FACULTÉ DES ÉTUDES SUPÉRIEURES ET POSTOCTORALES

uOttawa

L'Université canadienne
Canada's university

FACULTY OF GRADUATE AND POSDOCTORAL STUDIES

Johnson Kuruvila
AUTEUR DE LA THÈSE / AUTHOR OF THESIS

Ph.D. (Electrical Engineering)
GRADE / DEGREE

School of Information Technology and Engineering
FACULTÉ, ÉCOLE, DÉPARTEMENT / FACULTY, SCHOOL, DEPARTMENT

Routing Algorithms for Ad hoc and Sensor Networks with a Realistic Physical Layer
TITRE DE LA THÈSE / TITLE OF THESIS

Amiya Nayak
DIRECTEUR (DIRECTRICE) DE LA THÈSE / THESIS SUPERVISOR

CO-DIRECTEUR (CO-DIRECTRICE) DE LA THÈSE / THESIS CO-SUPERVISOR

EXAMINATEURS (EXAMINATRICES) DE LA THÈSE / THESIS EXAMINERS

Miodrag Bolic	Ivan Stojmenovic
Thomas Kunz	
Stephen Olariu	

Gary W. Slater
Le Doyen de la Faculté des études supérieures et postdoctorales / Dean of the Faculty of Graduate and Postdoctoral Studies

ROUTING ALGORITHMS FOR AD HOC WIRELESS NETWORKS WITH A REALISTIC PHYSICAL LAYER

by

JOHNSON KURUVILA

THESIS

Presented to the Faculty of the Graduate School of

The University of Ottawa

in Partial Fulfillment

of the Requirements

for the Degree of

Doctor of Philosophy

The University of Ottawa

Library and
Archives Canada

Published Heritage
Branch

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque et
Archives Canada

Direction du
Patrimoine de l'édition

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence
ISBN: 978-0-494-18589-6
Our file Notre référence
ISBN: 978-0-494-18589-6

NOTICE:
The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:
L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

Dedicated

To My Family

and

To All My Teachers

Acknowledgements

Several people contributed to this thesis in a number of ways. Without their help and support, this work would not have been possible. I would like to take this time to thank them.

First and foremost, I want to express by deepest gratitude to my supervisors, Prof. Amiya Nayak and Prof. Ivan Stojmenovic for all their support during the course of this thesis work. Their expertise, promptness and generosity have been very instrumental in shaping the work presented in the thesis. I have been very lucky to have the opportunity to learn from and work with them.

I have received many comments and suggestions from the Thesis Proposal Committee for improving the content and presentation of this thesis. I want to thank the committee (Dr. Ivan Stojmenovic, Dr. Amiya Nayak, Dr. Thomas Kunz) for all the comments and suggestions.

I do not know how to express my appreciation to my wife and children, whose love, friendship, support, patience and devotion are beyond description.

JOHNSON KURUVILA

The University of Ottawa
October 2005

Abstract

The design and evaluation of existing routing protocols for ad hoc wireless networks normally assume an ideal physical layer model, where the message is received if and only if two nodes are within the transmission range. Routing protocols designed for this model show poor performance in simulators implementing more realistic models. In this thesis, we introduce a model that simplifies the realistic log-normal shadowing model by approximating the probability of packet reception based on distance between nodes. We then design several localized, position based routing algorithms with and without acknowledgements, with fixed message sizes. An appropriate MAC protocol for acknowledging the message is described. Localized position and acknowledgement based protocols are based on calculating ideal hop count, and optimizing expected progress. Improved, iterative versions of these protocols are also presented. These algorithms strive to optimize the expected hop count (EHC) measure in delivering the message from the source to the destination, where EHC takes into account all acknowledgements and retransmissions. We also propose several localized non acknowledgement-based algorithms. These protocols aim to maximize the probability of delivery of a packet from the source node to the destination node. Our performance evaluation shows that newly proposed localized protocols are competitive with global shortest weighted path based protocols, and superior to threshold based localized protocols that were also proposed in this thesis. We also studied the impact of imprecise location information on the performance of the suggested protocols.

Contents

List of Figures

Chapter 1

Introduction

1.1 Wireless Ad Hoc Networks

Due to their potential applications in various situations such as battlefield communications, emergency relief, search and rescue, environmental monitoring, etc., wireless ad hoc networks [5, 18, 23, 45] have recently emerged as a premier research topic. Such networks consist of hosts that communicate without a fixed infrastructure. Since there is no fixed infrastructure, a wireless ad hoc network can be deployed quickly. Such a network can be used in places where there is no other communication infrastructure present or where such infrastructure cannot be deployed because of cost, safety or security reasons. Communications take place over a wireless channel, where each host has the ability to communicate with others in its neighborhood, determined by the transmission range, R. Such a network is tolerant of the failure or departure of individual nodes, because the network does not rely on a few critical nodes for its organization or control. Additional nodes can be added easily to the network. The nodes are free to move and organize themselves arbitrarily and the topology may change rapidly and unpredictably [48]. Since there is no infrastructure, every host has to determine its environment when the network is formed.

Some of the main characteristics of mobile ad hoc networks are summarized below:

- **Dynamic topology:** Since the nodes are free to move arbitrarily, the network topology may change rapidly and arbitrarily.
- **Energy constrained operation:** Due to very limited energy availability (normally, batteries), energy conservation issues are very important in mobile ad hoc networks.
- **Limited physical security:** Mobile networks are prone to physical security threats.
- **Bandwidth constrained operation:** Wireless links have significantly lower capacity compared to hardwired links. Additional factors like multiple access, fading, noise and interference also contribute to reduced bandwidth.

1.2 Routing in Mobile Ad Hoc Networks

Routing is a fundamental and difficult problem in Mobile Ad Hoc Networks (MANETs). The difficulty is due to the fact that a MANET is a collection of mobile wireless nodes with no fixed infrastructure. In the routing task, a message is to be sent from a source node to some destination node. The nodes in the network may be static or mobile. The task of finding and maintaining routes in ad hoc networks is nontrivial since host mobility can result in unpredictable topology changes.

Factors such as multi hop connections, mobility, limited battery power and bandwidth constraints make the design of routing protocols a major challenge [48]. However, active interest in this area has resulted in a large number of routing algorithms and protocols. Many have proposed new routing solutions leveraging features from existing Internet routing algorithms [22,35,43]. Interest within the Internet Engineering Task Force (IETF) is also growing as evidenced by the formation of a working group with a charter to develop a framework for routing in MANET. A review and performance analysis of some of these protocols are presented in [50] [13].

Some of the qualitative properties of MANET routing protocols are:

- **Distributed operation:** Even for small networks, the route computation must be distributed due to the dynamic nature of MANETs.
- **Loop-freedom:** As in any routing protocol, loop freedom is important for efficient use of resources and better overall performance.
- **Demand-based operation:** The routing protocol should be able to adapt to traffic on demand for efficient use of network energy and bandwidth resources. However, demand-based operation can result in increased delay.
- **Proactive operation:** In cases where increased delay is not acceptable (due to demand-based operation), proactive mode of operations should be supported.

Most of the MANET routing protocols belong to one of two major categories, namely on-demand (reactive) or proactive protocols. Proactive protocols attempt to maintain correct routing information for all nodes in the network at all times. On-demand routing protocols do not maintain correct routing information at all nodes at all times. Instead, such information is gathered on demand. Chapter 2 provides a brief survey of routing protocols and attempts to further classify them based on their characteristics.

In this thesis we are particularly interested in position based routing algorithms. In such algorithms, the source node is aware of the geographic position of the destination. Several location update schemes for efficient routing have been proposed. A review of such schemes can be found in [54]. A number of these proposed algorithms are non-local and require the complete knowledge and maintenance of the network topology. Recently, several *localized* routing algorithms have been proposed (a brief survey of them is given in [56]) where nodes do not require the complete network topological information to perform the routing task. More precisely, to perform the routing task, nodes require its own position and the position of its 1-hop neighbors (in some cases position of its 2-hop neighbors) and the position of the destination. Consequently, neighboring nodes are aware of distances between them.

1.3 Motivation for the Thesis

The transmission power of the nodes in MANET could be fixed or adjustable. When the transmission power is fixed, all nodes have a fixed transmission radius R, which can be defined in different ways. The design and evaluation of existing network layer protocols (with a few exceptions, discussed in Chapter 2) for MANETs assume an ideal physical layer model, where two nodes communicate if and only if the distance between them is at most R. In this model, known as the unit graph model (also referred to as the perfect-reception-within-range model), two nodes within the transmission radius can exchange correctly bits, packets and messages (we initially assume that messages are composed of a few fixed length packets, and packets are composed of fixed length bit-strings). This unique transmission radius value is used for communication at all layers within the unit graph model.

By using an ideal physical layer model, proper message reception is often assumed, if the destination is within the transmission radius. However, this is not true, and often results in message losses and retransmission of messages, hence impacting the routing protocol performance. The MANET community now has an increased understanding of the need for realistic physical layer models. Chapter 2, Section 2.3 reviews many of the recent results in this area. In this thesis, we apply the log normal shadowing model [49] to represent a realistic physical layer, for designing new, position based, localized algorithms.

By applying a realistic physical layer, the notion of transmission radius needs to be carefully defined and properly used in algorithms. The packet reception probability $p(x)$ depends on the probability $b(x)$ of receiving a bit successfully and on the length of the packet. There are three different ways of determining R so that such function can be applied in protocols. The radius R can be selected so that the probability of receiving a single bit, that is, BER (bit error rate) is 0.5. The second option is to divide a message into fixed size packets, and transmit each packet individually. In this case, R can be determined so that packet error rate at distance R is 0.5. It obviously depends on packet length. The error rate for acknowledgements is then also 0.5 at distance R, since acknowledgements are assumed to be single packets with equal packet length, therefore the same probability for their reception is used. This interpretation for R appears to be the most convenient for deriving protocols and various acknowledgement schemes and we follow this approach in Chapters 3 and 4. The third option is to decide R for each message separately, so that the probability of receiving a message is 0.5 at distance R. In this case R depends on message length, and acknowledgements do not have the same probability of being received. The design of algorithms with variable length packets can be a good future extension to the work presented in this thesis.

1.4 Assumptions

We assume that each node has a low-power Global Position System (GPS) receiver, which provides the position information of the node itself. If GPS is not available, the distance between neighboring nodes can be estimated on the basis of incoming signal strengths. Relative co-ordinates of neighboring nodes can be obtained by exchanging such information between neighbors [39]. We also assume that all nodes in the network have a fixed transmission power and hence fixed transmission radius. For designing the MANET routing protocols, we have studied the case with fixed data packet length. The acknowledgement packets are assumed to be of the same size as the data packets.

1.5 Contributions of this Thesis

The basic contributions made in this thesis are outlined below. To the best of our knowledge, this is the first study of localized, position based routing algorithms in MANET with and without acknowledgements, considering a realistic physical layer.

In this thesis, we introduce a model that simplifies the realistic log-normal shadowing model by approximating the probability of packet reception based on distance between nodes. A *MAC* layer protocol is proposed and analyzed, to be used with acknowledgements, between two nodes. Then, several localized, position based, greedy routing algorithms for ad hoc wireless networks, with acknowledgements are proposed. These protocols are based on calculating ideal hop count, and optimizing expected progress. Improved, iterative versions are also presented. These algorithms strive to optimize the expected hop count (EHC) measure in delivering the message from the source to the destination, where EHC takes into account all acknowledgements and retransmissions. The proposed protocols include *IHCR, Expected Progress* schemes and variants, *Projection Progress* schemes and variants and *tR-Greedy* schemes. These results were published in the *IEEE Journal of Selected Areas of Communications* [29]. An initial version of this paper was published in the proceedings of the *1st IEEE Int. Conf. on Mobile Ad-hoc and Sensor Systems (MASS)* [28]

We considered the design of similar protocols without acknowledgements and proposed a number of new protocols. These protocols aim to maximize the probability of delivery of a packet from the source node to the destination node. These results will be published in the *Journal of Parallel and Distributed Computing* [30]. An earlier conference version was published in the proceedings of the *1st Int. Workshop on Algorithms for Wireless and Mobile Networks (A-SWAN)* [27].

We also studied the impact on imprecise location information on the performance of these protocols and concluded that the impact is significant.

Survey articles covering the proposed approach, protocols and results were also published in the *Computer Communications Journal* [59] and the *IEEE Communications Magazine* [58].

The localized nature of the protocols presented in this thesis avoid the energy expenditure and communication overhead needed to build and maintain the global topological information. The simulation results show that the performance of the new localized algorithms is close to the performance of the shortest (weighted) path algorithms, which require global knowledge, which is a good achievement.

It is anticipated that the direction of research presented in this thesis will soon receive more attention in the ad hoc networks research community.

1.6 Thesis Outline

The reminder of this thesis is organized as follows.

Chapter 2 briefly surveys ad hoc routing protocols and some of the existing physical layer models. The log-normal shadowing model is explained in more detail. We also briefly survey some recent publications that consider the application of realistic physical layer models in the design of routing protocols for ad hoc and sensor wireless networks.

In Chapter 3, we first derive an expression for packet reception probability in the log-normal shadowing model. The packet reception probability function is then approximated for ease of computation in our protocol design. We propose a MAC layer protocol to be used between 2 nodes. Then, several new localized, hop-count optimal, acknowledgement based routing algorithms for ad hoc and sensor networks are proposed. Simulation results and comparative studies of these protocols are also presented.

In Chapter 4, many new non acknowledgement-based algorithms are proposed, along with simulation, performance and comparative study results.

Chapter 5 presents the overall summary and highlights the significance of the work presented in the thesis. Concluding remarks and suggestions regarding future directions and possible extensions of the work presented in this thesis are also offered.

Chapter 2

Literature Review

2.1 Routing Protocols for Ad Hoc Networks

As outlined in Section 1.2, routing is a fundamental problem in MANETs. The fact that a MANET is a collection of mobile wireless nodes with no fixed infrastructure adds to the difficulty of the routing problem. A routing algorithm describes procedures that should be followed for computing route information between network nodes.

In recent years, many routing protocols have been proposed for MANETs. There have also been several works comparing the performance and characteristics of these protocols [8, 13, 16, 32, 50, 51]. The large variety of routing protocols reflects the fact that these protocols implement different strategies and exhibit different key characteristics. We can classify MANET routing protocols into various categories based on their key characteristics. However, it is important to observe that these categories are not disjoint. Some of the main categories include:

- Uniform vs. non-uniform protocols
- Hierarchical topology/clustered routing

- Proactive vs. on-demand routing protocols
  - On-demand or reactive protocols
  - Proactive or table driven protocols
  - Hybrid Protocols
- Position based protocols

Some additional protocol characteristics such as *full vs. reduced topology information*, *use of broadcast messages*, *use of source routing*, *distance-vector routing vs. link-state routing*, *past history vs. prediction methods* and *recovery strategies employed* can also be used to further classify MANET routing protocols.

