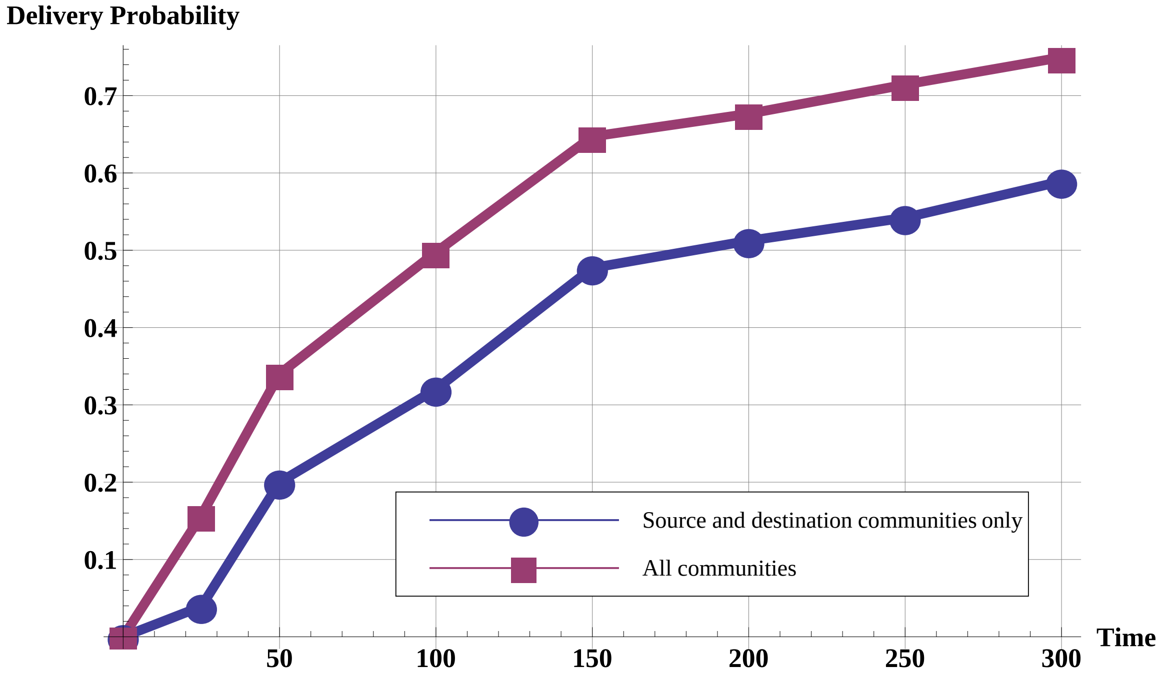


Figure 4.5: The delivery probability when the intermediate community has the same number of nodes as the source and destination communities.

