

**PHYSICAL LAYER IMPACT ON WIRELESS MOBILE
AD-HOC NETWORK PERFORMANCE**

by

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Abstract

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by

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In this thesis, we propose performance optimization challenges of ad hoc networks using cross layer design. Due to size and mobility requirements of the nodes that make up these networks, the routing protocols employed often must deal with limited performance. Thus, it is necessary to consider models and constraints at multiple layers when we explore network performance limits. The formulations of these cross-layer problems are usually in very complex forms and are mathematically challenging.

We introduce effective mathematical tools that can model time varying wireless channels in a discrete time domain. These mathematical tools, known as Markov models, have been proved as very proficient way of modeling wireless communication parameters such as channel fading statistics and Bit Error Rate (BER) performance.

We start the analysis of wireless channel first using 2-state Markov model, which in spite of network performance enhancement, cannot be very efficient in all scenarios, since wireless channel characteristics dynamically change in time. Next we demonstrate that using higher order of Markov chains, it is possible to implement a more realistic channel. However, increasing the number of states increases the computational complexity. Thus, we use a 3-state Markov model of the wireless channel as a tradeoff between complexity and the performance.

We propose an optimal algorithm on how the physical layer channel state information can be translated into the QoS parameters in higher layers. Since a cross-layering between the physical layer and the routing protocol has been proven to be significant, we introduce a development of physical layer-constrained routing algorithm that switches between the best possible routes as a function of Signal to Noise Ratio (SNR). We explore cross-layer adaptation of the route selection to channel conditions, to optimize network throughput. We propose a physical layer aware routing that switches between the best possible routes as a function of SNR.

Furthermore, to improve the performance of wireless ad-hoc networks, we implement a new metric based on the channel SNR information and lifetime of the links, for optimal route discovery. Introducing this new parameter, called Link Lifetime (LLT), we show how we can reduce the control overhead by avoidance of frequent routes reestablishment, and realize sudden route maintenance in mobile ad hoc networks.

Finally using numerous simulations, we analyze the performance of an ad-hoc routing protocol. Our results indicate that employing this new metric of LLT and 3-state Markov chain model, we achieve more stable routes, thus, dramatically improving the overall performance of a mobile ad-hoc network.

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Table of Contents

1. Introduction.....	1
1.1. Motivation	1
1.2. Contribution	4
1.3. Thesis Outline	6
2. Wireless Channel Model.....	7
2.1. Introduction	7
2.2. Wireless Channel Model	8
2.3. Interference impact.....	10
2.4. Introduction to Finite State Markov Chain	11
2.5. Finite State Markov Chain Model.....	12
2.6. Conclusion.....	15
3. Modeling Wireless Channel with 2-State Markov Chain Model.....	17
3.1. Introduction	17
3.2. 2-State Markov Model	19
3.3. Related work	20
3.4. Simulation Model.....	22
3.5. Overview of DSR.....	25
3.5.1. The DSR Route Discovery.....	26
3.5.2. DSR Route Maintenance.....	28
3.5.3. Route Cache	29
3.5.4. Replying to RREQ using Cached Routes	30

3.6.	DSR with Cross - Layer Design (CLD)	30
3.6.1.	Route Discovery.....	31
3.6.2.	Route Maintenance	32
3.7.	Simulation of DSR with CLD	36
3.8.	Overview of Optimized Link State Routing Protocol (OLSR)	39
3.8.1.	Neighbor/Route Discovery	40
3.8.2.	Routing Table Calculation	40
3.8.3.	Route Maintenance	41
3.9.	OLSR with Cross – Layer Design (CLD)	42
3.10.	Simulation of OLSR with CLD	44
3.11.	Performance Metrics.....	45
3.12.	Conclusion	50
4.	Modeling Wireless Channel with 3-State Markov Chain Model.....	51
4.1.	Introduction	51
4.2.	Route Discovery (3-State).....	54
4.3.	Route maintenance (3-State)	58
4.4.	Simulation results.....	59
4.5.	Conclusion.....	61
5.	Link Lifetime based Routing	65
5.1.	Introduction	65
5.2.	Related Work.....	67
5.3.	OLSR with Cross - Layer Design (SNR and LLT).....	69
5.4.	Simulation of OLSR Protocol Under Different Radio Propagation Models.....	73

5.5. Conclusion.....	83
6. Conclusion and Future Work.....	85
6.1. Conclusion.....	85
6.2. Future Work.....	86
Bibliography.....	88

List of Figures

Figure 2-1 State diagram of Finite State Markov Chain.....	14
Figure 3-1 Two state Markov Model	19
Figure 3-2 Wireless LAN Workstation Node Model with CLD.....	23
Figure 3-3 MANET Station Node Model with CLD	24
Figure 3-4 Process model of IP.....	24
Figure 3-5 A part of OPNET code with performed modifications	25
Figure 3-6 Route discovery process in DSR.....	27
Figure 3-7 Route maintenance process in DSR	29
Figure 3-8 Finding cached routes in DSR.....	30
Figure 3-9 RREQ messages during the route discovery with Link State	31
Figure 3-10 Route Discovery Process for DSR with CLD.....	35
Figure 3-11 Route Maintenance Process for DSR with CLD.....	36
Figure 3-12 Trajectory_1 Profile	37
Figure 3-13 Trajectory_2 Profile	38
Figure 3-14 Network Scenario with DSR Protocol	38
Figure 3-15 Trajectory_3 Profile	44
Figure 3-16 Network Scenario with OLSR Protocol.....	44
Figure 3-17 Routing Overhead (bits/sec) for DSR and DSR with CLD.....	47
Figure 3-18 Average Throughput (kbits/sec) for DSR and DSR with CLD.....	48
Figure 3-19 End-to-End Delay (sec) for all connections for DSR and DSR with CLD ..	48
Figure 3-20 Average Throughput (kbits/sec) for OLSR and OLSR with CLD.....	49

Figure 3-21 Routing Overhead (bits/sec) for OLSR and OLSR with CLD.....	49
Figure 3-22 Average Delay(sec) for OLSR and OLSR with CLD.....	50
Figure 4-1 Three-State Markov model of a channel.....	52
Figure 4-2 Received SNR for a link vs. simulation time.....	54
Figure 4-3 Route Discovery Process.....	56
Figure 4-4 Route Maintenance <i>DSR with CLD (3-State)</i>	57
Figure 4-5 Average end-to-end delay(sec) (DSR, 3-State).....	62
Figure 4-6 Average network throughput (kbits/sec) (DSR, 3-state).....	63
Figure 4-7 Routing traffic received (bits) (DSR, 3-state).....	63
Figure 4-8 Average data dropped (DSR, 3-state).....	64
Figure 5-1 Network Example. Route selection in traditional OLSR.....	72
Figure 5-2 Part of code inserted in the OPNET Pipeline stages.....	77
Figure 5-3 SNR variations in time for a specific receiver-Node 70.....	79
Figure 5-4 Network Throughput vs. Simulation time with Free-Space and Log-Normal Shadowing Model.....	79
Figure 5-5 Network Throughput vs. Simulation time with and without CLD.....	80
Figure 5-6 Network Throughput vs. Simulation time in Rayleigh fading channel.....	80
Figure 5-7 Average Number of Packets Dropped vs Mobility Speed.....	81
Figure 5-8 Average Network Delay in sec. vs Mobility Speed.....	81
Figure 5-9 Average number of TC Messages sent vs Mobility Speed.....	82
Figure 5-10 Number of MPRs in the network vs Mobility Speed.....	82

List of Tables

Table 1. The parameters values and the simulation parameters used in our scenario with DSR and OLSR.....	45
Table 2. Parameters values in the simulations of OLSR with CLD and LLT	84

Acronyms

CLD	Cross Layer Design
DSR	Dynamic Source Routing
FSMC	Finite State Markov Chain
LLT	Link Lifetime
MANETs	Mobile Ad-Hoc Networks
OLSR	Optimized link state routing protocol
QoS	Quality of Service
SNR	Signal to Noise Ratio

Chapter 1

Introduction

1.1. Motivation

The explosive increase in wireless packet-data applications, such as wireless web browsing, real-time mobile multimedia streaming, and interactive applications motivates the rapid development of the next-generation mobile wireless networks. The associated communication channels and traffic patterns in mobile wireless networks are more unpredictable than the traditional wired networks. On the other hand, the future multimedia applications impose stringent and diverse Quality of Service requirements, which cannot be satisfactorily addressed through the traditional layering network-protocol architecture which is a widely known, well accepted framework for communication systems.

The layered networking architecture has been the key to the enormous success and widespread usage of the Internet, as well as the initial development of wireless systems. The success of the layered architecture has been its ability to provide modularity and transparency between the layers.

However, in order to support the revolution of new applications, a new era of network architectures has emerged. A major challenge is to understand at a fundamental level how to best design and control these networks, referred to as “wireless ad-hoc networks”.

Mobile Ad-Hoc Networks (MANETs) are networks of mobile devices that are formed in an ad-hoc manner. The devices that participate in such networks have wireless communication capabilities with limited range transmitters, and thus can directly communicate with other devices that are within their range. Some of the devices occasionally volunteer to forward some of the messages they receive, or in other words, act as routers, thereby forming a multi-hop network with a wider reach. Yet, there is no fixed infrastructure, the network is continuously changing, and routers are elected on demand. In other words, the networking issues are handled in an ad-hoc manner.

Ad hoc networks have emerged recently as an important trend of future wireless systems. The evolving wireless networks are seriously challenging the traditional OSI layered design. In order to provide high capacity wireless access and support new multimedia network, the various OSI layers and network functions should be considered together while designing the network.

Actually, system performance improvements for wireless ad hoc networks could arise from some communications between different layers, considering certain smart

interactions between them in the system design. This general concept is known as cross-layer optimization.

Correspondingly, a cross-layer design paradigm would be needed to achieve transmission protocol stack performance while meeting these new challenges. The cross-layer designs and protocols tend to be very essential approaches for the mobile wireless and ad hoc networks where unpredictable variables such as node mobility, node density, and network dimensions make the diverse and stringent wireless QoS requirements even harder to satisfy.

Traditionally, network protocols are divided into several independent layers. Each layer is designed separately, and the interaction between layers is performed through a well defined interface. The main advantage of this type of approach is architectural flexibility. One implementation of a layer can be seamlessly replaced with another implementation. For example, if an old protocol has to be replaced with a newer one, there is no need to modify the rest of the network stack.

The Cross layer concept is a new way to see the quality of service in the network. It does not consist in the addition of reservation mechanisms of bandwidth or any other ad-hoc mechanism, but in adapting the current mechanisms at one level to the underlying levels.

In this thesis, we discuss performance optimization challenges of ad hoc networks and cross-layer design. Ad hoc wireless networks were implemented by using Network Simulator, OPNET, and the wireless physical and network layer of two types of routing protocol models have been included in the simulation. Simulations show that the

performance begins to drop due to congestion, the mobility and fading, which cause the route failures and packet loss in wireless environment.

To improve the performance for wireless networks, we implemented a signal strength aware cross-layer design. The network layer adaptively selects a transmission path based on the channel signal strength and link lifetime information from physical layer. This information is sent to a routing protocol as a stability aware routing metric for optimal route discovery. We modified the source codes in Physical layer and the routing of the ad-hoc network protocols. The simulations show that physical layer aware routing, improves the network performance in terms of throughput, overhead, and end-to-end delay.

1.2. Contribution

Unlike infrastructure based networks in which routers are usually considered to be trusted entities, in ad-hoc networks, routing is performed by the devices themselves. Thus, there is a high risk that some of the links between nodes of an ad-hoc network would could easily broke down. Therefore, the possibility of having broken links, respectively the paths in the system, motivates the development of reliable broadcast protocols for ad-hoc networks.

The common theme of most research in this area is the optimization of the physical layer performance measures without considering a cross layer approach to evaluate the interaction of physical layer with higher layers in improving the network performance measures.

Since the interaction between layers is significant in the design and implementation of wireless ad-hoc networks, we have attempted to address this interaction studying first the effect of the Physical Layer notion in the Quality of Service performance of wireless networks. Some of the most important inherent properties of the Physical Layer that make the design of protocols more complicated, include the attenuation of radio signals over long range communications called path loss, and the fading effect caused by multipath propagation. In order to mitigate these effects, we have to use more sophisticated reception algorithms, considering many important issues such as fading effects and the interference caused by multiple active sources.

Our main contribution in this work is to design optimal communication algorithms which are based on cross-layer approach, mainly considering the interaction between Physical and Network layer in the design and performance evaluation of protocols.

Our work presented in this thesis aims at contributing to the persistent evolution of wireless communications. The thesis evaluates different aspects of cross layer design by studying the potential benefits of interactions among the physical and network layers. For analysis of upper layer characteristics, a simplified physical layer model has to be chosen to model the physical layer characteristics. In this dissertation we first employ the widely used 2-state Markov model, which, despite network performance enhancement, cannot be very efficient in all scenarios. Using 3-state Markov model we demonstrate more accurate network results.

Our focus is on the design, analysis, and performance evaluation of the routing protocols for ad hoc networks. These constitute as the extension and adaptation of the

existing reactive and proactive routing protocols, which introduce a new paradigm in the context of route selection. Theoretical analysis and computer based simulations show that the modified versions of these protocols outperform their standard versions. It is also shown that the appropriate modeling of the wireless channel behavior is the basis for finding network aware cross layer processing algorithms which are capable of exploiting the predictability of the links' lifetime during the route selection. The link lifetime prediction is realized using the mean sojourn time of the states in FSMC.

1.3. Thesis Outline

This thesis is outlined as follows. In Chapter 2, we present the channel model of the system and study the impact of Physical Layer in the routing decision in ad-hoc networks, modeling wireless channel with Finite State Markov Chain. In Chapter 3, we address the effect of joint cooperation between Physical and Routing Layers, and the resulting network throughput increase due to this interaction, using two-state Markov Modeling of the channel. In Chapter 4 we show how increasing the number of states in FSMC results in increasing the network throughput under a multihop communication setting, evaluating the performance of an ad-hoc protocol. In order to gain more insight to the problem of multi hop communication we further study the issue of the wireless communication channel in Chapter 5, in the context of common radio channel impairments like multipath fading, path loss and interference, and numerically show the performance gain achieved by optimally choosing the routes based on the new metric, Link Lifetime. Finally the concluding remarks and future work are given in Chapter 6.

Chapter 2

Wireless Channel Model

2.1. Introduction

The major problem with transmitting information over wireless channels is the issue of link reliability. Wireless channels have high channel bit error rate and limited bandwidth. The high bit error rate degrades the quality of transmission and the network performance. The notion of a link in wireless ad hoc networks is different from that in the wired network, where the link exists between two nodes only if they are connected by a physical medium. Each wireless node can communicate with any other node within its transmission range, which depends on the SNR at the receiver and the coding scheme used by the transmitter.

The quality of wireless channel among the mobile nodes is time varying due to fading, shadowing and pathloss. Given that the shortest-path metric does not take into account the physical channel variations of the wireless medium, it is desirable to select

the routes with minimum cost based on some other metrics which are aware of the wireless nature of the underlying physical channel. In self-organized network, there are many other metrics to be considered: Power, Packet Loss, Maximum available bandwidth etc. These metrics should come from a cross-layer approach in order to make the routing layer aware of the local issues of the underlying layers.

2.2. Wireless Channel Model

The signal transmitted from a mobile node to others, loses part of its power along the way. This happens because of the distance it travels and the terrain across which it travels. The radio wave (signal) propagation is generally modeled by the combination of *large scale* and *small scale* propagation models [1].

Large-scale fading is due to the distance loss and shadowing effects and changes relatively slowly. As the node moves over longer distance, the average signal strength gradually decreases. This way large scale fading is of interest, because the movement tendency of the nodes enables us to discover routes which are more likely to fail.

On the other hand, node movement over short distances may cause the rapid variation of the received signal strength, thus, giving rise to small scale fading. Small scale fading can be modeled by Ricean fading (with line of sight) or Rayleigh fading (with no line of sight).

Slow fading can be caused by events such as shadowing, where a large obstruction such as a hill or large building obscures the main signal path between the transmitter and the receiver. The amplitude change caused by shadowing is often

modeled using a log-normal distribution with a standard deviation according to the log-distance path loss model.

The simplest path loss model is well known free space model, which predicts the received power as a deterministic function of distance. The communication range with this model is represented as an ideal circle. But in reality, the received power at certain distance is a random variable due to multipath propagation effects. Since, the free space model predicts the mean received power at distance d , a more general model, so called the shadowing model has to be used.

The shadowing model extends the ideal circle model to a richer statistic model: nodes can only probabilistically communicate when near the edge of the communication range.

The more realistic physical layer includes a channel with both path loss and shadowing. This consists of two parts. The first one is known as path loss model, which also predicts the mean received power at distance d , denoted by $P_r(d)$. It uses a close-in distance, d_0 , as a reference. $P_r(d)$ is computed relative to $P_r(d_0)$ as follows.

$$\frac{P_r(d_0)}{P_r(d)} = \left(\frac{d}{d_0} \right)^\beta, \dots(2.1)$$

where β , is called the path loss exponent, and is usually empirically determined by field measurement. The value of β for free space propagation model is 2.

Since the path loss is usually measured in dB the previous eq. becomes

$$\left[\frac{P_r(d)}{P_r(d_0)} \right]_{dB} = -10\beta \log\left(\frac{d}{d_0}\right) \quad \dots(2.2)$$

The second part of the propagation model reflects the variation of the received power at certain distance. It is a log-normal random variable, that is, it is of Gaussian distribution if measured in dB. The overall shadowing model is represented by

$$\left[\frac{P_r(d)}{P_r(d_0)} \right]_{dB} = -10\beta \log\left(\frac{d}{d_0}\right) + \chi_{dB}, \dots(2.3)$$

where χ_{dB} is a Gaussian random variable with zero mean and standard deviation σ_{dB} , which is called the shadowing deviation, and is also obtained by measurement. Eqn.(3) is also known as a log-normal shadowing model.

2.3. Interference impact

In a wireless ad-hoc network, because nodes share a common channel, interference usually has a greater impact than noise.[2]. In addition, thanks to in-band transmissions from nodes that are out of range, but close enough to cause interference, as well as crosstalk from near-band transmissions, the interference level can have large, rapidly changing values. Hence we focus on the SINR, rather than the SNR, signal to noise ratio.

Computation of interference and noise at each receiver is a critical factor in wireless communication modeling, as this computation becomes the basis of SINR (Signal to Interference and Noise Ratio) or SNR (Signal to Noise Ratio) that has a strong

correlation with PER (Packet Error Rate) on the channel. The power of interference and noise is calculated as the sum of all signals on the channel other than the one being received by the radio plus the thermal (receiver) noise. The resulting power is used as the base of SNR, which determines the probability of successful signal reception for a given packet [3].

Thus, a communication between two nodes u and v is successful if the SINR (Signal to Interference and Noise Ratio) at the receiver v is above a certain threshold which depends on the desired transmission characteristics (e.g channel, data rate etc.). More formally, denoting the signal strength of a packet from node u (sender) at node v (receiver) by $P_v(u)$, a packet on the link (u,v) from node u to node v is correctly received if and only if SINR is above a certain threshold.

$$SINR = \frac{P_v(u)}{N + \sum_{w \in v'} P_v(w)} \geq \delta \dots(2.4)$$

where N is the background noise, v' is the set of nodes simultaneously transmitting and δ is a constant which depends on the data rate, channel characteristics, modulation scheme etc.

Since in a realistic channel the interference cannot be excluded, from now on, we will refer to SINR as SNR. Accordingly, N represents the background noise plus the total interference of all neighboring transmissions.

2.4. Introduction to Finite State Markov Chain

Wireless has proved to be one of the most important and fastest growing fields of communications especially during last few decades. To achieve reliable communication,

we model a wireless channel to analyze its performance and to find ways to improve the reliability of a particular system.

In our work we perform the stochastic analysis of a Wireless communication channel. Our study is based on a Finite State Markov Model. The channel switches between different states. Each state corresponds the probability that a packet sent by the transmitter will be received by receiver or will be lost. The transition between the different states of the channel is administrated by a Markov chain; this Markov chain is not observed directly, but the received packet provides some probabilistic information about the current state of the channel.

2.5. Finite State Markov Chain Model

The signal-to-noise ratio (*SNR*) experienced by mobile terminal is complex mobility-dependent stochastic process resulting in three fading components each of which significantly influence performance of the wireless channel: pathloss component, shadowing and multipath.

If we consider Rayleigh fading channel, then the received signal is the sum of signals with different phases caused by different paths, which can be modeled as a random variable. In a multipath propagation environment with additive Gaussian noise, received SNR has also the Rayleigh distribution with probability density function

$$p(\gamma) = \frac{1}{\bar{\gamma}} \exp\left(-\frac{\gamma}{\bar{\gamma}}\right) \quad \dots(2.5)$$

Where $\bar{\gamma}$, is the average SNR, which is physical layer depended and can be expressed as

$$\bar{\gamma} = P_t - L_i - P_N - L_p \quad \dots(2.6)$$

Where P_t (dBm) is the transmitter output power, L_i (dB) is the implementation loss, due to connecting cables or antenna patterns, P_N (dBm) is the receiver hardware related noise power and L_p (dB) is the radio propagation path loss which general expression can be found as

$$L_p = G_1 + G_2 \log_{10} f_c + G_3 \log_{10} d \quad \dots(2.7)$$

G_1 , G_2 , G_3 are constants corresponding to application scenarios, f_c is the carrier frequency and d is the distance between the transmitter and receiver.