2.1.1 Uniform vs. non-uniform protocols

A uniform protocol does not apply any special role to any nodes, while non-uniform protocols assign special roles to some nodes [16]. Clustering protocols are usually non-uniform. Some examples of non-uniform protocols include *CEDAR - Core-Extraction Distributed Ad Hoc Routing* [53], *HSR - Hierarchical State Routing* [21] and *LANMAR - Landmark Routing Protocol* [42]. Examples of uniform protocols include *DSDV -Destination Sequenced Distance Vector* [43] and *DSR - Dynamic Source Routing* [22].

2.1.2 Hierarchical topology/clustered routing

Hierarchical or clustered protocols use clusters to introduce some structure into the dynamic nature of the ad hoc network. Clusters are normally represented by a dedicated node called the *cluster-head.* The cluster-heads are usually responsible for managing communication within a cluster and are aware of nodes joining or leaving the cluster.

Cluster formation and the election of cluster-heads is usually a significant effort in this category of routing protocols, resulting in increased signalling traffic. However, once clusters are formed, a significant amount of routing traffic can be localized to the cluster. Cluster-heads exchange summarized cluster information, reducing the overall network signalling traffic.

Examples of routing protocols in this category include *HSR - Hierarchical State Routing* [21], *LANMAR - Landmark Routing Protocol* [42] and *FSR - Fisheye State Routing* [41].

2.1.3 Proactive vs. on-demand routing protocols

The classification of protocols into proactive and on-demand categories is based on how the routing information is gathered and maintained by the protocol.

Proactive or table-driven routing protocols attempt to maintain correct routing information on all nodes in the network at all times. When the network topology changes, nodes are updated about the change and routing tables are updated as well. Proactive protocols can be further divided into protocols that update routing information at regular intervals and protocols that update only when certain events occur. *Event driven* protocols send update packets only when there is a change in the topology, while protocols that are updated at regular intervals send their topology information to other nodes at regular intervals, irrespective of any topology changes.

Examples of event driven proactive protocols include *DSDV - Destination Sequenced Distance Vector* [43], *WRP - Wireless Routing Protocol* [35], *TORA - Temporally Ordered Routing Algorithm* [40] and *GSR - Global State Routing* [10].

Regularly updated proactive protocols include *LANMAR* [42], *FSR* [41] and *OLSR -Optimized Link State Routing* [11].

On-demand routing protocols will not maintain correct routing information at all nodes at all times. Instead, such information is gathered on demand. A route request and a route selection process must be performed before a message can be sent out. This leads to an initial setup delay for messages, if the route is not known at the start. Applications that use on-demand routing protocols need to be tolerant of such initial set-up delays. The main advantage of an on-demand routing protocol is that the communication overhead on the wireless channel is reduced. Examples of on-demand routing protocols include *ABR - Associativity Based Routing* [62], *AODV - Ad hoc On demand Distance Vector* [44] and *DSR - Dynamic Source Routing* [22]

Hybrid protocols use both proactive and on-demand routing techniques. *ADV - Adaptive Distance Vector Routing* [6] and *ZRP - Zone Routing Protocol* [19] are examples of hybrid routing protocols.

2.1.4 Position based protocols

There exists a vast amount of literature devoted to position based routing in MANETs. In such algorithms, the source is aware of the geographic position of the destination. Several location update schemes for efficient routing have been proposed. A review of such schemes can be found in [54]. A number of these proposed algorithms are non-local and require the complete knowledge and maintenance of the network topology. Recently, many *localized* routing algorithms have been proposed, where nodes do not require the complete network topological information to perform the routing task. Surveys of position based routing algorithms can be found in [34, 56].

2.1.4.1 Localized Greedy Algorithm

Finn [17] proposed a localized greedy scheme.

In a greedy scheme, a node currently holding the message will forward

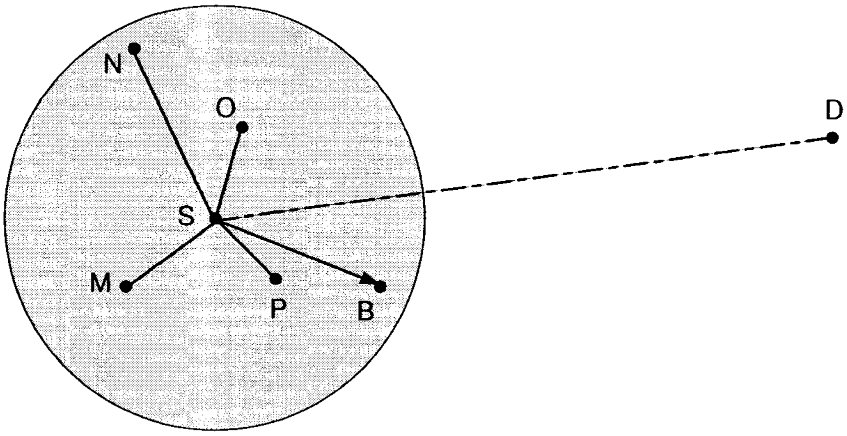


Figure 2.1: Greedy routing.

it to the neighbor that is closest to the destination. Only nodes closer to the destination than the current node are considered. The general idea of greedy routing is illustrated in Figure 2.1. In Figure 2.1, the source node S will forward the message to node B, since it is the closest to the destination D. While making the forwarding decision, among all nodes within the transmission region (M, N, O, P, B), the candidate nodes are only O, P and B since these are the only nodes closer to the destination D than the source node S.

If regular hop count is the only performance measure, greedy schemes do very well. This is because, from among the neighbors, the farthest node (from the source, but closest to the destination) is always selected as the preferred choice, thereby reducing unwanted intermediate nodes.

2.1.4.2 Random Progress (RP) Algorithm

In *Random Progress* algorithm [38], the node currently holding the message will forward it to any other node that is closer to the destination than itself. In Figure 2.2, following the Random Progress routing scheme, node S could forward the message to nodes A, B, E, F or G.

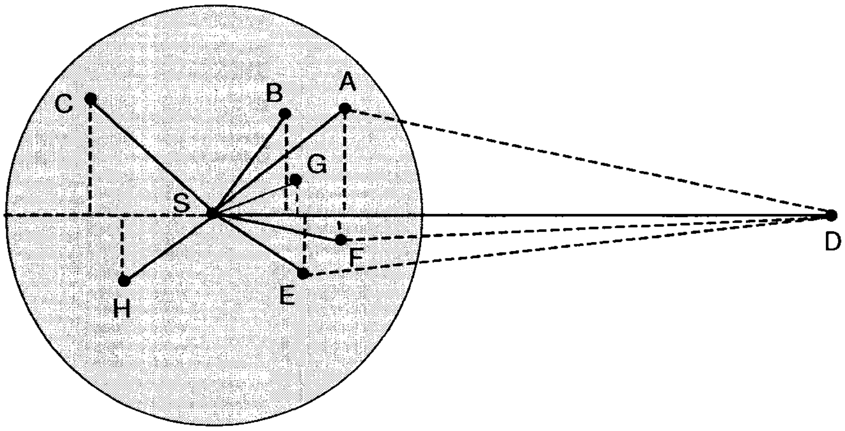


Figure 2.2: RP, NFP, MFR, DIR, NC Routing.

2.1.4.3 Nearest Forward Progress (NFP) Algorithm

In *Nearest Forward Progress* algorithm [20], the source node S holding the message will forward it to the nearest forward progress node. In Figure 2.2, the source node S will forward the message to B, since it is the node with the minimum forward progress. Forward progress of any node is the positive projection of the line connecting the source and the particular node onto the line connecting the source and the final destination.

2.1.4.4 Most Forward within Radius (MFR) Algorithm

In *Most Forward within Radius* algorithm [61], the node currently holding the message will forward to the neighbor with the most forward progress. In Figure 2.2, the source node S will forward the message to node A. However, if we followed the greedy scheme, node S will forward the message to node F, since it is closest to the destination D.

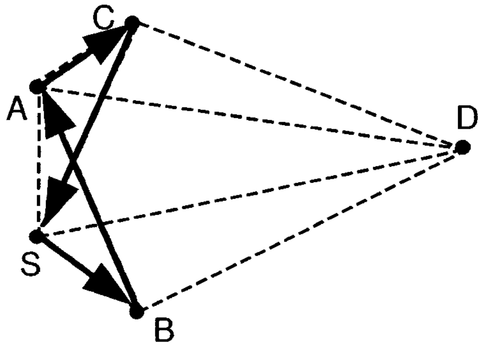


Figure 2.3: Loops in DIR algorithm.

2.1.4.5 Compass Routing or DIR Algorithm

There are several distributed protocols, which do routing based on the direction of the destination. In *Compass Routing* or *DIR* algorithm [25], the source node uses the location information for the destination to calculate its direction. The source node then forwards the message to a neighbor, which has the closest direction towards the destination. This process is repeated until the destination node is hopefully reached.

In Figure 2.2, the source node S currently holding the message will forward it to F, since it has the closest direction towards the destination D. However, the major drawback of the *DIR* approach is that it is not loop free, as illustrated in Figure 2.3 for a message originating from node S to node D.

2.1.4.6 Nearest Closer (NC) Algorithm

The NC (Nearest Closer) algorithm was introduced in [55]. In NC algorithm, a node S currently holding a message will forward it to a neighbor that is nearest to S, but closer to destination D than S.

In Figure 2.2, the source node S will forward the message to node G, which is closest to S among the nodes that are closer to destination D than S.

2.1.4.7 FACE and GFG routing Algorithms

FACE routing [7] is a position-based routing algorithm for planar geometric graphs. The FACE routing algorithm propagates a packet along those faces of the planar subgraph which are intersected by the line segment connecting the source to the destination. This routing algorithm needs only constant memory. Another milestone achievement is the localized greedy-face-greedy (GFG) algorithm, proposed in [7], which guarantees delivery under ideal MAC layer and correct position information. It applies the greedy algorithm whenever possible, and restores to face routing in recovery mode.

2.2 Physical Layer Models

In this section, we first briefly describe some of the existing physical layer models. A rich set of models and tools for analyzing the physical layer is presented in [49]. Then, we discuss the log-normal shadowing model in detail.

Most of the published results in MANET routing and broadcasting are based on free-space or two-ray ground propagation models, which are simplistic and idealistic physical layer models [47]. However, in real scenarios, the received signal strength is not only dependent on the distance between the transmitter and the receiver but also on the environment. Moreover, subsequent transmissions with the same transmission power, between the same nodes in the same environment are not received with the same signal power. This means that, depending on the threshold for correct reception, the message may or may not be received based on some random events. Following [47], a realistic physical layer is modelled using the shadowing propagation model, where the noise element is modelled by a Gaussian distribution. A brief description of the different propagation models is given below.

2.2.1 Free Space Model

The free space model is the simplest propagation model and is used when the transmitter and the receiver share a clear unobstructed line-of-sight. This model is very useful for satellite and line-of-sight microwave radio links. The received power level is predicted as a decaying function of the distance d between the transmitter and the receiver. The free space model is an ideal model and the transmission range is assumed to be a perfect sphere. If the receiver is within this transmission range it receives all messages sent by the transmitter. Otherwise, the messages are lost.

The received power in the free space model is given by the following formula:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

where

- $P_r(d)$ is the received power at distance d
- P_t is the transmitted power
- G_t is the transmitting antenna gain
- G_r is the receiving antenna gain
- λ is the wavelength
- L is the system loss ($L \geq 1$)

The free space model breaks down for small d values and yields good results only in the *far field* region, which is defined to be $d > \frac{2D^2}{\lambda}$ where D is the largest linear dimension of the antenna.

2.2.2 Two-ray Ground Propagation Model

The two-ray ground propagation model considers a direct path and a ground reflection path between the transmitter and the receiver. For long distances, it is shown that this model is more accurate than the free space model [49]. The received power can be expressed as

$$P_r(d) = \frac{P_t G_t G_r {h_t}^2 {h_r}^2}{d^4 L}$$

where h_t and h_r are the heights of the transmitting and receiving antennas and d is the distance between transmitter and receiver. The two-ray ground model also represents an ideal model when the transmission range is a perfect sphere.

2.2.3 Shadowing Propagation Model

The free space and two-ray ground models predict that the transmitted power decays as a function of distance. The shadowing model is a statistical model. The mean received power at a distance d is computed relative to $P_r(d_0)$ (since the free space and two-ray ground models do not hold for $d = 0$) as

$$[\frac{P_r(d)}{P_r(d_0)}]_{db} = -10\beta \log(\frac{d}{d_0}) + X_\sigma$$

This is called the log-normal shadowing model (in dBs). The shadowing model consists of two components, the path loss model, where d_0 is the reference distance, β is the loss exponent. X_σ is a Gaussian random variable with zero mean and standard deviation σ. Both β and σ are obtained by measurements.

The average path loss $\overline{PL}$ for an arbitrary distance d can be expressed as a function of distance, using the path loss exponent β, as follows:

$$\begin{aligned} \overline{PL}(d) &\propto [\frac{d}{d_0}]^\beta \\ \overline{PL}[dB] &= \overline{PL}(d_0) + 10\beta \log[\frac{d}{d_0}] \end{aligned}$$

With log-normal shadowing model,

$$\begin{aligned} PL(d)[dB] &= \overline{PL}(d) + X\sigma \\ &= \overline{PL}(d_0) + 10\beta \log[\frac{d}{d_0}] + X_\sigma \end{aligned}$$

$$P_r(d)[dBm] = P_t[dBm] - PL(d)[dB]$$

$$P_r(d)[dBm] = P_t[dBm] - \overline{PL}(d_0) - 10\beta \log[\frac{d}{d_0}] - X_\sigma$$

where X_σ is the 0 mean random variable (in dB) with standard deviation of σ (in dB). The free space propagation model is used to calculate details at the reference distance d_0.

2.3 Physical Layer Considerations in Protocol Design

The work presented in this thesis has been inspired by recent observations made in [3,4,12,47]. Qin and Kunz [47] concentrate on the impact of a realistic physical layer (shadowing propagation model) on the performance of well known *AODV* [44] and *DSR* [22] on-demand wireless routing protocols. *AODV* and *DSR* are non position-based routing schemes, where a source issues route discovery requests via blind flooding (each node receiving a route request message will retransmit it once), and the destination replies to the source using a memorized path. Qin and Kunz [47] proposed new signal power thresholds for route discovery to enable the selection of links with sufficiently strong signal strength and reduce some protocol control messages. They report a significant increase in the packet delivery ratio and a decrease in packet latency, and suggest that link status is a better metric than hop count for selecting routes in shadowing models.