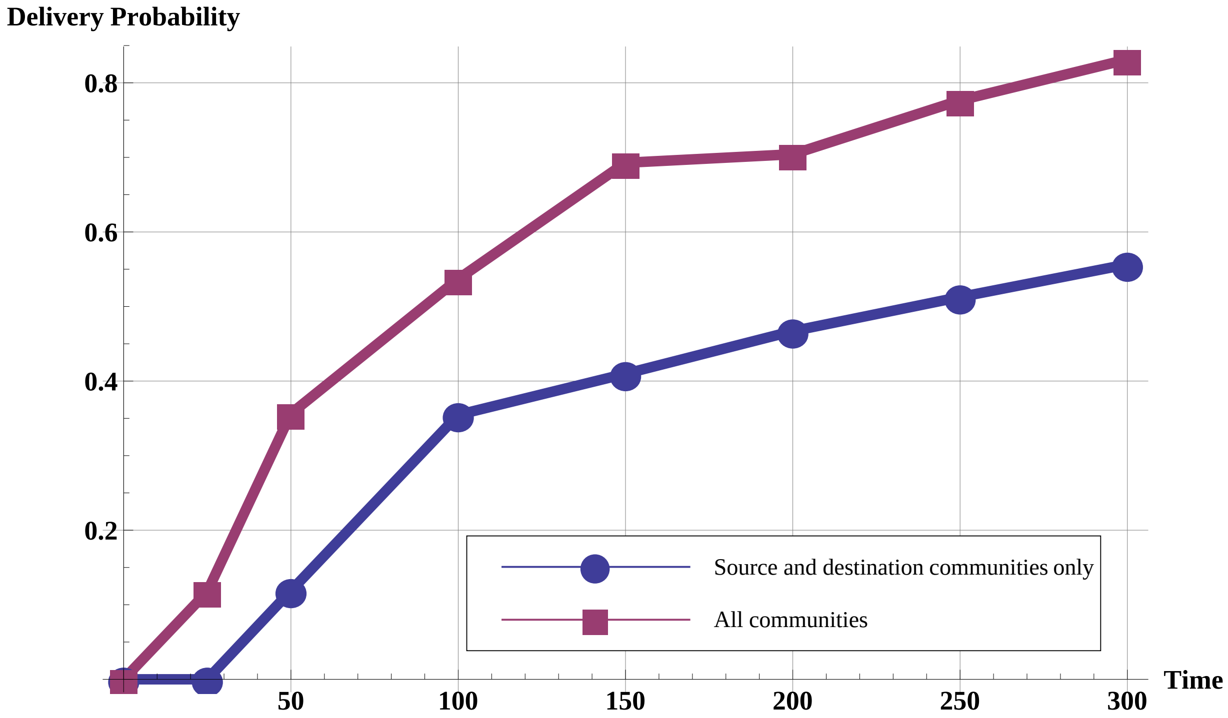


Figure 4.6: The delivery probability when the intermediate community has twice the number of nodes as the source and destination communities.

Chapter 5

Network Coding in Intermittentely Connected Networks

The previous chapters evaluated the performance of ICN routing protocols in terms of the message delivery probability when complete or fragmented messages are routed. This chapter investigate the delivery probability when messages are combined using network coding (NC). The use of message replication and NC in an ICN are compared in terms of the delivery probability.

Message replication is the process of exchanging messages between nodes. This implies that a message is copied to an encountered node intact without dividing the message or combining it with other messages. In this work, a message is limited to l copies in the network to limit the overhead. A message is exchanged when two nodes A and B meet if the following three conditions are satisfied. First, the message has not previously been received by the recipient node. Second, the number of copies disseminated is less than l. Third, the nodes are within range long enough for the message transfer to be completed.

The use of network coding in data transmission was introduced in [24]. In this case, linear combinations of previously received messages can be transmitted. For example, a three node topology where nodes A and C want to exchange messages via an intermediate node B is shown in Fig. 5.1. Node A (resp. C) sends message x_a (resp. x_c) to B, which then broadcasts the modulo 2 sum of x_a and x_c. Both A and C can recover the message from the other node using knowledge of their own message. Using the sum of the messages reduces the number of transmissions from 4 to 3 compared to sequential transmission (without network coding).

In general, M messages can be encoded using random linear network coding (RLNC) [31]. With RLNC, $x_1, \ldots, x_M$ are encoded as

$$f = \sum_{i=1}^{M} \varphi_i x_i \tag{5.1}$$

where φ_i is a coefficient randomly selected from a large finite field $\mathbb{F}_z$, $z = 2^y$ with, e.g. $y = 16$. A destination is able to retrieve the x_i (i.e, decode the messages), if N linearly independent encoded messages (combinations of the M messages), are received where $N \geq M$. Since z is large, the encoded messages are independent with high probability. For example, assume there are three messages and the destination receives three encoded messages f_i given by

$$\begin{aligned} f_1 &= \varphi_{11}x_1 + \varphi_{12}x_2 + \varphi_{13}x_3 \\ f_2 &= \varphi_{21}x_1 + \varphi_{22}x_2 + \varphi_{23}x_3 \\ f_3 &= \varphi_{31}x_1 + \varphi_{32}x_2 + \varphi_{33}x_3. \end{aligned} \tag{5.2}$$