In one word given the physical layer conditions, the average received SNR enables us to characterize the channel variation at the physical layer using the finite state Markov chain channel model, known as FSMC.

The basic requirement for defining a Markov process is to specify the probability of making the next transition state for each state in the process and for each transition time.

$$P_r(s_{n+1} = j | s_n = i)$$

Thus must be specified for $1 \leq i, j \leq N$, where i, j denote the state index and n is the discrete time index.

The $N \times N$ transition probabilities that describe the Markov process are generally represented by $N \times N$ transition probability matrix generally denoted as P . The transition probability matrix of a Markov process can be graphically represented with the transition

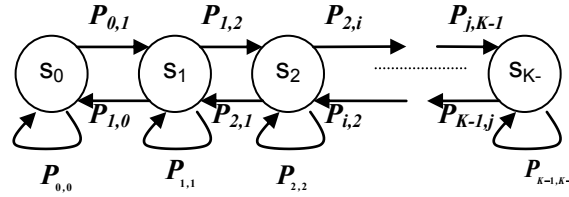


Figure 2-1 State diagram of Finite State Markov Chain

diagram, where the nodes represent the states of the process itself.

Let $S = \{s_1, s_2, \dots, s_K\}$, denote the state space of a stationary Markov chain with K states. State's space S is that of K different channel states with corresponding SNR thresholds, Γ_k , in increasing order [4].

$$0 = \Gamma_0 < \Gamma_1 < \Gamma_2 < \dots < \Gamma_{K-1} < \Gamma_K = \infty \quad \dots(2.8)$$

The channel is in state k , if the received SNR is between Γ_k and Γ_{k+1} .

$$S_k; \Gamma \in [\Gamma_k, \Gamma_{k+1}] \quad k = 0, 1, 2, \dots, K-1 \quad \dots(2.9)$$

Considering the mobility of the nodes, their motion of a certain speed causes the Doppler frequency, f_m , then the number of times that the received signal crosses the given threshold, Γ_k , in the positive or negative direction only, is known as the level crossing rate of level Γ_k , and is given with

$$N(\Gamma_k) = \sqrt{\frac{2\pi\Gamma_k}{\bar{\gamma}}} f_m \exp\left(-\frac{\Gamma_k}{\bar{\gamma}}\right) \quad \dots(2.10)$$

$$f_m = \frac{f_c v}{c} \quad \dots(2.11)$$

f_c is the carrier frequency, v speed of the node and c is the speed of light.

Thus the transition probabilities from state s_k , to state s_{k+1} , $P_{k,k+1}$, can be expressed as a ratio of the level crossing rate at threshold Γ_{k+1} , and the average number of signal segments per second staying in state s_k .

The transition probabilities can be approximated as

$$P_{k,k+1} = \frac{N(\Gamma_{k+1})T_p}{\pi_{kk}}, \quad k = 1, 2, \dots, K-1 \quad \dots(2.12)$$

$$P_{k,k-1} = \frac{N(\Gamma_k)T_p}{\pi_{kk}}, \quad k = 2, 3, \dots, K \quad \dots(2.13)$$

where T_p is the packet transmission time and

$$\pi_{kk} = \int_{\Gamma_k}^{\Gamma_{k+1}} p(\gamma) d\gamma = \exp\left(-\frac{\Gamma_k}{\bar{\gamma}}\right) - \exp\left(-\frac{\Gamma_{k+1}}{\bar{\gamma}}\right) \quad \dots(2.14)$$

Consequently knowing the transition probabilities the steady state probabilities can be calculated as

$$P_{kk} = \begin{cases} 1 - P_{k,k+1} - P_{k,K-1}, & \text{if } 0 < k < K \\ 1 - P_{01}, & \text{if } k = 0 \\ 1 - P_{K,K-1}, & \text{if } k = K \end{cases} \quad \dots(2.15)$$

$$P_C = [P_{ij}]_{(K+1) \times (K+1)} \quad \dots(2.16)$$

where P_C is the transition matrix of the FSMC model.

2.6. Conclusion

The goal of this chapter was to develop the terminology, definitions, and basic concepts of modeling a random wireless channel that can be a function of time, frequency and speed. These concepts include shadowing effects, the impact of interference and multipath propagation effect.

Errors introduced by a wireless medium are more frequent and profound than contemporary wired media. Some of these errors, which are not corrected by the physical layer, result in Medium Access Control layer bit errors and packet losses. Design of wireless protocols and applications can benefit substantially from a thorough understanding of these inter layer impairments. We evaluate and propose Finite State Markov-based stochastic chains to model the channel behavior for both bit errors and packet losses.

Chapter 3

Modeling Wireless Channel with 2- State Markov Chain Model

3.1. Introduction

Routing in MANET (Mobile Ad Hoc Network) is challenging due to the dynamic nature of network topology and the resource constraints. To maximize the channel resource utilization and minimize the network transfer delay along the path, the shortest path with minimum hops scheme is often adopted.

Reference [24] shows that routing in multi-hop wireless networks using the shortest-path metric is not a sufficient condition to construct good quality paths, because minimum hop count routing often chooses routes that have significantly less capacity than the best paths that exist in the network. Specially, the nodes near the center of the network carry high loads when the routing protocol uses shortest path route strategy.

However, the quality of wireless channel among the mobile nodes is time varying due to fading, shadowing and pathloss. Given that the shortest-path metric does not take

into account the physical channel variations of the wireless medium, it is desirable to select the routes with minimum cost based on some other metrics which are aware of the wireless nature of the underlying physical channel. In self-organized network, there are many other metrics to be considered: Power, Packet Loss, Maximum available bandwidth etc. These metrics should come from a cross-layer approach in order to make the routing layer aware of the local issues of the underlying layers.

In this chapter we perform the stochastic analysis of a Wireless communication channel. Our study is based on a Finite State Markov Model. The channel switches between different states. Each state corresponds the probability that a packet sent by the transmitter will be received by receiver or will be lost. The transition between the different states of the channel is administrated by a Markov chain; this Markov chain is not observed directly, but the received packet provides some probabilistic information about the current state of the channel. The major problem with transmitting information over wireless channels is the issue of link reliability.

Wireless channels have high channel bit error rate and limited bandwidth. The high bit error rate degrades the quality of transmission and the network performance. The notion of a link in wireless ad hoc networks is different from that in the wired network, where the links exists between two nodes only if they are connected by a physical medium. Each wireless node can communicate with any other node within its transmission range, which depends on the SNR at the receiver and the coding scheme used by the transmitter.

3.2. 2-State Markov Model

Now our attention will be given to the realization of wireless channels, first considering the simplest case of a channel having only two states, and observing the errors generated by this channel. The generation of an error depends upon a threshold

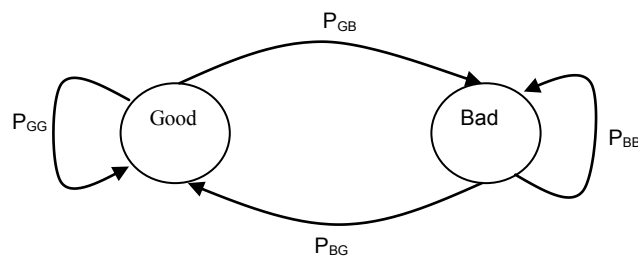


Figure 3-1 Two state Markov Model

level, which is the probability of generating error. If the probability is less than the threshold, the error probability can be neglected. If the probability is higher than the threshold, then it is assumed that the error is generated. This is known as simplified two state Markov chain channel model or Gilbert-Elliot model. In this model the source has two states: G (for good or no errors) and B (for bad or burst errors).

We use P_{GB} to denote the transition probability from state “Good” to state “Bad”, and use P_{BG} to denote the transition probability from state “Bad” to state “Good”. Due to the nodes’ mobility, both probabilities are functions of the nodes’ mobility profile and the channel parameters. Transition probability matrix and steady state probabilities are given with the expressions below.

$$R = \begin{bmatrix} P_{GG} & P_{GB} \\ P_{BG} & P_{BB} \end{bmatrix} \quad \dots(3.1)$$

$$\pi = \begin{bmatrix} \frac{P_{GB}}{P_{BG} + P_{GB}} & \frac{P_{BG}}{P_{BG} + P_{GB}} \end{bmatrix} \quad \dots(3.2)$$

The channel is assumed to either be in a “Good” state or in a “Bad” state during a packet transmission. We consider the situation in which the success of a packet transmission in a given state is determined by comparing the received SNR to a threshold. Above the threshold, the packet is decoded successfully with probability 1. Otherwise it is lost with probability 1.

The value of SNR threshold is not chosen arbitrarily, it is a function of the maximum symbol error probability of the channel that our application and protocol can assume. It was shown that the SNR is related to the packet length [34]. However SNR threshold using the multipath fading channel is considerably different from the additive white Gaussian noise (AWGN) channel [25]. Given the parameters in our scenario first we calculate average received SNR and then select appropriate SNR threshold for the specified packet error rate.

3.3. Related work

In [5], the paper introduces an enhanced MAC protocol for multi-channel and multi-rate IEEE 802.11 which enables wireless ad hoc networks to opportunistically exploit the presence of frequency diversity in this way: if the signal to noise ratio on the current channel is not favorable, mobile nodes can opportunistically skip to better quality

frequency channels enabling data transmission at a higher rate. This maps the channel conditions at the PHY layer to the MAC. The channel reservation control packets employed at the MAC layer can be utilized at the physical layer in exchanging channel estimation information to enable an adaptive selection of a spectrally efficient transmission rate. In addition to this, [6], explains how the channel adaptive information gathered at the MAC layer can be communicated to the routing layer via different routing metrics for optimal route selection.

In [7], the authors describe and analyze how the existing ad-hoc routing protocols, reactive and proactive, differ in the mechanisms they use to select paths, detect broken links, and buffer messages during periods of link outage. But current routing protocols favor routing traffic based on shortest path, thus causing a bottleneck. Given that the shortest-path metric does not take into account the physical channel variations of the wireless medium, it is desirable to select the routes with minimum cost based on some other metrics which are aware of the wireless nature of the underlying physical channel. In self-organized network, there are many other metrics to be considered: power, packet loss, maximum available bandwidth, etc. These metrics should come from a cross-layer approach in order to make the routing layer aware of the local issues of the underlying layers. Authors in [8] explored three primitive physical layer parameters: interference, packet success rate, and data rate to determine the best path. But using three metrics in the same time is not an easy task, which raises the complexity of the routing algorithm. The paper addresses the routing problem analytically, and it shows that if the metrics are well defined it is an NP-Complete Problem.

One more paper suggests that routing should take into account physical layer characteristics. In particular, the bit error rate (BER) at the end of a multi-hop route may, under certain conditions, represent a good pointer of the physical layer status [9], however the performance evaluation of any routing protocol was not presented.

Reference [9] presents a cross-layer ad-hoc routing approach based on link connectivity assessment in network topology and suggests a framework for proactive enhancements to the OLSR protocol. Authors deploy an IEEE 802.11b based vehicular network and demonstrate the effectiveness of link-quality assessment based enhancements in improving the performance of inter-vehicle ad hoc routing.

In our approach, the objective is to propagate the information, particularly, SNR, from the physical layer up to the routing to improve the performance of the existing protocols. The performance of these routing protocols, traditional DSR and DSR with CLD, and OLSR and OLSR with CLD, are analyzed by computer simulations based on OPNET Network Simulator [11]

3.4. Simulation Model

Our simulation model uses OPNET Network simulation tool, which provides a development environment supporting the modeling of communication networks and distributed systems.

The OPNET modeling architecture is structured in a hierarchical fashion: The Network, Node, Process, and External System modeling environments. Finite state machines provide a natural representation for protocols. In regard of ad-hoc protocols, all

MANET routing protocols in OPNET, are made a child process of IP. The advantage of making the MANET model a child process of IP is two-fold:

- Ease of interface to IP without any requirements of any ICIs (Interface Control Information) to be passed between modules
- No changes to the node model structure required

In order to improve the end-to-end performance of an ad hoc network, we develop a feedback control mechanism, therefore enhancing the node model structure of the wireless LAN workstation and that of the MANET station, thus making these as generic node models. This is shown below:

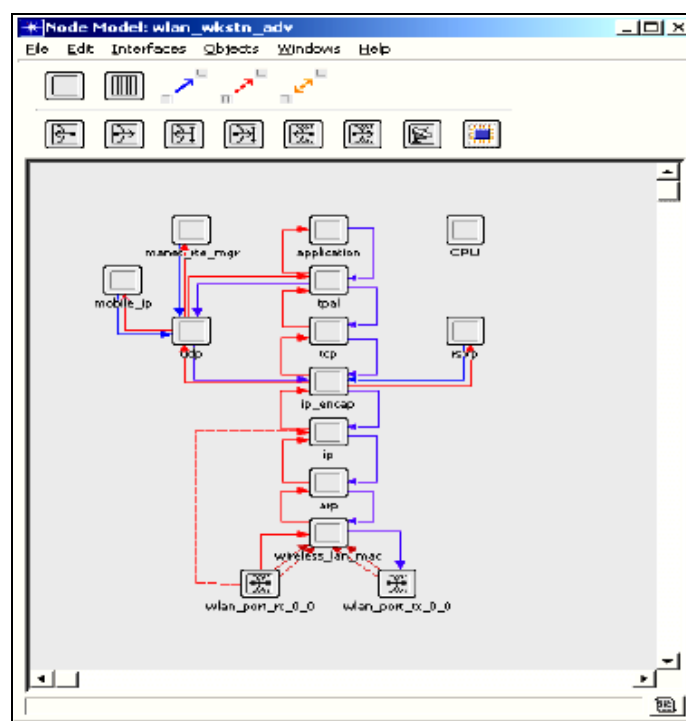


Figure 3-2 Wireless LAN Workstation Node Model with CLD


```

if (op_stat_local_read(RECEIVER_BUSY_INSTAT) < threshold)
{
    snr = op_stat_local_read(RECEIVER_BUSY_INSTAT);
    op_prg_log_entry_write(ip_log_handle,
        "WARNING(S):\n"
        " Local Statistics of SNR \n %f ",
        snr );
}
if (intf_ici_ptr == OPC_NIL)
{
    intf_ici_ptr = op_ici_create ("ip_param");
}
...
    if ((pkt_fields_ptr->protocol == IpC_Protocol_Dsr) ||
        (pkt_fields_ptr->protocol == IpC_Protocol_Tora))
    {
op_intrpt_schedule_call (op_sim_time(), 0,
ip_dispatch_stat_intrpt_handle, &snr);
        op_ici_attr_set (intf_ici_ptr, "rte_info_fields",
intf_ici_fdstruct_ptr);
        op_ici_attr_set (intf_ici_ptr, "rte_snr", snr);

        op_pk_ici_set (ip_pkptr, intf_ici_ptr);
        op_ici_attr_get (intf_ici_ptr, "rte_snr", &snr);
    }
}

```

Figure 3-5 A part of OPNET code with performed modifications

3.5. Overview of DSR

The Dynamic Source Routing (DSR) protocol was designed especially for MANET applications. Its main feature is that every data packet follows the source route stored in its header. This route gives the address of each node through which the packet should be forwarded in order to reach its final destination. Each node on the path has a routing role and must transmit the packet to the next hop identified in the source route.

Each node maintains a Route Cache in which it stores every source route it has learned. When a node needs to send a data packet, it checks first its route cache for a source route to the destination. If no route is found, it attempts to find one using the route discovery mechanism.

A monitoring mechanism, called route maintenance, is used in each operation along a route. This mechanism checks the validity of each route used.

The Dynamic Source Routing protocol (DSR) is a simple and efficient routing protocol designed specifically for use in multi-hop wireless ad hoc networks of mobile nodes. DSR allows the network to be completely self-organizing and self-configuring, without the need for any existing network infrastructure or administration. The protocol is composed of the two main mechanisms of "Route Discovery" and "Route Maintenance", which work together to allow nodes to discover and maintain routes to arbitrary destinations in the ad hoc network.

All aspects of the protocol operate entirely on-demand, allowing the routing packet overhead of DSR to scale automatically to only that needed to react to changes in the routes currently in use. The protocol allows multiple routes to any destination and allows each sender to select and control the routes used in routing its packets, for example for use in load balancing or for increased robustness. Other advantages of the DSR protocol include easily guaranteed loop-free routing, operation in networks containing unidirectional links and very rapid recover when routes in the network change. The DSR protocol is designed mainly for mobile ad hoc networks of up to about two hundred nodes, and is designed to work well with even very high rates of mobility.

3.5.1. The DSR Route Discovery

If node S wants to communicate with node D, it needs to find a route on demand by using the route discovery mechanism. Node S broadcasts a Route Request packet in the network. This Route Request contains the address of the initiator, the address of the

target, a field sequence number (set by the initiator and used to identify the request), and a route record. The latter is the field where a record of the sequence of hops taken by the Route Request is accumulated dynamically. Each node in the network maintains a table in order to detect a duplicate Route Request packet received.

A node propagates the Route Request if it is not the target and if it is the first time it receives this packet. The first node receiving this Request that has a valid route in its route cache for node D initiates a Route Reply packet back to node S. This Route Reply contains the list of nodes along the path from node S to node D. The first part is the information gathered along the path of the Route Request (that is, from node S to the node replying); the rest of the list is the information found in the route cache of the replying node. Moreover, it may occur that destination node D itself receives a Route Request packet, e.g. no node along the way before node D has an accurate route from node S to node D in its route cache. In this case, node D sends a Route Reply packet containing the path just created dynamically from source S to destination D, i.e., the path traversed by the first Route Request packet received by node D. This path is the minimum delay route from node S to node D. Node D discards all Route Request packets corresponding to the same route discovery process after the arriving of the first one.

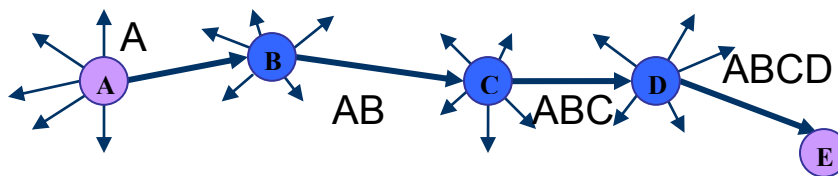


Figure 3-6 Route discovery process in DSR

3.5.2. DSR Route Maintenance

The route maintenance mechanism ensures that the paths stored in the route cache are valid. If the data link layer of a node detects a transmission error, the node creates a Route Error packet and transmits it to the original sender of the data packet. This Route Error packet indicates which link is “broken”, i.e., the node that detected the error and the node it was trying to reach. When a node receives a Route Error packet, it removes the link in error from its route cache and for each route containing this link, truncates the route from the hop before the broken link. In order to have feedback on the status of each hop, several acknowledgement mechanisms may be used, e.g. acknowledgement at the MAC layer level, request of an explicit acknowledgement from the next-hop receiver in the data packet header, or passive acknowledgement (that is, a node overhears the next node forwarding its packet).

For example:

- Node A is sending a packet to E using the route A-B-C-D-E. A is responsible for the correct delivery of the packet to B. B is responsible for the correct delivery of the packet to C and so on. The correct delivery can be assured through an acknowledgement.
- A node like C tries to forward the message and waits for the acknowledgement. C will retransmit the message a fixed number of times if no acknowledgement arrives.
- After that, C will initiate a route error message.

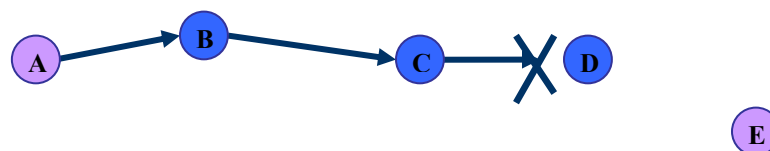


Figure 3-7 Route maintenance process in DSR

3.5.3. Route Cache

Each node implementing DSR MUST maintain a Route Cache, containing routing information needed by the node. A node adds information to its Route Cache as it learns of new links between nodes in the ad hoc network; for example, a node may learn of new links when it receives a packet carrying a Route Request, Route Reply, or DSR source route.

Likewise, a node removes information from its Route Cache as it learns that existing links in the ad hoc network have broken; for example, a node may learn of a broken link when it receives a packet carrying a Route Error or through the link-layer retransmission mechanism reporting a failure in forwarding a packet to its next-hop destination.

Anytime a node adds new information to its Route Cache, the node SHOULD check each packet in its own Send Buffer to determine whether a route to that packet's IP Destination Address now exists in the node's Route Cache (including the information just added to the Cache). If so, the packet SHOULD then be sent using that route and removed from the Send Buffer.

3.5.4. Replying to RREQ using Cached Routes

A node receiving a Route Request for which it is not the target, searches its own Route Cache for a route to the target of the Request. If it is found, the node generally returns a Route Reply to the initiator itself rather than forwarding the Route Request. In the Route Reply, it sets the route record to list the sequence of hops over which this copy of the Route Request was forwarded to it, concatenated with its own idea of the route from itself to the target from its Route Cache. However, before transmitting a Route Reply packet that was generated using information from its Route Cache in this way, a node must verify that the resulting route being returned in the Route Reply, after this concatenation, contains no duplicate nodes listed in the route record. Figure illustrates a case in which a Route Request for target E has been received by node B, and node C already has in its Route Cache a route from itself to E.