Couto *et al.* [12] proposed to use the *expected transmission count metric* (ETX) for finding high throughput paths on multi-hop wireless networks. The ETX metric takes into account the effects of link loss ratios, asymmetry in the loss ratios between the two directions of each link and interference among links of a path. Then they apply the ETX metric to $DSDV$ and DSR routing protocols and show that the ETX metric improves performance. The protocols are tested on a 29 node IEEE 802.11 test-bed. Their observations are based on a real implementation, without giving any theoretical results or analysis in support of the observations.

Banerjee and Misra [3, 4] considered the cost of retransmitting messages due to link errors, and derive some optimal formulas and protocols for minimum energy routing. They considered separately end-to-end retransmissions EER (no acknowledgement or error recovery between any two links on a path) and hop-by-hop retransmissions HHR (where a message is retransmitted between two nodes until it is received and acknowledged correctly). They first observed that the BER associated with a particular link is a function of the ratio of received signal power to the ambient noise. In the variable-power transmission, they concluded that the cost is optimal if a transmitter adjusts transmitting power to ensure that the signal strength received by the receiver is independent of the distance d between two nodes. The optimality measure selected to make this conclusion is unclear. It is used, however, as a basis for making other conclusions. One immediate consequence of this approach is that, since reception power is fixed, the link error rate between any two nodes is fixed; therefore, the probability p_{link} used in their expressions is a fixed number. It also follows that the transmission power is proportional to d^{β}, where d is the distance between two nodes S and D and β is the path loss exponent. The authors then derived optimal minimum energy paths in EER case. The optimal number of hops N to minimize energy for transmission, assuming that retransmissions from S and D are done until the message is received, is computed. The cost of acknowledging back from destination to source is not considered. In the ideal case, additional nodes are placed so that the distance between them is $\frac{d}{N}$. The energy for N such transmissions is $N(\frac{d}{N})^\beta$. The probability of receiving the message correctly after N hops is $(1 - p_{link})^N$. Thus, a message will be sent an expected $\frac{1}{(1-p_{link})^N}$ times before being received correctly. Thus, the expected energy after retransmissions if necessary, is $\frac{N(\frac{d}{N})^\beta}{(1-p_{link})^N}$. This is then considered as a function of N, with d and p_{link} being fixed, to derive the optimal value for N, which depends only on β and p_{link}. However, since the *optimal* value for N is independent of the distance d between source and destination, the same derivation can be recursively repeated between any two nodes in N intervals between S and D (thus producing N^2 intervals instead of N intervals), to arrive at even more power efficiency with the same arguments. This is clearly contradictory. In fact, with the energy model used, the optimal value for N is indeed infinitely large. However, if the computing cost and minimal reception power are taken into account, the optimal value of N is a finite number. The authors also considered the HHR case, using similar arguments.

Nadeem and Agrawala [36] define energy efficiency as the expected number of bits for sending a packet between two nodes, which is then extended to cumulatively measure energy efficiency of a route. In their approach, a message is divided into packets of variable size. The fragmentation of messages into variable size packets is supported by the well-known IEEE 802.11 MAC layer protocol. The optimal packet length is described by a formula that depends on the BER, the number of bits in the message overhead and number of preamble bits transmitted with each packet [36]. After all packets are accumulated at the receiver, a new optimal packet size for the next hop is determined. They assume that acknowledgements are packets with a much smaller number of bits and do not consider them in the cost, to simplify the derivation.

Draves *et al.* [14] modified DSR [22] to select a better route by using link quality information. The modified DSR is called Link-Quality Source Routing (LQSR). They conducted a detailed empirical evaluation of three link-quality metrics - ETX [12], per hop Round Trip Time [1] and per hop packet pair [24] and compared them against the minimum hop count metric using a 23 node wireless test-bed. They noted that the ETX metric has the best performance when nodes are stationary; when nodes are mobile, the hop-count metric outperforms all other link quality metrics.

Zhao *et al.* [63] reported packet delivery measurements for a sixty-node test-bed in different indoor and outdoor environments. They studied the impact of the wireless link on packet delivery at the physical and MAC layers by testing different encoding schemes and traffic loads.

Zuniga and Krishnamachari [64] use mathematical techniques from communication theory to model and analyze low power wireless links. Their analysis identifies the causes of transition regions, the quantification of their influence and derive expressions for packet reception rate as a function of distance. They also derive expressions for the width of the transitional region.

In [2], the authors propose an improved route selection technique, based on the Medium Time Metric (MTM), in multi-rate MANETs. The medium time metric is proportional to the time it takes to transmit a packet on a given link. This metric selects the paths that have the highest capacity. The primary advantage of this technique is its simplicity.

In [52], the authors study geographic routing in the context of lossy wireless networks. Using a realistic link loss model, they develop a mathematical analysis and simulation study and propose novel blacklisting and neighbor selection strategies in geographic routing protocols.

From the various studies cited above, it is clear that while designing routing protocols for wireless ad hoc networks, it is very important to consider the impacts of a realistic physical layer model. The perfect-reception-within-range assumption (using an ideal physical layer) while designing and analyzing routing protocols need to be revisited considering message losses and retransmission requirements due to signal fading in a realistic environment. Also, localized, position based routing algorithms reduce the overall communication requirements of MANET protocols, especially in an environment with constraints on bandwidth and energy utilization. Realistic physical layer models have not been considered so far in the design of position based routing algorithms for MANETs.

Chapter 3

Acknowledgement-based Routing Algorithms with a Realistic Physical Layer

In this chapter, using the log-normal shadowing model, we first introduce an expression for packet reception probability $p(x)$ for receiving a packet successfully as a function of distance x between two nodes. This packet reception probability is then approximated for the purpose of ease of computation, to be used in our new protocols. Then, a new media access control (MAC) layer protocol that can be used between two nodes in a MANET is proposed. Using this MAC protocol, we propose and design several new hop-count optimal, localized, position based routing algorithms for ad hoc networks. All the proposed protocols are simulated and their performances compared with the performance of similar localized protocols and global algorithms.

3.1 Probability of Reception in Log-normal Shadowing Model

The log-normal shadowing model can be used for area coverage calculations [15]. The probability that the received power at a location x exceeds γ can be given as:

$$Pr[P_r(x) > \gamma] = Q[\frac{\gamma - \overline{P_r(x)}}{\sigma}] \tag{3.1}$$

where

$$Q[z] = 0.5[1 - erf[\frac{z}{\sqrt{2}}]] \tag{3.2}$$

$$Pr[P_r(x) > \gamma] = 0.5(1 - erf[\frac{\gamma - \overline{P_r(x)}}{\sqrt{2}\sigma}]) \tag{3.3}$$

We use the equation 3.3 above as the probability $b(x)$ of receiving a bit successfully. The probability of receiving a packet, $p(x)$ is then $p(x) = b(x)^L$, where L is the length of the packet. Note that here we do not assume the existence of any error correcting scheme to recover any incorrectly received bits. Figure 3.1 plots the probabilities of bit and packet reception, with $\beta = 2$ and $L = 80, 120, 160$, using the shadowing propagation model. β is the path loss exponent that varies between 2 and 6. The bit transmission radius B is defined as the distance for which $b(B) = 0.5$ and the packet transmission radius R is defined as the distance for which $p(R) = 0.5$ is satisfied.

The exact computation of $p(x)$ to be used in routing protocol decisions, is a time consuming process, and is based on several measurements (e.g. signal strengths, time delays, global positioning system data) which are already causing some errors. It is therefore advisable to consider a reasonably accurate approximation that can be determined quickly. With the aim of minimizing errors as much as possible, we designed the following approximation function for $p(x)$. We approximate it by

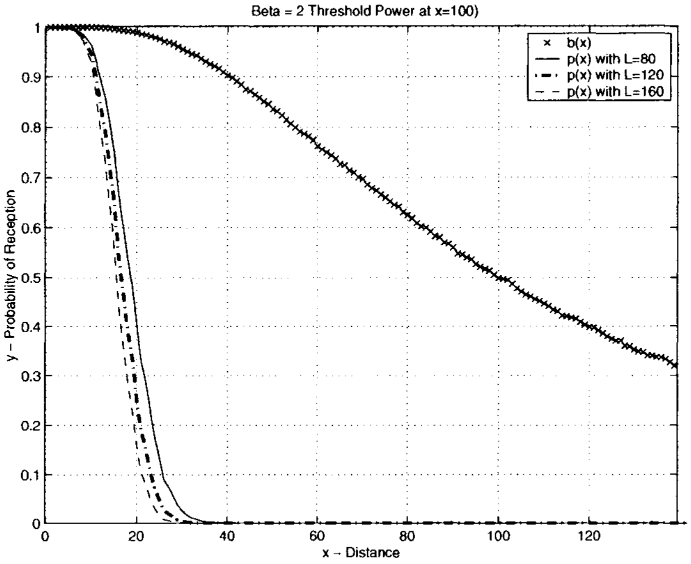


Figure 3.1: $b(x)$, and $p(x)$ with $L = 80, 120, 160$ for $\beta = 2$

$$P(x) = \begin{cases} \left(1 - \frac{(\frac{x}{R})^{2\beta}}{2}\right) & x < R \\ \left(\frac{(\frac{2R-x}{R})^{2\beta}}{2}\right) & x \geq R \end{cases}$$

where β is the power attenuation factor, with fixed value between 2 and 6. We received satisfactory precision with this approximation for $\beta = 2$ and $\beta = 4$ values. One can observe that the power attenuation factor in the approximation is 2β rather than β. This is due to approximating packet probability rate rather than bit probability rate, and the greater impact of packet length on packet reception at larger distances. We anticipate that, in general, power attenuation factor $q\beta$ can be used, where q depends on L. In this thesis, the notation $p(x)$ is used, although the results were in fact derived using its approximation $P(x)$.

Figures 3.2 and 3.3 show the difference between $p(x)$ and the selected approximation $P(x)$ for $\beta = 2, 4$ and $L = 120$. The observed relative error of the approximation is below 4% for $x \leq 2R$.

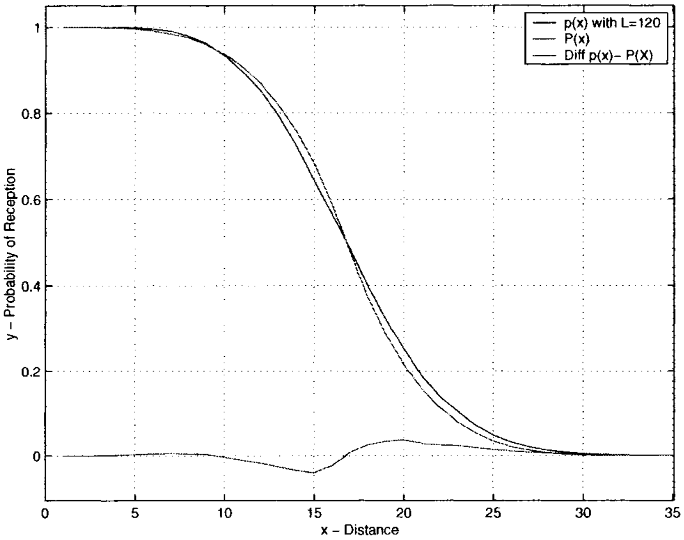


Figure 3.2: $p(x)$, $P(x)$, and $p(x) - P(x)$ graphs for $L = 120$, $B = 100$, $\beta = 2$)

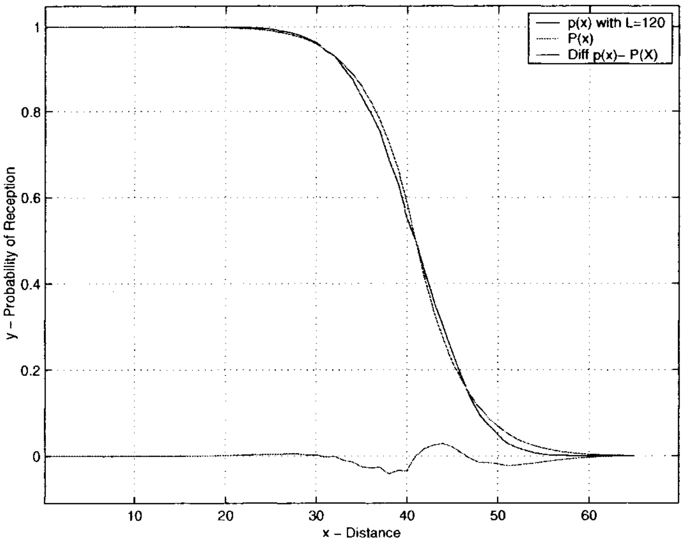


Figure 3.3: $p(x)$, $P(x)$, and $p(x) - P(x)$ graphs for $L = 120$, $B = 100$, $\beta = 4$)

3.2 MAC Layer Protocol Between Two Nodes

We consider a hop-by-hop retransmission (HHR) routing protocol, where the sender of a packet requires an acknowledgement from the receiver. To simplify our protocols and analysis, we assume that the receiving node needs to send separate acknowledgement and forwarding packets to the previous and the next nodes on the route.

A simple MAC layer communication protocol between two nodes in MANET can be described as follows. After receiving a packet from the sender node, the receiver node sends u acknowledgements. If the sender does not receive an acknowledgement, it then retransmits the original packet. An expression to calculate the expected number of messages in this protocol is then derived, which is the proposed measure of *hop count* between two nodes. This new *hop count* measure includes re-transmissions by the sender and acknowledgements by the receiver. Both the acknowledgement and data packets are assumed to have the same length. This hop count measure between two nodes can also be used as link weight in the shortest hop count path routing algorithm, for performance comparisons.

Let S and A be the sender and receiver nodes, respectively, and let $|SA| = x$ be the distance between them. The generic protocol for sending a packet from S to A is described as follows:

```
S-recd-ack=false Repeat
   S sends packet to A
   If that packet is received at A
     {A sends u acks to S;
      If one ack received at S
        then S-recd-ack=true}
Until S-recd-ack
```

The probability that A receives the packet from S is $p(x)$ and the probability that it does not receive the packet is $(1 - p(x))$. The probability that S receives a particular acknowledgement from A is $p(x)$. Therefore, the probability that S does not receive any of the u acknowledgements is $(1 - p(x))^u$. Thus, the probability that S receives at least one of the u acknowledgements from A is $1 - (1 - p(x))^u$. Then, $p(x)(1 - (1 - p(x))^u)$ is the probability that S receives an acknowledgement after sending a packet and considers the packet received (therefore stops transmitting further packets). The expected number of transmissions at S before a packet is received is

$$\frac{1}{[p(x)(1 - (1 - p(x))^u)]}$$

Each of these packets is received at A with probability $p(x)$. If received correctly, it generates u acknowledgements. The total expected number of acknowledgements sent by A is then

$$\frac{u \times p(x)}{[p(x)(1 - (1 - p(x))^u)]} = \frac{u}{[(1 - (1 - p(x))^u)]}$$

The total expected hop count between two nodes at distance x can then be written as

$$\frac{1}{[p(x)(1-(1-p(x))^u)]}+\frac{u}{[(1-(1-p(x))^u)]}$$

Figure 3.4 shows the expected hop count for different u values ($u = 1, 2, 3, 4$). For low values of x, the best choice of u is 1. However, for larger values of x, the probability of receiving the packet $p(x)$ becomes low, and therefore, once received, a packet may need to be retransmitted a few times for successful acknowledgement and a different value of u could be more efficient. Figure 3.5 illustrates the expected hop count vs. distance plot near R. It is clear from Figure 3.5 that each value of u is an optimal choice for some range of x values for best expected hop count performance. For example, for $x <\approx 97$, the optimal u value is 1 and for x between 97 and 103, $u = 2$ is optimal for the best expected hop count result.