This can be written as $F_M = \phi\ X_M$ where

$$\phi = \begin{bmatrix} \varphi_{11} & \varphi_{12} & \varphi_{13} \\ \varphi_{21} & \varphi_{22} & \varphi_{23} \\ \varphi_{31} & \varphi_{32} & \varphi_{33} \end{bmatrix}, \ X_M = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}, \ F_M = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix}.$$

Then matrix inversion can be employed to retrieve the message vector

$$X_M = \phi^{-1} F_M \tag{5.3}$$

The chapter is organized as follows. The chapter starts by discussing the related work to network coding in ICNs. Next, the intermittently connected network (ICN) model is presented. Based on this model, the delivery probability of the message is derived. Based on the driven probability, the network coding success factor (NCSF) is calculated. NCSF provides a measure of the improvement in the delivery probability when network coding is employed versus using message replication. Finally, some conclusions are given by the end of the chapter.

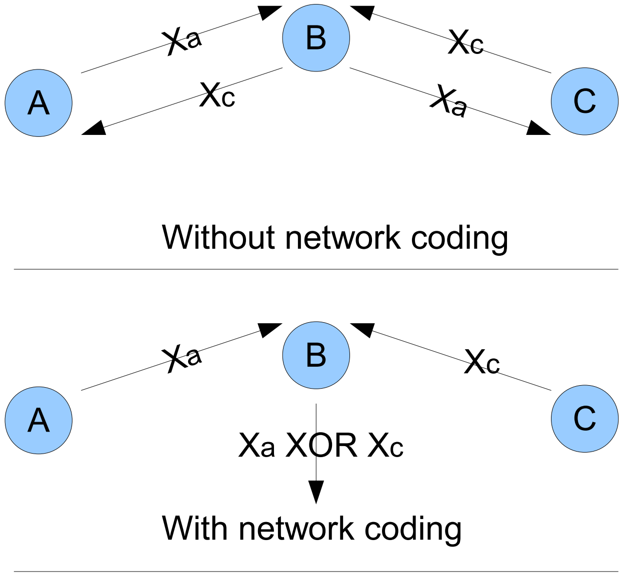


Figure 5.1: An example of network coding.

5.1 Related Work

Network coding has been employed to reduce the network bandwidth required (achieve the maximum information flow), in wired networks [24]. It has also been used to improve wireless broadcast networks [25, 26] and unicast networks [27, 28]. However, these results assume a dense network with high connectivity and so are not applicable to ICNs.

The benefits of network coding in ICNs have been studied for broadcast transmission in [29] and unicast transmission in [30]- [32]. Unicast transmission is the focus of this work. In [30], the epidemic routing protocol was employed, whereas in [31] messages were transferred based on the connectivity with other network nodes. Only simulation results are presented in [30, 31]. The benefits of network coding when epidemic routing is employed was analyzed in [32] using ordinary differential equations. The results presented here differ from those in [32] as follows:

1) In [32], the benefits of network coding are presented in terms of resource usage. In particular, the buffer occupancy is analysed when network coding is employed. Here, the delivery probability is analyzed to determine the improvement with network coding based on the number of encoded messages M.

2) In [32], results are presented for the Epidemic routing protocol [1], whereas the analysis presented here is applicable to any ICN routing protocol.

3) In this work, an explicit expression is presented for the delivery probability improvement when network coding is employed rather than message replication.

5.2 Intermittently Connected Networks

Consider a network with N nodes, and let the probability of a node meeting the destination D of a message be γ. Assume a node S has M messages to be delivered to D, i.e., S has encountered M nodes with messages for D. For comparison purposes, we assume S will give a message (with or without using NC), to the first l nodes it encounters and then these message are discarded. Further, when two nodes meet it is assumed that there is sufficient time to exchange only one message.