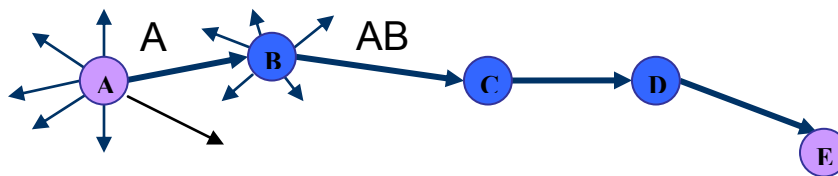


Figure 3-8 Finding cached routes in DSR

3.6. DSR with Cross - Layer Design (CLD)

We implement the physical parameter aware routing metric by modifying the dynamic source routing (DSR) [12] protocol. We demonstrate the benefits of inter layer interactions in low mobility scenarios, applying the routing metric to route discovery and the route maintenance.

3.6.1. Route Discovery

To perform a route discovery, if the source node doesn't have the valid route in its cache, it starts with the broadcasting of a route request (RREQ) packet that contains the address of the initiator, the address of the target, the request identifier, and the route record. Besides the information required for DSR such as the destination address and the sequence number, the node includes a physical layer parameter which indicates the quality of the path. Here, we are using SNR as the physical layer parameter.

In the route record field, each node appends its address as a hop sequence only if:

- it did not detect a duplicate RREQ and
- the value of the SNR is higher than the required threshold.

So whenever a node receives a RREQ packet, the physical parameter -SNR is determined and if the value of SNR is less than the required threshold, then the RREQ packet is discarded. This is shown in Figure 3-9, below.

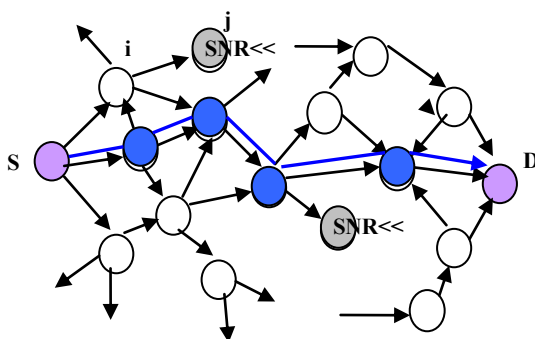


Figure 3-9 RREQ messages during the route discovery with Link State (SNR << link with SNR lower than SNR threshold)

From Figure.3-9, for example, we can see that node j, measuring the received SNR, has detected that the link (i-j) SNR is less than the required SNR threshold; therefore, it does not propagate the RREQ any further and will not be potential transit node in the path.

If the above criterion is satisfied and the node is not the target it propagates the route request again. When the destination node receives the RREQ message, it initiates the route reply, RREP, packet back to the source node. This route reply contains the list of nodes along the path from source to destination. Since SNR is used as criteria in the selection of the routes, we have to ensure that during the route maintenance phase, all existing routes meet the criteria of exceeding SNR threshold, otherwise such route is invalid.

When the RREP reaches its destination, the source node begins using this route for delivery of the packet, which at the same time meets the QoS criteria set by the SNR threshold.

3.6.2. Route Maintenance

Route maintenance is DSR's standard operation mode. While in route maintenance, DSR routes data packets using the source route. On receiving a data packet, a node unicasts the packet to the node listed as the next hop in the source route. If the link to the next node is broken, the node detecting the failure sends a route error packet back to the sender.

Nodes overhearing the route error packet invalidate entries in their routing caches as needed. Upon receiving the route error packet, the sender attempts to find a new route

to the destination node in its cache, and if none is found, switches to the route discovery mode.

Even though DSR has the maintenance mechanism, it is applied only during the packet transmission. To maintain the route “freshness”, in this approach during the route reply, each node will keep track of its first neighbor from which it has received the RREP message for the first time.. Periodically this node will send some kind of “HELLO messages” to its first neighbor along the path. This node replies with ACK but only when the link status is “Good”, which is determined by the SNR value.

The absence of this control message within a certain period of time, which is determined with `TIME_EXPIRY`, means that it has to inform the nodes in its upstream link sending the RRER message. When RRER message reaches the source node, it updates its cache and deletes the existing path with the broken link.

If the link state was not considered, the neighbor sensing would not give accurate results. Control messages have small packet size compared to a data packet and are sent with lower data rate, which makes them more likely to reach a receiver than a data packet, especially over weak links. Using link quality criteria, it is possible to detect a longer route when link quality is changing to “Bad”. .If the SNR of the link does not improve for a period of time determined with `TIME_EXPIRY`, then the link layer realizes that this degradation may be due to a change of the topology, so it informs the network layer about the unavailability of the link.

`TIME_EXPIRY` is determined as the mean sojourn time that the channel remains in the “Bad” state. Again from the two state Markov chain channel model we can derive the mean duration of the “Bad” state in this way:

1. First we suppose that the fading is slow enough that the packet with a certain length remains in the same state during the packet transmission time, T_p . This means that the state transitions only will happen in the packet boundaries.
2. Knowing the packet length, we calculate packet transmission time and SNR threshold.
3. For a given SNR threshold, there always exists probability of error, which we denote as p_G , in the “Good” state and p_B , in the bad state.
4. If we indicate P_{GG} , Probability that a channel will remain in the “Good” state and P_{BB} , the probability the channel will remain in the “Bad” state, then the mean duration time of a good state, T_G , and that of a bad state, T_B , are given by

$$T_G = \frac{T_p}{1 - P_{GG}}, \dots(3.3)$$

$$T_B = \frac{T_p}{1 - P_{BB}} \dots(3.4)$$

The flow charts for route discovery and route maintenance are shown below.

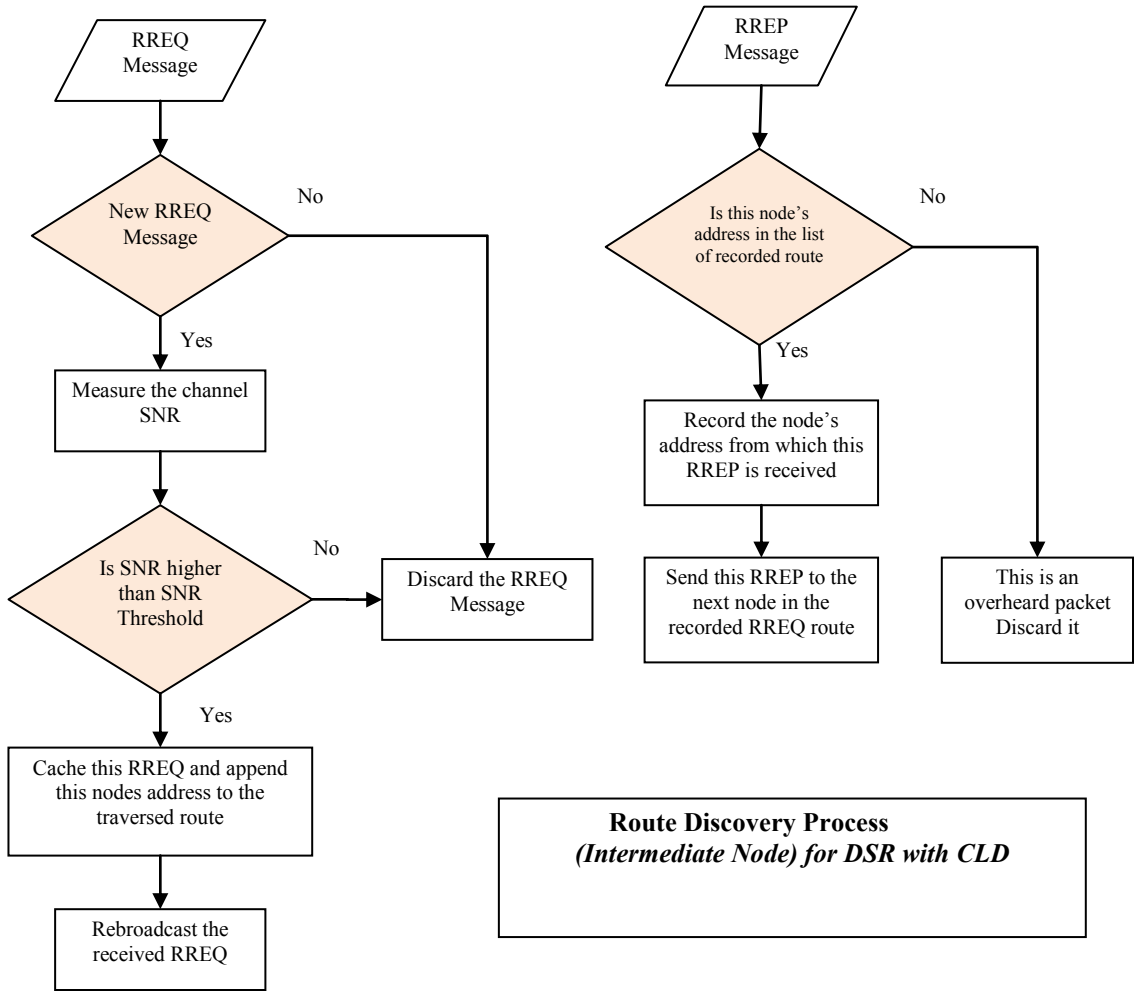


Figure 3-10 Route Discovery Process for DSR with CLD

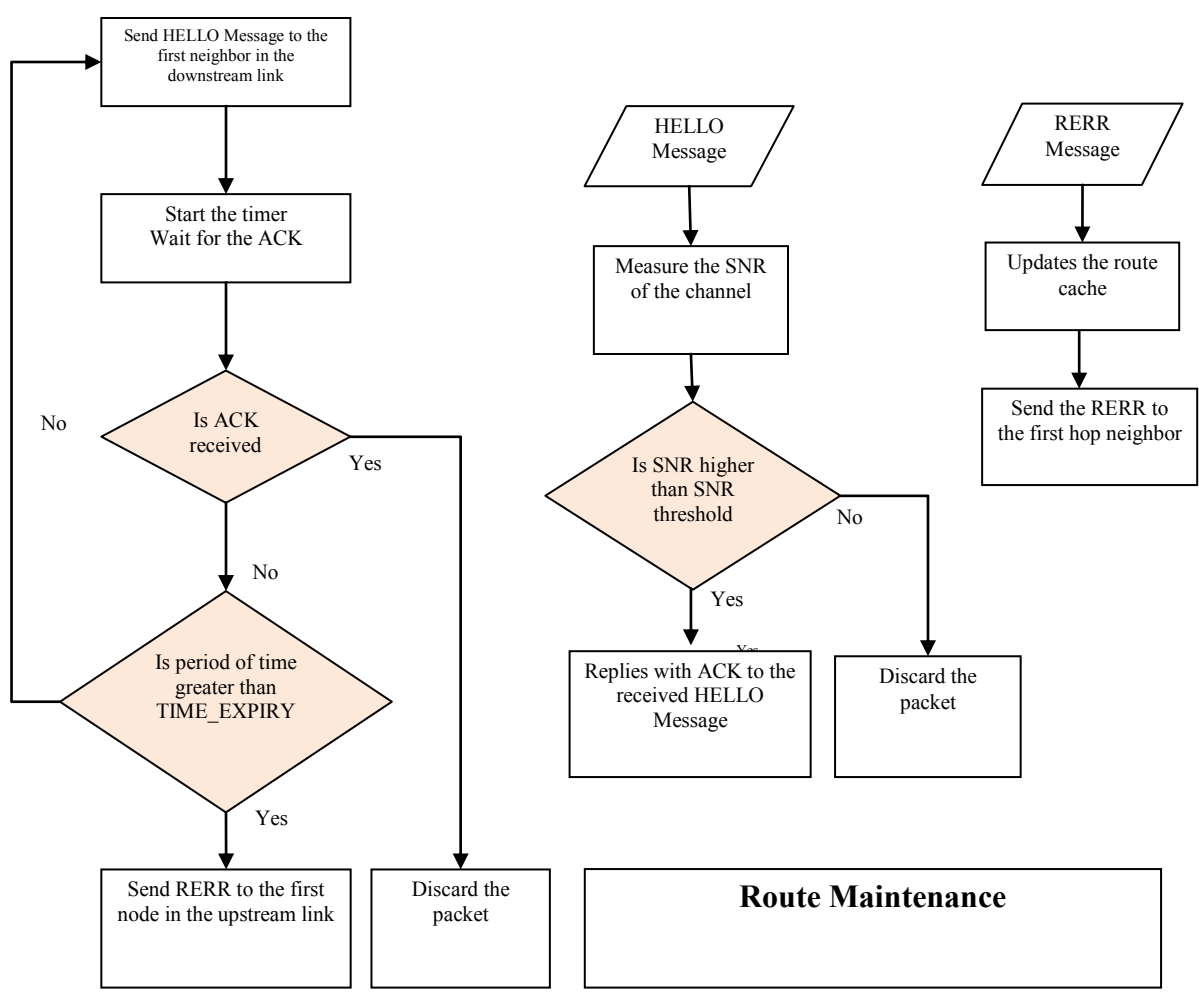


Figure 3-11 Route Maintenance Process for DSR with CLD

3.7. Simulation of DSR with CLD

The cross-layer algorithm described above was implemented and evaluated in OPNET v 11. We present results using the scenario investigating the performance benefits of DSR with CLD in wireless mobile environment. All the nodes in the network

are configured to work under ad hoc mode. We used the IEEE 802.11 Wireless LAN model with the ad hoc network configuration.

A network of size (4000 x 4000) m² was chosen, but the size of the network is not restricted. The nodes in our scenario are mobile but the position of wireless nodes is arbitrarily chosen. The mobility assigned to each node during simulation within OPNET is an important factor in the performance of the protocol. Each node is assigned a trajectory, which is generated from the traffic simulator. The trajectories profiles are presented in Figures 3-12 and 3-13. The network model for the ad-hoc network is shown in Figure 3-14.

	X Pos (km)	Y Pos (km)	Distance (m)	Altitude (m)	Traverse Time	Ground Speed	Wait Time
1	0.000	0.000	n/a	0.000	n/a	n/a	00.00s
2	0.015	1.564	1,563.781	0.000	16m15.31s	3.587	10m00.00s
3	-0.685	1.474	705.626	0.000	19m49.35s	1.327	00.00s
4	-1.430	-0.372	1,391.147	0.000	7m57.88s	9.320	00.00s

Figure 3-12 Trajectory_1 Profile

Edit Trajectory Information

Trajectory name: md2

	X Pos (km)	Y Pos (km)	Distance (m)	Altitude (m)	Traverse Time	Ground Speed	Wait Time
1	0.000	0.000	n/a	0.000	n/a	n/a	00:00s
2	0.015	1.564	1,563.781	0.000	15m15.31s	3.587	10m00:00s
3	-0.665	1.474	705.626	0.000	13m49.35s	1.327	00:00s
4	-1.430	-0.372	1,891.147	0.000	7m57.88s	9.320	00:00s

Coordinates are relative to object's position

Ground speed in: m/hr

Distance in: meters

Altitude in: meters

Insert Delete Redefine... OK Cancel

Figure 3-13 Trajectory_2 Profile

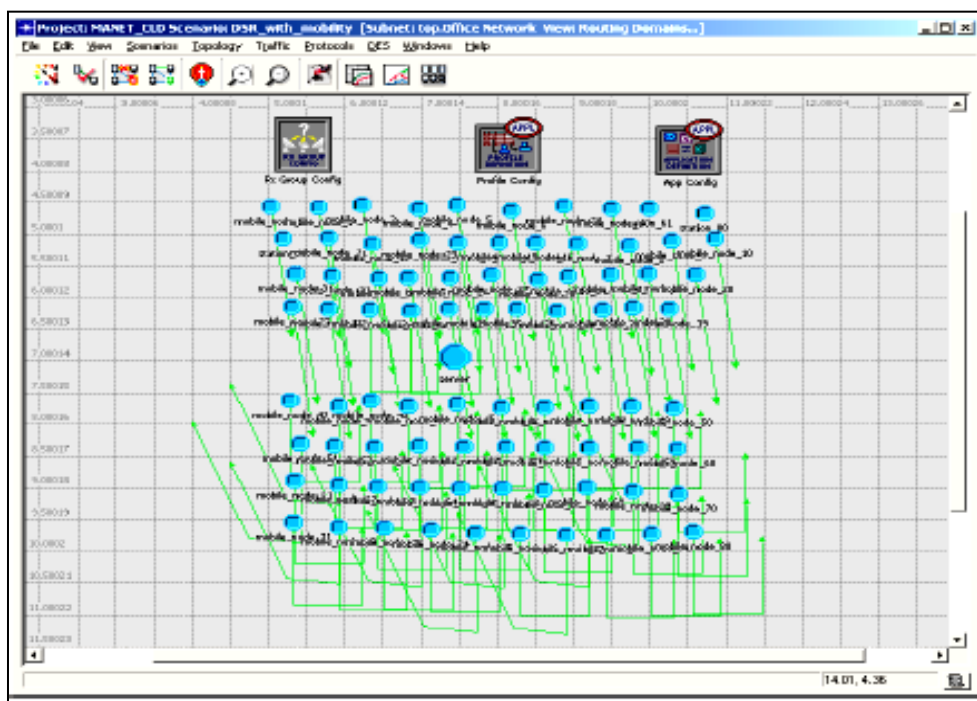


Figure 3-14 Network Scenario with DSR Protocol

3.8. Overview of Optimized Link State Routing Protocol (OLSR)

Optimized Link State Protocol (OLSR) [13] is a proactive routing protocol, so the routes are always immediately available when needed. OLSR is an optimization version of a pure link state protocol. So the topological changes cause the flooding of the topological information to all available hosts in the network. To reduce the possible overhead in the network protocol uses Multipoint Relays (MPR). The idea of MPR is to reduce flooding of broadcasts by reducing the same broadcast in some regions in the network. Another reduce is to provide the shortest path. The reducing the time interval for the control messages transmission can bring more reactivity to the topological changes.

OLSR uses two kinds of the control messages: HELLO and Topology Control (TC). HELLO messages are used for finding the information about the link status and the host's neighbors. With the HELLO message the Multipoint Relay (MPR) Selector set is constructed which describes which neighbors has chosen this host to act as MPR and from this information the host can calculate its own set of the MPRs. the HELLO messages are sent only one hop away but the TC messages are broadcasted throughout the entire network.

TC messages are used for broadcasting information about own advertised neighbors which includes at least the MPR Selector list. The TC messages are broadcasted periodically and only the MPR hosts can forward the TC messages.

3.8.1. Neighbor/Route Discovery

A node sends a HELLO message to identify itself and to report a list of neighboring mobile nodes. From a HELLO message, the mobile node receives information about its immediate neighbors and 2-hop neighbors, and selects MPRs accordingly .

A TC message originates at an MPR node announcing who has selected it as an MPR. Such messages are relayed by other MPRs throughout the entire network, enabling the remote nodes to discover the links between an MPR and its selectors.

Periodic HELLO messages are used to establish neighbor links and to distribute MultiPoint Relays (MPRs), determined by algorithm. MPR nodes are some selected nodes that have more connectivity to other nodes. These nodes have two main advantages:

- a) Reduce the amount of flooded messages, and
- b) Find the shortest path.

With the reduction of control messages, OLSR can react quickly to topological changes.

3.8.2. Routing Table Calculation

MPR set maintains a set of neighbors that are selected as MPRs, while MPR selector set records a set of MPR-selector tuples and describes the neighbors that have been selected by this node as MPRs.

Topology information base (TIB) maintains topology information about the network. This information is acquired from Topology Control (TC) messages and is used for routing table calculations. Each node maintains a routing table which allows it to route data, destined for the other nodes in the network. The routing table is based on the information contained in the local link information base and the topology set. Therefore, if any of these sets are changed, the routing table is recalculated to update the route information about each destination in the network. By default, OLSR the neighbor state holding time is set to be 3 times the value of the default OLSR HELLO interval; the OLSR TIB holding time is 3 times the default value of the TC interval. TIB and link tuple timers' expiry interval equals the TIB holding time interval.

3.8.3. Route Maintenance

HELLO messages track link connectivity. Topology Control (TC) messages, distributed by MPRs, propagate link state information throughout the network, and are broadcast periodically as well as when there is a change to the topology.

Control traffic consists of periodic HELLOs and TC messages. Overhead is controlled by MPR broadcast and redistribution of TC messages throughout the network, rather than broadcasts of link state from each router.

When new nodes join the network, a node detects its new neighbors with a link-sensing process by sending periodic HELLO message. When nodes leave the network, or links between nodes go down, the corresponding link state in the link set and neighbor state in the neighbor set will be removed after the state holding timers expire.

In addition, periodic topology control (TC) messages help recover from loss of topology information caused by state corruption or nodes restarting. It is clear that the internal state maintenance in each node is related directly to the refresh intervals and so changing these will impact the protocol as a whole.