We can devise a mechanism to dynamically calculate the value of u for a given probability $p(x)$, such that $u * p(x) = 1$. This value of u is the one for which the expected number of received acknowledgements is 1, hence the best choice. Thus, the best choice of u for a given $p(x)$ is $round(1/p(x))$. This choice can be further optimized by using delayed rounding-off ($round((1/p(x)) - .1)$ to reduce the hop count variations between u transitions. In our simulations, depending on the value of $p(x)$, we dynamically calculate the optimal u value. It has been confirmed that the dynamically calculated u values using this method are optimal and the same for different ranges of x, as in Figure 3.5.

Thus the choice of u does not need to be fixed in the MAC protocol. It can be dynamically calculated using the $p(x)$ value for optimal hop count performance. This expected hop count can be used as a weight in the Dijkstra's shortest path algorithm to derive hop count optimal paths between any two nodes. We have used it as a hop count optimal and best possible scheme and have compared it with the performance of the newly proposed localized schemes,

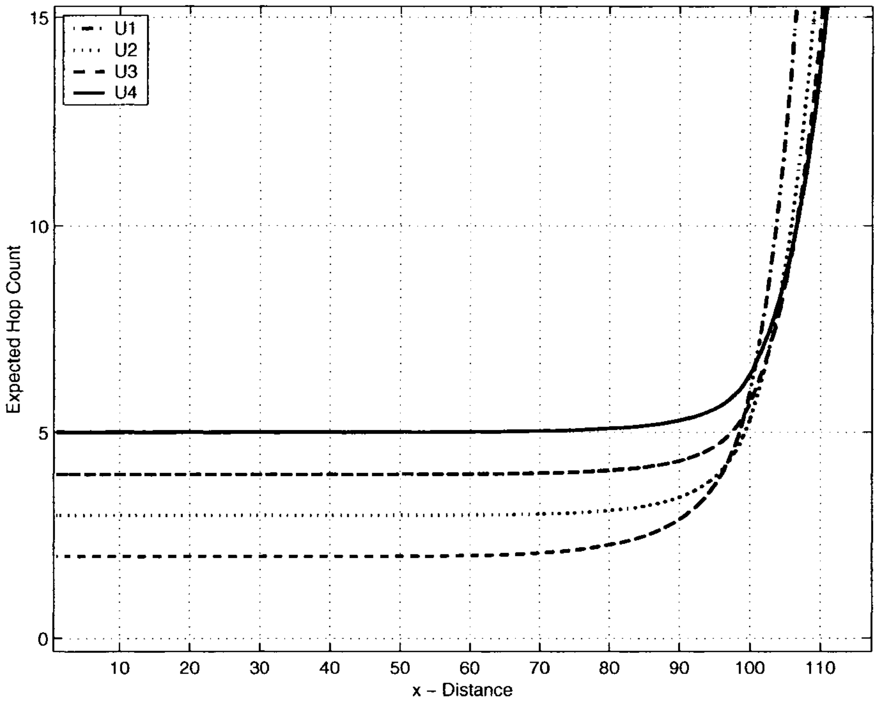


Figure 3.4: Expected hop-count vs. distance for $u = 1, 2, 3, 4$ ($\beta = 4$, $R = 100$).

IHCR, *aEPR* based algorithms, *ProjectionProgress* based algorithms and *tR–greedy*, described in Sections 3.4.1, 3.4.2, 3.4.3, 3.4.4 and 3.4.5.

3.3 Optimal packet forwarding distance is less than transmission radius

In this section, we show that the optimal packet forwarding distance to minimize the hop count is less than the transmission radius R. To derive this result, we place $(n - 1)$ equally spaced additional nodes between source S and destination D, along the straight line joining S and D. Thus, $x = d/n$ the distance between two consecutive nodes is $x = d/n$. We now derive the optimal values for n and x, by finding the expected hop count of such placement, and finding its minimum

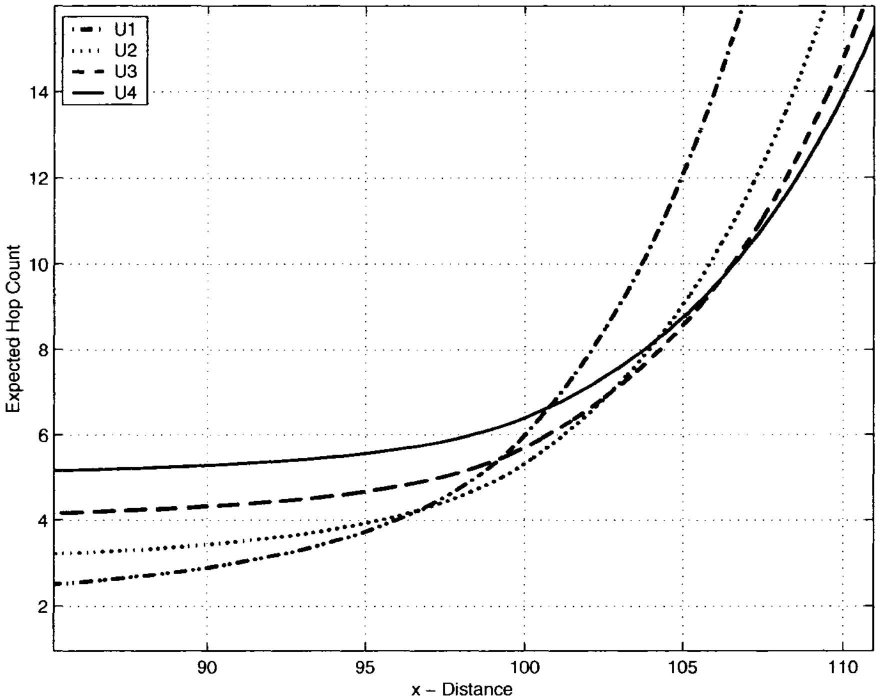


Figure 3.5: EHC vs. distance closer to R for $u = 1, 2, 3, 4$ ($\beta = 4$, $R = 100$).

analytically. We then show that such an ideal placement is achieved for $x < R$.

By applying the earlier analysis in Section 3.2, the total expected hop count from source to destination is

$$\frac{d}{x}\left[\frac{1}{[p(x)(1-(1-p(x))^u)]} + \frac{u}{[(1-(1-p(x))^u)]}\right].$$

In order to discuss optimizing a function independently of a particular distance d, and of a particular transmission radius R, we consider then optimizing instead the function

$$h(x, u, \beta, R) = \frac{R}{x}\left[\frac{1}{[p(x)(1-(1-p(x))^u)]} + \frac{u}{[(1-(1-p(x))^u)]}\right]$$

	u = 1	u = 2	u = 3
$\beta = 2$	0.7272R	0.8335R	0.8920R
$\beta = 4$	0.7902R	0.8680R	0.9065R

Figure 3.6: Optimal Forwarding distances with $u = 1, 2, 3$ for $\beta = 2, 4$.

	u = 1	u = 2	u = 3
$\beta = 2$	3.4572 d/R	4.2271 d/R	5.1674 d/R
$\beta = 4$	2.8519 d/R	3.7755 d/R	4.7952 d/R

Figure 3.7: Ideal Expected Hop Count with $u = 1, 2, 3$ for $\beta = 2, 4$.

Once the optimal forwarding distance is computed, the Ideal Hop Count (IHC) measure is calculated by substituting x with the optimal forwarding distance in the above equation.

For $\beta = 2$ and $u = 1$, using our approximation for $p(x)$, we derived the minimum 3.4572 at $x = 0.7272R$, and the ideal expected hop count (IHC) was $3.4572\frac{d}{R}$. The optimal forwarding distances and ideal expected hop count values for different $u = 1, 2, 3$ and $\beta = 2, 4$ are given in Figures 3.6 and 3.7.

From Figure 3.7, we can deduce that the ideal hop count measure $(IHC(u, \beta, R))$ is always minimal for $u = 1$. This is due to the fact that optimal forwarding distance is always smaller than the transmission radius R, for which $u = 1$ is the optimal u value.

Figure 3.8 shows $h(x, u, \beta, R)$ as a function of x, for $\beta = 2$. We can observe that the expected hop count values are low in the range approximately $0.60R$ to $0.90R$ for $u = 1$, about 50% higher at $x = R$ and very high for $x > R$. For small

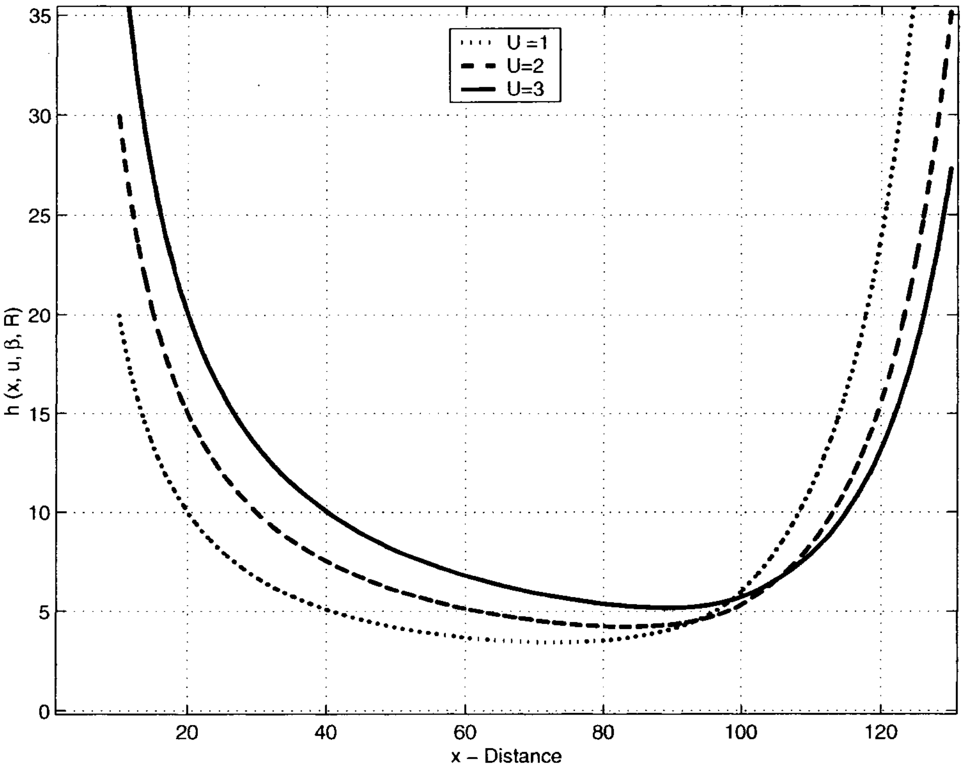


Figure 3.8: Expected Hop Count measure as a function of distance x, for different u values ($R = 100$, $\beta = 2$).

x, the expected hop count is very high (and is not even shown in the figure, where x starts from $0.1R$).

3.4 New Position-based Routing Algorithms

In this section we propose a number of localized, position-based routing algorithms with hop-by-hop acknowledgements.

3.4.1 Ideal Hop Count Routing (IHCR) Algorithm

This protocol is named *Ideal Hop Count Routing* (*IHCR*) since it is based on the ideal packet forwarding, presented in the previous Section 3.3.

Let C be the node currently holding the packet destined for D. Node C will forward it to a neighbor A (closer to the destination than itself) that minimizes the sum of the expected hop count measure from C to A and the ideal hop count between A and destination D (as derived in the previous section). More precisely, the neighbor A that minimizes

$$\left[\frac{1}{[p(x)(1-(1-p(x))^u)]}+\frac{u}{[(1-(1-p(x))^u)]}\right]+\frac{a}{R}\times IHC(1,\beta,R)$$

is selected by node C, where $x = |CA|$ and $a = |AD|$. The value of u is dynamically calculated based on distance $x = |CA|$, as described in Section 3.2. Only neighbors closer to the destination than C are considered for forwarding the messages. In the last term for calculating the ideal hop count, the value for u is fixed at $u = 1$, since that choice gives the best expected performance in ideal conditions as shown in Section 3.3. The forwarding process continues until the destination is reached, or a node is reached that has no neighbor closer to the destination, in which case the algorithm fails to find a route.

3.4.2 Expected Progress Routing Algorithms

In this section we present the Expected Progress Routing algorithms and its variants. Since these algorithms have hop-by-hop acknowledgements, it is referred to as Expected Progress Routing algorithms with acknowledgements (aEPR).

Let the current node holding the message be C, the destination be D, and let A be a neighbor of C. Let $|CD| = c$, $|AD| = a$ and $|CA| = x$. The progress made by forwarding from C to A is $(c-a)$. The regular greedy scheme maximizes $(c-a)$, by sending to a neighbor closest to the destination (minimizes a).

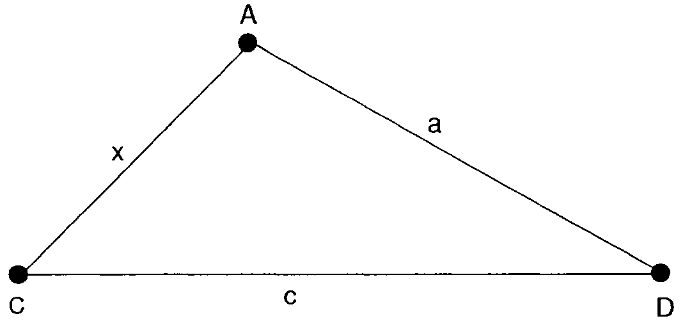


Figure 3.9: Selecting the *best* neighbor A in localized routing schemes.

3.4.2.1 aEPR Algorithm

The progress that can be made by sending a packet to A is probabilistic. In $aEPR$ algorithm, a node C currently holding the packet will forward it to a neighbor A (closer to the destination than itself) that maximizes the expected progress, which is the product of the probability of successful delivery of the packet from C to A and the progress made ($|CD| - |AD|$) by forwarding to A. In $aEPR$ algorithm, the neighbor node A that maximizes $p^2(x)(c-a)$ is selected to forward the message from C.

