# Performance Analysis of Wireless Ad Hoc Networks

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# Summary

The *central result* of this thesis states that protocols for ad hoc wireless networks at various levels of the OSI stack should be considered as a single algorithmic construct. This is demonstrated by varying interaction effects between distinct MAC layer and routing layer protocols, and other system input variables. Contrary to the previous works we have utilized a sophisticated statistical analysis of high dimensional experimental data to back this assertion. This approach is a significant contribution to methodological reasoning about performance of ad hoc wireless networks.

The *motivation* of this thesis stems from the earlier work by H. Balakrishnan and his colleagues, and the recent results of the group around Ch. Perkins, S. Das, and E. Royer. In their Infocom 2000 paper these authors conclude by saying – *"This observation also emphasizes the critical need for studying interactions between protocol layers when designing wireless network protocols"*. In this thesis we have undertaken exactly this sort of study. However, we have not restricted ourselves to studying of algorithmic interaction but extended this to other input variables such as speed of nodes, movement pattern, topology, injection rate of packets etc. Also, contrary to previous approaches to studying protocol interactions, we have resorted to a rigorous statistical method.

A *rigorous* formal analysis is of paramount importance for the design of protocols for ad hoc networks, and their (system) performance analysis. Previously, such an analysis was based on human expertise with the obvious lack of credibility and limited scope. The approach presented in this thesis allows for a sophisticated analysis of high dimensional experimental data. It opens a way to systematic performance analysis of large scale ad hoc systems not limited to quantities of basic output variables such as latency of packets or throughput. Additionally, it provides an in-sight into quality of non-linearities present in ad hoc networks. It can also serve as means for an easy characterization of ad hoc networks, for their testing, and benchmarking.

The *idea* behind this thesis was to concentrate on understanding of behavior of ad hoc networks rather than on design of new communication protocols. New protocols are often later found hard to evaluate with respect to performance, and the level of their suitability for a given task is very hard to quantify. We have decided to go in the opposite direction and the result is a methodology that allows for a very exact evaluation of the performance of ad hoc systems covering very fine performance measures such as the level of interaction among input variables. This is an important step forward as no previous performance study offers a methodological insight into behavior of ad hoc networks. Previously, understanding of ad hoc networks was based more on one's feel for a given setup rather than on a formal approach.

Besides standard types of synthetic static and mobile networks we have based some of our results on a realistic radio topology derived from the city of Portland, Oregon. The realistic radio topologies were produced by our *experimental framework* that is based on TRANSIMS, a tool for microscopic modeling, and simulation of vehicular, and pedestrian traffic. Novel results about robustness of realistic ad hoc networks with respect to transceiver, and link failures have been obtained.

Based on results in this thesis we would like to conclude by stating that no combination of MAC and routing layer protocols at a given injection rate of packets, speed of nodes, topology, movement pattern, number of active connections etc. was found to perform best with respect to the usual Quality of Service measures. This is a direct consequence of protocol design within the classical 7-layer OSI classification. Under this hierarchical classification protocols are divided into seven basic groups based on their functionality. Design of a protocol is then often completed in isolation from design of protocols at other levels of the OSI stack. This subsequently leads to undesirable *side effects* which frequently cause deterioration in the over-all performance. This fact further underscores the importance of the methodology proposed in this thesis.

## Keywords

Ad hoc wireless network; OSI protocol stack; protocols with monolithic, inter-layer or integrated design.

# Zusammenfassung

Das zentrale Ergebnis dieser Arbeit besteht in der Feststellung, daß Protokolle für drahtlose Adhoc-Netzwerke auf verschiedenen Ebenen des OSI-Protokollstacks nicht isoliert voneinander betrachtet werden sollten, da Interaktionen zwischen MAC- und Routingprotokollen (und anderen Eingabegrößen des Systemes) nachgewiesen werden können. Für diesen Nachweis wurden in der vorliegenden Arbeit erstmals umfangreiche experimentelle Daten zahlreicher Faktoren unter Anwendung fortgeschrittener statistischer Methoden analysiert. Damit leistet diese Arbeit einen bedeutenden Beitrag zur methodischen Leistungsanalyse von Adhoc-Netzwerken.

Die Motivation für diese Arbeit geht auf frühere Arbeiten von H. Balakrishnan und jüngere Ergebnisse der Gruppe um Ch. Perkins, S. Das und E. Royer zurück. Diese Autoren beschlossen ihren Beitrag auf der Konferenz “Infocom” im Jahr 2000 mit den Worten *“Diese Beobachtung betont zusätzlich die Notwendigkeit, Interaktionen zwischen verschiedenen Protokollebenen zu erforschen, wenn Protokolle drahtloser Netzwerke entworfen werden sollen”*. Die vorliegende Arbeit beschränkt sich dabei jedoch nicht nur auf die Protokolle selbst, sondern bezieht außerdem andere Eingabegrößen des Systemes wie die Geschwindigkeit und das Bewegungsprofil der Knoten, die Topologie, die Paketrate usw. in ihre Betrachtungen ein. Darüberhinaus werden hier im Gegensatz zu früheren Ansätzen zur Untersuchung von Protokoll-Interaktionen streng statistische Methoden angewendet.

Eine solche streng formale Herangehensweise ist von höchster Bedeutung für den Entwurf von Protokollen für Adhoc-Netzwerke sowie deren Leistungsanalyse. Analysen früherer Arbeiten basieren auf menschlichem Experten- bzw. Erfahrungswissen mit beschränkter Gültigkeit und Glaubwürdigkeit. Der in der vorliegenden Arbeit verfolgte Ansatz hingegen erlaubt eine anspruchsvolle Analyse umfangreicher experimenteller Daten zahlreicher Faktoren. Er eröffnet Möglichkeiten einer systematischen Leistungsanalyse von großen Systemen, die nicht auf grundlegende Ausgabegrößen wie Latenzzeit und Durchsatz begrenzt ist. Außerdem bietet er Einblicke in den Grad von Nichtlinearitäten innerhalb von Adhoc-Netzwerken. Er kann zudem dazu dienen, Adhoc-Netzwerke in einfacher Weise zu charakterisieren, zu erproben und in ihrer Leistungsfähigkeit zu vergleichen.

Basierend auf den Ergebnissen dieser Arbeit kann festgestellt werden, daß für vorgegebene Eingabegrößen keine Kombination aus MAC- und Routingprotokollen als optimal bzgl. herkömmlicher Bewertungskriterien für Dienstequalität bezeichnet werden kann. Dies ist eine direkte Konsequenz aus dem Protokollentwurf gemäß dem klassischen OSI-Protokollstack. Der Entwurf eines Protokolles wird in dieser Sicht oftmals isoliert von Protokollen anderer Ebenen vorgenommen. Dies führt in der Folge zu unerwünschten Nebeneffekten, die häufig eine Verschlechterung in der Gesamtleistung nach sich ziehen. Diese Tatsache unterstreicht zusätzlich die Bedeutung der in dieser Arbeit vorgestellten Methodik.

## Schlagworte

Drahtlose Ad hoc Netze; OSI-Schichtenmodell; Protokollinteraktion.

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# Contents

# Chapter 1

# Introduction and Motivation

## 1.1 Overview

Ad hoc wireless mobile networks do not rely on any fixed infrastructure in the form of wireline or base station in order to foster data communication. This paradigm is depicted in Figure 1.1. There we have nine mobile nodes[1] taking part in an ad hoc network. The circles around nodes show the *current* transmission radius of a given node. It is obvious that if two nodes lie in the transmission radii of each other they can communicate. In Figure 1.2 we have transformed the ad hoc network of Figure 1.1 into a connectivity graph. An edge represents the fact that two nodes can hear each other. Suppose we would like to setup a data connection[2] between nodes $A$ and $B$. Data packets will need to get forwarded over intermediate nodes. One such a path can be formed with the help of nodes $C$ and $D$. This path is not unique, and other possibility would be the path formed with nodes $E$, $F$, and $D$. Optimality of a path is often measured in the number of hops needed for data packets to reach the destination node. The choice of path depends on the routing protocol that is trying to find a path to destination that has the lowest number of hops (or other metric).

Mobility is inherent to ad hoc networks. This property is depicted in Figure 1.3. The Figure shows a situation after nodes $B$ and $H$ move. A new path from node $A$ to the destination node $B$ is needed. Data packets can now get forwarded over nodes $E$, $F$, $G$, and $H$. In order to find a new path to the destination the routing protocol has to initiate a new path search. Depending on when routing protocols gather routing information we can divide them into two basic classes. *Proactive* routing protocols

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[1] Nodes are either transmitters, receivers or both. For simplicity we use the term *node or transceiver* when we mean either of these.

[2] For simplicity, in this thesis we use the term “connection” also for connectionless protocols such as UDP.

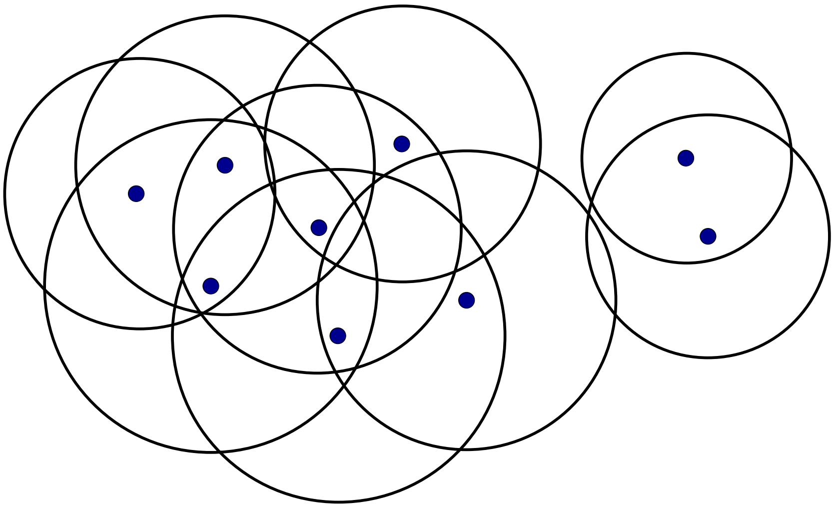

Figure 1.1: An Ad Hoc Network with nine nodes. The nodes are shown with their respective transmission radii.

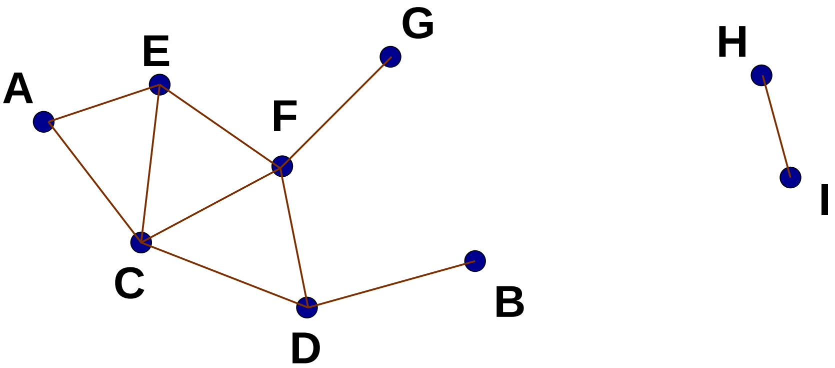

Figure 1.2: The Ad Hoc Network from Figure 1.1 in the form of a connectivity graph. An edge between two nodes shows that the two nodes can hear each other. Suppose we would like to send data from node $A$ to node $B$. Intermediate nodes $C$ and $D$ are needed for packets forwarding. The path to the destination is not unique and the data packets can get forwarded also over nodes $E$, $F$, and $D$ depending on the route provided by the routing protocol. Nodes $H$ and $I$ are isolated from the rest of the network and no data exchange is possible between these two parts.

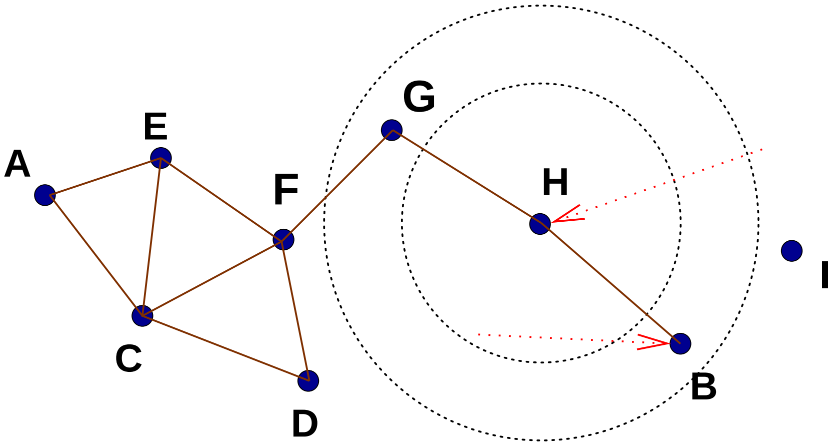

Figure 1.3: The Ad Hoc Network from Figure 1.2 after Nodes $B$ and $H$ move. Packets from node $A$ to $B$ have to get forwarded over nodes $E$, $F$, $G$, and $H$. Node $I$ stays isolated. Dotted circles around the node $H$ depict the capability of changing the transmission radius dynamically depending on communication requirements.

try to collect routing information to all nodes disregarding whether the routes will ever be used. A representative of this class is Destination Sequenced Distance Vector protocol (DSDV) [PB94]. On the contrary, *reactive* or *on-demand* routing protocols search for routes to destination on the need-to-know basis. Examples of on-demand protocols are Dynamic Source Routing protocol (DSR) [JM96], Ad Hoc On-Demand Vector Routing protocol (AODV) [PR99], or Location Aided Routing protocol (LAR) scheme 1 [KV98]. In both cases the search mechanism is using control packets that are introduced to the ad hoc network. These control packets are transported over the same wireless medium as data packets and thus are a source of collisions. Most routing protocols are built on the assumption that if node $A$ can hear node $B$ then the same applies to node $B$. This is not true in general and unidirectional links induced by variations in transmission radii are common. Unidirectional links often lead to data loss. This problem is being addressed in specifications for DSR, AODV, or LAR scheme 1.

Medium Access Control (MAC) protocols are needed to negotiate access to the wireless medium for each node. Simultaneous transmission of neighboring nodes would cause packet losses. Therefore a mechanism to guarantee unshared access to the wireless medium for a given node is central to a successful data communication. CSMA uses *carrier sensing* to control the access to the medium. This access method has however a fundamental weakness in the form of the *hidden terminal* problem [Al93]. Suppose that we have three nodes $A$, $B$, and $C$ where both $A$ and

$C$ can hear $B$ and vice versa, but $A$ and $C$ cannot hear each other. If node $A$ senses no carrier and starts data transmission to the node $B$ then node $C$ unaware of this data transmission can send data to node $B$ as well, thus corrupting all data coming from node $A$. This problem was partially solved in MACA [Ka90] by introduction of control packets at the MAC layer level. This mechanism relies on the exchange of RTS and CTS[3] control packet pairs to eliminate the hidden terminal problem. IEEE 802.11 DCF incorporates both the carrier sensing from CSMA and RTS-CTS control packets from MACA. Furthermore, it uses *virtual carrier sensing*. Virtual carrier sensing mitigates certain dynamic deficiencies of the RTS-CTS mechanism. It is implemented in the form of Network Allocation Vector (NAV) for each node. NAVs store information about the next scheduled attempt to gain access to the wireless medium for a given node. This information is also propagated to neighboring nodes. These nodes adjust their schedules based on this information. Also the basic RTS-CTS-DATA reservation schema has become an RTS-CTS-DATA-ACK schema in IEEE 802.11 DCF with significantly improved performance. These additions have improved fairness characteristics, however, in [LNB98] authors point out deficiencies in the fairness as well.

In general, each protocol can be classified within the 7-layer OSI protocol stack. The layers from the lowest to the highest layer are: physical, link, network, transport, session, presentation, and application. Routing and MAC protocols fall into the network layer, and link layer[4], respectively. The advantage of this classical hierarchical classification is that protocols at different levels can be designed in isolation with respect to their functionality. The disadvantage is that such an isolated design often introduces *undesired side-effects* to other levels of the OSI stack. This is especially true for mobile wireless systems where the bandwidth is scarce, and motion of nodes is often rapidly changing. In later chapters we will come back to this issue in more detail. We will demonstrate that for example side-effects from the routing protocol can adversely affect the requirements that are put on the companion MAC protocol; such situation usually leads to profound performance deterioration.