3.9. OLSR with Cross – Layer Design (CLD)

The Optimized Link State Routing Protocol (OLSR) [13] is developed for mobile ad hoc networks. It operates as a table driven and proactive protocol, thus exchanges topology information with other nodes of the network regularly. The nodes which are selected as a multipoint relay (MPR) by some neighbor nodes announce this information periodically in their control messages. Thereby, a node announces to the network, that it has reachability to the nodes which have selected it as MPR. In route calculation, the MPRs are used to form the route from a given node to any destination in the network. The protocol uses the MPRs to facilitate efficient flooding of control messages in the network.

Each node maintains information about the set of neighbors that have selected it as MPR. This set is called the "Multipoint Relay Selector set" (MPR selector set) of a node. A node obtains this information from periodic HELLO messages received from the neighbors.

We propose the routing algorithm which selects the route that provisions a higher SNR along its hops to the destination.

When a node is initially detected via a HELLO message it is entered in the neighbor table, but it is selected as MPR and broadcast to other nodes via HELLO

messages only if the SNR to this neighbor is found to be above SNR threshold. This neighbor is considered during routing table calculation. This way, the risk of sending data packets to a neighbor to which SNR is below some threshold, and having them dropped, is avoided.

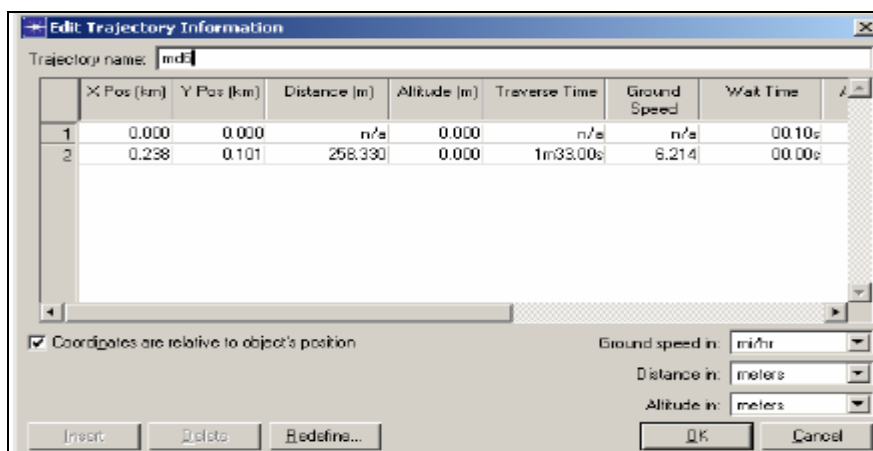
The OLSR with CLD selects the minimum hop count route, providing the link meets the requested SNR threshold. If several routes exist, the route with the highest available SNR is chosen. It allows the route between the sender and receiver to adapt to changing network conditions and accordingly switch between nodes as the intermediate hop. A node running the OLSR with CLD protocol measures the average SNR to all its neighbors and distributes this information via HELLO messages. On receiving a HELLO message, the SNR to the neighbor entries is parsed and stored in the neighbor table. The routing protocol performance can hence be judged effectively by observing the change of route from receiver to sender node with respect to SNR variation to other nodes.

Each node in the network maintains topology information about the network. This information is acquired from Topology Control (TC) messages and is used for routing table calculations.

Routes are constructed through advertised links and links with neighbors. A node must at least disseminate links between itself and the nodes in its MPR-selector set, in order to provide sufficient information to enable routing only through the links with high SNR. This prevents calculation of routes passing through a weak link and this information being disseminated to other nodes in the network. Thus, only nodes which are connected to neighbors with high quality links, process the control and overhead information.

3.10. Simulation of OLSR with CLD

A network size in this scenario is (1000 x 1000) m², and only few nodes are mobile, which start moving after few seconds along the path specified by the trajectory during the simulation period. The trajectory profile is presented below.



	X Pos (km)	Y Pos (km)	Distance (m)	Altitude (m)	Traverse Time	Ground Speed	Wait Time
1	0.000	0.000	n/a	0.000	n/a	n/a	00.10s
2	0.238	0.101	258.390	0.000	1m33.00s	6.214	00.00s

Figure 3-15 Trajectory_3 Profile

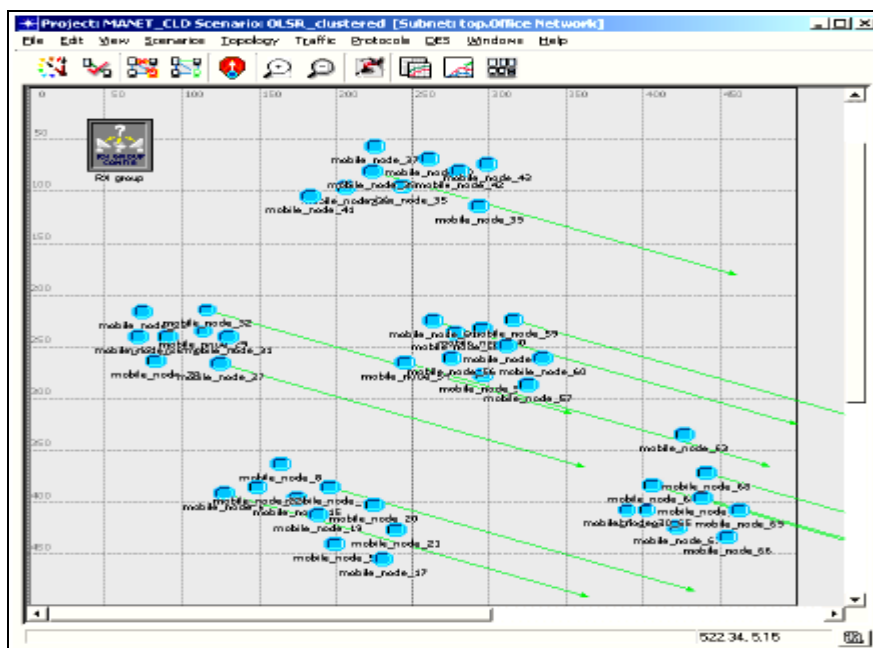


Figure 3-16 Network Scenario with OLSR Protocol

We use two different scenarios for simulation of DSR and OLSR, since our intention is not to compare the performance between these two protocols, but between these and their modified versions.

The traffic parameters are presented in the Table 1.

Parameters	Value	
Modulation Scheme	DSSS, BPSK	
Traffic rate	11 Mbps	
Mobility model	Random-Waypoint	
Propagation –Path loss	Two-Ray	
Propagation fading model	Rayleigh, Rician	
MAC protocol	802.11	
Carrier Frequency	2.4GHz	
Traffic	FTP	
Packet size	512 bytes	
Routing protocol	DSR	OLSR
Terrain dimensions	4000X4000m	1000x1000m
Simulation time	3600 s	180 s
Node numbers	80	50
SNR Threshold	8[dB]	20[dB]
Transmission Power	0.005 W	0.100 W
Transmission Range	1000 m	250 m

Table 1. The parameters values and the simulation scenarios used in our simulations

3.11. Performance Metrics

We simulated the traditional DSR routing protocol and DSR with CLD scheme, and OLSR routing protocol and OLSR with CLD. We compared their performance

observing the average end-to-end delay, the routing overhead, and the average throughput vs simulation time.

One of the primary objectives of an ad-hoc routing protocol is to maximize energy efficiency which can be measured by parameters such as routing overhead. Figures 3-17 and 3-21 show the comparison between this two protocols with their modified versions with CLD, with regard to routing overhead.

Clearly, DSR with CLD outperforms DSR allowing routes to be attained with significantly lower overhead since it is looking for more reliable paths. The nodes discard the RREQ messages if the SNR value is less than the requirement. Although the maintenance mechanism of the modified DSR needs periodical broadcast of HELLO messages, this control packets do not increase the routing overhead compared to the retransmitted data packets, which have significant larger packet size, since they carry the entire route in the header.

Average end-to-end delay of data packets includes all possible delays in the nodes and the links. As it is illustrated in Figures 3-19 and 3-22, DSR and OLSR have increased delay due to the buffering delays of route recoveries and the retransmission delays at the link layer. DSR with CLD and OLSR with CLD lead to better end-to-end delay performance because the nodes acquire sufficient information from physical layer to construct more reliable paths. The paths built from these links reduce the probability of failure, especially in the mobility scenario, thus improving the end-to-end delay.

Figures 3-18 and 3-20 present the visible improvement of average throughput of DSR with CLD and OLSR with CLD, which outperform traditional DSR and OLSR. When the channel conditions are poor retransmissions result in higher delays and this

leads to reduced throughput. Exchanging the information between physical layer and network layer, the network layer may adapt itself, selecting the most reliable paths, and thus achieving higher throughput.

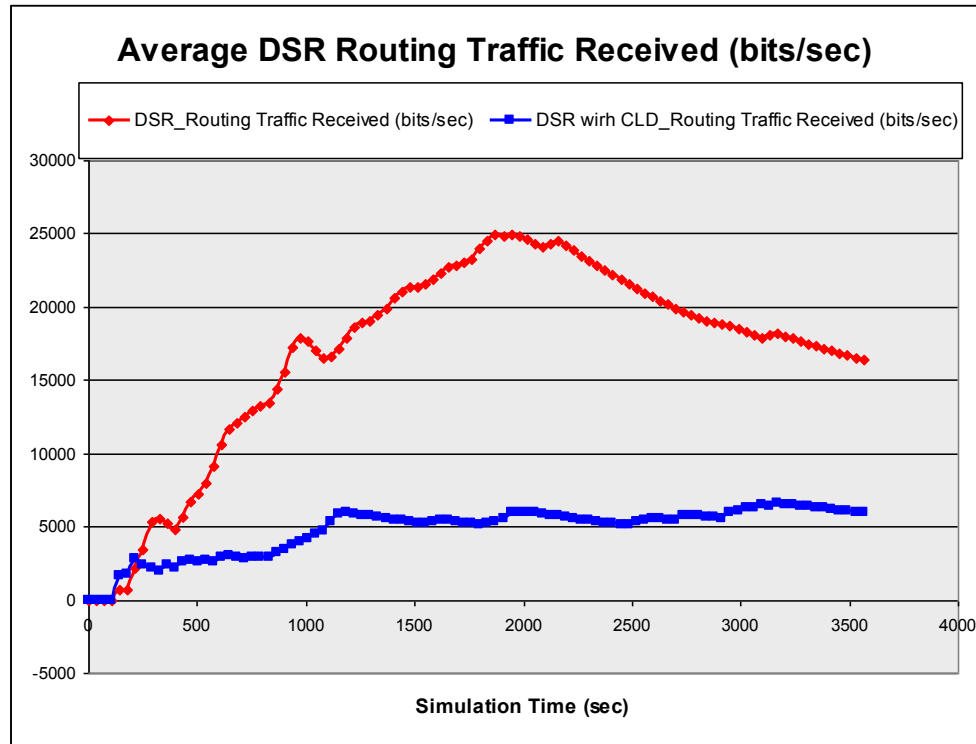


Figure 3-17 Routing Overhead (bits/sec) for DSR and DSR with CLD

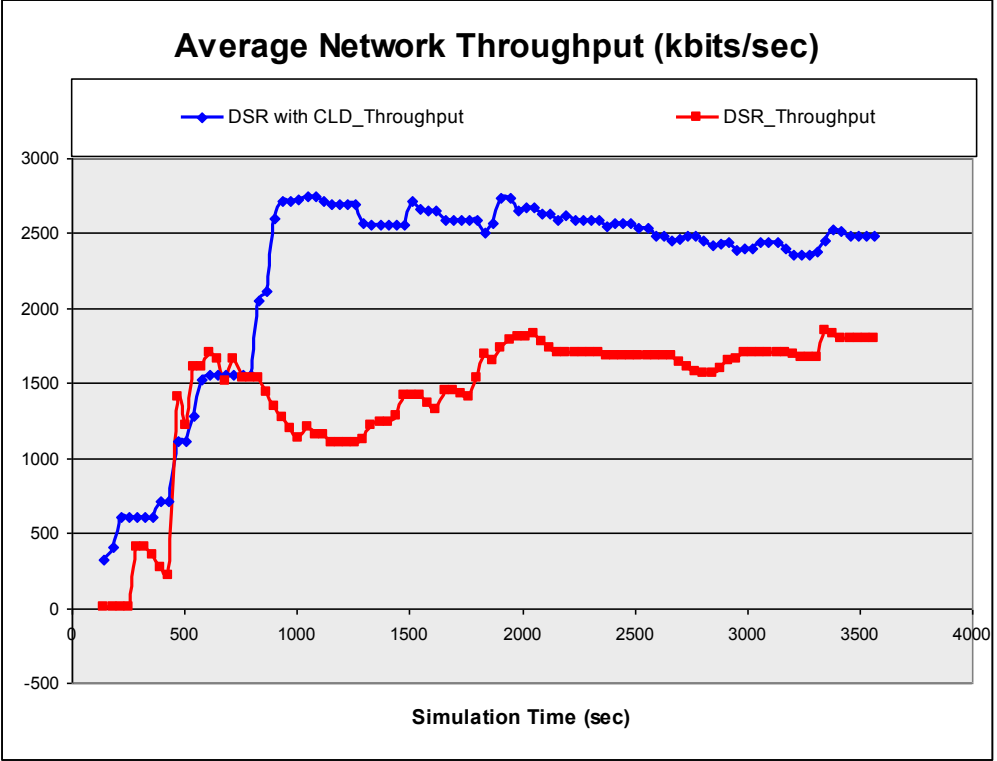


Figure 3-18 Average Throughput (kbits/sec) for DSR and DSR with CLD

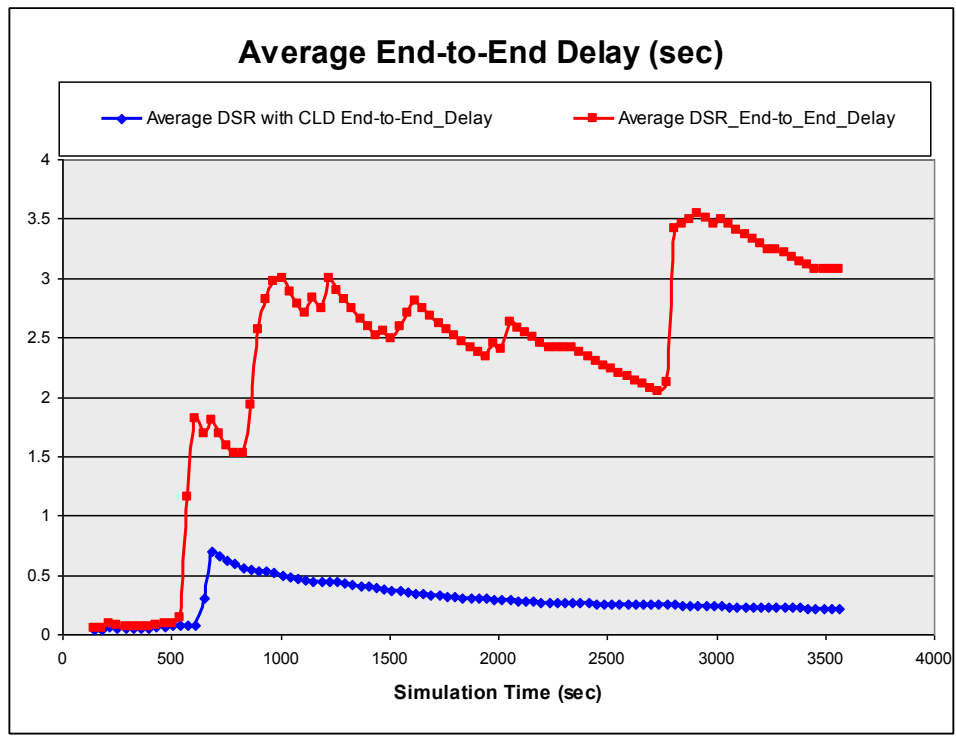


Figure 3-19 End-to-End Delay (sec) for all connections for DSR and DSR with CLD

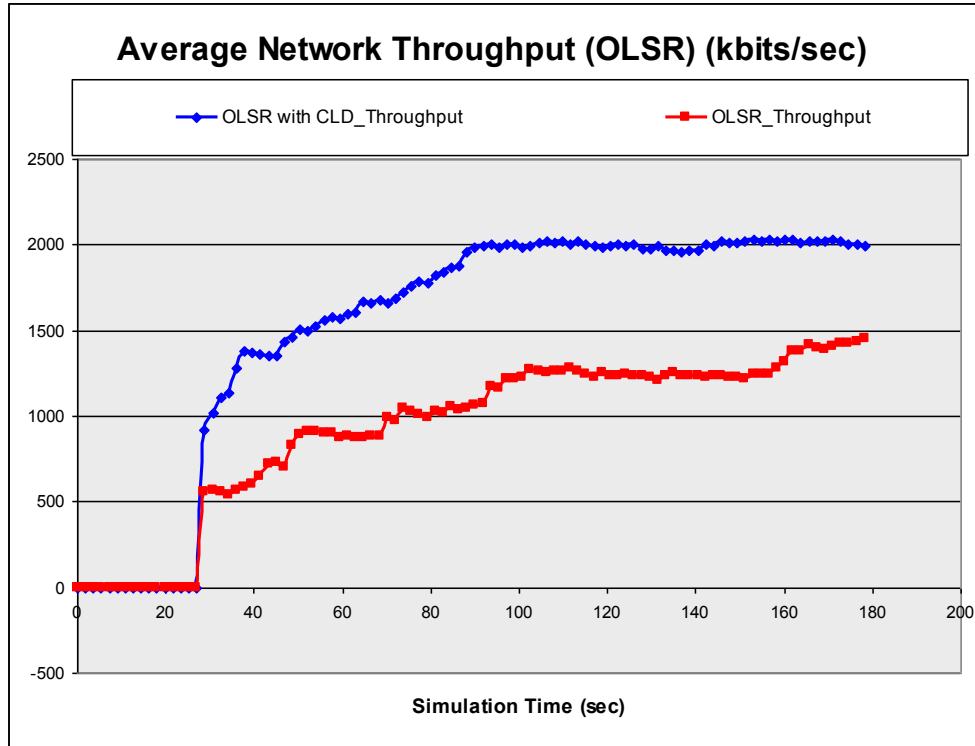


Figure 3-20 Average Throughput (kbits/sec) for OLSR and OLSR with CLD

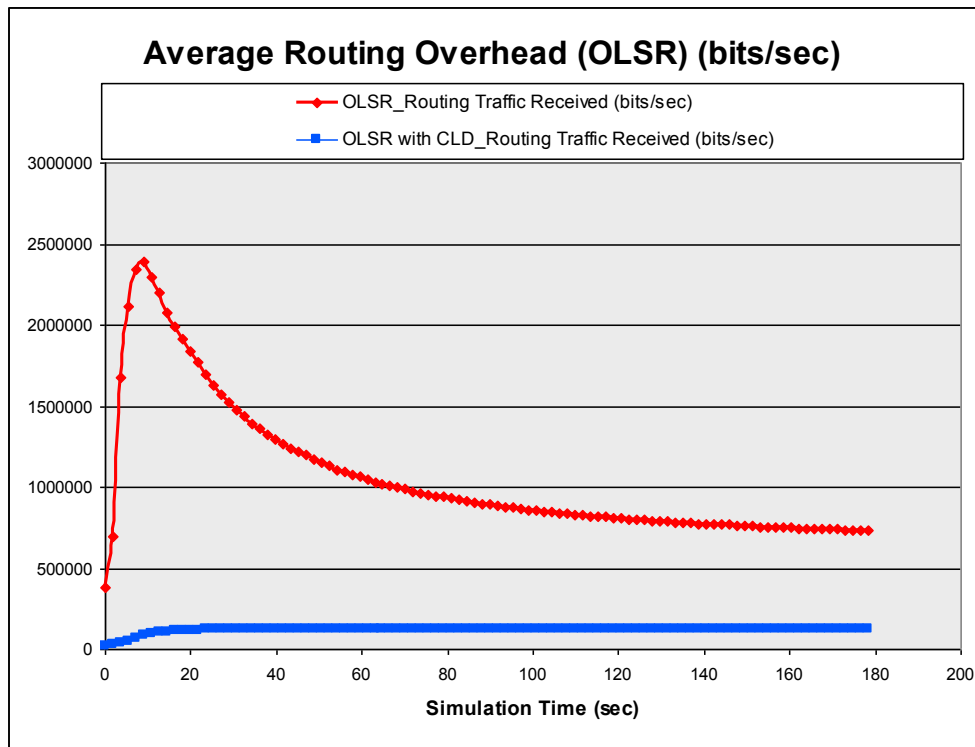


Figure 3-21 Routing Overhead (bits/sec) for OLSR and OLSR with CLD

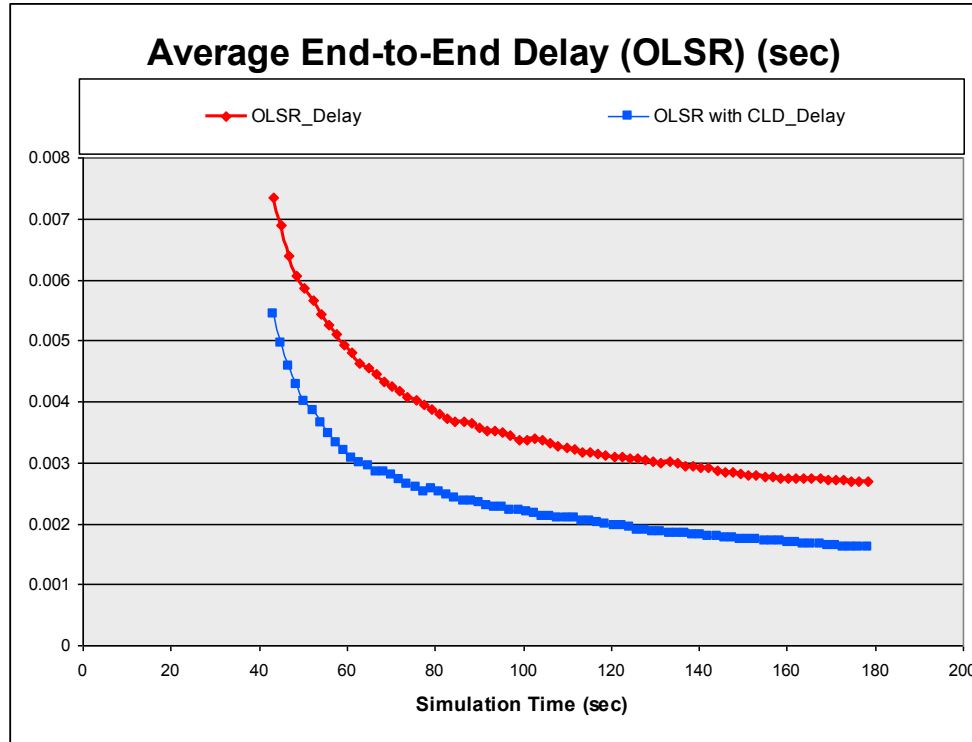


Figure 3-22 Average Delay(sec) for OLSR and OLSR with CLD

3.12. Conclusion

The main goal of this chapter is to describe our approach for modeling cross-layer using 2-state Markov Chain Model. The traffic around a node may change more quickly in a mobile ad hoc network because nodes are joining or leaving neighbor groups, which may increase or decrease the interference. We present a network architecture that supports QoS in wireless ad hoc networks using the algorithm which monitors the channel conditions during data transmission and feeds this information to the routing layer. The motivation of this chapter was to explore the routing protocols with cross-layer design and present the benefits of this approach with its impact on the transport layer and overall network. The simulation results show that network throughput can be greatly improved and average packet delay can be significantly decreased by using cross-layer architecture.