3.4.2.2 aEPR-1 Algorithm

The progress that can be made by sending a packet to A can also be considered with respect to the cost measure for making such progress. The cost measure considered is the expected hop count. The expected hop count depends on the distance and the selected u number of acknowledgements.

First, consider the case where the u value is fixed as 1. In this algorithm, called $aEPR-1$, a node C currently holding the packet will forward to a neighbor A (closer to the destination than itself) that maximizes the ratio of expected progress and the cost for making that progress. Since the considered cost, expected hop count, is $\left[\frac{1}{p(x)^2}+\frac{1}{p(x)}\right]$, $aEPR-1$ will select the neighbor A that maximizes

$$\frac{(c-a)}{\left[\frac{1}{p(x)^2}+\frac{1}{p(x)}\right]}$$

3.4.2.3 aEPR-u Algorithm

Now consider the variant of the aEPR algorithm where the best value of u is dynamically selected. The best value of u is approximated as $u = round((1/p(x)) - .1)$. The expected hop count is then

$$f(u,x) = \frac{1}{[p(x)(1-(1-p(x))^u)]} + \frac{u}{[(1-(1-p(x))^u)]}$$

This variant, called $aEPR-u$, will select a neighbor A that maximizes $(c-a)/f(u,x)$ to forward the message.

3.4.3 Projection Progress Routing Algorithms

Let the current node be C, destination be D, and A be a neighbor of C. Let $|CD| = c$, $|AD| = a$ and $|CA| = x$.

Projection progress based algorithms differ from $aEPR$ schemes only in the progress measure. Instead of $(c-a)$, the progress is measured as the dot product $(|CD| \cdot |CA|)$. In the *ProjectionProgress* scheme, a node C, currently holding a packet, will forward it to a neighbor A (closer to the destination than itself) that maximizes $p^2(|CA|)(|CD| \cdot |CA|)$, where $|CD| \cdot |CA|$ is the dot product of two vectors.

By substituting this new progress measure in $aEPR-1$ and $aEPR-u$, we obtain two new routing schemes called $1-Projection$ and $u-Projection$ progress, respectively.

3.4.4 Iterative aEPR and Projection Progress Algorithms

We also propose the improved iterative variants of $aEPR$ and $ProjectionProgress$ algorithms. In the *Iterative aEPR*, first, as in $aEPR$, a node C currently holding the message will find a neighbor A that maximizes $p^2(|CA|)(|CD|-|AD|)$. Then, an intermediate node B (closer to the destination than C, if it exists) is found (that is neighbor to both C and A) which satisfies $EHC(|CB|)+EHC(|BA|) < EHC(|CA|)$ and has the minimum $EHC(|CB|) + EHC(|BA|)$ measure. This process is iteratively repeated until no improvement is possible. Node C will then forward the message to the selected neighbor B, which then applies again the same scheme for its own forwarding. A pseudo code of the algorithm can be written as

```
Current Node C, Destination D,
Find best nEPR Neighbor A such that
          p^2(|CA|)(|CD|-|AD|) is maximum
Candidate_node, M = A.
Repeat
 Min = EHC(|CM|); Selected_Neighbor,
       N = M (Candidate_node)
 For each neighbor B of C
         (which is closer to D than C)
   If B is neighbor of M (Candidate_node)
      If EHC(|CB|) + EHC(|BM|) < Min
        Min = EHC(|CB|) + EHC(|BM|);
        Candidate_node, M = B
      End
   End
Until Candidate_node,
```

```
M = Selected_Neighbor, N.
```

The *iterative projection progress* is identical to $IaEPR$, except that the first node is found using the projection progress algorithm.

3.4.5 Greedy Forwarding

The well known greedy routing scheme, proposed by Finn [17], works as follows. Node C, currently holding the message, will forward it to the neighbor (among neighbors closer to the destination than itself) that is closest to the destination. This algorithm is unambiguous with the existing definition of transmission radius in the ideal unit graph model. However, with a realistic physical layer, it can receive different interpretations. We modify the neighborhood definition of the greedy routing scheme to accommodate the log-normal shadowing model as follows. Consider as neighbors all nodes that are located at a distance at most tR from C. Among these nodes that are closer to the destination than C, select the one that is closest to the destination, to forward the message.

It was observed that the packet reception probability drops to near 0 at distance $2R$. Therefore the value $t = 2$ may be interpreted as sufficient to include all neighbors with a sufficient packet probability rate to establish communication with C via some repeated hello messages. For example, if the packet probability rate is 0.2, it is expected that one out of five transmitted hello messages can reach the neighboring nodes, so that node might be used for forwarding messages. However, such choices do not necessarily lead to optimal values for expected hop counts. As will be seen in experimental results, a neighbor at a distance close to $2R$ may have an extremely high expected hop count. We therefore believe that a better performance will be achieved if $t < 2R$. In the simulations, we tested for different choices of t.

3.5 Experimental Results

In this section, we present the results of our simulation study. For the simulation, we use a 300×300 area for the placement of wireless nodes. Each of n nodes ($n = 250$) is placed uniformly at random inside the square area.

Dijkstra's shortest path scheme was used to test network connectivity, and only connected graphs were used in measurements. The network density d is defined as the average number of neighbors per each node using the unit graph model. Two nodes are considered neighbors in this graph if and only if the distance between them is at most hR, where $p(R) = 0.5$ and hR is the distance such that $p(hR) = w$, for suitably selected threshold value w. Based on our approximation function, and value $w = 0.05$, the obtained $h = 1.4377$. We select d as an independent variable, and then find the appropriate value for R, which depends on network area size. Then this value of R is used in the approximation $P(x)$ for $p(x)$. The proposed experimental design allows for flexibility in the neighbor definition by selecting appropriate density. For example, if two nodes are considered as neighbors only when their distance is at most tR, then the corresponding density d' of a graph is approximately $d' = (t/1.4377)^2 d$, where d is the density that corresponds to $1.4377R$ neighbors. All the density values reported in tables are with respect to $1.4377R$ neighbors. We tested for $d = 6, 8, 10, 20, 24, 32, 40$ and 80. The average values are reported over 500 simulations (graphs). The value of u is dynamically calculated based on the $p(x)$ value. We have used $\beta = 2$. We tested some other parameter settings, but the relative comparison remained the same.

We compared the success rates and expected hop count performance of $IHCR$, $aEPR$, $IaEPR$, $aEPR{-}1$, $aEPR{-}u$, *Projection Progress, Iterative Projection Progress, 1-Projection, u-Projection progress, tR-greedy* for $t = 1$, $t = 1.25$

Algorithm	Number of Nodes : 250							
	Density (with 1.4377R neighbors)							
	6	8	10	20	24	32	40	80
Ideal	0.548	0.604	0.651	0.826	0.853	0.892	0.908	0.948
Shortest Path	1	1	1	1	1	1	1	1
aEPR	1.326	1.352	1.373	1.129	1.060	1.061	1.040	1.036
I aEPR	1.308	1.351	1.357	1.119	1.057	1.060	1.040	1.036
aEPR-1	1.307	1.344	1.382	1.128	1.063	1.064	1.036	1.035
aEPR-u	1.360	1.388	1.444	1.156	1.082	1.071	1.043	1.035
IHCR	1.333	1.343	1.372	1.124	1.061	1.061	1.033	1.033
Proj Progress	1.324	1.328	1.360	1.128	1.065	1.071	1.048	1.064
I Proj Progress	1.317	1.323	1.354	1.120	1.063	1.070	1.047	1.064
1-Projection	1.312	1.331	1.366	1.123	1.061	1.073	1.051	1.070
u-Projection	1.345	1.375	1.422	1.129	1.077	1.077	1.051	1.070
1.4377R Greedy	3.469	3.911	4.141	5.532	5.751	6.399	6.668	7.415
1.25R Greedy	1.568	1.682	1.820	2.293	2.462	2.587	2.653	3.009
R Greedy	1.028	1.053	1.075	1.148	1.163	1.215	1.248	1.281

Figure 3.10: Hop Count Dilation of the algorithms for different densities ($\beta = 2$).

and $t = 1.4377$ and shortest path algorithms (where link weights are computed as explained in Section 3.2). The *ideal* routing, where nodes between sender and destination can be placed at will, was also added as a reference. We measured hop counts only for source-destination pairs where all of competing methods successfully found their routes to destination (with the exception of very low densities where the success rate of R and $1.25R$ greedy methods are near zero; in these cases the protocols were ignored while averaging expected hop counts). We define the *hop count dilation* as the ratio of the expected hop count performance of the specific algorithm to that of the shortest path. The hop count dilation ratios are given in Figure 3.10. Figure 3.11 gives the success rate of these algorithms.

It can be observed from the tables that $IHCR$, $aEPR$ and Projection progress based localized algorithms had very similar performances. Therefore, all the schemes remain candidates for future extensions (e.g. to routing scheme with guaranteed delivery). Most importantly, at higher densities, $aEPR$, $IaEPR$, $aEPR{-}1$, $aEPR{-}u$, $IHCR$, $ProjectionProgress$, $IterativeProjectionPrgress$ and $1-Projection$ protocols had only relatively small additional hop counts with respect to the shortest weighted path algorithms, which requires global information. This is a very important achievement for localized routing schemes.

The performance of $tR - greedy$ routing algorithm was very dependant on the selected t value. For higher t, both success rates and hop count measures increased. The success rate for $t = 1$ and $t = 1.25$ was low, while hop count for $t = 1.4377$ was high. We tested more values of t in $tR - greedy$ algorithm ($t = 1.4, 1.6, 1.7$) but received either very high hop count or low success rates, and value $t = 1.25$ appeared to be nearly the best possible. Therefore, we concluded that $tR{-}greedy$ scheme is inferior to the other localized routing schemes proposed in this thesis.

Algorithm	Number of Nodes : 250							
	Density (with 1.4377R neighbors)							
	6	8	10	20	24	32	40	80
Shortest Path	100%	100%	100%	100%	100%	100%	100%	100%
aEPR	36%	52.7%	80%	99.3%	100%	100%	100%	100%
I aEPR	36%	53.3%	80%	99.3%	100%	100%	100%	100%
aEPR-1	36.2%	56.7%	79.3%	99.3%	100%	100%	100%	100%
aEPR-u	36.4%	52.7%	82%	99.3%	100%	100%	100%	100%
IHCR	32.8%	44.7%	80%	99.3%	100%	100%	100%	100%
Proj Progress	35%	49.3%	79.3%	99.3%	100%	100%	100%	100%
I Proj Progress	35%	50%	79.3%	99.3%	100%	100%	100%	100%
1-Projection	35.4%	52.7%	79.3%	99.3%	100%	100%	100%	100%
u-Projection	36.6%	52.7%	80.7%	99.3%	100%	100%	100%	100%
1.4377R Greedy	48.4%	70%	88.7%	99.3%	100%	100%	100%	100%
1.25R Greedy	14.2%	29.3%	58.7%	99.3%	100%	100%	100%	100%
R Greedy	0.6%	2%	3.3%	76%	90.7%	98%	100%	100%

Figure 3.11: Success rate of the algorithms for different densities ($\beta = 2$).

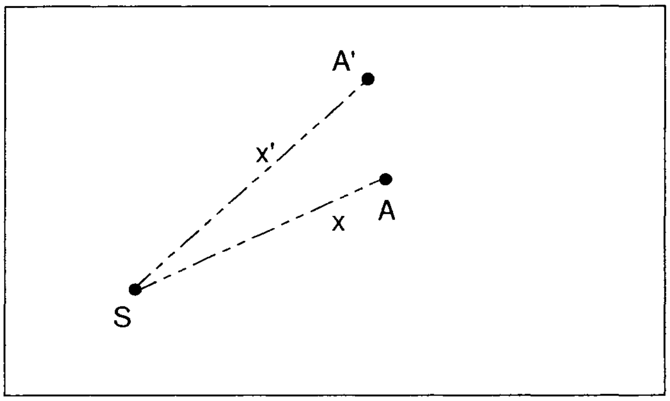


Figure 3.12: Imprecise location of node A.

3.6 Impact of Imprecise Location Information

We also studied the impact of imprecise location information on the performance of the routing protocols proposed in this chapter.

Consider node S that is currently holding the message, but has imprecise information about its neighbors. For a neighbor A of S, assume A' be the imprecise location as known to S at a distance x', as illustrated in Figure 3.12.

The expected hop count measure, as believed by node S in covering the message and acknowledgement packets between S and A is $f(x', u')$, due to the imprecise location information of A. This EHC value is used by node S in our proposed algorithms (in computing progress, cost measure etc.), for selecting the appropriate neighbor node for message forwarding. No messages are sent while making the forwarding neighbor selection and it is done solely by applying the selection criteria for each of the algorithms, based on the perceived location of the neighbor nodes as known to node S. Once the neighbor node is selected, node S forwards its message to the selected neighbor A, using the MAC protocol proposed in Section 3.2.

Once the message is sent by S, node A receives it with probability $p(x)$, and computes the correct u value as required by the MAC protocol after establishing the distance x between the nodes S and A. The expected hop count measure between nodes S and A is then $f(u, x)$, while $f(x', u')$ measure was used in the selection of node A.

Node A then repeats the same process as described above to reach the destination node. The EHC value for the route between the source node and the destination node is then computed by adding the individual EHC values between the intermediate nodes in the path.

The simulation environment was set up as follows. Once the nodes were placed in the simulation area, we generated an error in the location information and applied it to the nodes. A random distance value which varies between 0 and MAXERROR, where MAXERROR is a selected percentage of the transmission radius, was first generated. We tested with distance errors ranging up to 120% of the transmission radius. Then, we generated a random angle, and the node co-ordinates were changed by the generated distance and the angle as shown in Figure 3.13, placing it anywhere in the circle which has the maximum distance error as its radius and the current node co-ordinates at its center. In Figure 3.13, node A appears to be at the location (x', y') to its neighbors, but moves to location (x, y) for final EHC computations.

With the location error applied, we simulated and studied the performance of the proposed protocols. For the simulation, we used a 300×300 area for the placement of wireless nodes. Each of n nodes ($n = 250$) was placed uniformly at random inside the square area. We always started with connected graphs, with a fixed density of 32. Then location errors, generated as described above, were applied for studying the performance of the various protocols. During the simulations, once a forwarding node was identified, we kept it in the route, even if, in reality, it was outside the neighborhood definition. The results are shown in

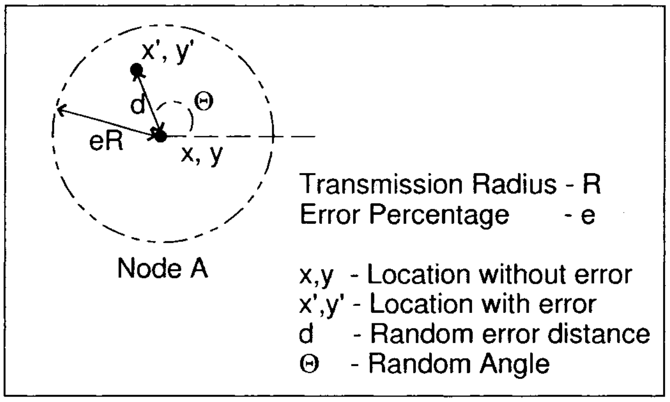


Figure 3.13: Location error generation.