Wireless ad hoc networks are in the future expected to consist of thousands or even millions of nodes. The movement of nodes will depend on social and technical environments in which the networks will be deployed. Currently, movement of nodes is modeled with mobility models such as Random waypoint mobility model [JM96], Exponentially correlated random model [RS98], etc. These models belong with the large family of *synthetic* models which were designed to approximate behavior of mo-

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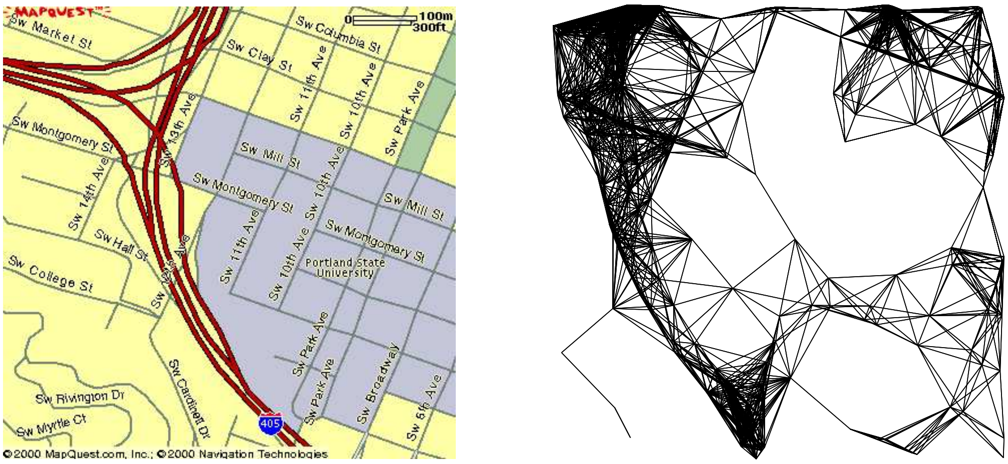
[3] RTS is Ready To Send, and CTS is Clear To Send.

[4] If addressing issues of MAC protocols are not considered.

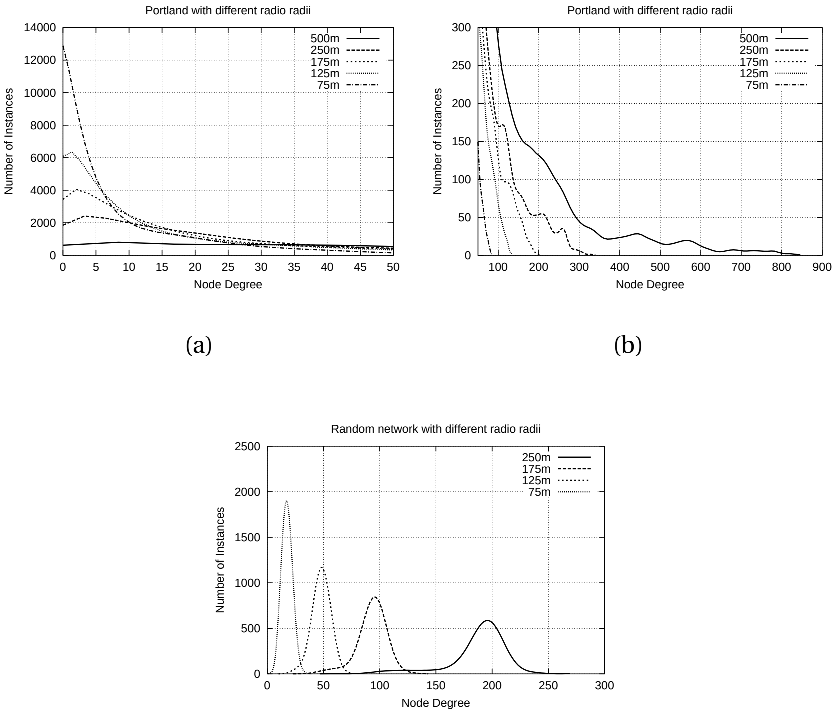
bile users in certain situations. We refer the reader to [Ca+02] for a thorough review of such mobility models for ad hoc networking. These models specify in detail the velocity of each node at any instant of time; obstacles and other limiting issues are usually in these models not considered. They can be divided into two basic groups: models that control movement of each node independently, and group models in which node movement is coordinated within groups. Qualitatively different are models that respect the underlying infrastructure in form of obstacles, or roads. In Figure 1.4 we show an example of ad hoc network that observes the basic road infrastructure. The node distribution on $(x, y)$ plane was computed with TRANSIMS [BB+00, TR], a tool for microscopic modeling and simulation of vehicular traffic. In Figure 1.5 we can see that node degree distribution is different in case when a realistic spatial distribution is considered, and when a random uniform distribution is applied. The latter concept is a usual initial set-up of many synthetic mobility models including the random waypoint model.



(a) (b)

Figure 1.4: Realistic ad hoc network. The size of area is 1 km ×1 km. The interstate I-405 is visible and is going from the north to the south-east. The top left corner also shows the US highway 26 merging into I-405. From left: (a) street map from MapQuest, (b) connectivity graph when a uniform radio radius of 125 meters is assigned to all ($\sim 185$) participating nodes.

We conclude this section by noting that pioneering effort towards better understanding of ad hoc networks was undertaken in **PRNET** (Packet Radio Network) [JT87], and **SURAN** (Survivable Adaptive Networks) [SW] projects sponsored



(a) (b)

(c)

Figure 1.5: Distribution of node degrees for the city of Portland and adjacent areas; radii were assigned uniformly to all nodes. From left: (a) Portland (**89,264** nodes), we can see a change in distribution with decreasing radio radii; small radio radius causes a high number of low connected nodes. (b) Portland – detail of the graph in (a), we notice the periodic nature of the distribution. (c) $5$ km$\times$$5$ km area with 25,000 nodes uniformly randomly positioned. Random uniform node positioning is regularly used for simulation of mobile ad-hoc networks. We can see the difference between the distribution of node degrees of these graphs and the underlying distribution induced by a *realistic* traffic in the city of Portland at 7:54am. Number of instances is the number of nodes (in absolute terms) that have a given node degree.

by the Defense Advanced Research Project Agency (DARPA). Interest in ad-hoc networks for mobile communications has also resulted in a special interest group for Mobile Ad-hoc Networking within the Internet Engineering Task Force (IETF) [MC].

## 1.2 Fundamental Challenges in Performance Analysis of Ad Hoc Wireless Networks

In this thesis we delve into the problem of performance of wireless ad hoc networks. In this area we focus on the following challenges:

1. Performance of ad hoc wireless networks with respect to basic Quality of Service (QoS) measures under various scenarios.

2. Interactions among protocols at different levels of the OSI stack. Impact of other input parameters such as nodal speed, data packet injection rate, network topology etc. on over-all interaction; this includes mixed interaction between these input parameters, and communication protocols. *This is the main goal of the thesis.*

3. Graph theoretic properties of ad hoc wireless networks and their impact on performance with focus on robustness against failure of nodes and wireless links.

Based on the above formulated challenges we have restated the goals of this thesis as follow.

### 1.2.1 Goal #1

Ad hoc wireless networks are to be deployed under very challenging conditions, and in situations that are even hard to envision at this time. However, under the current continually dropping prices of wireless equipment it is possible that ad hoc networks will be in the future formed of thousands or even millions of communicating nodes. An example of such a network could be an information and emergency system for vehicular traffic. In such a system each car, or truck would have an integrated communications unit based on the ad hoc networks' principle.

The fundamental challenge is, however, to guarantee some basic level of the QoS. This task is an important undertaking, especially, in situation where any large scale deployment of ad hoc networks does not yet exist. In the literature, basic effort in this direction has been done on basis of simulative experimentation [DPR00, BM+98]. Result of such experimentation is usually a set of measured output parameters that are, to a certain extent, able to characterize the performance of the given network under the specific setting. Across experiments it is often very difficult to compare. Indeed, results published in different scientific documents are often stand-alone results that lack the capability of generalization; they are devoid of preciseness, characterization, expressiveness, and credibility.

Therefore, it is important to approach any performance analysis of ad hoc networks in a more directed, and addressed way. Examples of such approaches are studying performance with respect to basic graph theoretic measures. By imposing a certain quantitative level of e.g. path lengths, or minimum cuts it is possible to study response of ad hoc networks to changes in these parameters. Such a directed, and addressed study is the Goal #1 of this thesis.

### 1.2.2 Goal #2

From the early stages of research in the field of ad hoc networks until now, improvements in communications protocols have been mainly done on the premise that different communication needs are serviced by different protocols at various levels of the OSI stack. This classical structure allows for an easy design of specialized protocols for specific tasks such as routing, or wireless medium access. The fundamental problem under these assumptions is whether performance of ad hoc networks is affected by choice of specific combination of protocols from different levels of the OSI stack.

This problem has been partially approached in [RLP00]. Again, the results in the mentioned literature lack the desired generality, and are hard to interpret. Therefore, new approaches need to be examined in order to obtain a better picture on issues connected with interaction of protocols at different levels of the OSI stack, interaction of other input variables such as nodal speed, data packet injection rate, network topology, packet size, etc., and mixed interaction among protocols and input parameters. It is obvious that an interaction can be loosely interpreted as non-linear behavior due to choice of specific protocol, or specific level of an input parameter. The Goal #2 is to devise a rigorous approach to argue effectively about such interactions, and their effects on over-all performance.

### 1.2.3 Goal #3

In contrast to simulative experimentation, where the basic performance is derived from a complete and detailed simulation of each protocol, it would be an interesting option to describe and approximate expected performance through basic graph theoretic measures. These measures could be for example distribution of node degrees, distribution of shortest paths, network diameter, clustering coefficient, or matching size. An interesting question is whether these measures show a strong phase change behavior when the critical value for a given measure is reached.

In order to obtain a realistic perspective on the performance of ad hoc networks, it is desired to compute such graph theoretic measures on a large and credible sample of data. In our case, this data is based on TRANSIMS, a tool that is able to produce realistic snapshots of vehicular, and pedestrian traffic.

Goal #3 of this thesis is to compute the above mentioned graph theoretic measures, and argue about their impact on performance and robustness of ad hoc wireless networks.

## 1.3 Contributions of Thesis

The main discerning factor between results presented in this thesis and other results in the literature is that we have designed and employed a strict method based on statistical analysis to reason *rigorously* about performance, and *interaction effects* within ad hoc networks. This area is currently a very hot topic within ad hoc networking. A recent IRTF draft titled *"Interlayer Interactions and Performance in Wireless Ad Hoc Network"* [LSR01] stresses its importance.

Statistically, interaction between two factors is said to exist when effect of a factor on the response variable can be modified by another factor in a significant way. Thus understanding the interaction between input parameters such as nodal speed and packet injection rate can be easily captured using statistical methods. Similarly, we say that protocols interact if the behavior (semantics) of a protocol at a given layer varies significantly depending on the protocols above or below it.

This method allowed to analyze interactions in a formal framework. Such an analysis has been missing prior to this thesis. We have decided to base the statistical analysis on Analysis of Variance (ANOVA). Unquestionably, there are alternatives available to ANOVA that are able to handle much more complex statistical problems than those introduced in this thesis, however, in our case, ANOVA is fully sufficient given the size of sample space available and the problem under investigation. Prior to this thesis, investigation of interaction effects within ad hoc networks was based on “expert knowledge” rather than on *systematic* approach. The main advantage of the systematic approach presented in this thesis is that it is capable of *dichotomized* decision making about the existence of an interaction between two, or more factors. This is accomplished at a given level of significance. The ability to understand and quantify interactions is central to engineering of future high performance protocols for ad hoc networks. Future protocols will be able to avoid unwanted interactions and use synergy effects for increased performance.

Our method has led to a multitude of results. We have showed that there is no combination of routing and MAC layer protocols that would perform best under any condition characterized by traffic, speed of nodes etc. Contrary to the previous works we have identified the sources of performance degradation caused by suboptimal choice of protocols at different levels of the OSI stack.[5] This has led to the main result that protocols at different levels of the OSI stack need to be considered as a single algorithmic construct. This fact has been intuitively known prior to this thesis but a deeper understanding was missing together with a more direct proof. Additionally to studying protocol interaction we give results for interaction among other parameters such as network topology, speed of nodes, injection rate of data packets etc. These parameters are uncontrollable from the point of view of a network operator and therefore their impact on performance is harder to avoid. The main result in this direction is a better knowledge about how interactions among these parameters can further deteriorate performance of an ad hoc network, or conversely, how synergy effects among these parameters could help.

To support our assertions we had to produce a large sample space for statistical analysis. Different simulation runs were based on distinct simulation seeds to guarantee “random variation”. The input parameters included all usual variables such as speed of nodes, movement pattern, topology, injection rate of data packets and others. The output parameters included number of data packets received, throughput, latency of data packets, number of control packets at MAC and routing layer of the OSI stack and their spatial distributions, and long term fairness. The total number of simulation runs necessary to produce the large sample space amounted to tens of thousands. In our efforts we were somewhat restricted by available simulators for ad hoc networks. Therefore we chose rather subtler simulation cases from which it was

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[5] We have done this for the MAC and routing layer protocols. It is possible to include protocols at all other levels of the OSI stack but that is beyond the scope of this thesis.

easy to draw conclusions. The universal goal were results that are easy to interpret and compare across. Therefore we decided to focus on qualitative performance yardsticks rather than on complex data sets of performance measures that are specific to a given setup. The method described in this thesis is a particular step towards better evaluation of complex simulation experiments and more importantly, an easier comparison of results across different setups.

In addition to standard types of *synthetic* static and mobile networks we have based some of our results on a realistic radio topology derived from the city of Portland in Oregon. We have computed basic graph theoretic measures for a snapshot of the realistic urban topology. We have also compared the performance of synthetic and realistic networks. These results have direct application in the design of ad hoc networks, and in design of realistic scenarios for large scale simulations.

## 1.4 Thesis Organization

The results of this thesis are organized as follow. In Chapter 2 we overview basic paradigms and protocols for ad hoc networks. We introduce the reader to the hidden terminal problem that is of paramount importance to understanding of ad hoc networks' performance. We overview routing protocols used in this thesis: Dynamic Source Routing (DSR), Ad-hoc On-demand Distance Vector Routing (AODV) and Location-Aided Routing (LAR). We give also a detailed insight into MAC layer protocols used: CSMA, MACA and IEEE 802.11 DCF. We also discuss protocols at the transport level, give basic insight into modeling of radio wave propagation, and review common mobility models. A short overview of simulators capable of simulating wireless networks in the ad hoc setup is included as well.

In Chapter 3 we introduce input, output (performance) parameters of ad hoc networks used in this thesis and methods of statistical analysis used to process them. We also discuss basic graph theoretic measures employed. Furthermore, we describe in detail the different flavors of interactions among input parameters and, in particular, among protocols at different levels of the OSI stack. Protocols at different levels of the OSI stack constitute an input parameter from the system's point of view and form a particular class of interactions, further referred to as *algorithmic interactions*. Detailed understanding of all flavors of interactions is one of the contributions of this thesis.

Chapters 4 through 7 form the core of this thesis. In Chapter 4 we show basic properties of *static* ad hoc networks. The main effects studied are (generalized) hidden terminal, network connectivity, and separator size and sparsity. We reason about these effects in settings that are easy to interpret. The main conclusion is that there is not a single protocol combination that would perform well under any network setup. This result motivates design of a highly adaptive class of communication protocols.

In Chapter 5 we have analyzed the variable and algorithmic interaction for three basic instances of *static* ad hoc networks. We have focused ourselves on interaction among MAC and routing layer protocols. Understanding such an interaction is considered central for better understanding of ad hoc systems (see e.g. [BS+97, KKB00, DPR00, DP+, RLP00]). In this chapter we introduce our approach to studying interactions based on ANOVA. This approach is completely new and prior to this thesis there was no method for easy decision making about presence or non-presence of interaction within an ad hoc system. We expect this method to play an important part in the design of future communication protocols.