Chapter 4

Modeling Wireless Channel with 3- State Markov Chain Model

4.1. Introduction

Gilbert-Elliot model is basic model and is not enough for modeling of the wireless channel in most cases. Hence we consider a more complex case where the channel consists of more than two states. Each state can have a different threshold level, and depending on a given threshold, we associate an error probability with that state. In our approach we use three state Markov chain model, where there are two good states, G1 and G2 and a single bad state, B. This gives us an insight for modeling wireless channels more accurately.

If we consider that the probability of transition from state G1 to state B and vice versa is very low, we can represent this with the flow diagram given below.

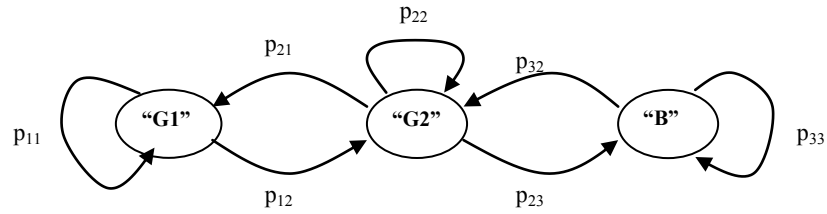


Figure 4-1 Three-State Markov model of a channel

Where the transition probabilities are given with the following matrix:

$$P = \begin{bmatrix} p_{11} & p_{12} & p_{13} \\ p_{21} & p_{22} & p_{23} \\ p_{31} & p_{32} & p_{33} \end{bmatrix} = \begin{bmatrix} p_{G1G1} & 1 - p_{G1G1} & 0 \\ p_{G2G1} & p_{G2G2} & 1 - p_{G2G2} - p_{G2G1} \\ 0 & 1 - p_{BB} & p_{BB} \end{bmatrix} \dots(4.1)$$

We consider the situation in which the success of a packet transmission in a given state is determined by comparing the received SNR, to the thresholds in each state, each of which has certain packet error probability.

In a physical layer model our point is to calculate the symbol error rate which in a wireless network is a function of SNR. If binary FEC is used then it may not be practical to determine the symbol error rate, since the error correction is performed at the bit level. Then the physical layer model calculates the bit error rate after FEC. Hence the bit error rate, BER, in each state can be obtained from a selected modulation scheme. Since we have used BPSK modulation scheme, accordingly, the BER, the probability of a symbol error for a given SNR threshold, Γ , can be calculated from

$$BER = f(\Gamma) = 1 - \Phi\sqrt{2\Gamma} \quad \dots(4.2)$$

$$\Phi(\Gamma) = \int_{-\infty}^r \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt \quad \dots(4.3)$$

Where $\Phi(\Gamma)$ is normal Gaussian function.

Given that we know the average BER and assuming that the bits in a packet can be considered to be independent from one another, the packet error rate, PER, can be expressed as a function of equivalent BER and the packet length L.

$$PER = 1 - (1 - BER)^L \quad \dots(4.4)$$

If we denote with PER_{thresh} , the maximum tolerable PER for an application, then the probability, P_{Correct} , of packet received correctly after k+1 retransmissions can be determined with

$$P_{\text{Correct}} = 1 - PER_{\text{Thresh}} \quad \dots(4.5)$$

$$PER_{\text{Thresh}} = (PER)^{k+1} \quad \dots(4.6)$$

The value of SNR threshold is not chosen arbitrarily, it is a function of the maximum packet error probability of the channel that our application and protocol can assume.

Given the parameters in our scenario, first we calculate average received SNR and then select appropriate SNR threshold for the specified packet error rate.

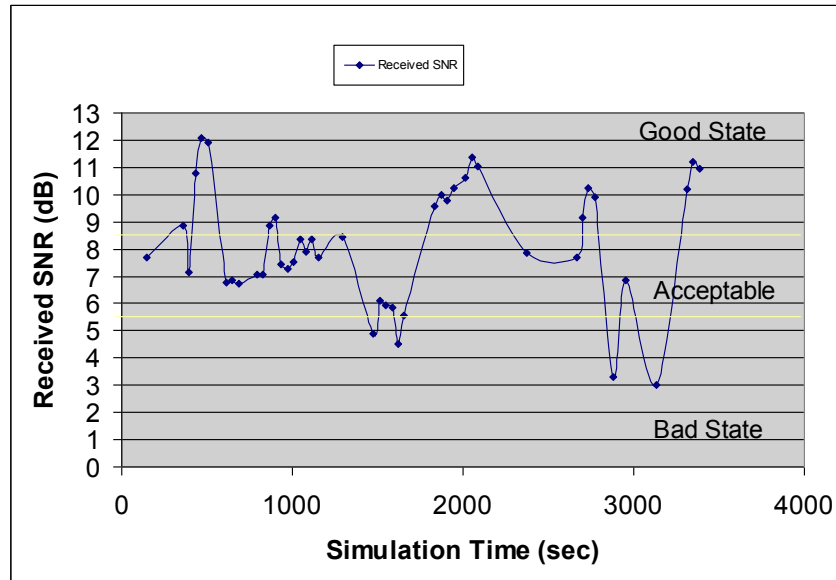


Figure 4-2 Received SNR for a link vs. simulation time
(SNR thresholds between three states are given with solid yellow lines)

We implement the physical parameter aware routing metric by modifying the dynamic source routing (DSR) [12] protocol. We demonstrate the benefits of inter layer interactions in low mobility scenarios, applying the routing metric to route discovery and the route maintenance.

4.2. Route Discovery (3-State)

To perform a route discovery, if the source node doesn't have the valid route in its cache, it starts with the broadcasting of a route request (RREQ) packet that contains the address of the initiator, the address of the target, the request identifier, and the route record. Besides the information required for DSR such as the destination address and the sequence number, the node includes a physical layer parameter which indicates the quality of the path. Here, we are using SNR as the physical layer parameter. To

implement three state Markov Chain, in the header of the RREQ packet is added a new field, NUM_FLAG, which indicates the number of links in “Excellent” state.

In the route record field, each node appends its address as a hop sequence only if:

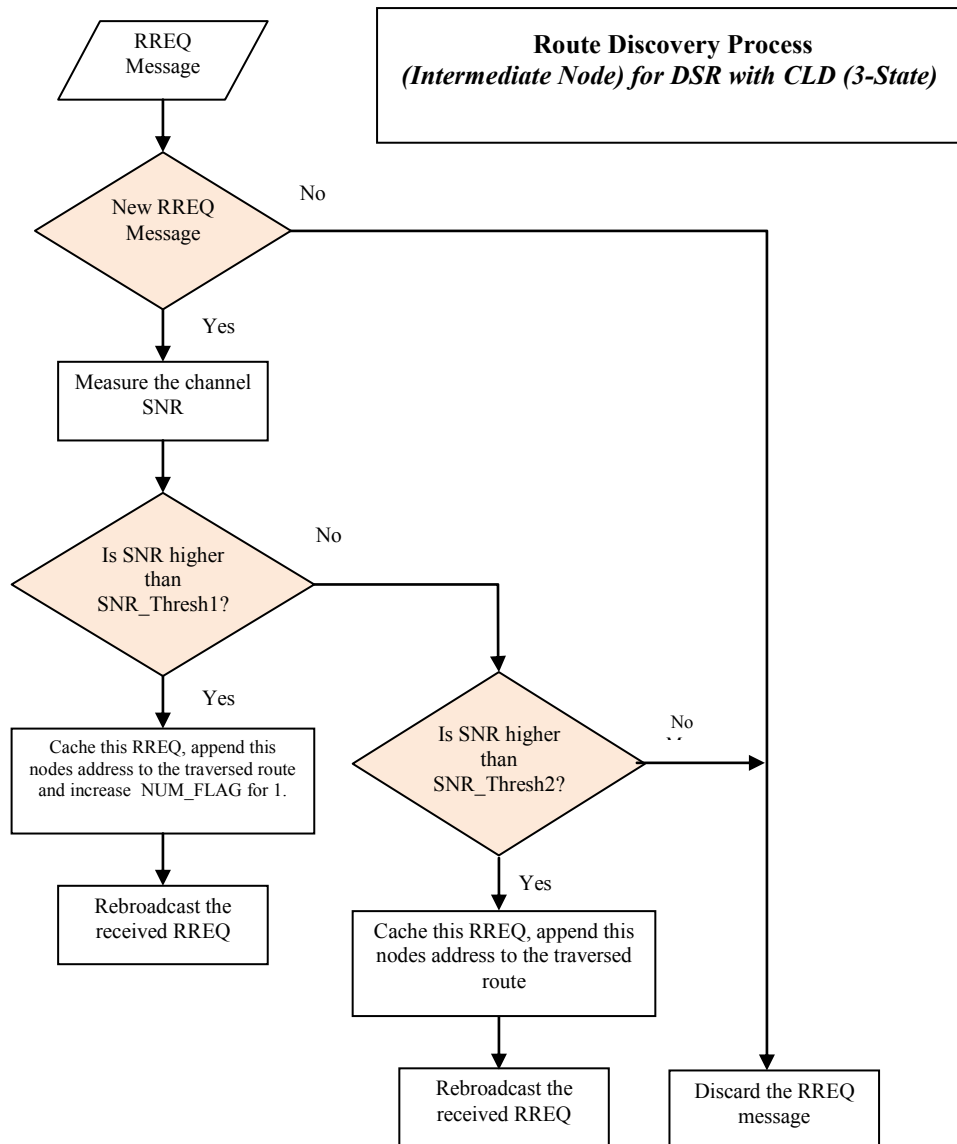
- it did not detect a duplicate RREQ and
- the value of the SNR is higher than the required threshold.

So whenever a node receives a RREQ packet, the physical parameter -SNR is determined and if the value of SNR is less than the required threshold, then the RREQ packet is discarded.

Besides, each node updates the value of NUM_FLAG field according to its current SNR value: if the link is considered “Excellent”, the value of NUM_FLAG is increased by 1. NUM_FLAG defines the number of “Excellent” links. Nonetheless, if “Excellent” link is not found, the “Fair” link may be selected. This ensures that the signal quality of the best links is always retained in the packet header.

If the above criterion is satisfied and the node is not the target it propagates the route request again. When the destination node receives the RREQ message, it initiates the route reply (RREP) packet back to the source node. The use of the signal quality information in the packet header allows the protocol to make an informed decision regarding selection of a communication path between source and destination nodes. The destination node replies to that RREQ, which has the higher value of NUM_FLAG. This route reply contains the list of nodes along the path from source to destination. Since SNR is used as criteria in the selection of the routes, we have to ensure that during the route maintenance phase, all existing routes meet the criteria of exceeding SNR threshold, otherwise such route is invalid. In this case, when a RREQ arrives at a node

that has a cache, we have to propagate the RREQ packet along the cached route to verify that the SNR threshold is met. When the RREP reaches its destination, thus guaranteeing QoS requirements, the source node selects this route for packets delivery.



**Figure 4-3 Route Discovery Process
(Intermediate Node) for DSR with CLD (3-State)**

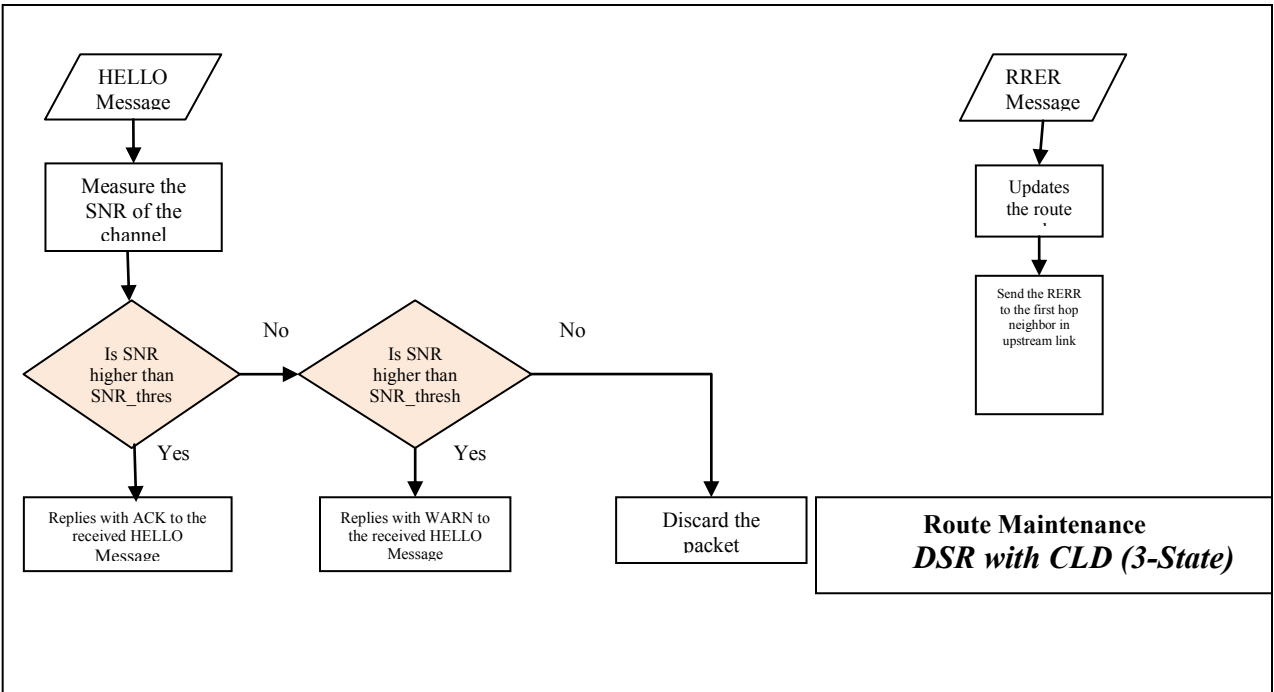
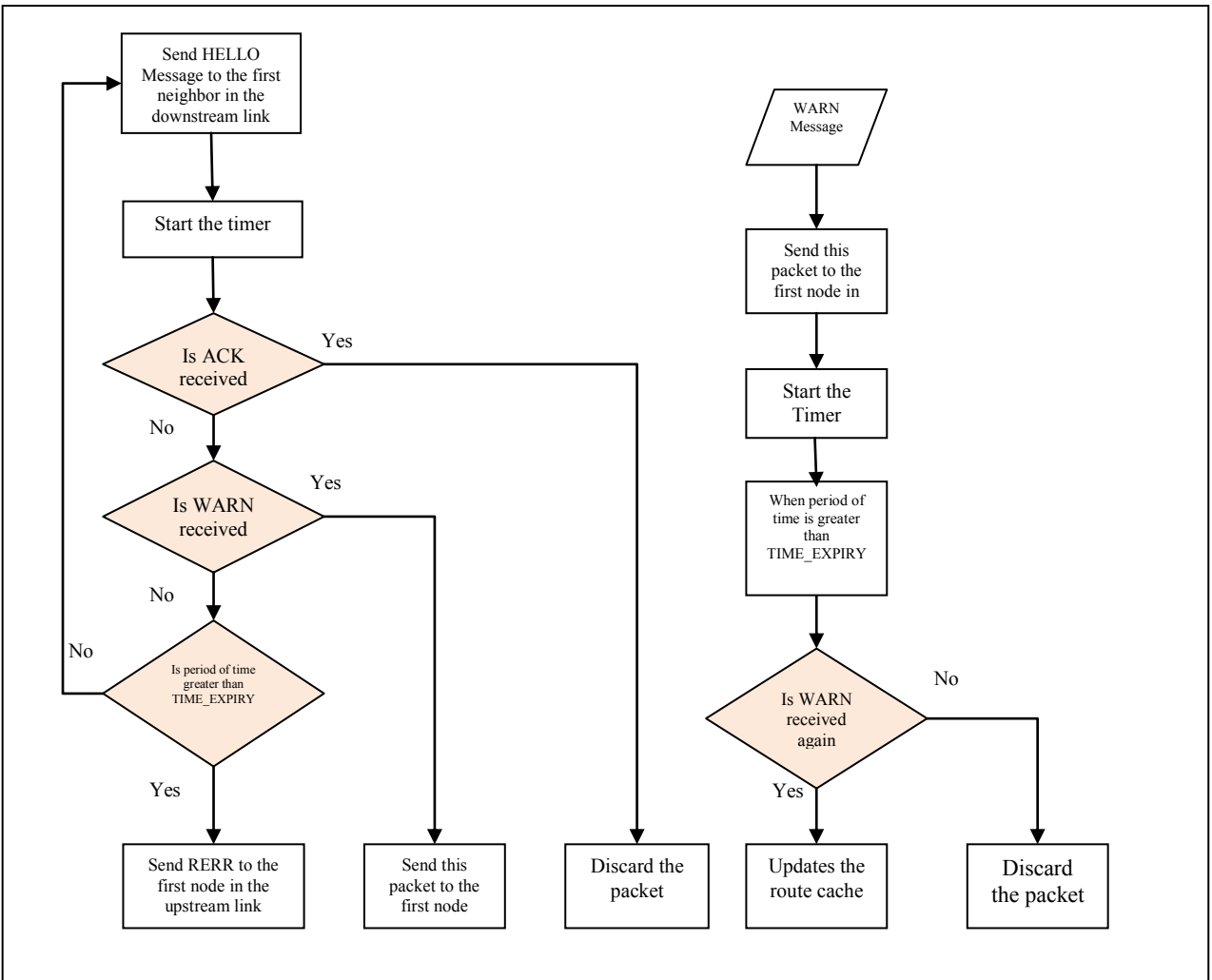


Figure 4-4 Route Maintenance DSR with CLD (3-State)



4.3. Route maintenance (3-State)

Route Maintenance is DSR's standard operation mode. While in route maintenance, DSR routes data packets using the source route. On receiving a data packet, a node unicasts the packet to the node listed as the next hop in the source route. If the link to the next node is broken, the node detecting the failure sends a route error packet back to the sender. Nodes overhearing the route error packet invalidate entries in their routing caches as needed. Upon receiving the route error packet, the sender attempts to find a new route to the destination node in its cache, and if none is found, switches to the route discovery mode.

Even though DSR has the maintenance mechanism, it is applied only during the packet transmission. To maintain the route "freshness", in this approach during the route reply, each node will keep track of its first neighbor from which it has received the RREP message for the first time.. Periodically this node will send some kind of "HELLO messages" to its first neighbor along the path. This node replies with ACK but only when the link status is in state "Good1", which is determined by the SNR threshold1. On the other hand if SNR value is less than SNR threshold1, but greater than SNR threshold2, the node replies with WARN message, which determines the state "Good2" of the link. When a node receives a WARN message, implies that the link is going down, therefore the source within a certain period of time could switch to an alternate route, if it exists or to start a new route discovery process.

The absence of the control message within a certain period of time, which is determined with TIME_EXPIRY, means that it has to inform the nodes in its upstream

link sending the RRER message. When RRER message reaches the source node, it updates its cache and deletes the existing path with the broken link.

TIME_EXPIRY is determined as the mean sojourn time that the channel remains in the “Bad” state.

$$T_B = \frac{T_p}{1 - P_{BB}} \quad \dots(4.7)$$

Where, T_p is packet transmission time.