Figures 3.15 and 3.14. All the reported results are averaged over 100 graphs. We also studied the performance of the shortest path and greedy protocols (1.4377R Greedy) with the same imprecise location information. The success rates of all the proposed protocols were significantly impacted after the location error exceeded 60%, while the impact on the shortest path and greedy algorithms was less significant. With imprecise location, the success rate is applicable to the shortest path algorithm as well, since the network may appear disconnected with the location error applied.

The hop count performance deteriorated with increasing location error. For most of the protocols, after 80% error, the hop count measure showed slight improvement. However, the performance of the tRGreedy algorithm deteriorated significantly due to the selection of nodes outside the neighborhood definition.

Based on these results, it can be observed that the impact of imprecise location information is significant for the proposed protocols. The performance of the shortest path and greedy algorithms are also significantly impacted. However, it can be argued that when error is significant due to imprecise location information, beaconless routing with a realistic physical layer is the answer. In

EPR with acknowledgments		
Error Percentage	Success Rate	Hop Count
0	100%	31.16
20	98%	34.32
40	76%	47.21
60	62%	53.58
80	46%	86.05
100	32%	80.53
120	34%	105.19

Projection Progress		
Error Percentage	Success Rate	Hop Count
0	100%	32.67
20	96%	35.35
40	60%	48.07
60	50%	91.68
80	48%	140.76
100	30%	81.99
120	26%	45.35

Figure 3.14: Protocol performance with location errors.

beaconless routing, information about neighbors of a node are not maintained. Instead, all suitable neighbors of the forwarding node participate in the next hop selection process and the forwarding decision is based on the actual topology of the network at the time a packet is forwarded. Beaconless position-based routing algorithms without physical layer considerations are proposed in [9].

Shortest Path		
Error Percentage	Success Rate	Hop Count
0	100%	29.85
20	100%	30.90
40	100%	36.38
60	100%	45.04
80	96%	1445
100	84%	175.86
120	82%	1679.39

1.4377R Greedy		
Error Percentage	Success Rate	Hop Count
0	100%	185.74
20	100%	248.81
40	100%	470696
60	93%	2.8096 E07
80	83%	1.0066 E08
100	73%	9.0833 E06
120	61%	8.4497 E08

IHCR		
Error Percentage	Success Rate	Hop Count
0	100%	31.25
20	96%	33.34
40	68%	41.80
60	44%	90.17
80	48%	71.49
100	32%	213.13
120	38%	74.73

Figure 3.15: Protocol performance with location errors.

Chapter 4

Non Acknowledgement-based Routing Algorithms with a Realistic Physical Layer

In this chapter, we present several new, position based, localized, routing algorithms for ad hoc sensor networks without any acknowledgements. These algorithms strive to maximize the probability of delivery of the packet from the source to the destination. The probability of delivery is defined as the product of all probabilities of successful delivery between two intermediate hops along the computed route.

4.1 EER (end-to-end routing) Routing Protocol

In the EER model, there are no hop-by-hop acknowledgements. When (and if) a message arrives at the destination, there may or may not be acknowledgements sent from the destination to the source node, as a routing task. We consider, for detailed study and experimentation, the no-acknowledgment variant of the EER model.

Consider the routing task of sending a message from source C to destination D. Consider intermediate nodes at distances $x_1, x_2, \ldots, x_n$. The probability that D receives the full message from C is $p(x_1)p(x_2), \ldots, p(x_n)$, which needs to be maximized. This is equivalent to maximizing $log(p(x_1)p(x_2), \ldots, p(x_n)) = log(p(x_1)) + log(p(x_2)) + \ldots + log(p(x_n))$. The shortest weighted path algorithm can be applied to find the route with maximal probability of delivering the packet by assigning $-log(p(x_1)), -log(p(x_2)), \ldots, -log(p(x_n))$ as the respective weights for the links.

In order to derive an ideal EER algorithm, consider placing $(n-1)$ equally spaced nodes between the source and destination nodes, S and D. Let $x = \frac{d}{n}$ be the distance between the two consecutive nodes, where $|SD| = d$. The probability of receiving a message at the destination D is $p(x_1)p(x_2), \ldots, p(x_n) = (p(x))^n$. By taking the logarithm, this can be written as $nlog(p(x)) = \frac{d}{x}log(p(x))$, which needs to be optimized for the optimal placement distance x and for calculating ideal probability.

By applying l'Hôpital's rule, and the approximation for $p(x)$, we can show that, for the function $\frac{d}{x}log(p(x))$, the optimal value of x is 0 and the ideal probability is 1.

Following this observation, a localized EER algorithm can be described as follows. The node C currently holding a message will forward it to a neighbor A (closer to the destination that itself) that maximizes the sum of logarithmic probability to deliver to A and ideal logarithmic probability of delivering from A to D. However, the ideal probability component is 1 (that is, the logarithmic probability is 0). Therefore, the algorithm simply forwards the packet to neighbor A that maximizes $p(x)$, where $x = |CA|$, which is the closest neighbor to C among nodes which are closer to D than C. The process continues until the destination is reached or a node is reached that has no neighbor closer to the destination.

The described localized algorithm will also be referred to as the NC (nearest closer) routing scheme. This localized routing scheme was already proposed in [55].

4.2 Expected Progress Routing (nEPR) Algorithm

Let the current node be C, destination be D, and A be a neighbor of C. Let $|CD| = c$, $|AD| = a$ and $|CA| = x$ (see Figure 4.1). The progress made by forwarding from C to A is $(c - a)$. A regular greedy scheme maximizes $(c - a)$, by sending to a neighbor closest to the destination (minimizes a).

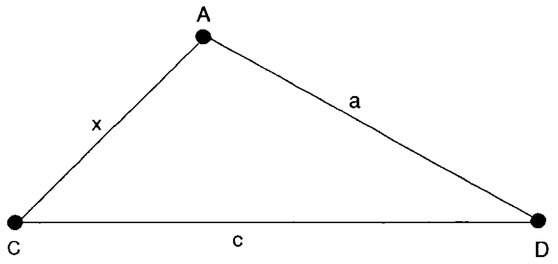


Figure 4.1: Selecting the *best* neighbor A in localized routing schemes.

The progress that can be made by sending a message to A is probabilistic. In non-acknowledged progress routing (*nEPR*) algorithm, a node C currently holding the message will forward to a neighbor A (closer to the destination than itself) that maximizes the expected progress, which is the product of the probability of successful delivery $p(x)$ of the message from C to A and the progress made $(|CD| - |AD|)$ by forwarding to A. Therefore, the neighbor A that maximizes

$p(x)(c - a)$ is chosen to forward the message.

4.3 Iterative Expected Progress Routing (InEPR) Algorithm

The Iterative Expected Progress Algorithm ($InEPR$) is an improved variant of $nEPR$. The algorithm can be described as follows. As in $nEPR$, a node C currently holding a message will first find a neighbor A that maximizes $p(|CA|)(|CD| - |AD|)$. Then, an intermediate node B (closer to the destination than C, if it exists) is found (that is neighbor to both C and A) which satisfies $p(|CB|)p(|BA|) > p(|CA|)$ and has the maximum $p(|CB|)p(|BA|)$ measure. This process is iteratively repeated until no improvement is possible. Node C will forward the message to the selected neighbor B which than applies again the same scheme for its own forwarding. A pseudo code of the algorithm can be written as

```
Current Node C, Destination D,
Find best nEPR Neighbor A such that
          p(|CA|)(|CD|-|AD|) is maximum
Candidate_node, M = A.
Repeat
 Max = p(|CM|); Selected_Neighbor,
       N = M (Candidate_node)
 For each neighbor B of C
         (which is closer to D than C)
   If B is neighbor of M (Candidate_node)
      If p(|CB|)p(|BM|) > Max
        Max = p(|CB|)p(|BM|);
        Candidate_node, M = B
```

```
        End
    End
Until Candidate_node,
        M = Selected_Neighbor, N.
```

4.4 Projection Progress Algorithms

Let the current node be C, the destination be D, and let A be a neighbor of C. Let $|CD| = c$, $|AD| = a$ and $|CA| = x$. Projection Progress based algorithms differ from $nEPR$ schemes in the progress measure only. Instead of $c - a$, progress is measured by the dot product $(CD \cdot CA)$. In the *ProjectionProgress* scheme, a node C, currently holding a packet, will forward it to a neighbor A (closer to the destination than itself) that maximizes $p(|CA|)(CD \cdot CA)$.

The iterative projection progress scheme is very similar to $InEPR$, except that the first candidate node A is found using the projection progress method, (maximizes $p(|CA|)(CD \cdot CA)$), instead of $nEPR$ scheme.

4.5 Experimental Results

In this section, we present the results of our simulation study. The experimental setup used is exactly same as described in Section 3.5.

The two performance measures we have used to compare the new algorithms are the success rate and the probability of successful delivery. Success rate measures the rate of success in finding a route from the source to the destination in the attempted cases. The probability of successful delivery is the product of all probabilities of successful delivery along all hops of the computed route. The success rates in finding a route and probability of successful delivery

Algorithm	Number of Nodes : 250							
	Density (with 1.4377R Neighbors)							
	6	8	10	20	24	32	40	80
Shortest Path	1	1	1	1	1	1	1	1
EER (NC)	0.082	0.123	0.213	0.470	0.559	0.741	0.829	0.949
I nEPR	0.189	0.202	0.183	0.467	0.552	0.721	0.806	0.939
I Proj Progress	0.186	0.200	0.205	0.474	0.567	0.722	0.805	0.938
nEPR	0.010	0.019	0.024	0.059	0.077	0.114	0.151	0.267
Proj Progress	0.016	0.020	0.030	0.061	0.078	0.119	0.155	0.267
1.4377R Greedy*	1.372	1.381	1.439	26.51	39.5	114.9	351.1	5618.2
1.25R Greedy**	3.155	81.23	86.55	199.8	315	621	951	4329
R Greedy	0	0.023	0.074	0.0438	0.044	0.051	0.062	0.103

* All numbers to multiplied by E-7 ** All numbers to be multiplied by E-6

Figure 4.2: Probability Dilation of different algorithms, $n = 250$.

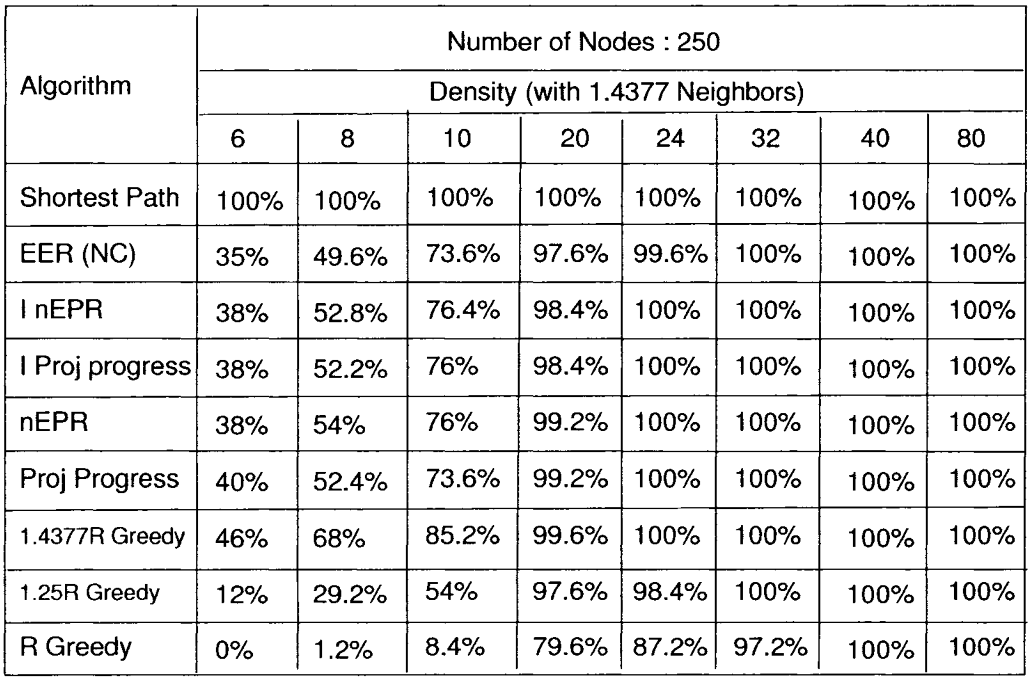
along the found route to the destination are computed for the $nEPR$, $InEPR$, Projection progress, Iterative Projection Progress and EER (NC) algorithms. Their performance is compared with that of tR greedy [28] (with t values 1, 1.25 and 1.4377), and globalized shortest (weighted) path algorithm. The weight assignment scheme is as described in Section 4.1. The probabilities of delivering along found routes are measured only for source-destination pairs for which respective routes were successfully found by all the considered schemes (with the exception of low densities where the success rate of R and $1.25R$ greedy methods were near zero; in these cases these protocols were ignored while averaging probabilities). The *probability dilation* is defined as the ratio of the successful reception probability of an algorithm to that of the shortest path algorithm.

The probability dilation measurements are given in Figure 4.2 for $n = 250$. The results we obtained give low probability even for the shortest weighted path algorithm (for example 0.00334884, 0.00684035, 0.0302591, 0.361463, 0.467599, 0.64934, 0.761852 and 0.933141 for densities 6, 8, 10, 20, 24, 32, 40 and 80 respectively). Among the eight localized routing schemes presented, EER (NC), $InEPR$ and Iterative projection progress schemes performed much better than the other schemes, on probability measure. In 50% of the cases, $EER(NC)$ performed slightly better than $InEPR$ and Iterative projection progress, contrary to our expectations. For the remaining 50%, $InEPR$ or Iterative Projection Progresses performed better than $EER(NC)$ on the probability measure. The performance differences between these three schemes were very narrow. These three schemes also stayed within reasonable limits to the probability measure achieved by globalized shortest weighted path scheme, which is a significant achievement for localized algorithms.

Figure 4.3 gives the respective success rates of these algorithms. On success rate measure, $InEPR$ and Iterative Projection Progress (also $nEPR$ and

Projection Progress) performed better than the EER (NC) scheme. When compared to the tR greedy schemes, all our localized schemes performed better.