In Chapter 6 we have extended results from the previous chapter to *mobile* ad hoc networks. These are based on the Exponentially Correlated Random Model (ECRM), the Random Waypoint Mobility Model and the Grid Mobility Model. Using our method we have empirically proven interactions in mobile ad hoc networks. We have showed that our results on interactions exhibit a decent level of robustness when a higher number of connections, and nodes is considered. Results in this chapter has led us also to the assertion that in order to improve the overall performance of ad hoc networks the protocols at various levels of the OSI stack need to be considered as a single algorithmic construct and not in isolation.

In Chapter 7 we discuss the impact of the structure of ad hoc networks on their robustness. We have computed basic graph theoretic measures for two types of synthetic and realistic ad hoc networks. An analysis in light of nodes and edges deletions and the impact of these deletions on over-all performance with respect to these graph theoretic measures is done. The general conclusion of this chapter is that structural properties are an important concept in reasoning about performance, but they do not provide as in-depth analysis as simulative experimentation.

We conclude this thesis with a chapter that sums up the results and points out possible new directions in research.

# Chapter 2

# Background and Related Work

## 2.1 Basic Definitions

Mobile ad-hoc network is represented as a dynamic graph $G = (E(t), V)$, where $E(t)$ is the set of edges at time $t$ and $V$ is the set of vertices or mobile nodes. Let $n = |V|$ be the number of nodes participating in mobile communication. Node $i \in V$ can hear node $j \in V$ if node $i$ is within radio range of $j$. Let $Hears(i)$ to be a set of nodes which node $i$ can hear. It is obvious that nodes $i$ and $j$ can hear each other if and only if $i \in Hears(j)$ and $j \in Hears(i)$.

The *radio range* of a transceiver is the geographic distance over which packets sent by the transceiver can be received. The distance metric used is the Euclidean ($L_2$) metric. Thus, if the range of a transceiver $A$ is $r$, then a packet sent by $A$ can be received only by the transceivers that are within or on the circle of radius $r$ centered at the point occupied by $A$. We note that different transceivers may have different ranges. Therefore in the light of the above definition, it is not true that if $i \in Hears(j)$ then $j \in Hears(i)$, or vice-versa, though it is a frequent assumption for many MAC and routing layer protocols.

In an ad hoc network, a *hop* refers to the movement of a packet directly from one transceiver $A$ to another transceiver $B$ which is within the range of $A$. In a wired backbone mobile network, a hop may refer to either the movement of a packet between a mobile unit and its base station or between a pair of base stations.

## 2.2 Radio Propagation

Radio range of a transceiver is under real conditions subject to many limitations. Most wireless systems are expected to operate in areas with abundance of occlusions in form of trees, walls, or buildings. Other important liming factors are the overground elevation of the transmitter and receiver, atmospheric conditions, speed of motion etc. According to [Ra96], radio propagation mechanism can be divided into three basic groups: reflection, diffractions, and scattering.

*Reflection* occurs when direct radio propagation is impossible due to an obstructing object that is of size many orders of magnitude larger than the wave length. As a result, radio waves are reflected in a direction away from the object.

*Diffraction* occurs when direct radio propagation is obstructed with an object with sharp edges. The direction of radio waves is changed due to these edges, and often results in bending of waves around the obstacle.

*Scattering* occurs when the medium through which a radio wave is being propagated consists of many objects that are of comparable size or smaller than the wave length, and at the same time, the number of these objects is high. Examples of such objects are sign posts, foliage, or even people.

A different phenomenon is understood under the term *fading*. Fading can occur when a wireless device that is receiving signal is moving. This results in rapidly changing conditions under which the radio signal is being received. The changing conditions are a consequence of reflection, diffraction, or scattering that are affecting the reception differently at each new position of the wireless device. This causes rapid fluctuations in the strength and phase of the received signal.

Models that attempt to describe the above mentioned propagation qualities can be loosely divided into small-scale, and large-scale models. Small-scale models describe situations in which propagation over distances proportional to wave length is considered; large-scale models describe situations when the distance between a given transmitter-receiver pair is many orders of magnitude higher than the wave length, usually measured in meters, or kilometers.

In this thesis we have only considered obstacle-free radio propagation therefore we will limit ourselves to the Free Space Propagation Model. Subsequently, we will shortly introduce the Two-ray propagation model that accounts for a simple instance of reflection. Details on other models can be found in [Ra96].

### 2.2.1 Free Space Propagation Model

The Free space propagation model attempts to describe radio wave propagation when no occlusions are present anywhere in-between the transmitter and the receiver. This model predicts that signal strength decays as a function of power of the distance; i.e., the decay obeys a power law function. The power received $P_r(d)$ with respect to distance is then given by the following equation:

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

where $P_t$ is the transmitted power, $G_t$ is the transmitter antenna gain, $G_r$ is the receiver antenna gain, $\lambda$ is the wavelength, $d$ is distance between the transmitter and the receiver, and $L$ is a system loss factor not related to propagation $(L \geq 1.0)$. System losses are usually due to line attenuation, filter losses, antenna losses, and other effects of lesser importance. Gain of antenna is related to its effective aperture $A_e$:

$$G = \frac{4\pi A_e}{\lambda^2}$$

The effective aperture is then related to the physical size of the antenna. $\lambda$ is related to the carrier frequency $f$ by

$$\lambda = \frac{c}{f}$$

where $c$ is the speed of light. The above equations show that signal strength decays proportionally to the inverse of square of the distance between the transmitter and the receiver.

### 2.2.2 Two-ray Propagation Model

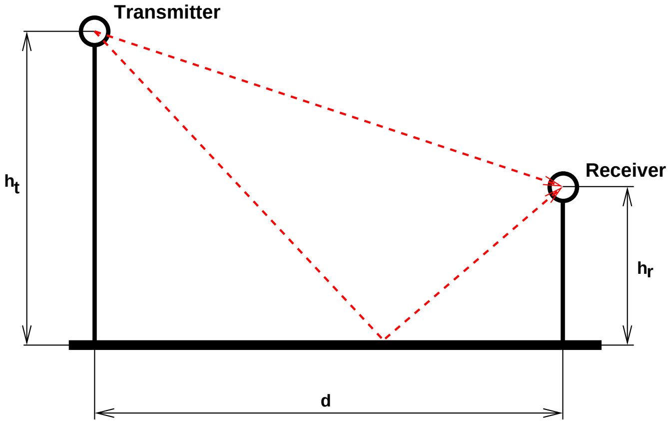

Figure 2.1: Two-ray radio propagation. Radio waves are propagated over both line-of-sight, and ground reflection paths. These facts are depicted as dashed lines.

The Two-ray propagation model attempts to take multiple path propagation, ground reflection, and elevation of the receiver and the transmitter, respectively, into account. These facts are depicted in Figure 2.1. Without going into details we note that under such setup the signal strength at the receiver can be given by

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

where $h_t, h_r$ is elevation of the transmitter and receiver, respectively. Thus, the received signal strength for large distances ($d \gg \sqrt{(h_t h_r})$ falls off with the fourth power of the distance $d$. This is a much faster rate of decay than with the Free space propagation model.

In our experiments we have been using the Two-ray propagation model. There were no obstacles of any kind, thus line-of-sight was always possible. In our computations we have also considered the impact of receiver noise; this type of noise is usually caused by thermal noise. This noise has been modeled as a constant factor.[1] Parameters for antenna gain, frequency, radio strength, noise factor etc. were adopted from standard IEEE 802.11 WiFi equipment.

## 2.3 Medium Access Control Protocols

In the 7-layer OSI classification of protocols, Medium access control (MAC) protocols are situated at the link level. The purpose of these protocols is to negotiate access to the wireless medium. In this section, we shortly discuss basic types of MAC protocols, and the approach that their designers chose to cope with problems not present in wireline communication.

### 2.3.1 The hidden terminal phenomenon

The hidden terminal phenomenon is unique to wireless networks. In these networks nodes have to rely upon the wireless medium to deliver data packets. Since it is highly improbable that each node will be able to communicate directly with any other node in the network, nodes will be limited in their capability of sensing on-going data transmission at other nodes. This will effectively hide those nodes from the carrier sensing node and give rise to the hidden terminal effect. Figure 2.2 illustrates this problem. We can see that $A, C \in Hears(B)$ but $B \in Hears(C)$ and $B \in Hears(A)$, i.e., $B$ can hear both $A$ and $C$ but $A$ can only hear $B$, and $C$ can only hear $B$. Suppose that both $A$ and $C$ would like to start sending packets to $B$. As $A$ cannot hear

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[1] This fact is denoted as Radio type: Accnoise in our tables describing experimental setup. It is in line with GloMoSim configuration files.

$C$, and $C$ cannot hear $A$, and there is no mechanism to prevent simultaneous data transmission, the wireless medium at $B$ will get corrupt by transmission from nodes $A$ and $C$. This will result in lost data packets and wasted bandwidth. This behavior is characteristic to the ALOHA protocol [Ab70] that was designed to work on very sparse networks in which the hidden terminal problem is partially eliminated.

Similar to the hidden terminal problem is the *exposed* terminal problem. Here we have four nodes $A, B, C, D$. Formally, the situation can be expressed as $B \in Hears(A)$, $A \in Hears(B)$ and $B, D \in Hears(C)$; $B$ is transmitting to $A$ and $C$ would like to start a transmission to $D$. However, $C$ senses the carrier of $B$ and therefore postpones its own transmission when it could have transmitted; i.e., $C$ could have started its own transmission but due to $B \in Hears(C)$ defers.

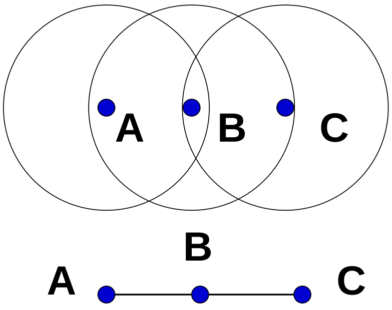

Figure 2.2: The hidden terminal effect. Node $B$ can listen to both $A$ and $C$, but $A$ and $C$ can only listen to $B$. This effectively hides $A$ from $C$ and vice-versa $C$ from $A$.

### 2.3.2 CSMA [Ra96]

CSMA is an acronym for Carrier Sense Multiple Access. As the name suggests, this protocol exploits capability of transceivers to listen to the on-going traffic in the adjacent area. This information is used to decide whether to start a data transmission, or whether to postpone this transmission until the channel gets idle, i.e., there is no carrier sensed. By monitoring the carrier CSMA improves efficiency by lowering collisions with neighboring transceivers. If CSMA senses carrier, the protocol has a built-in mechanism for delaying transmission. These mechanisms are called *back-off* algorithms. They come in several flavors – we refer reader to [Ra96] for an overview. A frequently used back-off method is the binary exponential back-off algorithm. This algorithm uses a variable size contention window to control access to the wireless medium. Each node starts with a predefined size of the contention window. The time that elapses before a node is allowed to start a data transmission is given by a random value chosen uniformly from the range of the contention window. If the node senses no carrier during this period it is allowed to transmit its data. After a successful transmission the size of the contention window is set to its minimum value. Otherwise, the size of contention window is doubled. The node also increments time-out counter associated with each data packet. If the counter reaches its maximum allowed value the data packet is removed from the data queue. The basic mechanism now repeats with the random number ranging over the increased contention window. The maximum size of the contention window is predefined during implementation. Unlike CSMA/CD, where CD stands for Collision Detection, in CSMA transceivers do not monitor the carrier during their own transmission. CSMA/CD usually implements this feature by interrupting the transmission (single channel), or transceivers need to have *listen-while-talk* capability.[2]

CSMA does not have any mechanisms to prevent the hidden terminal problem from occurring.

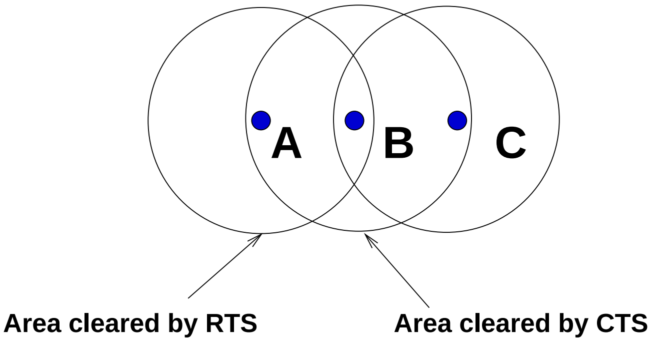

Figure 2.3: Exchange of RTS-CTS control packets for MACA. Node $A$ sends out an RTS control packet thus signaling its readiness to transmit data. Node $B$ replies with a CTS packet signaling to node $A$ that it is allowed to start the data transmission. The CTS packet is overheard by node $C$ as well. Node $C$ extracts information about the expected length of data transmission between $A$ and $B$ and postpones its data transmission accordingly.

### 2.3.3 MACA/MACAW [Ka90, BD+94]

MACA uses a different approach for channel acquisition than CSMA. Unlike CSMA, MACA does not reserve the channel at the originator of a transmission but rather at the destination for the transmission. This is done by exchange of an RTS-CTS pair

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[2] Note that thoughout this thesis we used a “pure” CSMA that does not implement any acknowledgement mechanism at the MAC layer.

of control packets. To start a transmission to a chosen destination, originator of the transmission sends an RTS (Ready-To-Send) control packet to the destination. The RTS control packet is overheard by both the destination and all nodes in the radio range of the originator. Nodes other than the destination will extract information about expected length of data transmission from the RTS packets and will adjust their transmission schedules accordingly. If the channel at the destination is idle, a CTS (Clear-To-Send) control packet is returned. Similarly, the CTS packet is overheard by all nodes in the radio range of the destination. These nodes will also adjust their schedules to the information contained in the CTS packet. Now, the originator is clear to send the data. If the CTS packet is not received within a timeout period the node will use a back-off mechanism to postpone its transmission. The exchange of the RTS-CTS pair is considered an atomic step to the MACA protocol. In [Ka90] authors do not specify which back-off algorithm should be used. The exponential back-off algorithm is the most commonly used. Many implementations also include capability of overhearing the data packets being transmitted, and thus deducing the end of transmission. In Figure 2.3 we illustrate the RTS-CTS exchange mechanism in a simplified three node setting. MACA efficiently alleviates the hidden terminal problem in many cases.

The motivation behind MACA was observation that congestion mostly occurrs at the destination rather than at the origin of transmission. MACA has been considerably improved in MACAW, see [BD+94]. MACAW elaborates on the three-way handshake of MACA. The basic RTS-CTS-DATA mechanism has become an RTS-CTS-DS-DATA-ACK mechanism. MACAW also explicitly specifies the back-off mechanism. Both extensions were aimed at improving the long term fairness of MACA.

Although both MACA and MACAW were designed to avoid the hidden terminal problem, the basic RTS-CTS-DATA handshake mechanism does not solve this problem. Figure 2.4 adopted from [FG95] gives an example when the handshake mechanism fails. Assume that node A wants to send a data packet to node B. It starts the three way handshake by sending an RTS packet at time $t1$. Node B replies with a CTS packet at time $t2$. However at the same time $t2$ node C sends an RTS packet to node B. This causes that the two transmissions collide and node C does not receive the CTS packet from B. At time $t3$ node A starts the data transmission to node B. Node C unaware of the CTS packet at time $t2$ will try to resend the RST packet at time $t3$. This control packet collides with the data packet from node A and efficiently corrupts the data. This example demonstrates a need for carrier sensing mechanism.

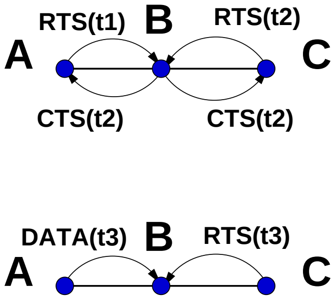

Figure 2.4: With no carrier sensing mechanism or listen-while-talk capability the transmissions of control packets at time $t2$ collide. This results in the corruption of the data packet transmitted at time $t3$ from node $A$.

### 2.3.4 IEEE 802.11 DCF [802.11]

The design of the IEEE 802.11 DCF communication protocol is based on CSMA and MACA/MACAW MAC layer protocols.[3] The protocol adopted the carrier sensing functionality of CSMA and the handshake of MACA/MACAW. Unlike MACA, 802.11 uses an ACK control packet to acknowledge successful transmission of data packets. The three way handshake of MACA thus has become an RTS-CTS-DATA-ACK four way handshake. In addition 802.11 uses a virtual carrier sensing mechanism in the form of a network allocation vector (NAV). NAV represents the time in which the medium will become available. NAV is continually updated through duration values in each control or data packet. A duration value corresponds to the time needed to finish a four way handshake. Other features of 802.11 include (but are not limited to):

1. The time at which nodes are allowed to transmit packets is slotted. Timer synchronization support is part of the IEEE 802.11 standard.