4.4. Simulation results

The cross-layer algorithm described above was implemented and evaluated in OPNET v 11 [11].

We present results using the scenario investigating the performance benefits of DSR with CLD in wireless mobile environment. All the nodes in the network are configured to work under ad hoc mode. We used the IEEE 802.11 Wireless LAN model with the ad hoc network configuration.

A network of size (4000 x 4000) m² was chosen, but the size of the network is not restricted. The nodes in our scenario are mobile but the position of wireless nodes is arbitrarily chosen. The mobility assigned to each node during simulation within OPNET is an important factor in the performance of the protocol. Each node is assigned a trajectory, which is generated from the traffic simulator. This will provide realistic node movement. Mobility of a mobile node generates a Doppler shift, which is a key parameter of fading channel.

A three-state Markov model was used for the links on a path. The SNR thresholds are chosen from the packet loss probabilities of the states.

We simulated the traditional DSR routing protocol and DSR with CLD scheme in mobile environment. We compared their performance observing the average end-to-end delay, the routing overhead, and the average throughput vs simulation time.

One of the primary objectives of an ad-hoc routing protocol is to maximize energy efficiency which can be measured by parameters such as routing overhead. Figure 4-7 shows the comparison of routing overhead for two state and three state channel modeling when using DSR and modified version of this protocol.

Clearly, DSR with CLD outperforms DSR allowing routes to be attained with significantly lower overhead since it is looking for more reliable paths. The nodes discard the RREQ messages if the SNR value is less than the requirement. Although the maintenance mechanism of the modified DSR needs periodical broadcast of HELLO messages, this control packets do not increase the routing overhead compared to the retransmitted data packets, which have significant larger packet size, since they carry the entire route in the header.

Errors introduced by a wireless medium are more frequent and profound than contemporary wired media. Some of these errors, which are not corrected by the physical layer, result in Medium Access Control (MAC) layer bit errors and packet losses. Design of wireless protocols and applications can benefit substantially from a thorough understanding of these MAC layer destructions. In Figure 4-8, the MAC layer data dropped is presented. We show that when using the cross layer optimization and three state Markov model, there is a visible improvement with respect to MAC layer data loss.

Average end-to-end delay of data packets includes all possible delays in the nodes and the links. As it is illustrated in Figure 4-5, DSR has increased delay due to the buffering delays of route recoveries and the retransmission delays at the link layer. DSR with CLD leads to better end-to-end delay performance because the nodes acquire sufficient information from physical layer to construct more reliable paths. The paths built from these links reduce the probability of failure, especially in the mobility scenario, thus improving the end-to-end delay.

The mobile ad hoc networks were used to collect data and transfer packets. The throughput of packets transmitted is one of the parameters to evaluate the networks efficiency. Observing from Figure 4-6, cross layer optimization of DSR made visible improvement of average throughput, which outperforms traditional DSR. When the channel conditions are poor retransmissions result in higher delays and this leads to reduced throughput. Exchanging the information between physical layer and network layer, the network layer may adapt itself, selecting the most reliable paths, thus achieving higher throughput.

4.5. Conclusion

In this chapter we applied a cross-layer design concept using the physical layer parameters as one of the metrics to the routing algorithm. We have applied this technique to the DSR protocol and showed the improvements in the various routing protocol performance parameters.

Based on our observations, we conclude the following: The two state Markov model, known as Gilbert-Elliot model which was widely used in the research to evaluate

the communication system is not enough for modeling a real channel. By applying the higher order of Markov chains, it is possible to implement a more realistic channel. However, increasing the number of states increases the computational complexity. Consequently we used a three state Markov model of the wireless channel as a trade off between complexity and the performance.

Our results indicate that the cross-layer design using three state Markov chain provides a better improvement in the routing protocol performance when compared to the traditional DSR routing protocol or the two state Markov chain model [36]

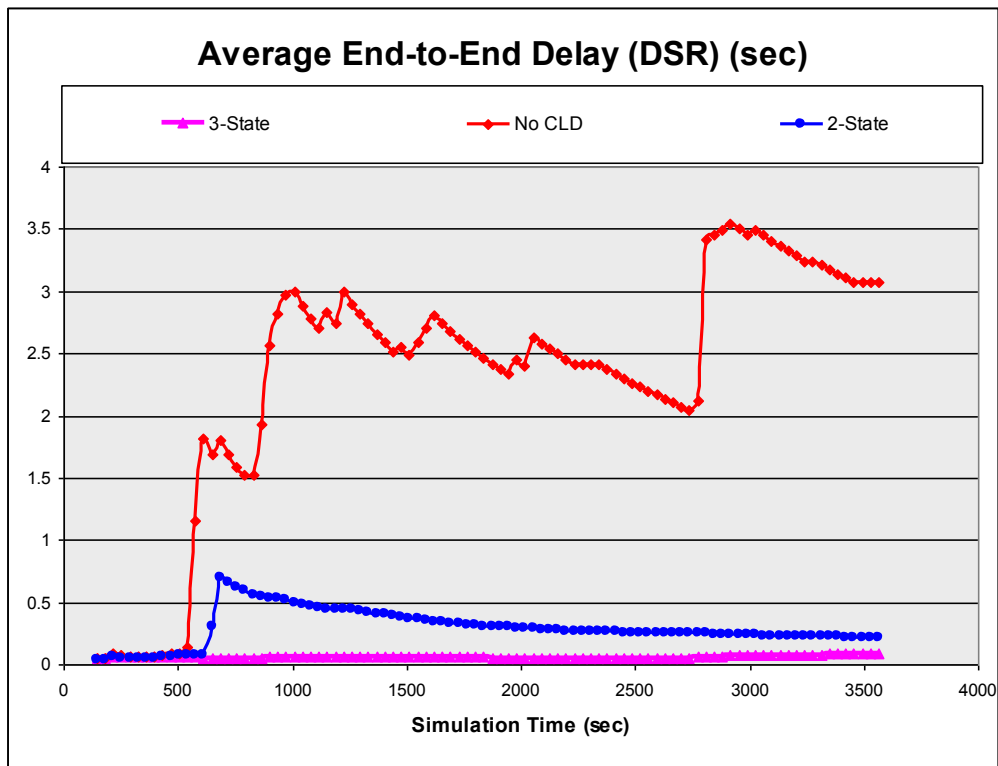


Figure 4-5 Average end-to-end delay(sec) (DSR, 3-State)

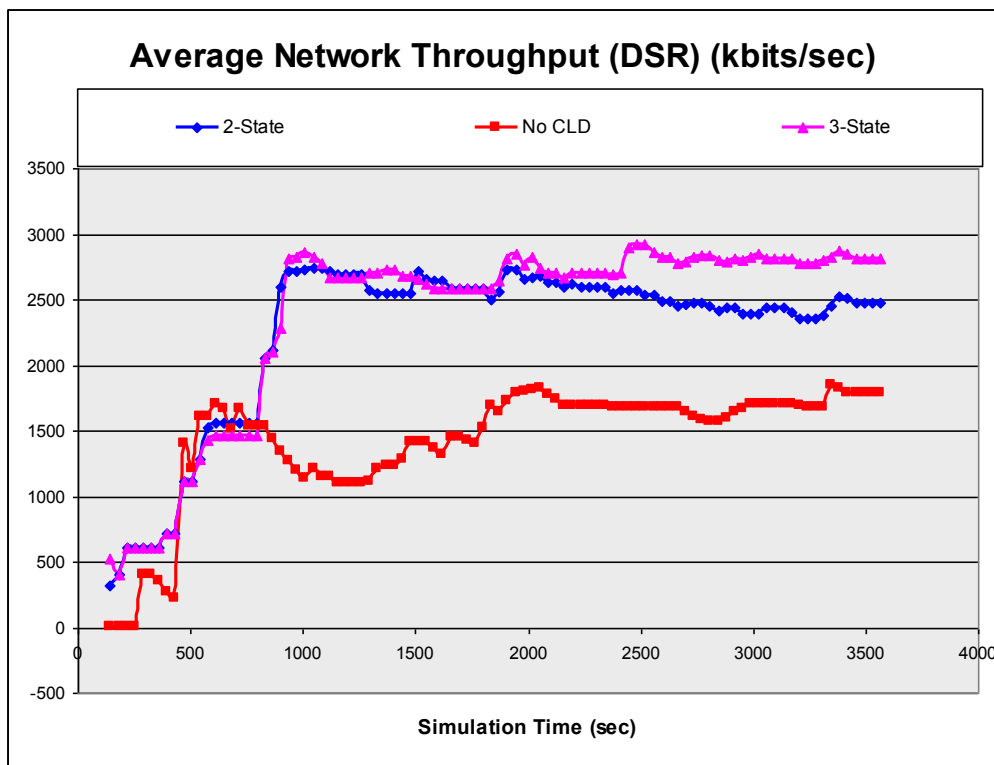


Figure 4-6 Average network throughput (kbits/sec) (DSR, 3-state)

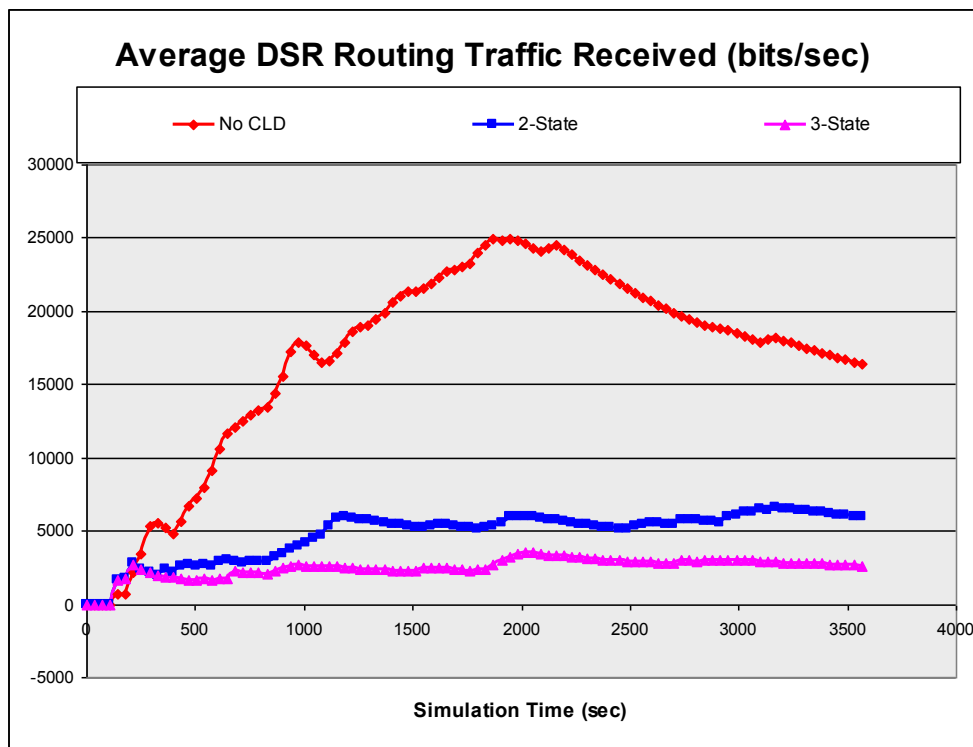


Figure 4-7 Routing traffic received (bits) (DSR, 3-state)

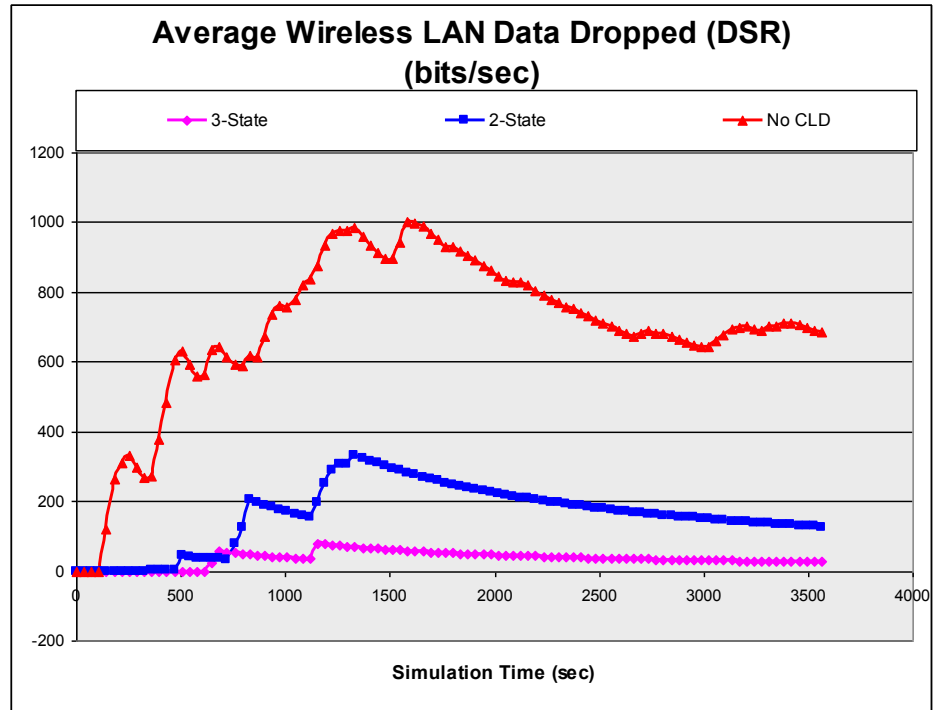


Figure 4-8 Average data dropped (DSR, 3-state)

Chapter 5

Link Lifetime based Routing

5.1. Introduction

The layered networking architecture has been the key to the enormous success and widespread usage of the Internet, as well as the initial development of wireless systems. The success of the layered architecture has been its ability to provide modularity and transparency between the layers.

However, in order to support the revolution of new applications, a new era of network architectures has emerged. A major challenge is to understand at a fundamental level how to best design and control these networks, referred to as “wireless ad-hoc networks”.

Since human-operated devices will more likely be used indoor, it leads to many issues related to the strength of signal fading in this environment. Recently, it has been suggested that a possible interaction might exist between various parameters of the ad-

hoc networks and, more precisely, between the propagation model and the routing protocol.

Our focus is laid on the Physical layer which has a great impact on the performance of the system, being responsible for the nodes connectivity and overall network throughput. This is known as cross-layer design, which unlike the traditional architecture allows information exchange between OSI layers. The cross-layer design is very promising field of investigation. The use of physical (PHY) layer information in the routing decision, which we implemented in our work, is the result of the cross-layer dialogue between the PHY and the Network layers.

As an example we demonstrate the usefulness of the use of Link Lifetime as a metric in the selection of routes, thus modifying the Optimized Link State Routing (OLSR) protocol. In this work we address the problem of link and route stability, focusing particularly on the multipoint relay (MPR) selection method, as well as that of determining the optimal path for any pair of nodes.

Through actual simulation runs, we show that the modified OLSR protocol is more responsive to variations in network connectivity and can take preemptive actions in choosing stable and durable routes. The main contribution of this work is as follows: introduction of link-quality evaluation methodology based on SNR and link lifetime, for enhanced adaptability of ad-hoc routing in a dynamically changing topology.

The rest of this chapter is organized as follows. Section 2 surveys related work. Section 3 examines the wireless communication channel model, and describes common radio channel impairments like multipath fading and path loss, while the impact of interference is explained in section 4. Section 5 elaborates the Finite State Markov Chain

model of the channel. Section 6 presents the overview of OLSR protocol followed by analytical cross-layer framework based on signal quality and link lifetime route selection. Section 7 then presents simulation-based evaluation results. Finally, the chapter finishes with concluding remarks of our work.

5.2. Related Work

Node mobility causes links between nodes to break frequently, thus terminating the lifetime of the routes containing those links. An alternative route has to be discovered once a link is detected as broken, incurring extra route discovery overhead and packet latency. A simple solution to reduce the frequency of this costly discovery procedure is to choose a long lifetime route carefully during the route discovery phase rather than a simple random shortest-path route scheme. Reference [14] studies the effect of node mobility in the link lifetime distribution noting that the smaller the moving probability p , the longer lifetime a link tends to have. When both nodes are not moving ($p = 0$), the link never breaks. But in wireless propagation environment small scale fading makes it difficult to recognize the node's moving tendency and cannot be simply ignored.

Link lifetime plays an important role in routing protocols design and performance. There has been some investigation into the estimation and predictability of link lifetimes. Reference [15] examines many predictors in urban environments, however, such predictors would require knowledge of the location of the node, the path loss across the link, and the age of the link.

In [16] authors present a new design of the Movement Prediction based Routing concept (MOPR) [17], concept, which is more adapted to vehicular networks conditions.

They consider that each vehicle in the network is supposed to have locally available all its neighbor's movement information (position, speed, and direction). By knowing the movement information of vehicles involved in the routes (including source and destination), MOPR can roughly predict their positions in the near future in order to predict the lifetime of the link between each pair of vehicles in the path. Both, [16] and [18] rely on information provided by a Global Positioning System (GPS) about the current positions and velocities of two neighboring nodes to predict the expiration time of a link. However communicating the movement information to all the neighbors through the control messages, increases the routing overhead in the network and our intention is to reduce it in order to achieve improvement in routing performance.

The Route-Lifetime Assessment-Based Routing (RABR) [19] uses an affinity parameter based on the measured rate of change of signal strength averaged over the last few samples in order to estimate the lifetime of a link. A metric combining the affinity parameter and the number of links in the route is then used to select routes for TCP traffic. However, shadow and multipath fading experienced by the received signal make the estimation of link lifetime error prone.

In [20], authors propose a signal strength based service discovery (S3D) framework as a solution by steering the service discovery over reliable links. They show improvement in service delivery success ratio based on link quality aware service. The link quality is typically measured as Signal to Noise Ratio (SNR).

Reference [21] presents a cross-layer ad-hoc routing approach based on link connectivity assessment in network topology and suggests a framework for proactive enhancements to the OLSR protocol. Authors deploy an IEEE 802.11b based vehicular

network and demonstrate the effectiveness of link-quality assessment based enhancements in improving the performance of inter-vehicle ad-hoc routing. Every node in the network can maintain the history of averaged Signal to Noise Ratio values (SNR) to its neighbors., then from the average rate of change of SNR, is estimated the affinity between two nodes. Yet, the affinity between two nodes is only a prediction of the lifetime of the link.

5.3. OLSR with Cross - Layer Design (SNR and LLT)

In this section, we propose the routing algorithm which selects the route that provisions a higher SNR along its hops to the destination. When a node is initially detected via a HELLO message it is entered in the neighbor table, but it is selected as MPR and broadcast to other nodes via HELLO messages only if the SNR to this neighbor is found to be above SNR threshold. Since we model the wireless channel with three state Markov model, we take into consideration two SNR thresholds. Thus, if SNR of the link is found to be higher than the first threshold, the link is considered “Excellent”, but if its SNR is between two thresholds, that node is being selected as MPR according to the lifetime of the link. This neighbor is considered during routing table calculation.

The variations in signal strength, Figure 5-3, affect ad-hoc network protocols in a way that differs from other wired network architectures. For example, in regard to SNR value, a link may be considered “Excellent”, nevertheless, it may not be long living.. In mobile ad hoc networks, the impact of mobility on the link and route lifetimes is of major importance for the design of efficient MAC and network layer protocols [22].

In our work we propose a solution to this problem by introducing special algorithm dedicated to Link-Lifetime (LLT) estimation, which is based on the use of the normalized mean sojourn time in calculation of the LLT. This value is normalized in regard of maximum holding time of the routing table of the protocol. Besides this, the direction of the movement of the sending and receiving node can be determined by comparison of the previous SNR value, already stored in the neighbor table, and the new received SNR value: if the existing value is lower than the received one we say that the nodes are approaching each other. This mechanism is very efficient in calculating the stability of the link. Thus in our CLD mechanism we consider two constraints, which together characterize the new metric: stability.

The control packets HELLO and TC are generated in similar way. However, the HELLO packets, along with the neighbor sensing, now, are used to calculate the LLT based on the link SNR experienced during transmission from the neighbors. Using this information MPRs are selected among the one hop neighbors to reach all the two hop neighbors with the maximum LLT and SNR, as a new metric. MPRs, in turn transmit TC messages with link quality and LLT information to all the nodes in the network. This metric further is used as criteria in computing the routes between a source and the destination pair.

Each node in the network periodically generates HELLO messages and transmits to all the one hop neighbors. However, in the HELLO message's header are included two more fields: SNR and the speed of the source node for calculating the LLT metric. When a HELLO packet is received by a node, the SNR value is stored in the neighbor table. Besides, according to the speed of source node and the previous SNR, the

LLT of the link is computed by each node. This information is treated as the stability of the link and it is recorded in the neighbor table, too.

The criteria for MPR selection in OLSR with CLD protocol is to consider the SNR level of the one hop nodes as a link quality metric, and to select maximum lifetime links, to increase their stability.