5.2.1 Network Coding in an ICN

This section presents a comparison of message exchange using message replication and network coding. Figure 5.2 shows a node with $M = 5$ messages x_1, x_2, x_3, x_4, x_5 and assume $l = 10$ is the expected number of encountered nodes before discarding a message. Using replication, a message is forwarded to only 2 of the 10 encountered nodes. Thus, with message replication and M messages, the probability of a node delivering these messages (D_r) is

$$D_r = (\gamma)^M \times \left(\frac{l}{M}\right)^M . \tag{5.4}$$

In this case, $\frac{l}{M}$ copies of each message are transferred to the l encountered nodes. Conversely, if RLNC is employed, the ith encountered node receives an encoded message f_i which is a combination of the five messages with different coefficients φ_i. This allows the destination to retrieve the original messages if any five of the encoded messages are received. Thus, the delivery probability with network coding (D_n) is

$$D_n = (\gamma)^M \times \binom{l}{M} \tag{5.5}$$

Figure 5.2 shows the distribution of message copies with message replication and network coding. To investigate the advantage of using network coding in an ICN, D_r is compared with D_n. Since the probability of meeting the destination node is a common factor in both expressions, it can be ignored. It is easily shown that

$$\binom{L}{M} = \binom{l-1}{M-1} \times \frac{l}{M}, \tag{5.6}$$

and

$$\binom{L}{M} = \binom{l-2}{M-2} \times \frac{l}{M} \times \frac{l-1}{M-1}, \tag{5.7}$$

so that

$$\begin{aligned} \tbinom{l}{M} \quad &= \quad \tbinom{l-M}{M-M} \times \tfrac{L}{M} \times \tfrac{l-1}{M-1} \times \cdots \\ &\quad\ \times \tfrac{l-(M-1)}{M-(M-1)} . \end{aligned} \tag{5.8}$$

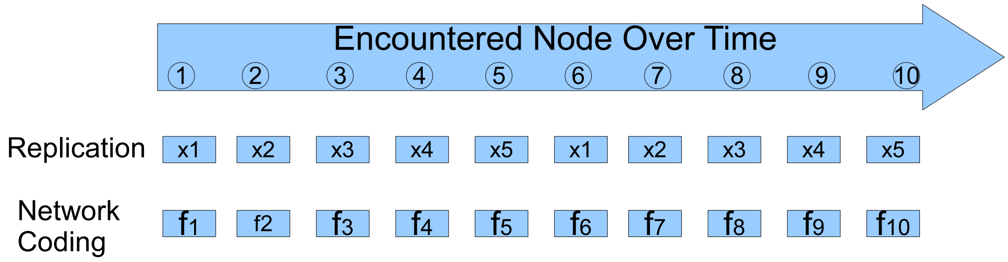


Figure 5.2: The distribution of l message copies using message replication and network coding.

Equation (5.8) can be written as

$$\begin{aligned}
\binom{l}{M} &= \frac{l}{M} \times \frac{l-1}{M(1-\frac{1}{M})} \ldots \times \frac{l-(M-1)}{M(1-\frac{M-1}{M})} \\
&= \frac{l}{M} \times \left(\frac{l}{M} \times \frac{1}{(1-\frac{1}{M})} - \frac{1}{M(1-\frac{1}{M})}\right) \cdots \\
&\times \left(\frac{L}{M} \times \frac{1}{(1-\frac{M-1}{M})} - \frac{M-1}{M(1-\frac{M-1}{M})}\right) \\
&= \frac{l}{M} \times \frac{l}{M} \left(\frac{1}{(1-\frac{1}{M})} - \frac{1}{l(1-\frac{1}{M})}\right) \cdots \\
&\times \frac{l}{M} \left(\frac{1}{(1-\frac{M-1}{M})} - \frac{M-1}{l(1-\frac{M-1}{M})}\right) \\
&= \left(\frac{l}{M}\right)^{M} \times \left(\frac{1}{(1-\frac{1}{M})} - \frac{1}{l(1-\frac{1}{M})}\right) \cdots \\
&\times \left(\frac{1}{(1-\frac{M-1}{M})} - \frac{M-1}{l(1-\frac{M-1}{M})}\right)
\end{aligned} \tag{5.9}$$

Define the network coding success factor (NCSF) as

$$\mathrm{NCSF} = \frac{D_n}{D_r} = \frac{(\gamma)^M \times \binom{l}{M}}{(\gamma)^M \times (\frac{l}{M})^M} = \frac{\binom{l}{M}}{(\frac{l}{M})^M}. \tag{5.10}$$