2. The four way handshake is only used if the data packet is greater than a certain predefined threshold. The default threshold is 128 bytes but can be tuned to unique requirements of different ad-hoc networks[4]. There are different retry counters associated with packets of size equal or less than the threshold and with packets greater than the threshold value. These limit the number of times a single packet can be retransmitted.

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[3] We will use IEEE 802.11 DCF and 802.11 interchangeably for simplicity.

[4] In all our simulations we have set this value to 0 bytes, i.e., the four way handshake has always been in use. This was done in order to simplify comparison between simulation experiments with different data packet sizes.

3. A node waits for period defined as Distributed Interframe Space (DIFS) after each successful transmission and before any carrier sensing mechanisms are applied. If the previous frame contained an error the node waits for a period defined as Extended Interframe Space (EIFS). In general, EIFS is much larger than DIFS.

4. 802.11 supports a large set of management capabilities. These include support for privacy services, power management, authentification, etc. See [OP] for details.

The data transmission starts with the originator using both the physical and virtual carrier sensing to determine whether the channel is or will be idle. Upon success a node starts the four way handshake. Otherwise, the binary exponential back-off algorithm will be used to postpone the transmission.

## 2.4 A Short Overview of Routing Protocols

Routing protocols are within the 7-layer OSI classification at the network level. Network level protocols take care of assigning unique addresses to communicating devices, and provide for valid source-destination routes. An example of an address management protocol is IP (Internet Protocol). This protocol incorporates functionality for dealing with network level addressing. Mobile IP [PJ96] is an extension in the direction of mobile networks where addressing is more challenging due to the nomadic nature of such networks.

Routing protocols for ad-hoc wireless networks can be divided into *proactive* and *reactive*. The latter are also known as *on-demand*. Proactive protocols try to gather all information about the network topology independent from the fact whether the information will be needed or not. This is accomplished through periodic broadcasts of routing tables which contain the local view of network topology for a given mobile node. Latency associated with route discovery is minimized since all routes are readily available if needed. The drawback is that the frequent global broadcasts limit the maximum size of ad-hoc networks that can be serviced. This approach requires as many as $O(n^2)$ control messages to guarantee that each node has complete information about the ad-hoc network. Besides communication complexity, most of the routes found are redundant. High memory requirements to store routes to any other node also raise issues such as power consumption. Destination-Sequenced Distance Vector Routing (DSDV) [PB94] is an example of proactive routing.

On-demand routing does not attempt to maintain a global view of the ad-hoc network at each node. Instead route discovery is initiated at each attempt to send a data packet. This is usually done by propagating a route request control packet over the ad-hoc network. Once the route request packet reaches the destination or an intermediate node with a route to the destination, a message in the form of a route reply control packet is sent back to the source. The advantage of this approach is that it eliminates periodic broadcasts and lowers memory requirements through acquisition of routes that are strictly necessary. Examples of on-demand routing are DSR, AODV.

Recently, many researchers advocated use of the Global Positioning System (GPS) in efficient routing. Based on GPS coordinates the authors suggested in LAR scheme 1 and scheme 2 to compute a zone within which the destination node is believed to be located. This approach decreases routing overhead and communication complexity.

We note that a common assumption of ad-hoc networks is that mobile nodes are willing to participate fully in the underlying protocols. Most notably, nodes are expected to forward packets to their neighbors if required so. Hostile behavior such as deliberate discarding or modification of data or control packets, or flooding the networks with unsolicited packets of any kind is not expected.

In this section we review the routing protocols used in our simulations: DSR, AODV, and LAR scheme 1.[5] These protocols all belong with the on-demand group of routing protocols.

### 2.4.1 Dynamic Source Routing Protocol (DSR) [JM96]

The Dynamic Source Routing Protocol (DSR) is a well known on-demand protocol introduced by Johnson and Maltz.

Each node in the network maintains routing information on nodes that are known to it. When a (source) node needs routing information, and this information is not in its node cache or the information has expired, the node initiates a *route discovery*. The node broadcasts a route request packet (RREQ) that contains the address of the source and destination node, and a unique id number. Each intermediate node checks whether it contains route information on the destination node. If not, it appends its address to the route request packet, and resends the packet to its neighbors. Addresses of intermediate nodes are used to ensure that a given node forwards the route request packet only once. The route reply (RREP) is either produced by an in-

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[5] We will use LAR scheme 1 and LAR1 interchangeably.

termediate node, or the destination node. In the former case, the route information of the intermediate node is used, and is appended to the reversed sequence of node addresses from intermediate nodes; in the latter case the route reply is formed completely by the destination node by reversing the sequence of node addresses from intermediate nodes. Once a complete route to the destination is known to the source this information is appended to the data packet.

*Route maintenance* is performed by the protocol if there is a fatal problem, e.g., a route was disconnected by a link failure. In this case the protocol generates a route error packet (RERR). Nodes upstream from the link failure adjust their node caches by removing the route information on routes beyond the failed link.

### 2.4.2 Ad-hoc On-demand Distance Vector Routing (AODV) [PR99]

The Ad-hoc On-demand Distance Vector Routing (AODV), introduced by Perkins and Royer, is an extension of DSDV in the direction of on-demand behavior. DSDV is based on the classical Bellman-Ford routing algorithm. In DSDV each node maintains a table that lists all available destinations, and routes to them in the form of hops count, and a sequence number to distinguish between old and new routes. Each node periodically transmits the routing table to its neighbors which incorporate that information into their own routing table. This basic exchange mechanism can be also triggered by significant changes in the network such as link failures. The routing table updates are sent either as incremental or full. Each node assigns a unique sequence number to the routing updates. The sequence number is used to keep track of new and old routes in node cache. AODV is trying to minimize the number of routing table updates by spawning this mechanism on need-to-know basis. When a source node needs to find a route to a destination it broadcasts a route request packet (RREQ). This packet is forwarded over the network and forwarding nodes store the node address from which the route request came for the first time in their routing tables. This information is later reversed and used by the route reply packet (RREP) to find the route to the source. Similarly to DSDV the route request packets use sequence numbers to ensure loop-free routes. When the route request packet encounters an intermediate node with information on the route to the destination, or the destination node itself, it follows the route used to reach this node and on the way updates routing tables of intermediate nodes with the routing information to the destination. This mechanism can be also initiated by link failure, or other fatal problems.

Similar to DSR, route error messages (RERR) allow AODV to adjust to the highly dynamic environment of ad hoc networks. If there is a link lost due to e.g. node movement, this fact is announced to all the nodes that lie down the path through subsequent forwarding of an RERR packet.

### 2.4.3 Location-Aided Routing (LAR), Scheme 1 [KV98]

Location-Aided Routing (LAR) comes in two flavors: Scheme 1 and Scheme 2. We shortly describe Scheme 1. In this protocol, complexity of routing is reduced by using the physical location information, i.e., by limiting the search to a smaller zone. This information is provided by the Global Positioning System (GPS).

The *expected zone* is produced from the information about the physical whereabouts of the destination node. Assume that the location information and speed at time $t_0$ is known. Then the expected zone is area expected to contain the destination node at time $t_1$. If the location information about the destination node is not known then the expected zone is the complete area of the ad-hoc network. This situation is likely to happen before coordinate information is propagated through the network.

The *request zone* for LAR Scheme 1 is the smallest rectangle that contains the source node and the expected zone. It follows that the size of request zone depends on the speed of the destination node and the time when exact whereabouts of the destination node were recorded for the last time.

Forwarding mechanism for LAR is similar to DSR. The main modification is that route request packets include coordinates of the request zone. Intermediate nodes are allowed to forward the route request only to nodes within the request zone. And in addition this request zone is not modified by forwarding nodes. We refer the reader to [KV98] for details on LAR Scheme 2.

## 2.5 Transport Protocols

Transport protocols offer end-to-end management of connections between two or more participating transceivers. From the point of view of processes that run at different transceivers, these protocols abstract from the detailed knowledge that is necessary to transmit data packets, and focus instead on basic issues connected to Quality of Service. An example is end-to-end acknowledgment of data packets. This service is implemented in TCP (Transmission Control Protocol) through ACK control packets. These ACK packets differ from link level ACK packets, as they are known from the IEEE 802.11 protocol, in the scope. For MAC protocols the scope is a *direct* wireless link, whereas for transport protocols the scope is the chain of wireless links from source to destination that is usually termed as connection.

Besides TCP, many transport protocols have been designed with different requirements in mind; see [IAC99] for a thorough review of transport layer protocols. UDP or User Datagram Protocol is a companion protocol to TCP. UDP does only guarantee very low level of Quality of Service; namely UDP does not guarantee that data packets will be received in the order in which they were originally transmitted, it does not offer any type of end-to-end acknowledgment through ACK packets therefore data packet loss is uncontrolled with possible duplicates, and it is not connection oriented. Not being connection oriented means that there is no permanent connection between source and destination. In general, UDP can be characterized as a protocol where Quality of Service depends on the success rate of protocols at lower levels of the OSI stack. We have used UDP in all experimental performance analysis; the reason was that we did not want to introduce any unnecessary functional complexity that could make performance evaluation harder.

We do not discuss protocols from other layers of the OSI stack. We merely note that throughout the thesis we have used CBR, or Constant Bit Rate data packet sources. A CBR source injects a data packet of a given size at a predefined interval; the injection interval is constant and usually in the order of tenths of second, or seconds.

## 2.6 Mobility Models for Ad Hoc Networks

Mobility models are necessary in order to describe movement of individual nodes, or groups of nodes. Many mobility models have been proposed in the literature. We limit this presentation to models that are closely related to those used in this thesis. We refer the interested reader to [Be01, Ca+02] for a thorough discussion of other mobility models.

The *random mobility model* is introduced in [ZD97]. The position of each transceiver at time $(t + 1)$ is a random displacement from its position at time $t$. This implies in essence that the speed and direction are both random variables that have no correlation with their current values. As discussed in the literature, this model tends to produce unrealistic choppy motion with sharp turns, sudden stops, etc.

In [BCSW98] the authors study an extention to the random mobility model. In this model the speed is held constant but direction is a random uniform variable over a specific range. In Ko and Vaidya's model [KV98], the transceivers can move along a pre-specified set of paths made up of segments. The segment lengths are exponentially distributed and the direction of each segment is chosen uniformly at random. Speed is also assumed to be uniformly distributed within a window of size $s$ around the current speed $v$. The model of Das et al [DCY00] selects a sequence of sub-destinations in an on-line fashion. When at a given sub-destination, the transceiver selects its next sub-destination and speed. It then travels to this sub-destination along a straight line connecting the current and the next sub-destination. This model can be seen to be an extension of the model of Basagni et al [BCSW98].

A very popular mobility model is the *random waypoint mobility model* discussed in [JM96]. This model specifies a sequence of pause and motion periods for each transceiver. During the motion period, a randomly chosen sub-destination is reached using a constant speed chosen uniformly at random between a minimum and maximum allowable limit. A recent paper [Be01] incorporates additional features into the random waypoint model with a view to making the model more realistic. In that work, speeds are limited to a few that are characteristic of automobiles. Further, the speed and direction are coupled with a minimum turn radius assuming a particular coefficient of static friction and a flat road. For other variants of the random waypoint model, see [Ha97, LH99].

In all the above discussed mobility models only the movement of individual transceivers is taken into account. Somewhat different are *group mobility models*. In these models, the set of transceivers is partitioned into groups. The movements of individual transceivers within a group are usually strongly correlated. Such models aim to provide realistic mobility data when ad hoc networks are used in an emergency response or a military setting. Basic models of this type proposed in the literature are *Exponentially Correlated Random Mobility* (ECRM) and *Reference Point Group Mobility* (RPGM).

The first is model is studied in [BH+98, HG+99, RS98]. Using this model, one can control the movement of a group independently of the movement of the other groups and the nodes within the group. At each step, a group undergoes a randomly chosen displacement along a randomly chosen direction.

More advanced is the second model proposed in [HG+99]. By an appropriate setting of the parameters, RPGM can mimic many other known mobility models. An informal description of this model is as follows. The transceivers are partitioned into a specified number of groups. Each group has a logical center which can be assigned a specific movement model. Transceivers within a group move together as a group within an annulus around the group center, with a small amount of random movement. Such movements can be readily implemented (for instance) by maintaining pre-specified lower and upper bounds on the distance of each point from its group center.

## 2.7 Simulation Tools

In this section we review two simulation tools, GloMoSim and NS2, that are free-to-use for educational purposes. Other tools that are commercially available are Qualnet [QN], and OPNET [ON]. Qualnet is a commercial version of GloMoSim. A survey of other simulation tool is in [Ce]. Here we concentrate on NS2 [Ba+99] and GloMoSim [BT+99].

### 2.7.1 NS2

NS2 is a complex simulation tool being developed by UC Berkeley, University of Southern California/ISI, the Lawrence Berkeley National Laboratory, and Xerox PARC. It is distributed with the source code, and compiles under various UNIX platforms, including Linux. A Windows(tm) version is also available.

We shortly summarize main parameters of NS2:

- User interface of NS2 is based on OTcl (Object Tool Command Language) [Otcl], an object extension to Tcl. The simulator itself is written in C++.

- Creation and deletion of all network entities (mobile nodes, links, traffic sources, tracing objects) is done directly from command line, or a batch file which is interpreted by the OTcl interpreter.

- NS2 package also contains NAM (Network Animator) which allows animated display of the trace file created during a simulation. For wireless networks, however, NAM can only display node movement.

- Modification or addition of a protocol is done in C++. This process is rather complicated as NS2 links the OTcl interpreter, and the designer has to have a profound knowledge of the OTcl interpreter internals.

- NS2 supports all basic routing protocols (DSR, DSDV, Tora), and MAC layer protocols (CSMA/CD, 802.11, Unslotted Aloha).

- NS2 is somewhat slower than GloMoSim; however, NS2 does not make use of any hierarchical partitioning, or parallel execution. PDNS [PDNS] is a parallel/distributed extension to NS2.

### 2.7.2 GloMoSim

GloMoSim is being developed by University of California Los Angeles. Unlike NS2, GloMoSim is a tool purely dedicated to wireless networks. It is based on Parsec [Pars], an extension to the C programming language for discrete event simulation models.

GloMoSim supports a variety of routing protocols (PR99, Bellman-Ford, DSR, Fisheye [PGC00], LAR scheme 1 [KV98], ODMRP [LSG00], WRP [MG96]), and MAC layer protocols (CSMA, IEEE 802.11 (DCF) and MACA).

Modification and addition of protocols is done in PARSEC. Network entities are created and configured in a simple text file. GloMoSim supports hierarchical partitioning of networks what has a profound influence on real time needed for simulations. According to [BT+99], a simulation comprising up to 10,000 nodes has been done.

In our experiments we used GloMoSim mainly due to its easier configurationability, and better performance. Other advantage was a higher number of wireless protocols for ad hoc networks.

# Chapter 3

# Analysis of Experimental Data

Depending on whether a variable (parameter) constitutes an input or output to a system we divide parameters into two basic groups: independent variables and dependent variables (or performance measures), respectively. The next few sections summarize relevant dependent and independent variables used in this thesis. Additionally, we review and explain basic statistical methods and graph theoretic concepts that we utilize.

## 3.1 Independent (Input) Variables

Depending on the research goal, we used in our experiments a subset of the following independent variables. For obvious reasons independent variables such as Node's speed are redundant for static ad hoc networks, and similarly, experiments designed to study let us say the influence of injection rate on latency of data packets might omit the routing protocol as one of the input parameters.

The independent (input) variables are (i) Routing protocol, (ii) MAC protocol, (iii) Nodal speed, (iv) Injection interval (rate)[1] for the data packets and (v) Network topology (dynamically changing over time).

## 3.2 Measures of Performance

The following five pieces of information (also called the dependent variable) were collected: (i) Latency: Average end to end delay for each packet as measured in seconds, (ii) Ratio of number of packets received to number of packets injected in percentage

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[1] We will use the terms *injection interval* and *injection rate* interchangeably. Injection rate is the inverse to injection interval.

points, (iii) Throughput in bits/second (bps), (iv) Adjusted number of control packets at MAC layer level per 1,000 data packets[2] and their spatial distribution, (v) Adjusted number of control packets at routing layer level per 1,000 data packets and their spatial distribution, (vi) Fairness: Assignment of resources to each of the connections.