Based on the experimental results, we can observe that for sparse networks $InEPR$ and *Iterative projection progress* schemes performed best among localized schemes, better than $EER(NC)$, while $tR - greedy$ methods appear extremely inferior. Therefore $InEPR$ and *Iterative projection progress* schemes are good candidates for use with a localized recovery routing scheme to guarantee finding a route.



Algorithm	Number of Nodes : 250							
	Density (with 1.4377 Neighbors)							
	6	8	10	20	24	32	40	80
Shortest Path	100%	100%	100%	100%	100%	100%	100%	100%
EER (NC)	35%	49.6%	73.6%	97.6%	99.6%	100%	100%	100%
I nEPR	38%	52.8%	76.4%	98.4%	100%	100%	100%	100%
I Proj progress	38%	52.2%	76%	98.4%	100%	100%	100%	100%
nEPR	38%	54%	76%	99.2%	100%	100%	100%	100%
Proj Progress	40%	52.4%	73.6%	99.2%	100%	100%	100%	100%
1.4377R Greedy	46%	68%	85.2%	99.6%	100%	100%	100%	100%
1.25R Greedy	12%	29.2%	54%	97.6%	98.4%	100%	100%	100%
R Greedy	0%	1.2%	8.4%	79.6%	87.2%	97.2%	100%	100%

Figure 4.3: Success Rates, $n = 250$.

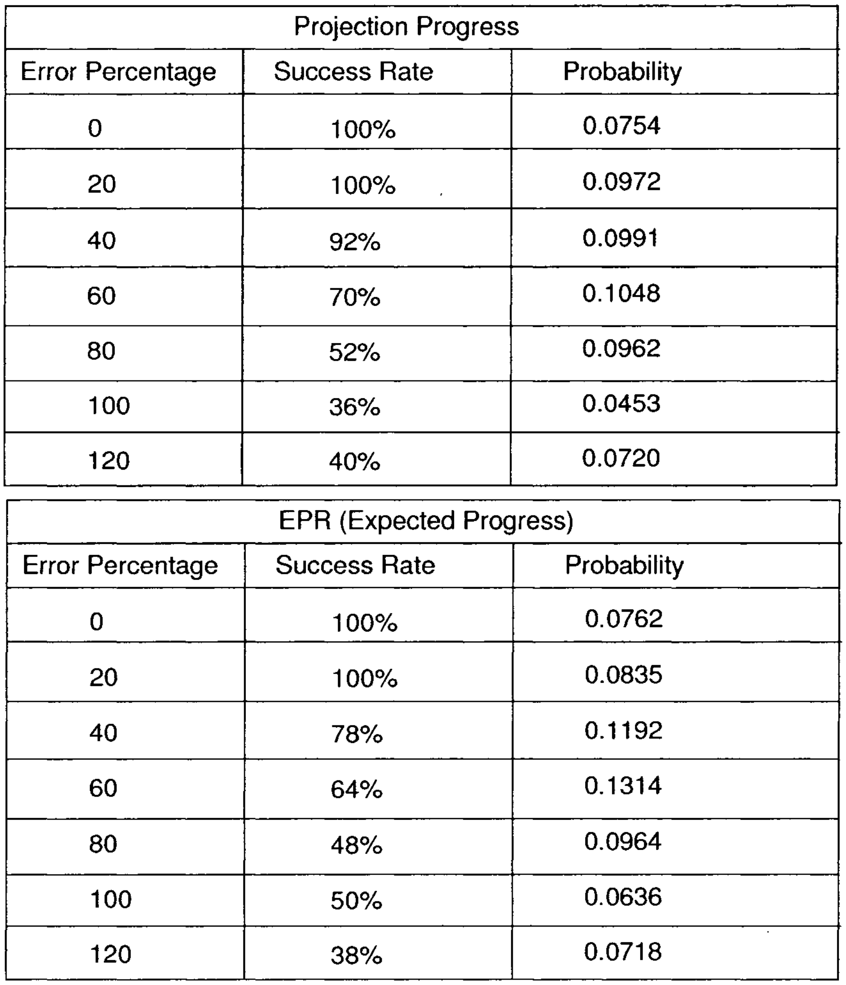
4.6 Impact of Imprecise Location Information

We also studied the impact of imprecise location information on the performance of the routing protocols proposed in this chapter. The details of distance error generation are the same as explained in Section 3.6. However, for non acknowledgement-based algorithms, the probability of successful delivery based on the perceived location of the neighbors is used in identifying the message forwarding nodes, instead of the expected hop count measure used in Section 3.6.

With the location error applied, we simulated and studied the performance of the proposed protocols. The simulation setup is identical as explained in Section 3.6.

The probability of successful delivery measure deteriorated with increasing location error for shortest path and NC algorithms. However, the probability performance of the tR-greedy, nEPR and Projection progress algorithms showed improvement. After further analysis of the results, it was observed that in the majority of cases, the probability performance deteriorated significantly. However, in some cases, with the location error, neighbors closer to the source node in reality got selected for message forwarding, with significantly higher probability, impacting the averages.

Based on these results, it can be observed that the impact of imprecise location information is significant for the proposed protocols. The performance of the shortest path and greedy algorithms is also significantly impacted by imprecise location information. As suggested earlier, it can be argued that beaconless routing with a realistic physical layer may be the solution to this problem.



Projection Progress		
Error Percentage	Success Rate	Probability
0	100%	0.0754
20	100%	0.0972
40	92%	0.0991
60	70%	0.1048
80	52%	0.0962
100	36%	0.0453
120	40%	0.0720

EPR (Expected Progress)		
Error Percentage	Success Rate	Probability
0	100%	0.0762
20	100%	0.0835
40	78%	0.1192
60	64%	0.1314
80	48%	0.0964
100	50%	0.0636
120	38%	0.0718

Figure 4.4: Protocol performance with location errors.

Shortest Path		
Error Percentage	Success Rate	Probability
0	100%	0.6456
20	100%	0.6256
40	100%	0.5510
60	100%	0.4213
80	98%	0.3727
100	92%	0.3731
120	82%	0.3684

1.4377R Greedy		
Error Percentage	Success Rate	Probability
0	100%	7.6314 * E-6
20	100%	5.7412 * E-5
40	100%	0.001663
60	100%	0.01527
80	82%	0.016349
100	74%	0.029877
120	70%	0.001069

NC		
Error Percentage	Success Rate	Probability
0	100%	0.4753
20	34%	0.3484
40	28%	0.3213
60	24%	0.1528
80	14%	0.2397
100	24%	0.0997
120	16%	0.1321

Figure 4.5: Protocol performance with location errors.

Chapter 5

Summary and Future Directions

This chapter gives an overall summary of the thesis and highlights the significance of the work presented. Concluding remarks and suggestions are offered regarding future work to extend the results presented.

5.1 Summary of the Thesis

The design and evaluation of existing routing protocols for MANETs normally assume an ideal physical layer model. By using an ideal physical layer model, proper message reception is often assumed, if the destination is within the transmission radius. However, this assumption is not true, and often results in message losses and retransmission of messages, negatively impacting the routing protocol performance. In this thesis, we applied a realistic physical layer model and studied its impact on routing protocol design for ad hoc and sensor networks by computing the probability of packet reception using the model. Then, we designed several localized, position-based routing algorithms with and without acknowledgements, with fixed message sizes. For designing acknowledgement based mechanisms, a new MAC layer (Media Access Control) protocol was presented. Several new acknowledgement-based protocols were also presented. These algorithms strive to optimize the hop-count measure in delivering the message from the source to the destination, where the hop-count measure takes into account acknowledgements and retransmissions required due to improper message reception. The success rate of finding a route from the source to the destination was also a studied measure of performance for these protocols.

Expected Progress Routing without acknowledgements (nEPR), *Iterative nEPR*, *Projection Progress Algorithm, Iterative Projection Progress*, and *EER* (end-to-end routing) were the newly proposed non acknowledgement-based algorithms. These protocols aim to maximize the probability of delivery of a packet from the source to the destination. The probability of delivery and the success rate in finding a route from the source to the destination were the studied performance indicators of these protocols.

All the newly proposed protocols were simulated and their performances studied and compared with other existing localized protocols and some global algorithms. It was promising to observe that the performances of the newly proposed algorithms were comparable with that of global protocols. We also studied the impact of imprecise location information on the performance of the suggested protocols.

Several researchers have already taken the direction proposed in this thesis for their research. Nayak and Stojemenovic [37] proposed to combine the expected progress routing with face routing to define a localized routing algorithm that guarantees delivery under realistic physical layer models. Especially for dense networks, their protocol *EFE* (Expected progress—Face—Expected progress) is shown to be efficient compared to the globalized shortest path algorithm.

Zuniga and Krishnamachari [64] use a similar approach to model and analyze low power wireless links. Their analysis identifies the causes of transition regions, the quantification of their influence and derive expressions for packet reception rate as a function of distance. In [52], the authors study geographic routing in the context of lossy wireless networks. Using a realistic link loss model, they develop a mathematical analysis and simulation study and propose novel blacklisting and neighbor selection strategies in geographic routing protocols.

In [33], the authors present a link metric called *normalized advance (NADV)* for geographic routing in ad hoc wireless networks. However, their proposal of *cost over progress ratio based routing* as generic framework was first proposed in [29, 58]. This framework was elaborated in [60]. The special case of packet error rate based routing considered in [33] is identical to the proposal in [28, 29]. Also, their power aware based routing is similar to the proposal in [26, 31].

5.2 Future Research Direction

The following are some future extensions to the work presented in this thesis.

In Chapters 3 and 4, we have studied the case with fixed packet length. The acknowledgement packets are assumed to be of the same size as the data packets.

Extensions to study the proposed routing algorithms for the case of variable packet length, where the length of the packet is adjusted to achieve optimality for transmission in each hop on the route, could be an immediate future task. Algorithms presented in Chapters 3 and 4 can be re-examined under the variable length packet scenario.

For the analysis presented in Chapters 3 and 4 of this thesis, a very simple packet reception model was considered. Once we consider the application of different modulation schemes and different coding techniques, the packet probability rate will be different. A new approximation of $p(x)$ is then needed in such scenarios. However, our approach and the routing algorithms remain the same. Appropriate *MAC* layer protocols may be required to accommodate considered coding schemes. Considering more sophisticated models for the physical layer (such as Raleigh fading), different modulation (such as ASK, FSK, PSK and variants) and encoding schemes (such as NRZ, 4B5B, Manchester) is a natural extension of the work presented here.

We also applied the progress based design approach used in this thesis to propose several power and cost optimal routing algorithms for ad hoc networks [26,31]. However, exploring the power/cost optimality of these algorithms with the application of a realistic physical layer will be an interesting research problem.

Several problems, including power and cost aware localized routing, adjusting *GFG* routing with guaranteed delivery [7,37], route discovery in reactive routing (when received signal strength is measurable, or position information is available) to take into account realistic physical layer are excellent future research areas. Solutions to other problems such as broadcasting also need to be reconsidered in the view of physical layer.

Bibliography

[1] A. Adya, P. Bahl, J. Padhye, A. Wolman, L. Zhou, "A multi-radio unification protocol for IEEE 802.11 wireless networks", *Proceeding of the First International Conference on Broadband Networks*, BroadNets 2004, pp. 344-354.

[2] B. Averbuch, D. Holmer, H. Rubens, "High Throughput Route Selection in Multi-rate Ad Hoc Wireless Networks", *Lecture Notes in Computer Science*, Springer-Verlang, Issue 2928, 2004, pp. 253-270.

[3] S. Banerjee, A. Misra, "Minimum Energy Paths for Reliable Communication for Multi-hop Wireless Networks," *CS-TR 4315*, Technical Report, Department of Computer Science, University of Meryland, College Park, Dec 2001.

[4] S. Banerjee, A. Misra, "Adapting Transmission Power for Optimal Energy Reliable Multi-hop Wireless Communication," *Wireless Optimization Workshop (WiOpt'03)*, Sophia-Antipolis, France, March 2003.

[5] S. Basagni, M. Conti, S. Giordano, I. Stojmenovic (eds.), "Mobile Ad Hoc Networking," IEEE Press and John Wiley and Sons, New York, 2004, ISBN: 0-471-373133.

[6] R. V. Boppana, S. Konduru, "An adaptive distance vector routing algorithm for mobile ad hoc networks," *Proceedings of the Twentieth Annual Joint*

Conference of the IEEE Computer and Communications Societies, 2001, Vol. 3, pp. 1753-1762.

[7] P. Bose, P. Morin, I. Stojmenovic, J. Urrutia, "Routing with guaranteed delivery in ad hoc wireless networks," *Wireless Networks*, Vol. 7, No. 6, 2001, pp. 609-616.

[8] J. Broch, D. A. Maltz, D. B. Johnson, Y.-C. Hu, J. Jetcheva, "A performance comparison of multi-hop wireless ad hoc network routing protocols" *MobiCom'98, Proceedings of the 4th Annual ACM/IEEE Inter. Conf. on Mobile Computing and Networking*, October 1998, pp. 85-97.

[9] M. Chawla, N. Goel, K. Kaliaichelvan, A. Nayak, I. Stojmenovic, "Beaconless position-based routing with guaranteed delivery for wireless ad hoc and sensor networks", *IFIP 1st International Conference on Ad-Hoc Networking, at 19th IFIP World Computer Congress*, Santiago, Chile, August 20-25, 2006 (to appear).

[10] T. Chen, M. Gerla, "Global State Routing: A New Routing Scheme for Adhoc Wireless Networks" *IEEE International Communications Conference*, ICC98, June 1998, Atlanta, GA, USA, pp. 171-175

[11] T. Clausen, P. Jacquet (Editors), "Optimized Link State Routing Protocol (OLSR), RFC 3626", *IETF Network Working Group*, October 2003.

[12] D. D. Couto, D. Aguayo, J. Bicket, R. Morris, "A high-throughput path metric for multi-hop wireless routing," *Proc. ACM Mobicom*, San Diego, 2003, pp. 134-146.

[13] S. Das, R. Castaneda, J. Yan, "Simulation Based Performance Evaluation of Routing Protocols for Mobile Ad Hoc Networks", *Mobile Networks and Applications*, 2000, Vol. 5, No. 3, pp. 179-189.

[14] R. Draves, J. Padhye, B. Zill, "Comparison of Routing Metrics for Static Multi-Hop Wireless Networks", *ACM Special Interest Group on Data Communications (SIGCOMM)* Portland, OR, August 2004, pp. 133-144

[15] A. Fanimokun, J. Frolik, "Effects of natural propagation environments on wireless sensor network coverage area", *2003 Southeastern Symposium on System Theory (SSST03)*, Morgantown, WV, March 16-18, 2003.