MPR selection algorithm can be described as follows:

- In the empty set of MPRs , first identify all two hop neighbors of a node u , which have only one neighbor in the one hop neighbor set, and add those nodes to the MPR set. If there are multiple neighbors from node u , select that neighbor as MPR, which results in greatest stability, means maximum SNR and LLT.
- Each node in the network that is selected as MPR, by at least one of its neighbors, transmits a TC message periodically. The TC messages in our algorithm are also modified to include the link quality and LLT between the MPR node and its selectors. TC messages are forwarded thorough the network like usual broadcast messages from the MPRs. Since only the MPRs generate the TC messages that contain link stability information, the overhead of the transmission is reduced significantly, in contrast to the traditional OLSR protocol.
- In the topology table of the nodes, each node maintains information about SNR and the LLT obtained from the TC messages. The routing table calculation is based on this information. The routing table of a node, enables it to route packets for other destinations in the network. It consists from the

entries such as the destination address, next hop address and the path lifetime from the source to the destination.

- The path lifetime, moreover, is calculated as the minimum lifetime of the consisting links.

This prevents calculation of routes passing through a weak link and this information being disseminated to other nodes in the network. Thus, only nodes which are connected to neighbors with high quality links: highest SNR and LLT, process the control and overhead information.

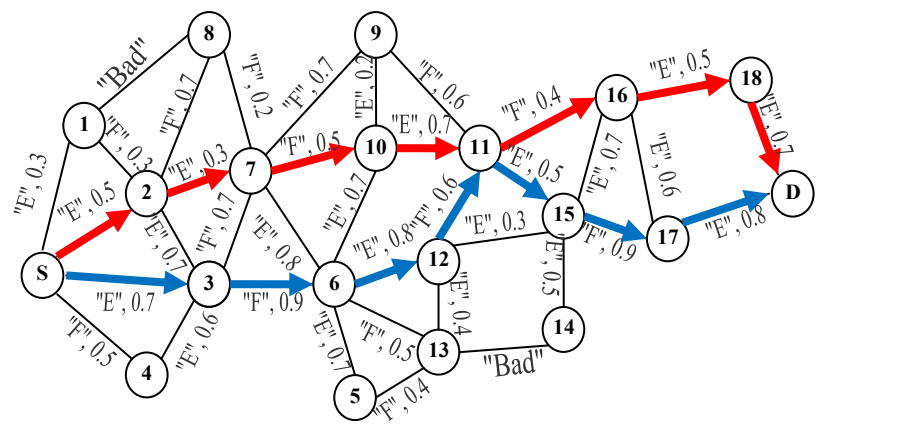


Figure 5-1 Network Example. Route selection in traditional OLSR
Route selection with SNR and LLT metrics

As an example, we will consider a network topology extended with the two metrics, which constitute the SNR and LL of the links. The letters indicate the link status and the number along the lines indicate the LL of the links in a successful transmission from a node to a neighbor node. The idea behind this is to select the MPRs in a way such

that all the 2 hop neighbors have the maximum lifetime of a path through the MPRs to the current node.

Now, we show how node S selects its MPRs based on the network depicted in Figure 5-1. For source node, S, we have two different routes: S-2-7-10-11-16-18-D and S-3-6-12-11-15-17-D. By the traditional method the first route will be selected. But this is not the most stable route. Let's start with the route selection on link by link bases. Node S has five possible routes: S-1-8, S-2-8, S-2-7, S-3-6, S-3-7 but it selects the highest SNR and maximum lifetime route, S-3-6. To reach 6, S selects 3 as MPR. Then to reach 8, it selects 2 as MPR. By following the same procedure, to reach 5, 12 and 13, node 6 is selected as MPR. To reach 8, 9 or 10, 7 is selected as MPR. To reach 15, nodes 12 or 13 may be selected as MPRs. But it accomplishes the best route if it selects node 12 as MPR. Furthermore to reach 16, the node 11 or 15 may be selected as MPR. By the algorithm described above, the node 11 is selected as MPR. And to reach D, the node 17 is selected as MPR.

5.4. Simulation of OLSR Protocol Under Different Radio

Propagation Models

While propagation models such as fading, shadowing and path loss are not part of the radio models in simulators, they control the input given to the physical layer models and have great impact on their performance. We first study the performance of traditional OLSR protocol in a specific network configuration comprising 100 nodes within an area

of the size of 1000×1000 meters. All other parameters of this scenario can be seen in the Table 1).

We will present results from two main propagation models:

- a) *Additive White Gaussian Noise (AWGN) and Free Space*
- b) *Rayleigh fading with log normal shadowing model*

The free space model with the Additive White Gaussian Noise, (AWGN), is used as a basic reference model and is also considered to be idealized propagation model. The AWGN is the noise in an ideal channel where no signal fading occurs. With this path loss model, even nodes far from the transmitter can receive packets, which can result in fewer hops to reach the final destination. Therefore, simulation results with the free space path loss model tend to be better than with other path loss models, such as log normal shadowing model.

We show that OLSR routing protocol performs very well with the free space path loss model. Keeping all other parameters constant, and employing log-normal shadowing model, the transmission range of the nodes drops about 40%, in regard of free space path loss model. However, one way to improve the transmission range with log-normal shadowing model is to increase the transmission power of the nodes, Figure 5-4, but this does not yield that the free space path loss model perform better, due to increased interference. For the battery operated nodes, increased power yields in short network lifetime. If the power of each simultaneous transmission is increased, signal and interference power increase proportionally while thermal noise power remains constant. Thus, at some point thermal noise becomes approximately negligible, i.e., the network

becomes interference-limited, and any further increase in transmission power provides essentially no benefit. [23].

Another way of increasing throughput is a cross-layer ad-hoc routing approach, explained in the previous section, based on link connectivity assessment, deploying the SNR, as a new metrics in route selection. Nodes will be selected as MPRs only if the links connected them are above some required threshold. The network throughput has almost the same enhancement with power adjustment. This can be seen in the Figure 5-5.

Our simulation model uses OPNET Network simulation tool, which provides a development environment supporting the modeling of communication networks and distributed systems. Undoubtedly, OPNET is the industry's leading environment for network modeling and simulation. However, as a packet-oriented simulation tool, it is not well suited for simulation at the physical layer which involves bits and signals in communication. By default, OPNET assumes a Gaussian channel model is used and does not consider any fading. The Gaussian channel is a much more idealized environment for communication than a fading channel. For any SNIR of practical interest, the bit error rate, BER in a fading channel is much higher than that in a Gaussian channel. In a consequence, it is difficult to simulate some prominent wireless communication effects, such as pathloss, fading, shadowing in OPNET.

Therefore to solve this problem, we add a Rayleigh fading channel model to OPNET and implement the fading effect in simulation by modifying the transiver pipeline stages. Second, it is found that the OPNET Wireless Suite uses a fixed value of the pathloss exponent without considering that different environments have different

pathloss exponents. In our enhanced wireless model, we add different pathloss exponents and the shadowing effect, again implementing as a function in pipeline stages. Figure 5-2.

Simulation results of the OLSR protocol performance are presented below, to verify our physical-layer enhanced wireless models and display their application in OPNET simulator.

The remainder of this section focuses on the cross-layer enhancement of the routing protocol, taking into account only the simulation of Rayleigh fading channel.

```

/* When using TMM, the TDA OPC_TDA_RA_RCVD_POWER will      */
/* already have a raw value for the path loss.              */
*/
if (op_td_is_set (pkptr, OPC_TDA_RA_RCVD_POWER))
    {
        path_loss = op_td_get_dbl (pkptr,
OPC_TDA_RA_RCVD_POWER);
    }
else
    {
        /* Cacclulate wavelength (in meters).

lambda = C / tx_center_freq;

        /* Get distance between transmitter and receiver (in */
        /* meters).
        */
        prop_distance = op_td_get_dbl (pkptr,
OPC_TDA_RA_START_DIST);

        /* Compute the path loss for this distance and
        /* wavelength.
        */
        if (prop_distance > 0.0)
            {
                /* Inputing Rayleigh factor/
                shadowing_factor =
op_dist_outcome(op_dist_load("normal", 0.0, 4.0));
                rayleigh_factor =
op_dist_outcome(op_dist_load("rayleigh", 1.0, 0.0));
                ***
                ***
                ***
            }

        /* Compute the in-band transmission power by multiplying */
        /* the transmission power with the overlap ratio between */
        /* the frequency bands of the transmitter and receiver.
        */
        chanmatch_status = op_td_get_int (pkptr,
OPC_TDA_RA_MATCH_STATUS);

```

Figure 5-2 Part of code inserted in the OPNET Pipeline stages

The ability of a routing algorithm to find an optimal route will be exposed by its throughput, packet loss and delay measurements.

Simulation results show that the OLSR protocol with CLD yields better performance compared to the best-effort OLSR protocol and significantly improves throughput by using our proposed algorithm. From the Figure 5-6, it can be seen that the cross-layer use encourages transmission over more stable links, thus achieving higher throughput values. On the contrary transmission over the poor channel conditions with low LLT, leads to the transmission with errors, and the higher number of dropped packet, Figure 5-7. As expected, we see fewer losses in OLSR with CLD, as our metric favors minimum loss paths. In addition to this, the packet transmission time will be reduced, leading to a smaller average delay. Original OLSR protocol has frequent route changes, which has a negative impact on the delay performance, because of the time needed for the nodes to update their routing tables, Figure 5-8.

The ability of a routing protocol to scale networks is highly dependent on its ability to control routing traffic overhead. Routing traffic contains messages that a routing protocol needs to establish new routes through a network, maintain routes or repair broken routes. These can be simple HELLO messages which are sent periodically to allow neighboring nodes to learn about the presence of fellow nodes or they can be TC messages containing routing tables. As seen from Figure 5-9, the routing overhead of the protocol, which main part are TC messages, is decreased accordingly to the quality of the links. TC messages are sent only when the change in network is determined. When links are chosen with good quality and stability, less TC messages will be sent, which causes lower number of MPRs selected, Figure 5-10. The main function of the Multi-Point Relay (MPR) of the Optimized Link State Routing protocol is to reduce the flooding overhead compared with classic flooding. When OLSR protocol has less MPRs, the

coverage of the TC broadcast traffic is narrower and adjacent nodes will be receiving less routing traffic.

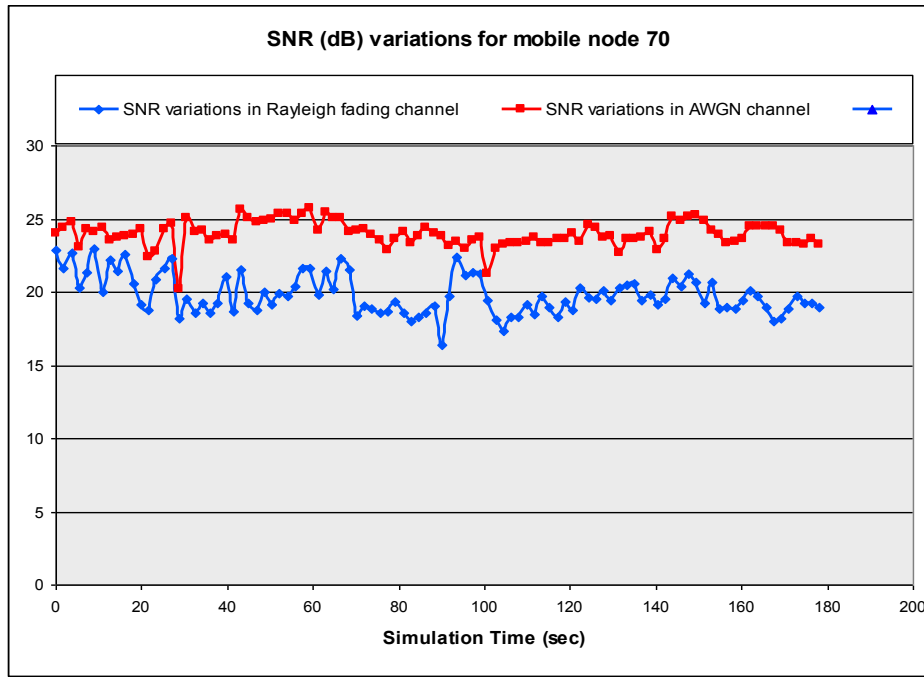


Figure 5-3 SNR variations in time for a specific receiver-Node 70

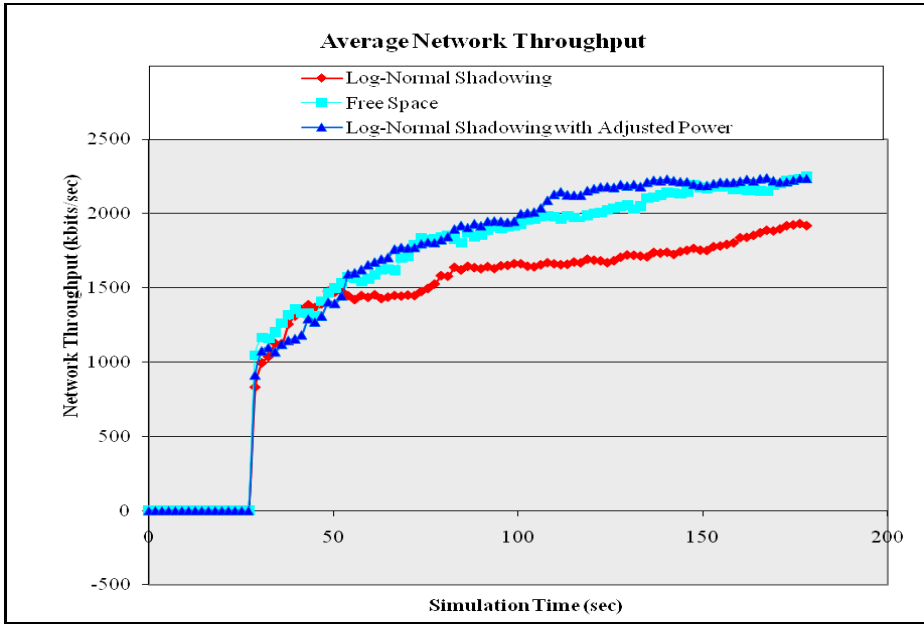


Figure 5-4 Network Throughput vs. Simulation time with Free-Space and Log-Normal Shadowing Model