Average number of packets received and latency is simply measured as arithmetic mean over $u$ independent simulation runs. The total number of samples per simulation run was proportional to the number of connections. We compute (long term) fairness ratio $q$ for each simulation run as allocation between the connection with the highest number of packets received and the sum of packets received for the remaining connections. More formally, let $n$ denote the number of connections, let $p_i$ be the number of packets received by connection $i$, let $p_{max} = max\{p_1, \ldots, p_n\}$, and let $k$ denote a connection such that $p_k = p_{max}$ then $q = \frac{p_{max} \times (n-1)}{\sum_{j \neq k} p_j}$. It follows that any deviation from $q = 1$ represents an inequitable allocation of resources. For $n = 2$ this ratio reduces to $p_1/p_2$ or $p_2/p1$. Note that for our simulations there has never been a case that $p_{max} = 0$ and $q$ was set to $100.0$ in the rare cases when the denominator equaled zero. Moreover, connections never shared sinks or sources, i.e., $\{source_1, \ldots, source_n\} \cap \{sink_1, \ldots, sink_n\} = \emptyset$. Fairness results in the form of graphs[3] get further adjusted. In case that $q > 6.0$ we set $q = 6.0$ to *emphasize smaller values* and subsequently this interval is normalized into $\langle 1, 2 \rangle$ interval. Finally, average fairness for $u$ simulation runs is $\frac{1}{u} \sum_{i=1}^{u} q_i$ where $q_i$ is the adjusted and normalized fairness for the $i$th simulation run. In a few cases for $n = 2$ we have plotted the average fairness so that the resources assigned to Connection 1 and Connection 2 could be uniquely identified. The result are graphs where $q$ was normalized into $\langle 1, 2 \rangle$ interval if $p_1 \leq p_2$ and into $\langle 0, 1 \rangle$ interval otherwise. Departure from $q = 1$ towards $2$ or $0$ means an inequitable assignment of resources with respect to Connection 1 or 2.

Alternatively, we use for the computation of (long term) fairness $p$ the Jain's Fairness Index [Ja91].[4] Suppose that $x_i$ is the number of data packets received by connection $i$ and $n$ is the number of connections. $p$ is then computed as $\frac{(\sum_{i=1}^{n} x'_i)^2}{n \sum_{i=1}^{n} x'^2_i}$. $x'_i$ is computed as $\frac{x_i}{\bar{x}_i}$ where $\bar{x}_i$ is the number of packets that should have been received according to user provided "fair" packet allocation. In all our computation we have as-

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[2] We adjusted the number of control packets at the MAC layer level to the number of data packets injected. This means that the number of control packets was divided by a factor of two at the injection rate of 0.05 second, by a factor of four at the injection rate of 0.025 second, and by a factor of eight at the injection rate of 0.0125 second.

[3] For statistical analysis the ratio has not been further adjusted or modified.

[4] When we use the Jain's fairness index we explicitely state so; in all other cases we use the fairness index defined just above.

sumed that such a fair allocation would be an equal number of data packets received for each connection. Such an allocation arguably disregards different levels of contention that each connection is facing due to the position of respective source-sink pair but is easy to compute, especially, for non-mobile networks. $p$ shows fairness of allocation on a $\langle 0.0, 1.0\rangle$ scale where $0.0$ and $1.0$ stand for unfair and fair, respectively. Average fairness measure is computed as arithmetic mean over $u$ independent simulation runs.

The distributions of MAC or routing layer control packets are computed as dependencies between a given number of control packets and the number of nodes using the given number of control packets for establishing access to the medium or engaging in route acquisition procedures. The $y$-axis shows the number of nodes in absolute terms.

**Spatial distribution of MAC and routing layer control packets.** Spatial distributions uniquely tie a given average number of control packets used to the geographical position of a node. Obviously, spatial distributions can only be computed for static networks. The total of MAC layer control packets for a node is computed as a sum of control packets sent out, i.e. for 802.11 a sum of RTS, CTS and ACK packets, and for MACA a sum of RTS and CTS packets. The total of routing layer control packets for AODV, DSR, and LAR scheme 1 is computed as a sum of RREQs, RREPs, and RERRs. The average number of control packets for a node is computed as an arithmetic mean over $u$ simulation runs. This number gets then adjusted to the number of data packets injected; i.e. if there are 2,000 data packets injected the average per node number of control packets is normalized by a factor of 2. Similarly for other injections rates; for 4,000 data packets it is normalized by a factor of 4, and for 8,000 data packets it is normalized by a factor of 8. This is done in order to make comparison over scenarios with different injection rate easier.

## 3.3 Characterizing Interaction of Independent Variables

In the introduction we have stated that studying interaction of input parameters is central to this thesis. Of particular interest is of course the interaction between the MAC and routing protocols, however, we do not limit ourselves to protocol interaction.

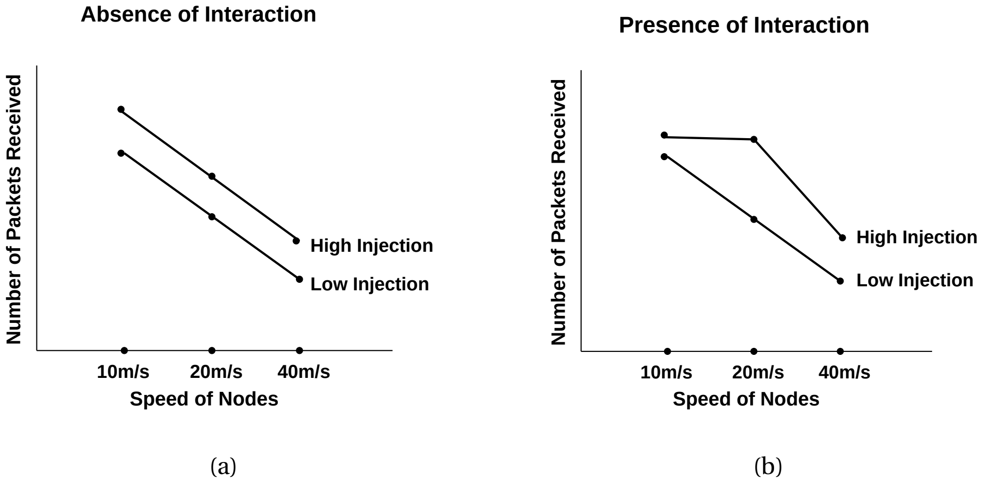

Figure 3.1: Interaction levels between Injection Rate and Speed of Nodes

### 3.3.1 Variable Interaction

Statistically, interaction between two factors is said to exist when effect of a factor on the response variable can be modified by another factor in a significant way. Alternatively, in the presence of interaction, the mean differences between the levels of one factor are not constant across levels of the other factor. We illustrate this by a simple example. Suppose we want to know if injection rate and speed of nodes interact in affecting the number of packets received. The dependent or response variable is the *number of packets received.* The independent variables (factors) are *injection rate and speed of nodes.* The goal is to test if there is interaction between injection rate and speed of nodes.

Our main concern is *not* if the number of packets received differs between different speed levels or whether the number of packets received differs between low and high injection rates. Our main concern is to determine if one injection rate performs relatively better (in terms of number of packets received) than the other for different speed levels. In other words, is there interaction between injection rate and the speed of nodes? If the difference between the mean number of packets received is the same for all speed levels for both injection rates, there is no interaction between injection rate and nodes' speed. Figure 3.1(a) shows absence of interaction between the injection rate and speed of nodes.

However, if the mean difference in number of packets received for different speed

| Speed | Low Inj | High Inj | Diff in High-Low Inj. |
|---|---|---|---|
| Mean Number of Packets Recd. | | | |
| 10m/s | 28.17 | 12.52 | 15.65 |
| 20m/s | 18.51 | 8.39 | 10.12 |
| 40m/s | 11.12 | 4.74 | 6.38 |
| Mean Value of Latency | | | |
| 10m/s | 0.61 | 0.81 | 0.20 |
| 20m/s | 1.21 | 1.28 | 0.07 |
| 40m/s | 2.02 | 1.91 | 0.11 |

Table 3.1: This table shows the mean value of the response variable for high-low injection rates and different speed of the nodes. The interaction is found to be significant in case of response variable **number of packets received** but insignificant in case of **latency**.

levels is significantly different for high injection rates versus low injection rate, an interaction between injection rate and speed of nodes is said to exist. Figure 3.1(b) shows the presence of interaction between the injection rate and speed of nodes. Table 3.1 illustrates the concept via the data collected from our simulations. The first three rows of the table show that the difference between the mean value of packets received at high and low injection rates is very different for the three speed levels. The $F$-test which is explained later finds this difference to be statistically significant and hence we conclude that speed and injection rates interact when number of packets is used as the response variable. In other words, one cannot explain the variation in number of packets by considering each of these parameters individually; some of the variation is due to the combination of the variables. The second part of Table 3.1 shows the mean value of latency. The difference in the mean value of latency at high and low injection rates is insignificant according to the $F$-test at different speed levels which implies that there is no interaction between speed and injection rates when latency is used as the response variable.

### 3.3.2 Algorithmic Interaction

In the context of communication networks, we also have another kind of interaction – algorithmic interaction. Such an interaction exists between two protocols (algorithms) operating at individual transceiver nodes of a communication network. Here we use the word *interaction* to mean that the behavior (semantics) of a protocol at a given layer in the protocol stack varies significantly due to another protocol at higher or lower level, or at the same level, in the protocol stack. Note that in contrast, speed and injection rates are variables and the value of one remains changed when we change the value of the other. Algorithmic interaction can be more subtle. First, the change in a response variable now is a result of the complicated causal dependencies between the two protocols $A$ and $B$ that mutually affect each other. Second, some of the effects of this interaction might be measurable while other effects might not be directly measurable. For instance, in case of routing protocols although the routing paths need not have common nodes, they might cause interaction between two MAC protocols operating at distinct transceivers that are not neighbors as a result of long range effects. These effects can typically be produced through intermediate sequence of routing paths. To make matters more complicated a routing protocol at a given node interacts with a routing protocol at another node. Thus we have interaction between: (i) two routing/MAC protocols running at two distinct and not necessarily adjacent nodes and (ii) a MAC and a routing protocol running at the same or distinct nodes. We illustrate this via our simulation experiments in the following chapters.

### 3.3.3 Analysis of Variance and F-test

Analysis of Variance (ANOVA) [Kl75] is a statistical tool to analyze experimental data under the so-called factorial design. Statisticians use the term factor for what is usually understood as input parameter by computer scientists. We will use the name factor in this short presentation on ANOVA.

In a factorial design each factor takes on several discrete value levels. These levels can represent facts such as “queue $q$ is full” or “queue $q$ is not full”. In this case we would have a factor with two levels; the two different levels would have to be represented by *dummy* values. When quantitative factors are used we can proceed further without any additional transformation; a design with both qualitative and quantitative values is also possible. If factor $f_i$ has $L_i$ levels then the total number of combination of levels can be expressed as $L_1 L_2 ... L_k$, where $i = 1, ..., k$; $k$ is the total number of factors. A factorial design with 4 factors each with 3 levels is often called a $3 \times 3 \times 3 \times 3$ or $3^4$ design.

Let us consider a simple factorial design with two factors each with $L_i$ or $L_j$ levels, respectively. Let $y_{ijn}$ denote $n$-th observation of a response (output) variable when factor 1 is at $i$-th level and factor 2 is at $j$-th level; the expected value of $y_{ijn}$ is denoted $\eta_{ij}$. In the design of experiments is then assumed:

$$y_{ijn} = \eta_{ij} + \varepsilon_{ijn} \qquad (i = 1, 2, ..., L_i; j = 1, 2, ..., L_j; n = 1, 2, ..., u)$$

where $u$ is again the number of replicates or simulation runs, $\varepsilon_{ijn}$ is the experimental, systematic error that includes noise. $\varepsilon_{ijn}$ is assumed to be normally and independently distributed. If we assume that no interaction between variables exists then the mean value of $y_{ijn}$ can be expressed as:

$$E(y_{ijn}) = \eta_{ij} = \mu + \alpha_i^1 + \alpha_j^2$$

where $\mu$ is the grand mean, $\alpha_i^1$ is the main effect of factor 1 at level $i$, and $\alpha_j^2$ is the main effect of factor 2 at level $j$. This situation corresponds to the parallel response curves as depicted in Figure 3.1(a). When an interaction between two factors exists the mean value of $y_{ijn}$ can be expressed as:

$$E(y_{ijn}) = \eta_{ij} = \mu + \alpha_i^1 + \alpha_j^2 + \alpha_{ij}^{1,2}$$

where $\alpha_{ij}^{1,2}$ is the effect of interaction between factors 1 and 2, at $i$-th and $j$-th level, respectively. Figure 3.1(b) depicts the situation when the interaction $\alpha_{ij}^{1,2}$ is significant. The grand mean $\mu$ can be expressed as:[5]

$$\mu = \frac{\sum_i \sum_j \eta_{ij}}{L_i L_j} = \eta_{..}$$

Respective effects $\alpha_i^1$, $\alpha_j^2$, $\alpha_{ij}^{1,2}$ can be then expressed as:

$$\alpha_i^1 = \frac{\sum_j \eta_{ij}}{L_j} - \mu = \eta_{i.} - \eta_{..}$$

$$\alpha_j^2 = \frac{\sum_i \eta_{ij}}{L_i} - \mu = \eta_{.j} - \eta_{..}$$

$$\alpha_{ij}^{1,2} = \eta_{ij} - \frac{\sum_j \eta_{ij}}{L_j} - \frac{\sum_i \eta_{ij}}{L_i} + \mu = \eta_{ij} - \eta_{i.} - \eta_{.j} + \eta_{..}$$

Analysis of Variance is finalized by computation of the (residual) sum of squares (SS) within and between levels, degrees of freedom (DF), mean square (MS) and the subsequent F-test. The sum of squares, degrees of freedom, and mean square *between levels* for a factorial design with a single factor and $L_i$ levels [6] can be expressed as: [7]

$$SS = \sum_i \sum_n (y_{i.} - y_{..})^2, \quad DF = L_i - 1, \quad MS = \frac{SS}{DF}$$

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[5] $\sum_i x_i = \sum_{i=1}^k x_i$, i.e. the sum of $x_i$ over $k$ samples.

[6] The model in this case would be $E(y_{in}) = \mu + \alpha_i$.

[7] The semantics of e.g. $y_{i.}$ is $\frac{\sum_n y_{in}}{u}$.

Similarly, the sum of squares, degrees of freedom, and mean square *within levels* for a factorial design with a single factor and $L_i$ levels can be expressed as:

$$SS = \sum_i \sum_n (y_{in} - y_{i.})^2, \quad DF = u(L_i - 1), \quad MS = \frac{SS}{DF}$$

The F-test statistic is then:

$$F_{L_i-1,u(L_i-1)} = \frac{MS_{\,between\ levels}}{MS_{\,within\ levels}}$$

If the factor has significant influence on the response variable then the numerator tends to grow and this makes the statistic significant. On the contrary, if the factor has no influence the statistic converges to $1.0$. F-test statistic for degrees of freedom $L_i - 1$ and $u(L_i - 1)$, and various levels of significance can be found precomputed in many statistics textbooks. This statistic can be extended to cases with arbitrarily many factors and levels but we omit this step as it is a rather straightforward extension. For other details on ANOVA and F-test we recommend the interested reader to consult [Kl75] or any other basic textbook on analysis of experimental data.

In Chapter 5 we show how this statistic coupled with a method for eliminating non-significant main or interaction effects can be used for analysis of ad hoc networks.

## 3.4 Graph theoretic measures

### 3.4.1 The model

Our setting consists of $n$ points in the plane, denoted by set $V$. Each point represents a sensor node. Given a radius $R$, $D_u$ denotes the disk of radius $R$ centered at $u \in V$. The (directed) interference graph $G(V, E)$ induced by these points is the following: the points in $V$ form the vertex set of $G$. Edge $(u, v)$ is in $E$ if $v \in D_u$; this is the disk graph model of sensor networks. When all the nodes have the same radius, the result is a unit disk graph for the sensor network, and we can think of these graphs as undirected. The radius associated with a sensor denotes the region of influence where the sensor's radio signal can be received. Notice that our interference graph model is quite simple: it does not account for occlusions (e.g. buildings, mountains, etc.), which reduce the range for a given transmission power level.