[16] L. M. Feeney, "A taxonomy of routing protocols in mobile and ad hoc networks", *Technical Report*, Swedish Institute of Computer Science, Box 1263, SE-164 29 Kista, October 1999.

[17] G.G. Finn, "Routing and addressing in large metropolitan-scale internetworks," *ISI Research Report*, ISU/RR-87-180, March 1987.

[18] S. Giordano, "Mobile Ad Hoc Networks," in *Handbook of Wireless Networks and Mobile Computing*, I. Stojmenovic (ed.), Wiley, 2002, pp. 325-346.

[19] Z. J. Haas, M. R. Pearlman, "The Zone Routing Protocol: A Hybrid Framework for Routing in Ad hoc Networks," *Ad Hoc Networking*, Addison-Wesley, edited by C. E. Perkins, 2001, pp. 221-253.

[20] H.C Hou, V.O.K Li, "Transmission Range control in multihop packet radio networks", *IEEE Transactions on Communications*, Vol. 34, No. 1, 1986, pp. 38-44.

[21] A. Iwata, C. C. Chiang, G. Pei, M. Gerla, and T. W. Chen, "Scalable routing strategies for ad hoc wireless networks", *IEEE Journal on Selected Areas in Communication*, 17(8), August 1999, pp.1369-1379.

[22] D. B. Johnson, D. A. Maltz, J Broch, "The Dynamic Source Routing Proto-

col for Multi-Hop Wireless Ad Hoc Networks", *Ad Hoc Networking,*Addison-Wesley, edited by C. E. Perkins, Chapter 5, 2001, pp. 139-172.

[23] J. M. Kahn, R. H. Katz, and K. S. J. Pister, "Next century challenges: Mobile networking for "smart dust"," in *International Conference on Mobile Computing and Networking (MOBICOM)*, 1999, pp. 271-278.

[24] S. Keshav, "A Control-theoretic approach to flow control", *Proceedings of the Conference on Communications Architecture and Protocols*, 1993, pp. 3-15.

[25] E. Kranakis, H. Singh, J. Urrutia, "Compass Routing on Geometric Networks", *Proc, 11th Conadian Conference on Computational Geometry*, August 1999, pp. 51-54.

[26] J. Kuruvila, A. Nayak, I. Stojmenovic, "Progress based localized power and cost aware routing algorithms for ad hoc and sensor wireless networks", *Third Int. Conf. on Ad-Hoc Networks and Wirelsss (ADHOC-NOW)*, Vancouver, BC, July 2004.

[27] J. Kuruvila, A. Nayak, I. Stojmenovic, "Greedy localized routing for maximizing probability of delivery in wireless ad hoc networks with a realistic physical layer", *CD Proc. 1st Int. Workshop on Algorithms for Wireless and Mobile Networks (A-SWAN)*, at Mobiquitous, ICST, Boston, August. 2004.

[28] J. Kuruvila, A. Nayak, and I. Stojmenovic, "Hop count optimal position based packet routing algorithms for ad hoc wireless networks with a realistic physical layer", *Proc. 1st IEEE Int. Conf. on Mobile Ad-hoc and Sensor Systems (MASS)*, Fort Lauderdale, October 2004.

[29] J. Kuruvila, A. Nayak, and I. Stojmenovic, "Hop count optimal position based packet routing algorithms for ad hoc wireless networks with a realistic

physical layer", *IEEE Journal of Selected Areas in Communications*, Vol. 23, No. 6, June 2005, pp. 1267-1275.

[30] J. Kuruvila, A. Nayak, I. Stojmenovic, "Greedy localized routing for maximizing probability of delivery in wireless ad hoc networks with a realistic physical layer", *Journal of Parallel and Distributed Computing*, Vol 66, Issue 4 (Special Issue), April 2006, pp.499-506.

[31] J. Kuruvila, A. Nayak, I. Stojmenovic, "Progress and location based localized power aware routing for ad hoc and sensor wireless networks", *International Journal of Distributed Sensor Networks* (to appear shortly).

[32] D. Lang, "A comprehensive overview about selected Ad Hoc Networking Routing Protocols", *Technical Report*, Mar 2003, Technische Universitt Mnchen, Department of Computer Science http://wwwbib.informatik.tu-muenchen.de/infberichte/2003/TUM-I0311.pdf

[33] S. Lee, B. Bhattacharjee, S. Banerjee, "Efficient Geographic Routing in Multihop Wireless Networks", *ACM Mobihoc*, Urbana-Champlain, USA, May 2005.

[34] M. Mauve, J. Widmer, H. Hartenstein, "A survey of position-based routing in mobile ad-hoc networks", *IEEE Network magazine*, Vol. 15, No. 7, November 2001, pp. 30-39.

[35] S. Murthy, J. J. Garcia-Luna-Aceves, "A Routing Protocol for Packet Radio Networks", *The First International Conference on Mobile Computing and Networking*, ACM MOBICOM'95, November 13-15, 1995, Berkeley, California, USA.

[36] T. Nadeem, A. Agrawala, "IEEE 802.11 fragmentation-aware energy-

efficient ad-hoc routing protocols," *The 1st IEEE International Conference on Mobile Ad-hoc and Sensor Systems MASS*, Fort Lauderdale, October 2004.

[37] A. Nayak, M. Stojmenovic, "Localized routing with guaranteed delivery and a realistic physical layer in wireless sensor networks", *Computer Communications, (Elsevier)*, to appear.

[38] R. Nelson and L. Kleinrock, "The Spatial Capacity of a Slotted ALOHA multihop packet radio network with capture" *IEEE Transactions on Communications*, Vol. 32, No. 6, 1984. pp. 684-694.

[39] D. Niculescu, "Positioning in ad hoc sensor networks," *IEEE Networks*, Vol. 18, No. 4, July 2004, pp. 24-29.

[40] V. D. Park, M. Corson, "A highly adaptive distributed routing algorithm for mobile wireless networks," *Proceedings of INFOCOM*, 1997, Sixteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Driving the Information Revolution, pp. 1405.

[41] G. Pei, M. Gerla, T. Chen, "Fisheye State Routing: A Routing Scheme for Ad Hoc Wireless Networks", *Proceedings of the IEEE International Conference on Communications*, New Orleans, LA, June 2000, pp. 70–74.

[42] G. Pei, M. Gerla, X. Hong, "Lanmar: Landmark routing for large scale wireless ad hoc networks with group mobility", *Proceedings of the ACM/IEEE Workshop on Mobile Ad Hoc Networking and Computing (MOBIHOC)*, Boston, MA. ACM/IEEE, August 2000, pp. 11-18.

[43] C. E. Perkins, P. Bhagwat, "Highly dynamic destinationsequenced distance-vector routing (dsdv) for mobile computers", *ACM SIGCOMM'94 Conference on Communications Architectures, Protocols and Applications*, 1994, pp. 234-244.

[44] C. E. Perkins, E. M. Royer, S. R. Das, "Ad Hoc On Demand Distance Vector (AODV) Routing" *IETF Mobile Ad Hoc Networks Working Group*, IETF RFC 3561.

[45] G.J. Pottie and W.J. Kaiser, "Wireless integrated network sensors," *Communications of the ACM*, Vol. 43, No. 5, 2000 pp. 551-558.

[46] J. Proakis, "Digital Communications", Third Edition, McGraw Hill Inc., New York, 1995.

[47] L. Qin, T. Kunz, "On-demand Rounting in MANETs: The Impact of a Realistic Physical Layer Model," *Proceedings of the Second International Conference ADHOC-NOW*, 2003, pp. 37-48.

[48] L. Qin, T. Kunz, "Survey on Mobile Ad Hoc Network Routing Protocols and Cross-Layer Design," *Technical Report SCE-04-14*, August 2004, Systems and Computer Engineering, Carleton University.

[49] T. S. Rappaport, "Wireless Communications: Principles and Practice", *Prentice Hall*, New Jersey, 1996, ISBN: 0-133-755363.

[50] E. M. Royer, C-K. Toh, "A review of current routing protocols for ad-hoc mobile wireless networks", *IEEE Personal Communications*, Vol. 6, Issue. 2, April 1999, pp. 46-55.

[51] N. Schult, M. Mirhakkak, D. LaRocca, J. Strater, "Routing in Mobile Ad hoc Networks", *Proceedings of Conference on Military Communications (MILCOM'99)*, 1999, pp. 10-14.

[52] K. Seada, M. Zuniga, A. Helmy, B. Krishnamachari, "Enery-efficient Forwarding Strategies for Geographic Routing in Lossy Wireless Sensor Networks", *SenSys'04*, November 3-5, 2004

[53] R. Sivakumar, P. Sinha, V. Bharghavan, "Cedar: a core-extraction distributed ad hoc routing algorithm," *IEEE Journal on Selected Areas in Communication*, Vol. 17, No. 8, August 1999, pp. 1454-1465.

[54] I. Stojmenovic, "Location updates for efficient routing in ad hoc networks," in *Handbook of Wireless Networks and Mobile Computing*, I. Stojmenovic (ed.), Wiley, New York, 2002, pp. 451-472.

[55] I. Stojmenovic, X. Lin, "Power aware localized routing in ad hoc networks," *IEEE Transactions on Parallel and Distributed Systems*, Vol. 12, No. 10, October 2001, pp. 1023-1032.

[56] I. Stojmenovic, "Position based routing in ad hoc networks," *IEEE Commmunications Magazine*, Vol. 40, No. 7, July 2002, pp. 128-134.

[57] I. Stojmenovic, X. Lin, "Broadcasting and activity scheduling in ad hoc networks", in: S. Basagni, M. Conti, S. Giordano, I. Stojmenovic (eds.), *Mobile Ad Hoc Networking*," IEEE Press and John Wiley and Sons, New York, 2004, ISBN: 0-471-373133.

[58] I. Stojmenovic, A. Nayak, J. Kuruvila, "Design guidelines for routing protocols in ad hoc and sensor networks with a realistic physical layer", *IEEE Communications Magazine*, March 2005, Vol. 43, No. 3, pp. 101-106.

[59] I. Stojmenovic, A. Nayak, J. Kuruvila, F. Ovalle-Martinez, E. Villanueva-Pena, "Physical layer impact on the design and performance of routing and broadcasting protocols in ad hoc and sensor networks", *Computer Communications (Elsevier)*, Vol. 28 Issue 10, June 2005, pp. 1138-1151.

[60] I. Stojmenovic, "Localized network layer protocols in sensor networks based on optimizing cost over progress ratio", *IEEE Network*, Vol. 20, No. 1, January/February 2006, pp. 21-27.

[61] H. Takagi and L. Kleinrock, "Optimal transmission ranges for randomly distributed packet radio terminals", *IEEE Transactions on Communications*, Vol. 32, No. 3, 1984, pp. 246-257

[62] C-K Toh, "A Novel Distributed Routing Protocol To Support Ad hoc Mobile Computing", *Proc. IEEE 15th Annual International Phoenix Conference on Computers and Communications*, IEEE IPCCC 1996, March 27-29, Phoenix, AZ, USA, pp. 480-486.

[63] J. Zhao, R. Govindan, "Understanding Packet Delivery Performance in Dense Wireless Sensor Networks", *Proceedings of ACM SenSys*, Los Angeles, November 2003, pp. 1-13.

[64] M. Zuniga, B. Krishnamachari, "Analyzing the Transitional Region in Low Power Wireless Links", *First IEEE International Conference on Sensor and Ad hoc Communications and Networks (SECON)*, Santa Clara, CA, October 2004, pp. 517-526.

Publications resulting from this Thesis

- **Journal Publications**

  1. J. Kuruvila, A. Nayak, and I. Stojmenovic, Hop count optimal position based packet routing algorithms for ad hoc wireless networks with a realistic physical layer, *IEEE Journal of Selected Areas in Communications*, Vol. 23, No. 6, June 2005, pp. 1267-1275.
  2. J. Kuruvila, A. Nayak, I. Stojmenovic, Greedy localized routing for maximizing probability of delivery in wireless ad hoc networks with a realistic physical layer, *Journal of Parallel and Distributed Computing*, Vol. 66, Issue 4 (Special Issue), April 2006, pp.499-506.
  3. I. Stojmenovic, A. Nayak, J. Kuruvila, F. Ovalle-Martinez, E. Villanueva-Pena, Physical layer impact on the design and performance of routing and broadcasting protocols in ad hoc and sensor networks, *Computer Communications (Elsevier)*, Vol. 28 Issue 10, June 2005, pp. 1138-1151.
  4. I. Stojmenovic, A. Nayak, J. Kuruvila, Design guidelines for routing protocols in ad hoc and sensor networks with a realistic physical layer, *IEEE Communications Magazine*, March 2005, Vol. 43, No. 3, pp. 101-106.

- **Conference Publications**

  1. J. Kuruvila, A. Nayak, and I. Stojmenovic, Hop count optimal position based packet routing algorithms for ad hoc wireless networks with a realistic physical layer, *Proc. 1st IEEE Int. Conf. on Mobile Ad-hoc and Sensor Systems (MASS)*, Fort Lauderdale, October 2004.
  2. J. Kuruvila, A. Nayak, I. Stojmenovic, Greedy localized routing for maximizing probability of delivery in wireless ad hoc networks with a realistic physical layer, *Proc. 1st Int. Workshop on Algorithms for Wireless and Mobile Networks (A-SWAN)*, at Mobiquitous, ICST, Boston, August. 2004.

- **Motivated by this work (in progress based power/cost aware routing)**.

  1. J. Kuruvila, A. Nayak, I. Stojmenovic, Progress and location based localized power aware routing for ad hoc and sensor wireless networks, Accepted for publication, *International Journal of Distributed Sensor Networks.*
  2. J. Kuruvila, A. Nayak, I. Stojmenovic, Progress based localized power and cost aware routing algorithms for ad hoc and sensor wireless networks, *Third Int. Conf. on Ad-Hoc Networks and Wirelsss (ADHOC-NOW)*, Vancouver, BC, July 22-24, 2004.

Vita

Name : Johnson T. Kuruvila

Qualifications : Bachelor of Engineering (Electronics & Communications).
Regional Engineering College, Surathkal, India
: Masters, (Computing & Information Science)
Queen's University, Kingston, Canada

Industry Experience : Graduate Engineer, Larsen & Toubro Ltd, India.
: Member of Research Staff, Central Research Labs.
Bangalore, India
: Member of Research Staff, Bell Northern Research.
Ottawa, Canada.
: Manager, Tera-bit Router Development
Nortel, Ottawa, Canada
: Lead Engineer, Networking
AcceLight Networks, Ottawa, Canada
: Director, Routing/MPLS Platforms
AcceLight Research, Ottawa, Canada

Memberships : Senior Member, IEEE

Publications : Around 15 (Journals & Conferences)