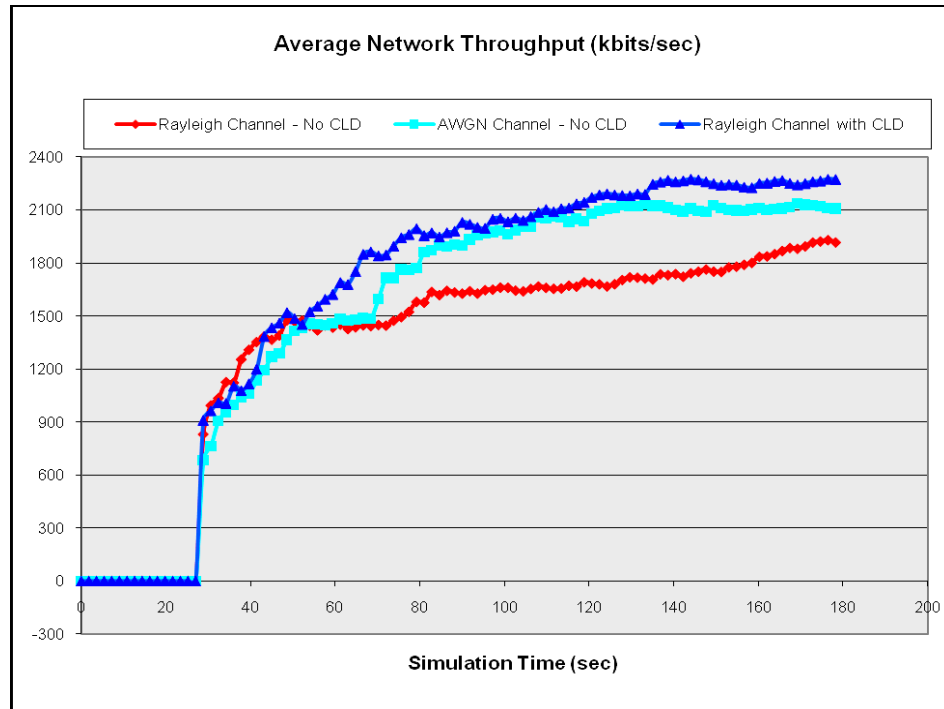


Figure 5-5 Network Throughput vs. Simulation time with and without CLD

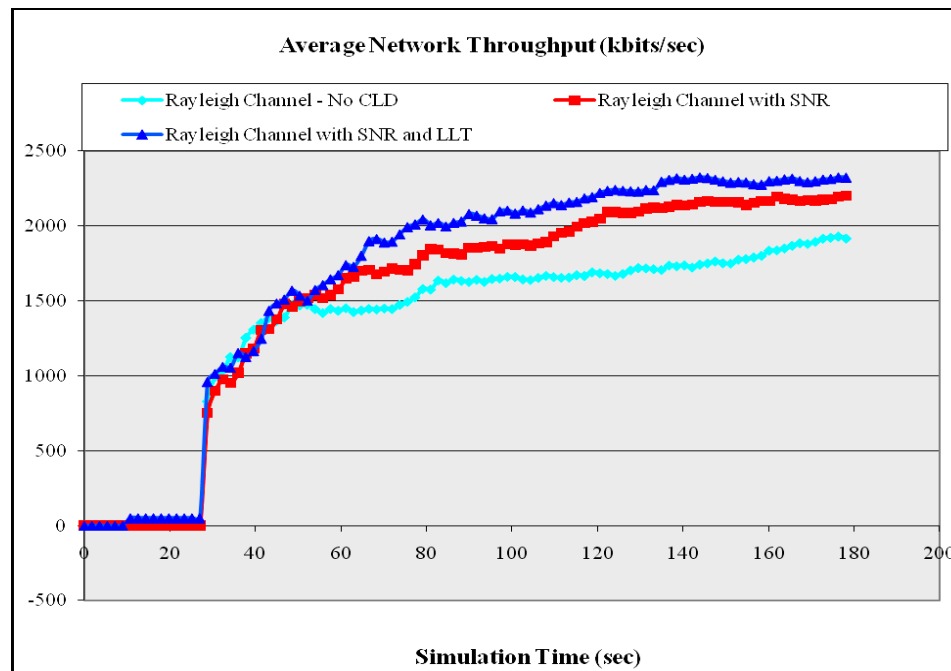


Figure 5-6 Network Throughput vs. Simulation time in Rayleigh fading channel

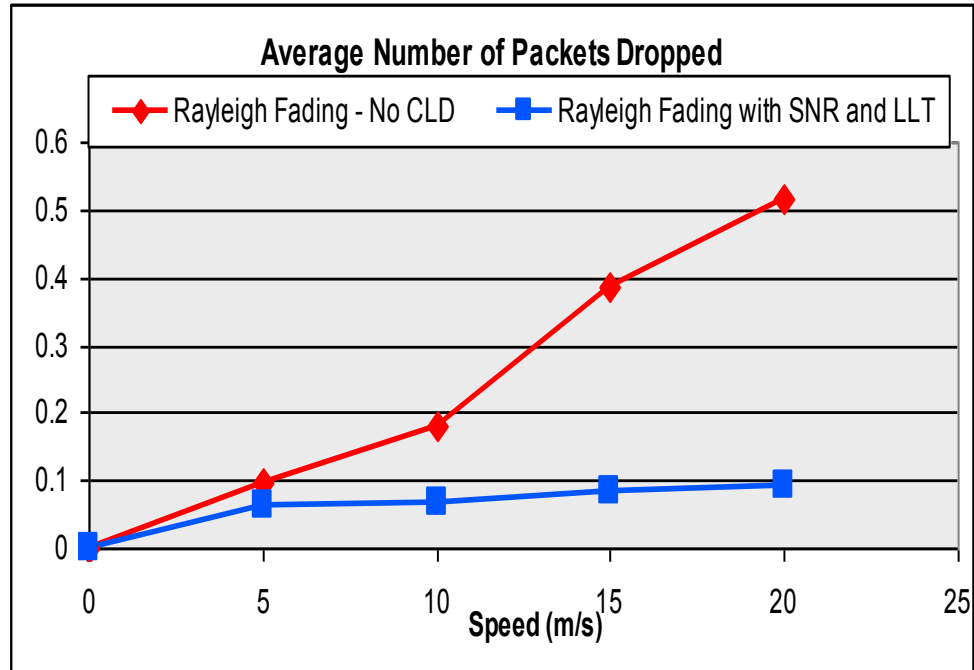


Figure 5-7 Average Number of Packets Dropped vs Mobility Speed

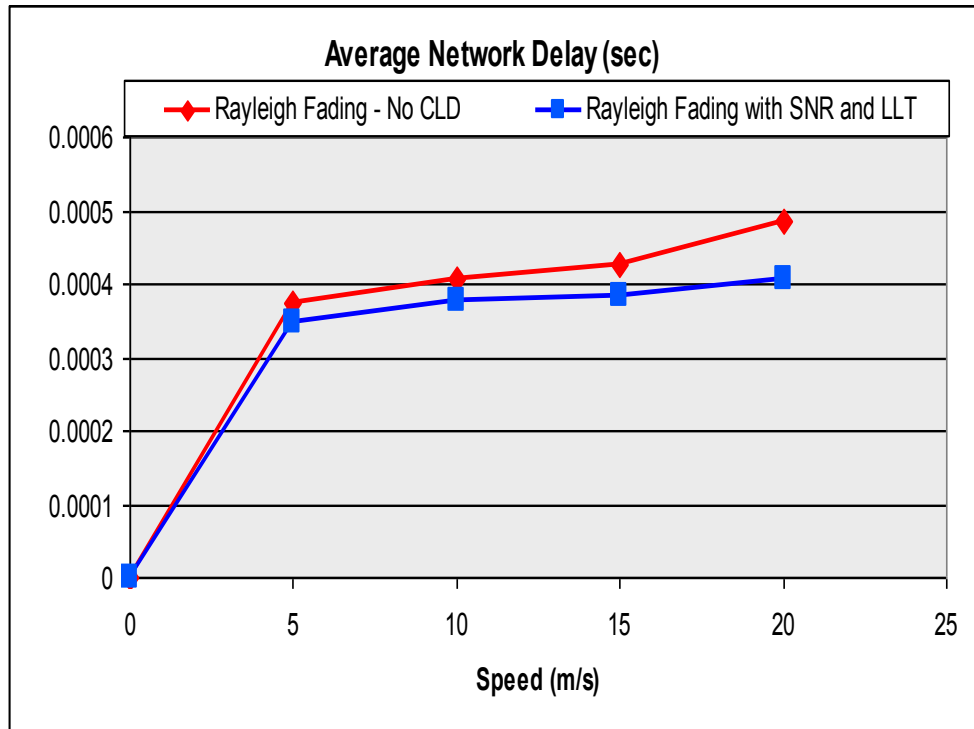


Figure 5-8 Average Network Delay in sec. vs Mobility Speed

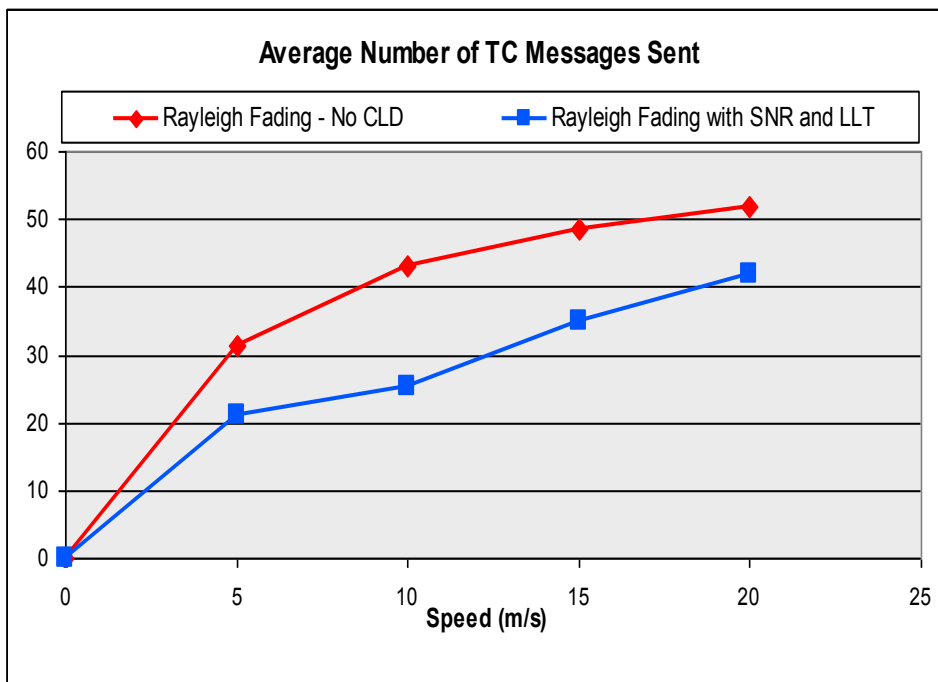


Figure 5-9 Average number of TC Messages sent vs Mobility Speed

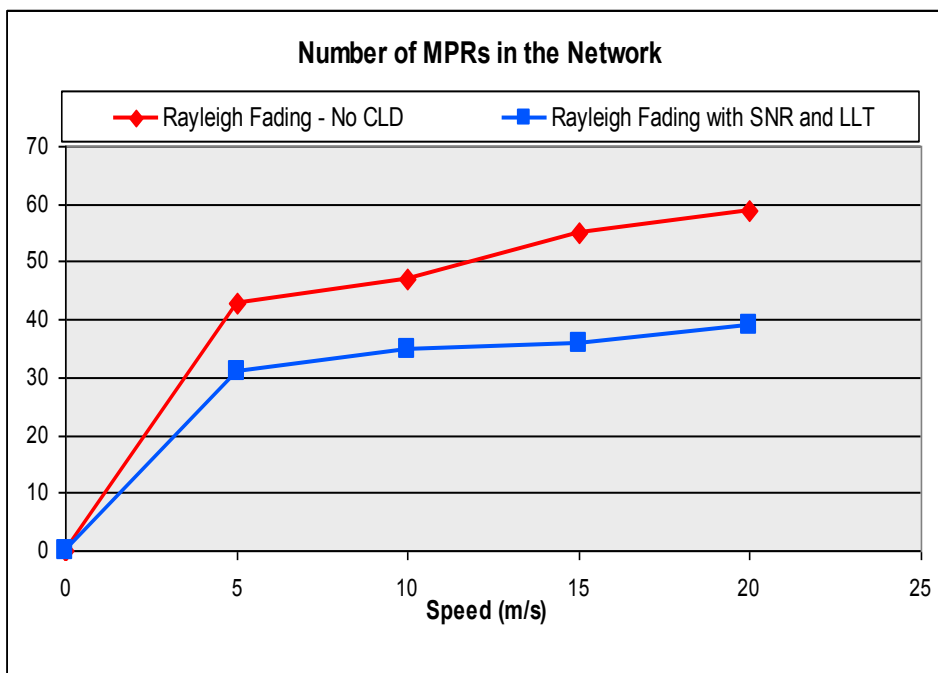


Figure 5-10 Number of MPRs in the network vs Mobility Speed

5.5. Conclusion

Using the above mentioned Rayleigh fading and shadowing model and considering the interference this chapter makes the following contribution:

It presents a network architecture that supports QoS in wireless ad hoc networks using the algorithm which monitors the channel conditions during data transmission and feeds this information to the routing layer. The motivation of this work was to explore the routing protocols with cross-layer design and present the benefits of this approach with its impact on the transport layer and overall network.

This chapter shows also how network throughput behaves for different path loss models. Moreover our results indicate that the network throughput under the multipath fading and shadowing is far less than that under the free space path loss model, which is used in the majority of existing studies. But it can be greatly improved by using the cross-layer architecture.

The goal of our work was not only to find a route from a source to a destination, but an optimal route that satisfies the end-to-end QoS requirement, in terms of quality and lifetime.

Parameters	Value
Modulation Scheme	BPSK
Traffic rate	1 Mbps
Radio Tx Power	0.005 W
Mobility model	Random-Waypoint
Propagation model	Rayleigh fading
MAC protocol	802.11
Packet size	512 bytes
Routing protocol	OLSR
Carrier Frequency	2.4 GHz
Terrain dimensions	1000mx1000m
Simulation time	180 s
Nodes number	100
Traffic	CBR
SNR Thresholds	22[dB] 17[dB]
Transmission Range	250 m
Speed	1-20 m/s

Table 2. Parameters values in the simulations of OLSR with CLD and LLT

Chapter 6

Conclusion and Future Work

6.1. Conclusion

The wireless channel is a widely used but rarely understood element in the design of communication systems today. One can often find people working with various parameters of a wireless channel without an understanding of the basics. Techniques for modeling and simulating channel conditions play an essential role in understanding network protocol and application behavior.

In this thesis we demonstrated how the modeling of the channel using Finite State Markov Chain analytical model yielded significant improvement in wireless ad hoc network protocol performance. Since computer simulation is often used to help predict many aspects of the behavior of communication channels, we introduced

- A mathematical model, which describes the channel, and
- Computer program used to imitate the channel behavior based on this model.

We presented a network architecture that supports QoS in wireless ad hoc networks using the algorithm which monitors the channel conditions during data transmission and feeds this information to the routing layer. We have applied this technique to the DSR and OLSR

protocols, and showed the improvements in the various routing protocol performance parameters.

We have also showed how network throughput behaves for different path loss models. Moreover our results indicate that the network throughput under the multipath fading and shadowing is far less than that under the free space path loss model, which is used in the majority of existing studies. But it can be greatly improved by using the cross-layer architecture.

The goal of our work was not only to find a route from a source to a destination, but an optimal route that satisfies the end-to-end QoS requirement, in terms of channel SNR and Link Lifetime.

6.2. Future Work

There are two main issues where our future work will be based: Trust and Security in MANETs.

Since mobile nodes in Mobile ad hoc network can move arbitrarily the topology may change frequently at unpredictable times. Transmission and reception parameters may also impact the topology. So it is very difficult to find and maintain an optimal route taking trust as a parameter.

Nodes in Mobile ad hoc network communicate over wireless links. Therefore efficient calculation of trust is a major issue in mobile ad hoc networks because an ad hoc network depends on cooperative and trusting nature of its nodes. As the nodes are dynamic the number of nodes in route selection is always changing thus the degree of trust also keep changing.

Whenever a node receives a request to relay traffic, it normally performs an action on the request while practically; intermediate node may not wish to consume their energy to carry some other node's traffic. This is known as malicious behavior of a node and that node is referred as a malicious node. It is very difficult to incorporate certification mechanism in ad hoc networks, because reliability and maliciousness has to be taken care as separate issues.

In wireless networks reliability and security is a global issue while trust is a local issue of the routing and so the trust based model has to be specifying a security analysis of the proposed model against attacks. Therefore there is need to develop a trust based model considering security as an important parameter, when developing routing protocol for wireless ad-hoc networks.

Bibliography

1. T. S. Rappaport, "Wireless Communications: Principles and Practice." Prentice Hall, 2002
2. Amir Salman Avestimehr, Suhas N. Diggavi, David N C. Tse "A Deterministic Model for Wireless Relay Networks and its Capacity", In Proceedings of Allerton Conference, 2007
3. Mineo Takai, Jay Martin, Rajive Bagrodia, "Effects of Wireless Physical Layer Modeling in Mobile Ad-hoc Networks", In Proceedings of the 2nd ACM International Symposium on Mobile Ad Hoc Networking & Computing, MOBIHOC 2001
4. Qinqing Zhang, Saleem A. Kassam, "Finite-State Markov Model for Rayleigh Fading Channels", In Proceedings of IEEE transactions on communications, vol. 47, no. 11, November 1999
5. Kanodia, V.; Sabharwal, A.; Knightly, E. "MOAR: a multichannel opportunistic auto-rate media access protocol for ad hoc networks", In Proceedings of Broadband Networks, BroadNets 2004, pp. 600 – 610
6. Wing Ho Yuen, Heung-no Lee, Timothy D. Andersen "A Simple an Effective Cross - layer Networking System for Mobile Ad Hoc Networks", PIMRC 2002, vol. 4, pp. 1952-1956

7. Novatnack, J.; Greenwald, L.; Arora, H. "Evaluating ad hoc routing protocols with respect to quality of service", In Proceedings of Wireless And Mobile Computing, WiMob 2005, vol. 3, pp: 205 – 212
8. Iannone, L. Khalili, R. Salamatian, K. Fdida, S. "Cross layer routing in wireless mesh networks", In Proceedings of 1st International Symposium of Wireless Communication Systems, 2004.
9. N. Wisitpongphan, G. Ferrari, S. Panichpapiboon, J.S. Parikh, and O.K. Tonguz "QoS Provisioning using BER-Based Routing in Ad Hoc Wireless Networks", In Proceedings of Vehicular Technology Conference, VTC 2005, vol.4, pp. 2483 - 2487
10. Jatinder Pal Singh, Nicholas Bambos, Bhaskar Srinivasan, Detlef Clawin "Cross-layer Multi-hop Wireless Routing for Inter- Vehicle Communication" 2nd International Conference on Testbeds & Research Infrastructures for the Development of Networks & Communities, TRIDENTCOM, 2006
11. The OPNET simulator www.opnet.com
12. D. B. Johnson, D. A. Maltz, and Y-C Hu., "The Dynamic Source Routing Protocol for Mobile Ad Hoc Networks (DSR)",. IETF Mobile Ad Hoc Networks Working Group, Internet Draft, 24 February 2003
13. T. Clausen and P. Jacquet, "Optimized link state routing protocol (OLSR)," RFC 3626, Oct. 2003.
14. Zhao Cheng, Wendi B. Heinzelman,, "Exploring Long Lifetime Routing (LLR) in ad hoc networks", 7th ACM international symposium on Modeling, analysis and simulation of wireless and mobile systems, 2004, pp. 203 - 210

15. Stephan Bohacek, Andjela Ilic, Vinay Sridhara, "On the Predictability of Link Lifetimes in Urban MANETs", 3rd International Symposium on Modeling and Optimization in Mobile, Ad-Hoc and Wireless Networks, WiOpt 2005, pp. 209-218
16. Hamid Menouar, Massimiliano Lenardi, Fethi Filali, "Improving Proactive Routing in VANETs with the MOPR Movement Prediction Framework" , In Proceeding sof 7th International Conference on ITS Telecommunications, ITST 2007
17. H. Menouar, M. Lenardi, and F. Filali, "A Movement Prediction based Routing Protocol for Vehicle-to-Vehicle Communications", 1st International Vehicle to Vehicle Communications Workshop, V2VCOM 2005
18. W. Su, S.-J. Lee, and M. Gerla, "Mobility Prediction and Routing in Ad Hoc Wireless Networks," International Journal of Network Management, vol. 11 , Issue 1 pp. 3 - 30, 2001
19. S. Agarwal, A. Ahuja, J.P. Singh, and R. Shorey, "Route-Lifetime Assessment Based Routing (RABR) Protocol for Mobile Ad-Hoc Networks," In Proceedings of Communications, ICC 2000, vol.3, pp. 1697 - 1701
20. Jinshan Liu, Val´erie Issarny, "Signal Strength based Service Discovery (S3D) in Mobile Ad Hoc Networks" In Proceedings of the 16th Annual IEEE International Symposium on Personal Indoor and Mobile Radio Communications, PIMRC, 2005
21. Jatinder Pal Singh, Nicholas Bambos, Bhaskar Srinivasan, Detlef Clawin, "Cross-layer Multi-hop Wireless Routing for Inter-Vehicle Communication" 2nd

- International Conference on Testbeds & Research Infrastructures for the Development of Networks & Communities, TRIDENTCOM, 2006
22. Vincent Lenders, Jorg Wagner, and Martin May, “Analyzing the Impact of Mobility in Ad Hoc Networks” International Symposium on Mobile Ad Hoc Networking & Computing , 2006, pp. 39 – 46
 23. N. Jindal, S. P. Weber, and J. G. Andrews, “Energy-Limited vs. Interference-Limited Ad Hoc Network Capacity”, In Proceedings of IEEE Transactions Nov. 2007
 24. D.S.J. De Couto, D. Aguayo, B.A. Chambers, and R. Morris, “Performance of multi-hop wireless networks: Shortest path is not enough,” In Proceedings of First Workshop on Hot Topics in Networks, HotNets-I, Oct. 2002
 25. Sayantan Choudhury and Jerry D. Gibson “Joint PHY/MAC Based Link Adaptation for Wireless LANs with multipath fading”, In Proceedings of IEEE Wireless Communications and Networking Conference, 2006
 26. Hongxia Sun, Herman D. Hughes, “Adaptive Multi-path Routing Scheme for QoS Support in Mobile Ad-hoc Networks”, In Proceedings of International Symposium on Performance Evaluation of Computer and Telecommunication Systems, SPECTS’2003, vol. 35, no.4, pp. 408-416
 27. Nabhendra Bisnik “Protocol Design for Wireless Ad hoc Networks: The Cross-Layer Paradigm”, Technical Report, ECSE Dept,RPI 2004
 28. M. Drini, T. Saadawi, “Cross Layer Design of Ad-HOC Network Routing with Implementations to OLSR and DSR”, In Proceedings of Networking and Electronic Commerce Research Conference, NAEC 2008.

29. Jatinder Pal Singh, Nicholas Bambos, Bhaskar Srinivasan, Detlef Clawin “Cross-layer Multi-hop Wireless Routing for Inter- Vehicle Communication” 2nd International Conference on Testbeds & Research Infrastructures for the Development of Networks & Communities, TRIDENTCOM 2006
30. Aytac Azgin and Marwan Krunz “Impact of Channel Modeling on the Performance of Wireless Scheduling Schemes”, VTC 2003-Fall.IEEE 58th Volume 3, Issue , 6-9 Oct. 2003
31. Muhammad Tahir, Sudip K. Mazumder, “Markov Chain Model for Performance Analysis of Transmitter Power Control in Wireless MAC Protocol: Towards Delay Minimization in Power-network Control” AINA 2007, pp. 909-916
32. Wei Liu and Yuguang Fang, “Courtesy Piggybacking: Supporting Differentiated Services in Multihop Mobile Ad Hoc Networks”, INFOCOM 2004, Vol. 3, No. 4, pp. 380-393
33. Sánchez-Salas, D.A Cuevas-Ruíz, J.L. “N-states Channel Model using Markov Chains” DOI 10.1109, CERMA 2007
34. Aduwo, A.; Annamalai, “Channel-aware inter-cluster routing protocol for wireless ad-hoc networks exploiting network diversity”, In Proceedings of Vehicular Technology Conference, VTC 2004, vol. 4, Issue , 26-29 pp. 2858 - 2862
35. Julio Aráuz, and Prashant Krishnamurthy“Markov Modeling of 802.11 channels” Vehicular Technology Conference, VTC 2003 IEEE 58th , vol. 2, pp. 771- 775
36. M. Drini, T. Saadawi “Modeling Wireless Channel for Ad-Hoc Network Routing Protocol”, ISCC, July 2008, pp. 549-555

37. Sumantra R. Kundu Kalyan Basu Sajal K. Das “Finite State Markov Model for Effective Bandwidth Calculation in Wireless Packet Networks” In Proceedings of the Third International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks, 2005, pp. 351 - 357
38. Shunan Lin, Shiwen Mao, Yao Wang, Shivendra Panwar “A Reference Picture Selection Scheme For Video Transmission Over Ad-Hoc Networks Using Multiple Paths” In Proceedings of ICME, 2001
39. Xinsheng Xia, Qilian Liang And Qingchun Ren “Bottom-Up Cross-Layer Optimization For Mobile Ad Hoc Networks” MILCOM 2005, vol. 4., pp. 2624-2630
40. Rancurel D. Roviras, J. Conan, And F. Castanikl “Effect Of Interleaving On A Markov Channel”. ICASSP 2000 vol. 5, Issue 2000, pp. 2661 – 2664
41. Syed A. Khayam and Hayder Radha “Markov-Based Modeling Of Wireless Local Area Networks” MSWiM 2003, SESSION: Emerging technologies: WLANs and WPANs pp. 100 - 107
42. Erwan Ermel, Paul Muhlethaler, “Using OLSR Multipoint Relays (MPRs) to estimate node positions in a Wireless Mesh Network” Research Report, INRIA, 2006
43. Prince Samar and Stephen B. Wicker, “Link Dynamics and Protocol Design in a Multihop Mobile Environment” IEEE Transactions on Mobile Computing, 2006, vol. 5, no. 9, pp. 1156-1172
44. Pedro Eduardo Villanueva-Pena, Thomas Kunz, “Extending Network Knowledge: Making Olsr A Quality Of Service Conducive Protocol”, In Proceedings of the

- International Conference on Communications and Mobile Computing, Vancouver, Canada, IWCMC, July 2006, pp. 103-108
45. Brent Ishibashi, Raouf Boutaba “Topology and mobility considerations in mobile ad hoc networks”, *Ad Hoc Networks*, vol. 3, issue 6, 2005, pp. 762-776
 46. Yang Cheng Huang, Saleem Bhatti, Daryl Parker, “Tuning Olsr” The 17th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Helsinki, PIMRC, 2006
 47. D. B. Johnson, D. A. Maltz, and J. Broch. “The Dynamic Source Routing Protocol for Multihop Wireless Ad Hoc Networks,” In *Ad Hoc Networking*, edited by Charles E. Perkins, Addison-Wesley, 2001, chapter 5, pp. 139-172
 48. T. S. Rappaport, A. Annamali, R. M. Buehrer, and W. H. Tranter, “Wireless Communications: Past events and a future perspective,” *IEEE Communications Magazine*, 2002, pp. 148-161
 49. M. Drini., T. Saadawi, “Performance of Ad-Hoc Routing Protocols with Link State”, In the Proceedings of 10th WSEAS Int. Conf. on Automation & Information , ICAI 2009
 50. X. Li, M. R. Lyu, J. Liu, “A Trust Model Based Routing Protocol for Secure Ad Hoc Networks”. In the Proceedings of IEEE Aerospace Conference, IEEEAC 2004, pp. 1286-1295
 51. M. Virendra, M. Jadliwala, M. Chandrasekaran, S. Upadhyaya, “Quantifying Trust in Ad-Hoc Networks”. In the Proceedings of IEEE international Conference on Integration of Knowledge Intensive Multi- Agent systems, KIMAS 2005

52. Er. Gurkirpal Singh, Er. Sarbjeet Singh “Routing Issues for Trust Based framework in Mobile Ad hoc Network” Proceedings of 2nd National Conference on Challenges & Opportunities in Information Technology, COIT 2008 RIMT-IET