### 3.4.2 The measures

Our experimental methodology for comparing the various ad hoc networks is based on the values of certain parameters of the graphs generated by those network (or their models). Below, we provide formal definitions of those graph theoretic parameters. Any reader interested in more complete descriptions of these metrics or others should consult one of the references on introductory or advanced graph analysis [We01, CL86, Wa99, AB02].

The degree (out-degree) $\delta_v$ of a vertex (node) $v$ in graph $G(V, E)$ is the number of edges incident on $v$. The neighborhood $N(v)$ of a vertex $v$ is the set of vertices connected by an edge to $v$. Let $\xi_v = |\{(w, w') : w, w' \in N(v)\}|$ denote the number of edges that exist among the neighbors of $v$ and let $\xi_v^{\max} = \delta_v(\delta_v - 1)/2$ denote the maximum possible number of such edges. The **clustering coefficient** $c_v$ of a vertex $v$ is defined as the ratio $\xi_v/\xi_v^{\max}$. A (simple) path $P$ from $u$ to $v$ is a sequence of edges $e_1, \ldots, e_k$, where $e_i, e_{i+1}$ have a common end point, $u$ and $v$ are end points of $e_1$ and $e_k$ respectively, and no vertices are repeated in $P$; the length of $P$ is $k$, the number of edges in it. The distance $d(u, v)$ between nodes $u$ and $v$ in $G$ is the length of a shortest path between $u$ and $v$.

The **diameter** of $G$ is given by $\max\{d(u, v) : u, v \in V\}$. The **radius** of $G$ is defined by $\min\{d(u, v) : u, v \in V\}$. For sets $A, B \subseteq V$, the distance $d(A, B)$ between $A$ and $B$ is defined as $\min\{d(u, v) : u \in A, v \in B\}$. We can extend the definitions of radius and diameter to graphs that are not necessarily connected as follows. The radius of a graph $G$ can be defined as the minimum value among the radii of all the connected components in $G$. Similarly, the diameter of a graph $G$ can be defined as the maximum value among the diameters of all the connected components in $G$.

For any two edges $e_1 = (u_1, v_1)$ and $e_2 = (u_2, v_2)$, the distance $d(e_1, e_2)$ between them is defined as the minimum distance between any pair of their vertices; that is, $d(e_1, e_2) = \min\{d(u_1, u_2), d(u_1, v_2), d(v_1, u_1), d(v_1, v_2)\}$. A subset $M \subseteq E$ of the edges is said to be a **distance-2 matching** if for any $e_1, e_2 \in M$, $d(e_1, e_2) \geq 2$.

Occasionally, distribution of the above defined measures for the underlying ad hoc network were computed. In case of the distribution of node degrees, the resulting graphs show a dependence between a given node degree and its occurrence for $r$ nodes in absolute terms. For other measures, distributions were computed analogously.

# Chapter 4

# Characterizing Performance of Ad-hoc Mobile Networks

To illustrate the complexity of ad hoc networks with respect to their expected performance we have designed three basic scenarios. These are to demonstrate the effect of classical wireless communications and graph theoretic properties on the performance of ad hoc networks. The setting are arguably very simple and were chosen in order to effectively reason about an issue. The goal is to see how (i) the network topology, (ii) the traffic injection interval, (iii) the spatial location of the source destination pairs, (iv) the combination of MAC, routing protocol and other input parameters all affect the performance of the protocols. Unlike most of the earlier studies, our scenarios were designed to understand the performance of the MAC protocols at the "network level" rather than at "link level", i.e. most of our scenarios consisted of source sink pairs that were at least 2 links apart. We briefly describe the scenarios below; additional details for each scenario are given in the section describing the results for that scenario.

## 4.1 Scenarios Description and Motivation

The three scenarios are:

1. **Effect of General Hidden terminal.** This scenario is motivated by the well known hidden terminal problem. It has been well documented that hidden terminal configuration causes CSMA to assign inequitable resources to connections. 802.11 overcomes this problem using the RTS/CTS/ACK mechanism. We

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This chapter is a result of joint work with Chris Barrett, Achla Marathe, and Madhav Marathe. See [BDM, BD+02a, BD+04a] for reference.

wanted to see if the random delays introduced by the network can mitigate the hidden terminal to some extent. We call this the *generalized hidden terminal scenario.*

2. **Effect of Network Connectivity.** In this scenario, our goal was to investigate the effect of network connectivity on MAC layer protocols. We consider successively denser network keeping the set of nodes constant. Another motivation for this scenario was to provide insights into optimal power settings for power aware MAC protocols. Intuitively, increasing the network density has two conflicting effects. On one hand, increasing the power range implies that paths between source destination pair tend to be shorter (the packets make faster progress towards their destination); this reduces the number of collisions that a packet might participate in. On the other hand, the network becomes dense (the node and edge connectivity); this implies that one is likely to encounter more spatial interference from adjacent radios. The second issue has been studied analytically by a number of authors for CSMA and ALOHA like protocols, most notable by Nelson, Kleinrock, Takagi and Tobagi [NK83, NK84, TK84, KT75, KT75a]. But no such analytical results are known for 802.11; moreover, the analysis in [NK83, NK84, TK84, KT75, KT75a] is done only on randomly distributed set of points.

3. **Effect of Separator size and sparsity.** In the final scenario, we aim to understand the effect of network sparsity and separator size on the performance of MAC protocols. Intuitively, it is obvious, that smaller separator imply higher probability of collisions and thus reduced performance. Again, as mentioned earlier, our broad goal is to look for network level effects as opposed to link level effects. The importance of separators has been well established in the study of circuit switched networks.

## 4.2 General results, Conclusions and Implications

A qualitative explanation of many of the results can be given. For instance, CSMA has low overhead since it does not have the RTS/CTS control mechanism; this makes collisions more likely but on the other hand allows for lower latency (at least for the connections that are given access) and adequate throughput for the connections that are scheduled. 802.11 has RTS/CTS mechanism; the overhead that such a control mechanism causes for small packets is evident from the degradation of 802.11 for small packet sizes. MACA appears to be probably the worst overall: it has high latency and inequitable resource allocation. The main conclusions of our study include the following:

1. The network connectivity, spatial location of connections, injection rate and packet size all play a crucial role in determining the performance of a media access protocol. While, the effect of last two parameters has been studied earlier to some extent [WS+97, BD+94], the effect of first two parameters has not been extensively studied to the best of our knowledge.

2. In general the following broad conclusions can be drawn: (i) higher injection rates, (ii) smaller packets and (iii) increased density of network affect the protocol performance adversely. Section 4.2 discusses this in more detail and provides qualitative reasons for this.

3. *No single protocol dominated the other protocols across various measures of efficiency.* This motivates the design of a new class of parameterized protocols that adapt to changes in the network connectivity and loads. We refer to these class of protocols as *parameterized adaptive efficient protocols* (PARADYCE).

4. All the protocols do an inequitable assignment of channel resources for high injection rate. We have deliberately refrained from calling this unfair: what does it mean to be fair is not obvious and has been subject of a extensive research in the past in Economics and Social Science.

   At least two notions of equitable resource allocations can be formulated: one in which we see how the protocol does in a particular run and one in which measure the relative resources assigned to each connections over a given set of runs. Using the other measure CSMA and MACA appear to have a more equitable resource assignment.

   Many researchers have in the past designed specific algorithms and argued (heuristically or formally) about the fairness of protocols. We believe that the topic deserves more attention. For instance [VBG99] propose distributed fair scheduling algorithm. The essential idea is to assign resources to each flow in proportion to the amount that is backlogged for that particular flow. In [NK+99], the authors have discussed per-node versus per-flow fairness. We merely point out that, each such proposed mechanism can have subtle side effects; the goal is merely to point out undertaking a more in-depth study.[1]

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[1] A very simple example will make the point. Consider for instance an adversary, who wishes to slow

5. The performance of MAC layer protocols is affected by the routes chosen by the routing layer. Not surprisingly, when two routes share many common nodes, their performance tends to be worse than in scenarios when the routes do not share many common nodes. More interestingly, MAC layer performance deteriorates even when routes do not intersect but come close enough. This result has an important implication in the context of making the routing protocols adaptive. Specifically, recent routing protocols have attempted to modify the routes after sensing the load on individual links (i.e. they are adaptive). But as we show, in some cases the effect of one path on the other is somewhat indirect. This makes the task of adaptive routing protocols complicated.

6. The performance of protocols varies significantly from one run to another with regards to the resources assigned to connections. CSMA (and also other protocols to some extent) tends to inequitably assign resources to the two connections. One of the reasons for this behavior is interaction of the MAC layer protocol with the routing protocol with subsequent impact onto the long term fairness.

7. No single MAC layer protocol could be termed as *dominating* in terms of performance. Moreover, different routing protocols when combined with different MAC layer protocols yielded varying performances. Again there appears to be no single routing protocol/MAC protocol combination that yields best performance as measured over the entire range of parameters and scenarios.

## 4.3 Experimental Setup

The experimental set up consists of a description of (i) the scenarios used, (ii) simulation setup, (iii) input and output variables. Simulation parameters are summarized in Figure 4.1.

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down a network without any goal of transmitting useful information. Furthermore, imagine the adversary to have control over the protocol stack. The adversary can easily compromise the network's good throughput by not implementing a voluntary back off scheme and thus flooding the intermediate nodes. If per flow fairness is implemented this will end up giving unusually high resources to this connections making the other connections have low throughput.

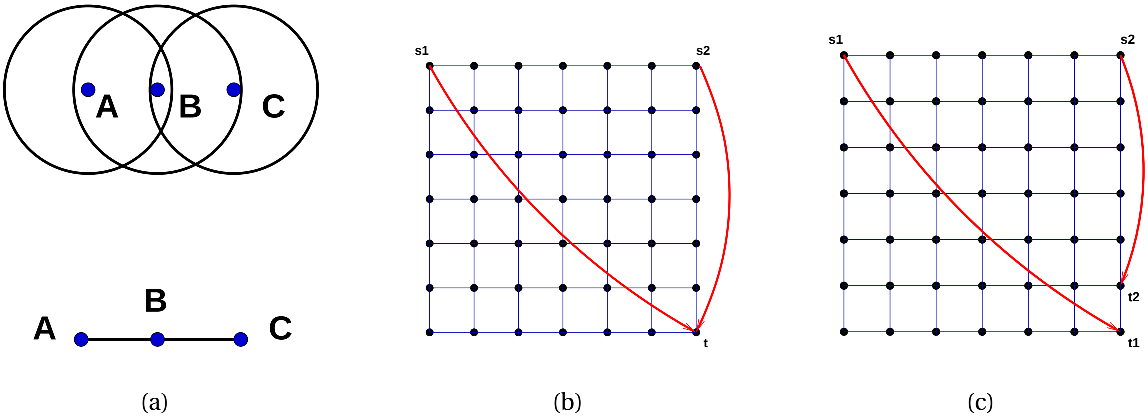
1. **Network Topology:** We describe the experiment specific topologies in respective sections.
2. **Number of connections:** We use two connections.
3. **MAC protocol:** IEEE 802.11 DCF, CSMA, MACA.
4. **Routing protocol:** AODV.
5. The initial packet size was 256 bytes, the number of packets per connection was 2,000, and the injection interval was 0.05 second. Each time the injection rate was increased by a factor of 2, we also reduced the packet size by a factor of 2 but increased the number of packets by a factor of 2. For example, if the injection interval was halved to 0.025 seconds then the new packet size was 128 bytes and the new number of packets was 4,000. This allowed us to keep the injection at input nodes constant in terms of bits per second. In the following text we refer to the injection rates 0.05, 0.025 and 0.0125 second as **Low**, **Medium** and **High** (L, M, H in figures), respectively.
6. Radio propagation model details are as follows: (i) Propagation path-loss model: two ray, (ii) Channel bandwidth: 1 Mb, (iii) Channel frequency: 2.4 GHz, (iv) Topography: Line-of-sight, (v) Radio type: Accnoise, (vi) Network protocol: IP, (vii) Connection type: UDP, (viii) In-band data and control, i.e., a single channel for both data and control packets.
7. **Simulator used:** GloMoSim 2.03.
8. Simulation runs: **30** with independent simulation seeds for any combination of input parameters.
9. The transmission range of transceiver was 125, 250, or 500 meters. In most cases the 250-meter range was used.
10. The simulation time was **100** seconds.
11. Hardware used in all cases was a PC running Linux (Mandrake or SuSE).
12. The following information was collected to measure the performance: (i) Average end to end delay for each packet as measured in seconds (latency), (ii) Total number of packets received, (iii) Throughput in bits/second, (iv) Total number of control packets at the MAC and routing layer level and (v) Spatial distribution of MAC and routing control packets.

Figure 4.1: Summary of Simulation Setup

## 4.4 Detailed Setup, Results and Analysis

### 4.4.1 Generalized Hidden Terminal Effect

We now discuss the experimental setup for the first experiment: effect of the generalized hidden terminal. The experimental design consists of three sub-scenarios and is depicted in Figure 4.2(a–c). Figure 4.2(a) depicts the base case; the classical hidden terminal setting. We have two connections: one from $A$ to $B$ and the other from $C$ to $B$. The setting is such that $B$ can hear both $A$ and $C$ but $A$ and $C$ cannot hear each other. Figure 4.2(b) depicts the first form of generalized hidden terminal setting. We have a grid-squared network and two connections shown by arrows from source to the destination. The arrows represent the rough flight path of packets: the path is not deterministic in general. As in the hidden terminal scenario, the connections have the same destination but different sources. Moreover, in contrast to the classical scenarios, the shortest path from source to destination for both connections is 3. This is the only difference. The rationale is the following: although the destinations are the same, the packets are likely to encounter random delays as they traverse the network and hence it is likely that the inequitable resource assignment problem for CSMA is mitigated to some degree. Figure 4.2(c) considers another variant. Here the destinations are not the same but very closely located spatially. Again, one would expect the inequitable resource assignment problem is mitigated to a degree.



(a) (b) (c)

Figure 4.2: Distinct sources. (a) Three-node hidden terminal, $B$ can hear $A$ and $C$, but $A$ and $C$ cannot hear each other; (b) Identical sinks; (c) Closely positioned sinks. For (b) and (c) the grid unit is 100 meters and the radio radius of each node is 250 meters.

**Broad Conclusions:** Results are shown in Figures 4.3, through 4.6, and in Tables 4.1

| Protocol | 802.11 | 802.11 | CSMA | CSMA | MACA | MACA |
|---|---|---|---|---|---|---|
| Case | a | b | a | b | a | b |
| **Connection 1** | | | | | | |
| Injection interval [s] | | | | | | |
| 0.1 | 0.0097 | 0.0105 | 0.0037 | 0.0083 | 0.0258 | 0.0095 |
| 0.05 | 0.0067 | 0.0065 | 0.0028 | 0.0042 | 0.0218 | 0.0055 |
| 0.025 | 0.0051 | 0.0043 | 0.0024 | 0.0022 | 0.0200 | 0.0035 |
| 0.0125 | 0.0032 | 0.0032 | 0.0020 | 0.0011 | 0.0610 | 0.0610 |
| **Connection 2** | | | | | | |
| Injection interval [s] | | | | | | |
| 0.1 | 0.0097 | 0.0055 | 0.0019 | 0.0046 | 0.0262 | 0.0057 |
| 0.05 | 0.0067 | 0.0034 | 0.0016 | 0.0026 | 0.0217 | 0.0035 |
| 0.025 | 0.0051 | 0.0025 | 0.0015 | 0.0016 | 0.0200 | 0.0025 |
| 0.0125 | 0.0021 | 0.0021 | 0.0016 | 0.0010 | 0.0578 | 0.0578 |

Table 4.1: Three-node hidden terminal – latency (average latency over 30 simulation runs). Case (a) The connections started at the same time. Case (b) The connections started with a difference of 1ms. Results correspond to Figure 4.2(a).