This provides a measure of the improvement in the the delivery probability when network coding is employed versus using message replication. Using (5.9), (5.10) can be simplified to

$$\begin{aligned}
\mathrm{NCSF} &= \left(\tfrac{1}{(1-\frac{1}{M})} - \tfrac{1}{l(1-\frac{1}{M})}\right) \times \cdots \\
&\quad \times \left(\tfrac{1}{(1-\frac{M-1}{M})} - \tfrac{M-1}{l(1-\frac{M-1}{M})}\right) \\
&= \left(\tfrac{l-1}{l}\right)\left(\tfrac{M}{M-1}\right) \times \cdots \\
&\quad \times \left(\tfrac{M}{l}\right)(l-M+1)
\end{aligned} \tag{5.11}$$

Since $l \geq M$, the worst case occurs when $l = M$, in which case NCSF $= 1$. The proof that NCSF> 1 when $L > M$ is as follows. Consider the first term in (5.11). This can be simplified to $\frac{l-1}{l} \times \frac{M}{M-1}$ which is greater than 1 when $l > M$. Next, consider the last term, which can be written as $M(1-\frac{M-1}{l})$. If $M(1-\frac{M-1}{l})>1$, then

$$\begin{aligned}(1-\tfrac{M-1}{l}) &> \tfrac{1}{M},\\ l &> \tfrac{M-1}{1-\frac{1}{M}},\\ l &> M,\end{aligned}$$

which holds. The remaining terms in (5.11) are $\frac{M}{i}\left(1-\frac{M-i}{l}\right)$, $1<i<M-1$, and using the same approach as above gives

$$\begin{aligned}\left(1-\tfrac{M-i}{l}\right) &> \tfrac{i}{M}\\ l\left(1-\tfrac{i}{M}\right) &> (M-i)\\ l &> \tfrac{M-i}{\left(1-\frac{i}{M}\right)}\\ l &> \tfrac{M(M-i)}{M-i}\\ l &> M.\end{aligned}$$

Thus each term in (5.11) is greater than 1 when $l>M$, so the product must be greater than 1 in this case.

5.3 Performance Evaluation

In this section, ICN performance is evaluated in terms of the delivery probability with and without network coding. The network coding success factor (NCSF) is used as a performance measure. Figure 5.3 shows the NCSF for $M=1$ to 5 for different values of l. A curve has been fit to the results for each value of l to show the trends. This figure shows that the benefits of using network coding increase as more messages are combined. This is also true as l/M increases.

ONE [21] is a discrete event simulator that combines movement modeling, routing simulation, visualization and reporting. Mobility models determine node movement in the simulator. Different mobility models including the random waypoint model (RWPM) are implemented in ONE. RWPM is a simple mobility model based on random directions and speeds. This model assumes completely random node movement, which is not realistic in a real world environment. Mobile devices are usually carried by humans, so it is more realistic to assume that nodes move towards a specific destination, then towards another destination, and so on. These destinations could be a mall or a restaurant, thus they may be called points of interest (PoI) in the