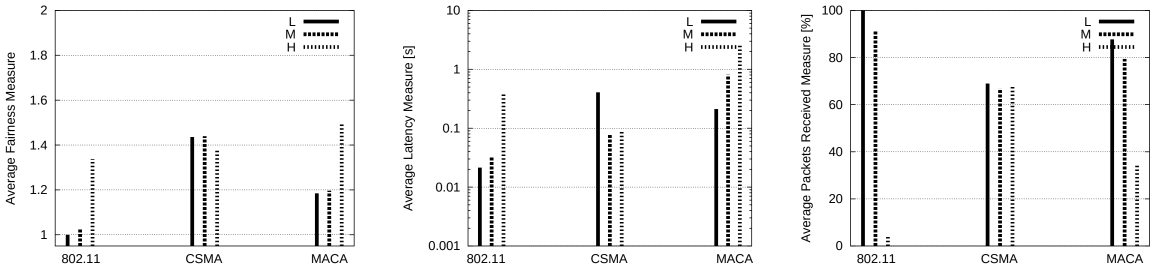


Figure 4.3: Distinct sources, identical sinks. Average fairness, latency and ratio of packets received. The graphs shows dependency of these parameters on injection rate (L = low injection rate, M = medium injection rate, H = high injection rate). These results correspond to scenario in Figure 4.2(b).

| Protocol | 802.11 | 802.11 | CSMA | CSMA | MACA | MACA |
|---|---|---|---|---|---|---|
| Case | a | b | a | b | a | b |
| **Connection 1** | | | | | | |
| Injection interval [s] | | | | | | |
| 0.1 | 999 | 999 | 0 | 998 | 494 | 998 |
| 0.05 | 1998 | 1998 | 1 | 1998 | 998 | 1998 |
| 0.025 | 3997 | 3997 | 1 | 3997 | 1973 | 3996 |
| 0.0125 | 7995 | 7995 | 2 | 7995 | 7188 | 7188 |
| **Connection 2** | | | | | | |
| Injection interval [s] | | | | | | |
| 0.1 | 999 | 999 | 0 | 999 | 506 | 998 |
| 0.05 | 1998 | 1998 | 1 | 1998 | 1001 | 1997 |
| 0.025 | 3997 | 3997 | 1 | 3997 | 1969 | 3996 |
| 0.0125 | 7995 | 7995 | 2 | 7995 | 7184 | 7184 |

Table 4.2: Three-node hidden terminal – packets received (over 30 simulation runs). Case (a) The connections started at the same time. Case (b) The connections started with a difference of 1ms. Results correspond to Figure 4.2(a). Notice that the averaged numbers of packets received were rounded to the closest integer; that mean the average of zero packets is possible, however, at some runs there were packets received.

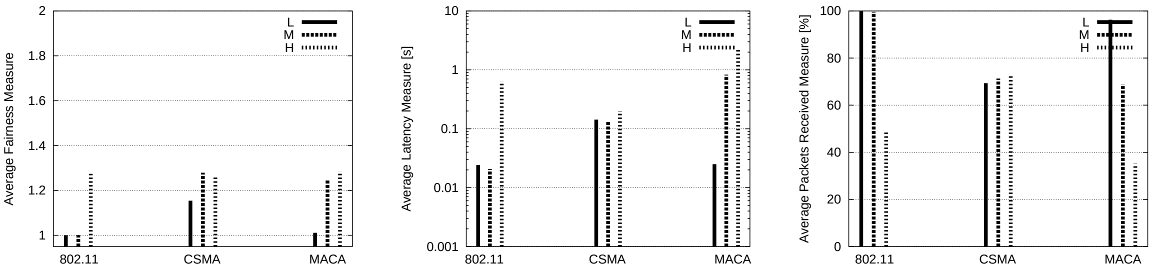
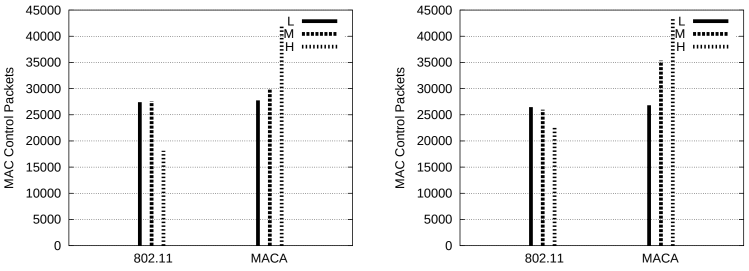


Figure 4.4: Distinct sources, closely positioned sinks. The graphs shows dependency of these parameters on injection interval.Average fairness, latency and ratio of packets received. The graphs shows dependency of these parameters on injection rate (L = low injection rate, M = medium injection rate, H = high injection rate). These results correspond to Figure 4.2(c).



(a) (b)

Figure 4.5: MAC layer control packets. (a) Identical sinks, (b) Closely positioned sinks. The figure shows the total of MAC layer control packets for 1,000 data packets sent.

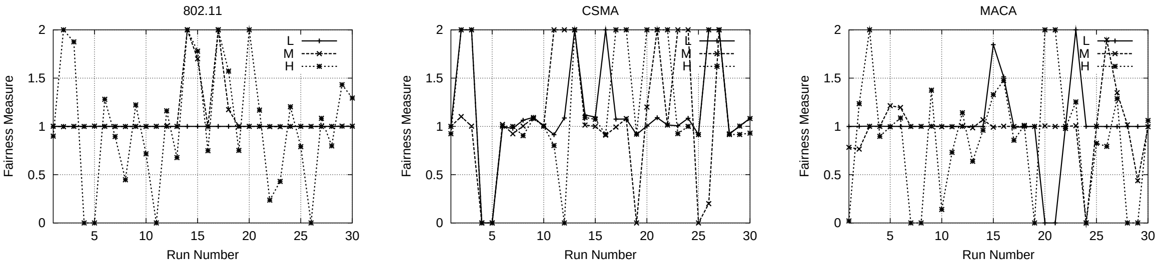


Figure 4.6: Fairness over a set of 30 runs for the three protocols. The $x$-axis shows 30 runs with different simulation seeds. The $y$-axis shows the fairness as a ratio of packets received for connection 1 to packets received for connection 2. These results correspond to Figure 4.2(b).

and 4.2. The plotted values are averaged over 30 runs with different random seed for each run of the simulator.

1. Looking at the numbers in Table 4.2 (results for Figure 4.2(a)), we see that CSMA essentially did not assign any resources when the connections started at the same time. In contrast, when the connections were started 1 millisecond apart, resources were assigned equitably. 802.11 did very well for both connections with and without any delays; in fact its performance was essentially indistinguishable. MACA's performance was somewhere in between the performance of CSMA and 802.11.

2. Results for the generalized hidden terminal scenario (Figure 4.3 and 4.4 for scenarios shown in Figures 4.2(b),(c)) show that in general with increasing injection rate the latency measure is slowly rising. The least sensitivity for this input parameter showed CSMA. On the other hand number of packets received falls steeply for 802.11 as one increases the injection rates. On the other hand CSMA again shows a more steady performance.

3. The results for the two variant hidden terminal scenarios (Figures 4.3 through 4.5 for scenarios shown in Figures 4.2(b),(c)) exhibit similar performance characteristics. In particular, as expected the random delays introduced by the network improved the fairness characteristics of CSMA considerably over its performance for scenario Figure 4.2(a).

4. Figure 4.6 shows the behavior of the three protocols w.r.t. fairness ratio discussed in the earlier Section. It shows that almost every run of the CSMA and MACA protocol produce inequitable assignment of resources to the two connections. CSMA assigns inequitable resources more frequently than MACA but MACA has much higher levels of inequitable resource assignment when they are so assigned.[2] 802.11 behaves quite well across low as well as high injection rates.

5. Figures 4.3 and 4.4 show that no single protocol dominates the other protocols across the three different performance metrics (fairness, throughput and latency) and over range of injection rates. This is an important conclusion and will be reinforced as we alter the scenarios.

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[2] This fact is somewhat subdued by the scaling and normalization on the fairness measure.

**Qualitative Explanations:** We provide plausible qualitative explanation for the above conclusions. First consider the relative behavior of 802.11 and CSMA. The RTS/CTS/ACK mechanism[3] in conjunction with IFS (Interframe spaces) of 802.11 reduces the probability of collisions. On the other hand, it sometimes (unnecessarily) reserves media space thus disallowing other transmitters to use the space even if they could have probably used it without causing collisions. Additionally the control packets (RTS/CTS/ACK) imply additional overhead on the system which increases latency and decreases the good throughput (also known as goodput). These opposing aspects of the control packets used in 802.11 makes the analysis of 802.11 complicated. Nevertheless note the following: at high injection rates we use smaller packets and thus the relative overhead of the control packets in 802.11 exceeds the gain obtained by decreasing the number of collisions. Furthermore, the paths used by the two connections are by and large distinct (except near the destination). Thus the collisions we are avoiding are primarily those that occur between packets belonging to the same connection (collisions that occur while transmitting packets over three consecutive links of a routing path). At low injection rates, the number of control packets are significantly smaller and we have larger packet sizes: thus implying a higher bandwidth utilization. Moreover, although the collision probability is low, recovering from collisions at link level as done in 802.11 using the ACK part helps its overall performance. Thus 802.11 does quite well at low injection rates but deteriorate substantially at higher injection rates. It appears that the time for a packet to travel over one link together with the time it takes to move the packet from input buffer to the output buffer is less than the time it takes to generate the next packet at the source. Thus packets transmitted using CSMA do not typically experience collisions in this case. CSMA on the other hand does not assign equitable resources to the connections. This fact is clearer on inspecting Figure 4.6, rather than Figure 4.3 that reports the average over 30 runs. The reason for this is clear: once one connection gets access to the channel, it prevents the other connection from acquiring any resources. More surprisingly, MACA in spite of using RTS/CTS control packets, also exhibits inequitable resource assignment. Thus it appears that the random delays used in 802.11 play an important role in improving the fairness characteristics of 802.11. CSMA and MACA on the other hand rely on the transport layer to recover from collisions and thus pay a high price when collisions do occur. The qualitative difference between 802.11 and MACA at high injection rates is due to the ACK and IFS mechanism present in 802.11.

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[3] We have been using the three-way handshake for all data packet sizes.

### 4.4.2 Effects of Connectivity

We now discuss the set up for the second experiment. It aims to understand the effect of graph connectivity on the performance of the MAC protocols. As in the case of first experiment we have three sub-scenarios. The first scenario consists of a grid graph. The second and third scenarios are obtained by progressively increasing the radio range of all transceivers. More formally: (i) first we set the radio range of transceivers to one grid unit, (ii) in the second case the radio range was set to 2.5 grid units, and (iii) in the last case the radio range was set to 5 grid units, i.e. the radio radii are 125, 250 and 500 meters respectively. The topology of these experiments is shown in Figure 4.7.

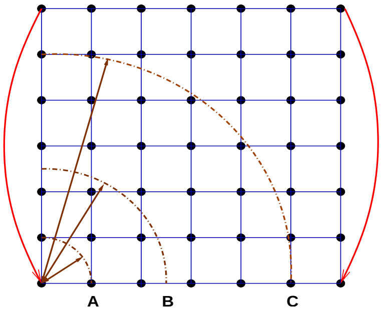


Figure 4.7: Two parallel connections, dense grid network with low, medium, and high connectivity. Circles show the radio range – (A) range is 1 grid unit: low connectivity, (B) range is 2.5 grid unit : medium connectivity, (C) range equals 5 grid units: high connectivity.

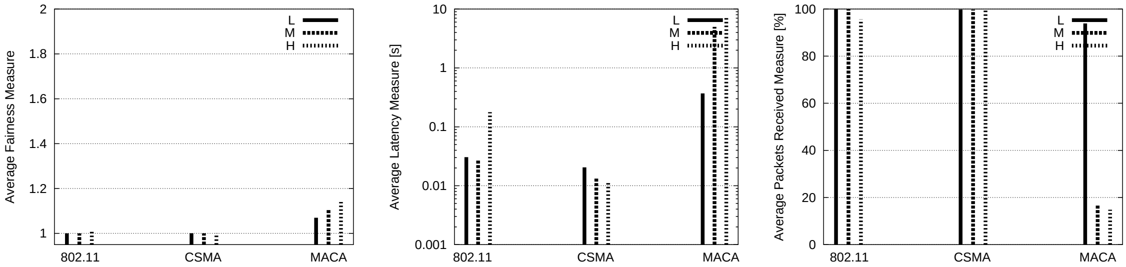


Figure 4.8: Grid network, low connectivity. Average fairness, latency and ratio of packets received. The plots correspond to Figure 4.7(A).

**Broad Conclusions:** The results are depicted in Figures 4.8 through 4.14. The graphs are again averaged over 30 runs with different random seeds for each run.

1. First note that increasing connectivity has a mild effect on latency and packets

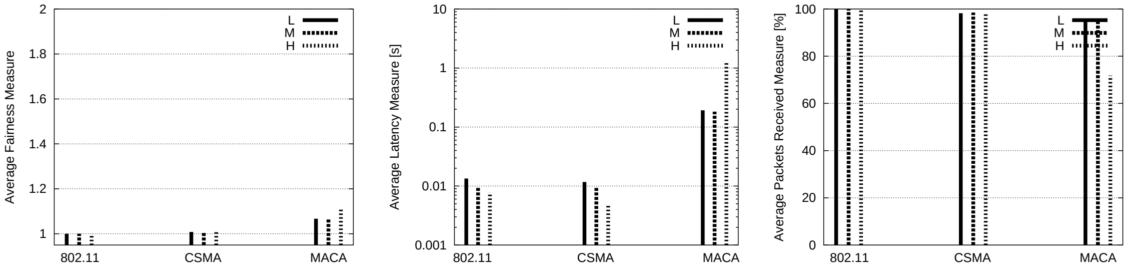


Figure 4.9: Grid network, medium connectivity. Average fairness, latency and ratio of packets received. The plots correspond to scenario described in Figure 4.7(B).

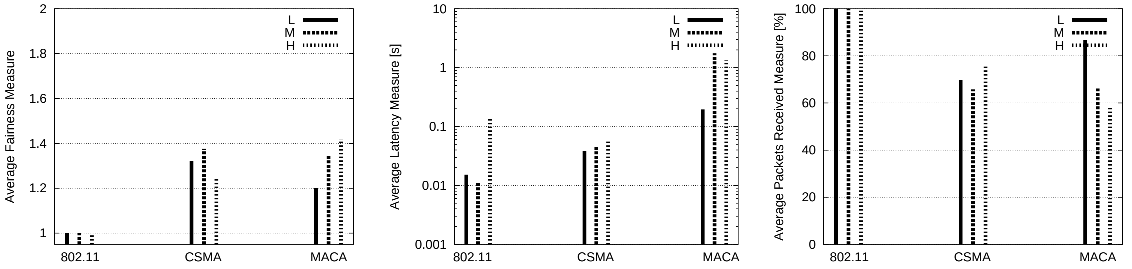
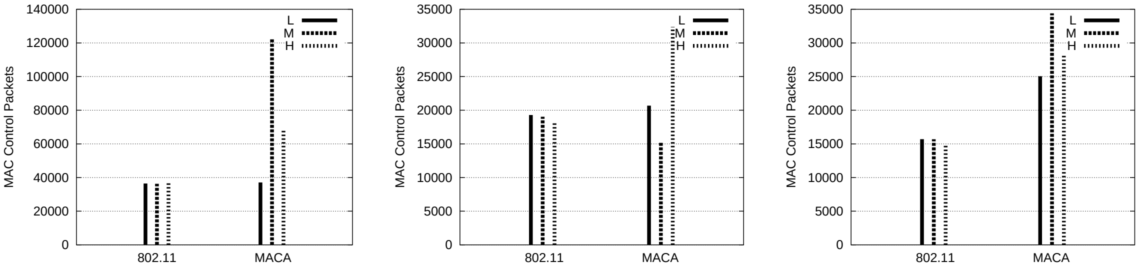
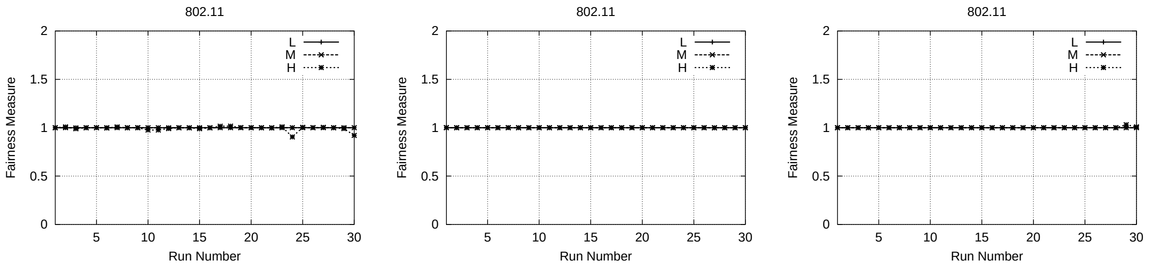


Figure 4.10: Grid network, high connectivity. Average fairness, latency and ratio of packets received. The plots correspond to scenario in Figure 4.7(C).