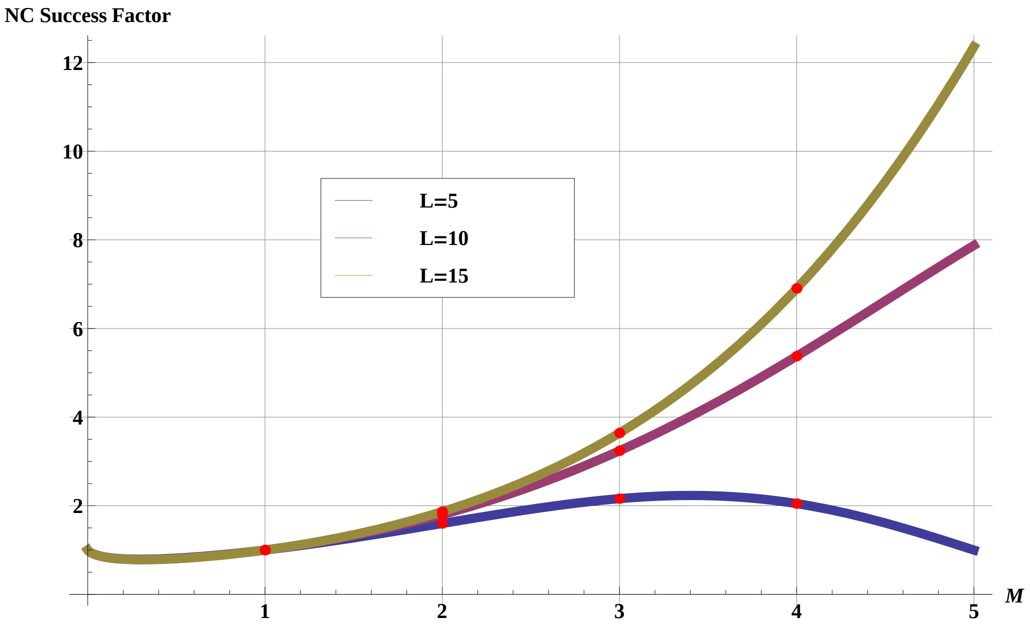


Figure 5.3: The network coding success factor (NCSF) for $M = 1$ to 5 and $l = 5, 10$ and 15.

network. The Helsinki City Scenario (HCS) is considered as a realistic simulation environment as it has nodes moving in the downtown Helsinki area. There are 160 mobile users moving by foot, 80 by car, and 12 by trams in the streets of downtown Helsinki. Each node represents a user moving with realistic speed along the shortest paths between different points of interest (PoIs) and random locations. The nodes are divided into four different groups having different PoIs and random probabilities are used to choose the next group-specific PoI or random place to visit. The trams follow real tram routes in Helsinki. The parameter settings are similar to those in [16]. The simulation area is 4500×3400 m^2. Table 5.3.1 summarizes the simulation parameters.

5.3.1 Simulation Results

The spray and wait routing protocol [2] is used to evaluate the delivery probability and overhead ratio. It is assumed that $l = 10$ nodes will be encountered by node S which has M messages to deliver to the destination D. Both message replication and network coding are used to disseminate messages. When message replication is used, each message is forwarded to $\frac{l}{M}$ nodes. When network coding is employed, (1) is used to encode the M messages for each encountered node. Thus the destination needs to receive any M of the l encoded messages to retrieve the original M messages.

Figures 5.4 and 5.5 show the delivery probability with message replication and network coding for $M = 2$ to 5. These figures show that network coding outperforms message replication. This is true even when M is small, and the advantage of using network coding increases as M increases. These results confirm the analysis given in the previous section. In particular, the NCSF indicates that the delivery probability with network coding should outperform message replication by a factor of 1.6 when $M = 2$ and 2.8 when $M = 3$. These values are similar to those shown in Figs. 5.4 and 5.5 at the end of the simulation time.

Table 5.1: The Simulation Parameters

Parameter	Value
Transmit Speed	250 kBps
Transmit Range	50 m
Message Size	0.5 - 4 MB
Buffer Size	2000 MB

5.4 Conclusion

The efficiency of network coding in an intermittently connected network (ICN) was considered. An analysis was presented to determine the delivery probability using network coding (NC). This showed that NC can significantly improve the delivery probability. This improvement was shown to increase with the number of encoded messages. These results were verified using a real world ICN simulation environment.

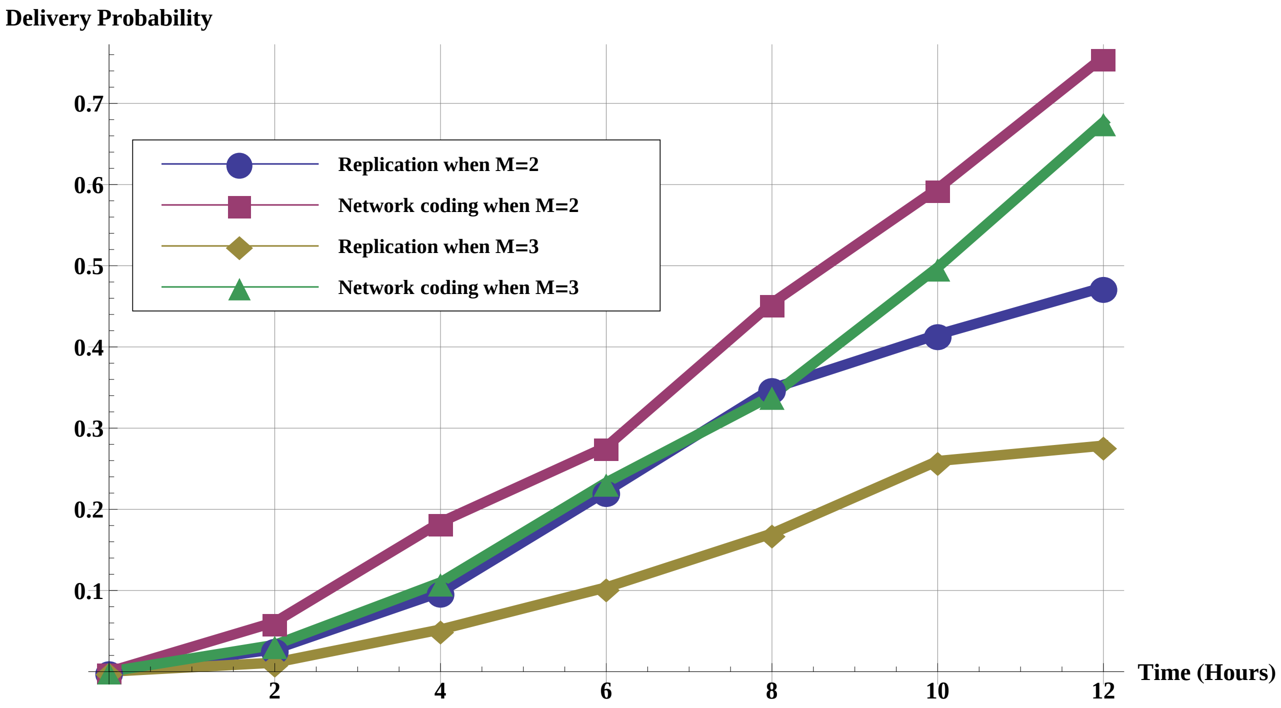


Figure 5.4: The delivery probability when network coding and message replication are employed with $M = 2$ and 3.

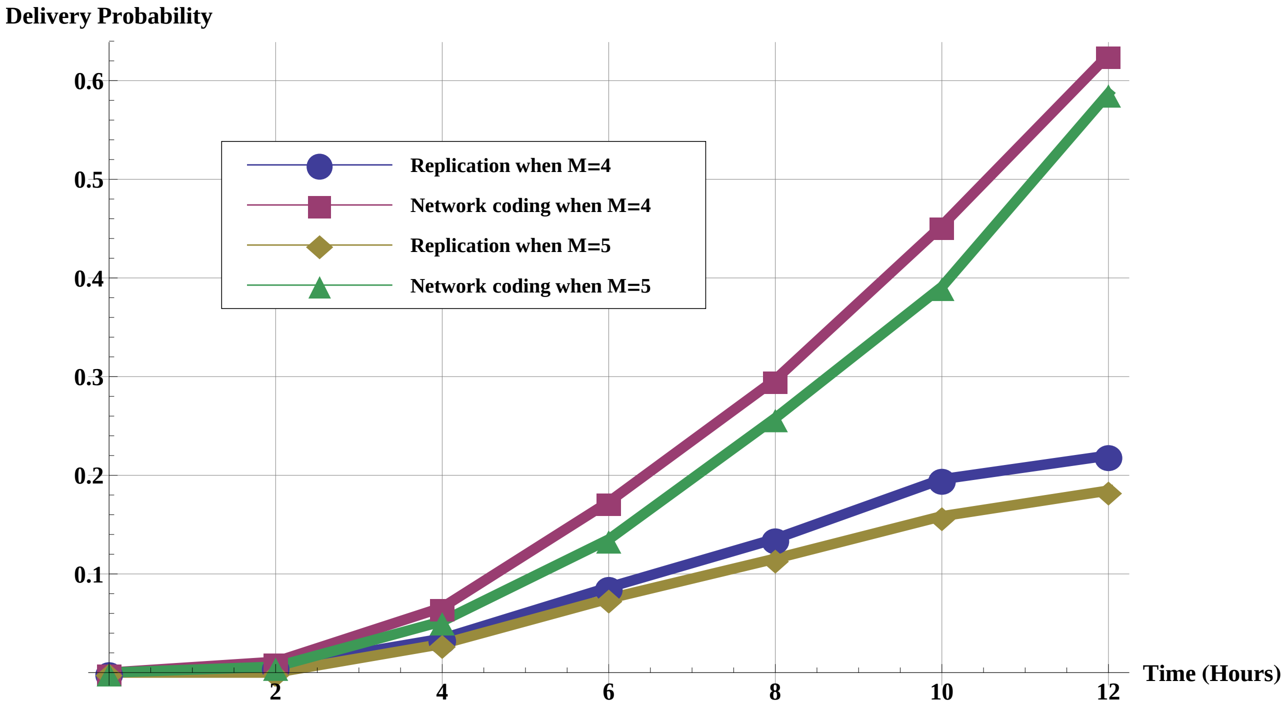


Figure 5.5: The delivery probability when network coding and message replication are employed with $M = 4$ and 5.

Chapter 6

Conclusions

6.1 Summary

This dissertation presented several methods to improve the message delivery probability in an intermittently connected network (ICN). These methods include dividing a message into fragments, transferring messages based on the social relationships between nodes, and combining messages that have same destination using network coding.

First, dividing a message into fragments was studied in Chapters 2 and 3. Chapter 2 focused on message fragmentation where all the fragments are required to reassemble a message at the destination node. Chapter 3 considered erasure coding in an ICN where only some fragments of a message are sufficient to reconstruct a message. The results in these chapters shown that fragmentation and erasure coding can improve the message delivery performance, but erasure coding typically outperforms fragmentation.

Next, the impact of using the social relationships between nodes to exchange messages in an ICN was studied in Chapter 4. Under this setting, a node must decide who best to give a copy of a message to in order to achieve a good delivery probability. A method to determine how many copies each node should receive was developed.

Chapters 2,3 and 4 considered the exchange of complete messages or message fragments. Chapter 5 presents the performance in an ICN when messages are combined using network coding. The benefits of network coding in an ICN are examined using quantitative analysis and simulation of a real environment.

6.2 Future Work

This section presents ideas for future work. As stated above, a variety of methods to improve the message delivery probability in ICNs has been presented in this dissertation. However, each chapter considered one proposed methodology. It would be interesting to combine these ideas or to identify analytically when it is best to employ each method. The following sections discuss some of these ideas.

6.2.1 Fragmentation under Social Networking Environment

Chapter 2 explored the efficiency of message fragmentation in ICNs. It was shown that fragmentation can improve the delivery probability, in particular when the number of encountered nodes is large. Chapter 4 presented the impact of social networking in ICNs. In particular, how messages should be copied to nodes from different communities, and how many copies of a message each node should receive to maximize the delivery probability. It would be interesting to study how many fragments encountered nodes from different communities should receive. The goal would be to develop a strategy for fragment distribution in a social networking environment.

6.2.2 Network Coding under Social Networking Environment

Chapter 4 identified three communities in a social networking environment, namely source node, destination node community, and other communities. Chapter 5 showed the benefits of message combination in ICNs using network coding. In the future, it would be interesting to use social networking concepts to combine messages using network coding. For example, a node may give a message to an encountered node from the destination community, which can then combine it with another message from this community. In fact, messages for each community can be combined. The question to be answered is how best to combine messages to improve the delivery probability in this environment?

6.2.3 The Impact of Message Size in Message Fragmentation or Combination

This dissertation presented three methods to exchange messages to improve the delivery probability. They can be exchanged as fragments, complete messages or combined with other messages. This raises the questions as to which approach a node should follow, and the effect of message size on this decision. For example, a node may decide to fragment a message when it is large, but how to identify whether a message is too large? This should be based on the size of the node buffers, and also on the contact history with other nodes. The goal would be to improve the message delivery probability in ICNs.

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