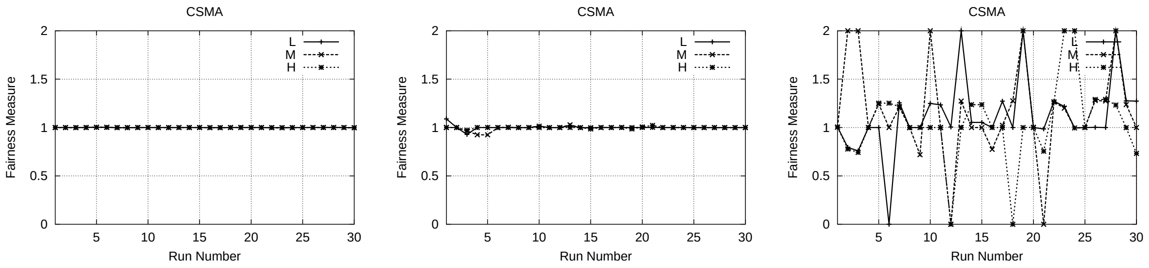
(a) (b) (c)

Figure 4.11: MAC layer control packets. (a) Low connectivity, (b) Medium Connectivity, (c) High connectivity. The figure shows the total of MAC layer control packets for 1,000 data packets sent.



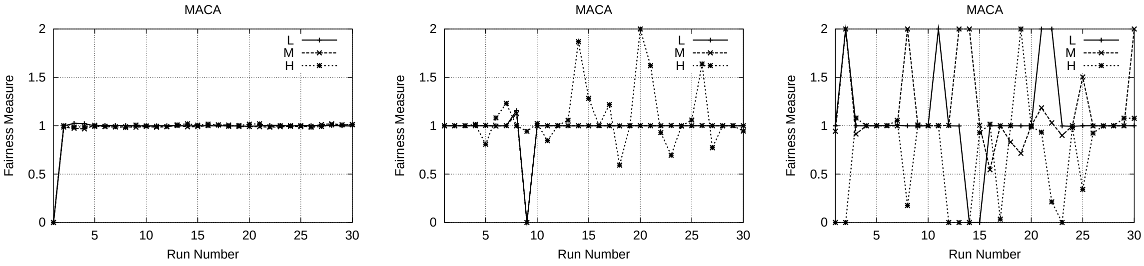
(a) (b) (c)

Figure 4.12: Fairness over a set of 30 runs for the three protocols. The $x$-axis shows 30 runs with different simulation seeds. The $y$-axis shows the fairness as a ratio of packets received for connection 1. and 2. These results correspond to Figure 4.7(A,B,C).



(a) (b) (c)

Figure 4.13: Fairness over a set of 30 runs for the three protocols. The $x$-axis shows 30 runs with different simulation seeds. The $y$-axis shows the fairness as a ratio of packets received for connection 1. and 2. These results correspond to Figure 4.7(A,B,C).



(a) (b) (c)

Figure 4.14: Fairness over a set of 30 runs for the three protocols. The $x$-axis shows 30 runs with different simulation seeds. The $y$-axis shows the fairness as a ratio of packets received for connection 1. and 2. These results correspond to Figure 4.7(A,B,C).

received for both 802.11 and CSMA. The number of packets received dropped somewhat at high connectivity and at high injection rate for CSMA and MACA. 802.11 showed a very stable performance with respect to this measure. The performance of MACA dropped considerably at higher injection rates. This was mainly due to increased control packets.

2. Comparing these results with the results in the previous section (Generalized Hidden Terminal) we see that all the protocols in general do better. This is because in this case the two connections interfere with each other to a much smaller extent.

3. The fairness characteristics also exhibit an intuitively expected behavior. At high connectivity both CSMA and MACA perform poorly; interestingly the performance was poor even at low injection rates. This can be seen by inspecting Figures 4.12–4.14. For low connectivity all protocols exhibit a very high level of fairness behavior. The main reason is simple – there is hardly any integration between the two connections in this case (Figure 4.7 (A)).

In average for the three levels of connectivity 802.11 performs very well, but CSMA dominates in case of lower connectivity. MACA's performance decreases with increasing connectivity.

**Qualitative Explanations:** We provide plausible qualitative explanation for the above conclusions. As we have observed 802.11 and CSMA had a fairly uniform performance at all connectivity levels. The main reason is that even at highest connectivity, there was one path for each connection that was not affected at all by the other connection. These paths are the sequence of nodes on the left and right edge of the graph. Thus if this path was indeed used then one would not expect any performance drop. On the other hand if a slightly different path was used by either connection, we have an interaction. The interaction can cause a performance drop if the injection rate was high enough. The reason is simple: as we have discussed in the previous scenario, even at high injection rates, the probability of interaction between packets on consecutive links was small if the connections did not interact. This is no longer true if the connections interact.

We note that although the routing paths need not have common nodes, they might be close enough so as to cause MAC layer interaction. In particular, consider the following setting illustrated in Figure 4.15. We have shown three paths from $1$ to $2$ and similarly $3$ paths from $3$ to $4$. The paths $1-6-2$ and $3-5-4$ are completely non-interfering. Paths $1-x-2$ and $3-x-4$ share the node $x$ and thus clearly interfere. The paths $1-y-2$ and $3-z-4$ are interesting. These paths do not share nodes but influence each other in that $y$ and $z$ cannot simultaneously transmit. This is because although they do not share nodes these paths influence each other. This holds since under the radio propagation model, nodes $y$ and $z$ can not simultaneously transmit.

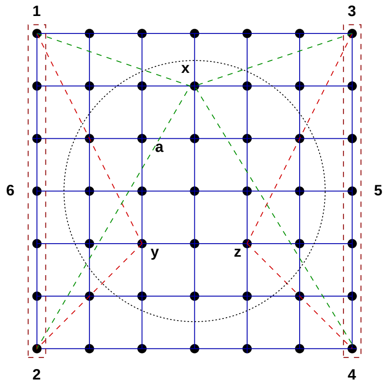


Figure 4.15: Figure illustrating that the routing paths need not intersect to be interfering.

### 4.4.3 Effects of Separator Size and Sparsity

We discuss the final experiment for static configuration. The experiments aim to understand the effect of sparsity and minimum cut in the network on the performance of MAC layer protocols. Like the first two cases, we have three sub scenarios. In the first scenario, we have our usual *grid-squared graph* and two connections that are going diagonally across. In the second scenario the grid size is $3 \times 15$ nodes, and in the third experiment we use a sparse near-grid of 53 nodes. The topologies are depicted in Figures 4.16, 4.17, and 4.18, respectively. The basic qualitative difference between the sub-scenarios is obvious. In the first case, the minimum cut of the graph is roughly $O(\sqrt{n})$ where $n$ is the number of nodes. The minimum path length is $4$ for both connections. The situation is close to the generalized hidden terminal scenario considered in Experiment 1. The difference is that the paths for the two connections may not intersect at all. In the second case, the minimum cut is a constant and thus independent of the size of the graph. The length of the paths on the other hand are $O(n)$, where $n$ again is the number of nodes in the graph. The second topology can be thought of as "stretching" the first topology in one direction. As a result, although the "vertical" cut in the $x$-direction is small the horizontal cut is $O(n)$. The third topology is somewhat different. Here both the horizontal and vertical cuts are small (a constant) as compared to graph size.[4] As a result, the situation portrayed can be viewed as a study of the tradeoff between connectivity (and thus multiple paths) on one hand and the increased interaction at the MAC layer. Another rationale for this study was to study the exposed and hidden terminal problems when the nodes being affected are not the end points but intermediate nodes.

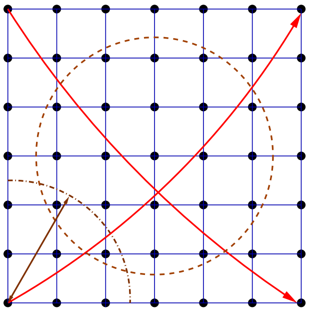


Figure 4.16: Grid-squared graph. Quarter-circle show the radio range of corner transceivers. The complete circle shows the range of transceiver that is at the canter of the grid. Minimum degree of the graph is 7 and the maximum degree is 20.

**Broad Conclusions:** The results are depicted in Figures 4.19, 4.20, and 4.21, respectively.

The performance of any of the protocols is extremely hit by these extreme cases of

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[4] Although all the grids are small as used in the experiments, it is easy to see how an infinite family of such grids can be created.

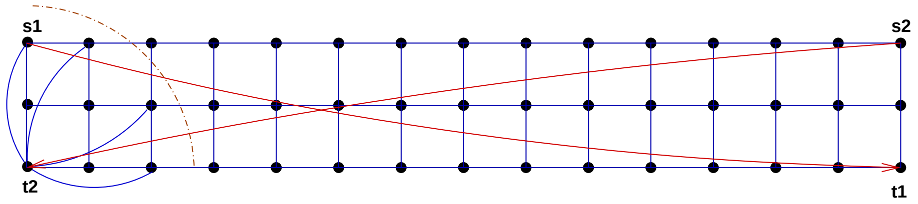


Figure 4.17: Long dense grid. The quarter-circle shows radio range from the lower left node. The node is effectively connected to seven other nodes. Minimum connectivity is 8, maximum connectivity is 16.

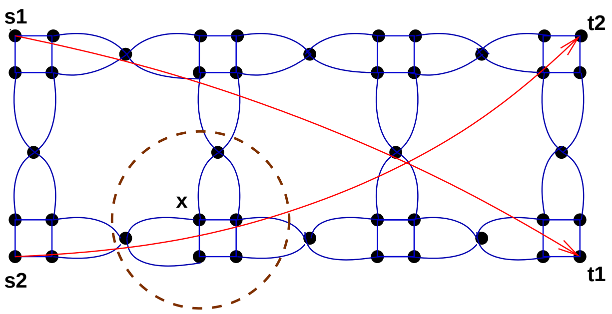


Figure 4.18: Long sparse graph. The figure shows the radio range for one of the nodes. The node has direct connection to four other nodes. Minimum connectivity is 4, maximum connectivity is 6.

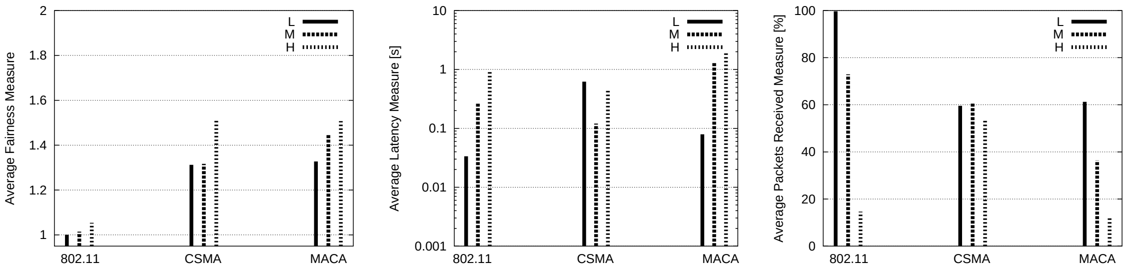


Figure 4.19: Grid-Squared graph. Average fairness, latency and ratio of packets received. The plots correspond to scenario in Figure 4.16.

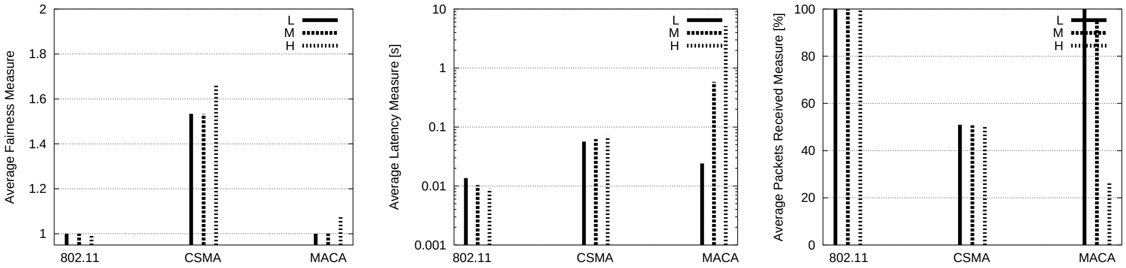


Figure 4.20: Long dense grid. Average fairness, latency and ratio of packets received. The plots correspond to scenario described in Figure 4.17.

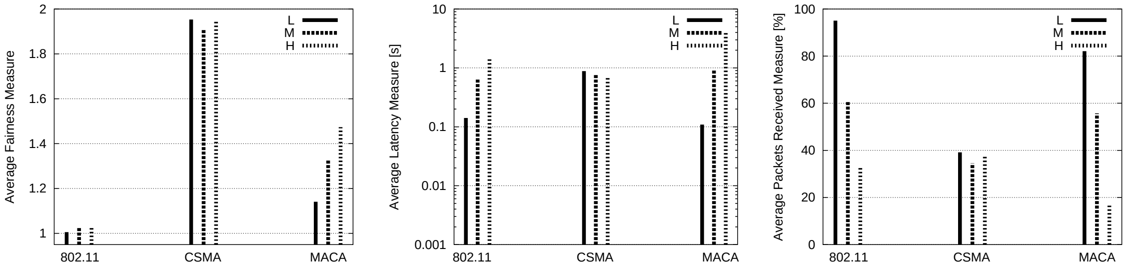
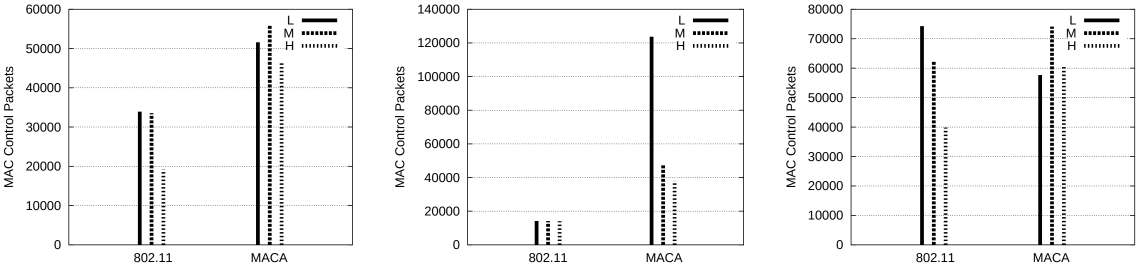


Figure 4.21: Long sparse near-grid. Average fairness, latency and ratio of packets received. The plots correspond to scenario in Figure 4.18.



(a) (b) (c)

Figure 4.22: MAC layer control packets. (a) Grid-squared graph, (b) Long dense grid, (c) Long sparse near-grid. The figure shows the total of MAC layer control packets for 1,000 data packets sent.

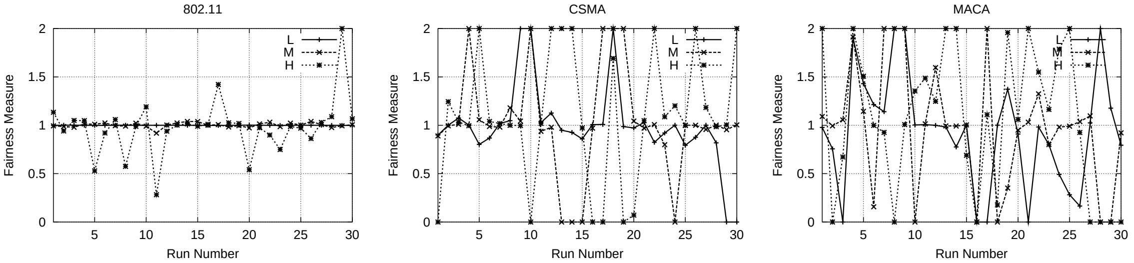


Figure 4.23: Results for scenario in Figure 4.16. Fairness over a set of 30 runs for the three protocols. The $x$-axis shows 10 runs with different simulation seeds. The $y$-axis shows the fairness as a ratio of packets received for connection 1. and 2.

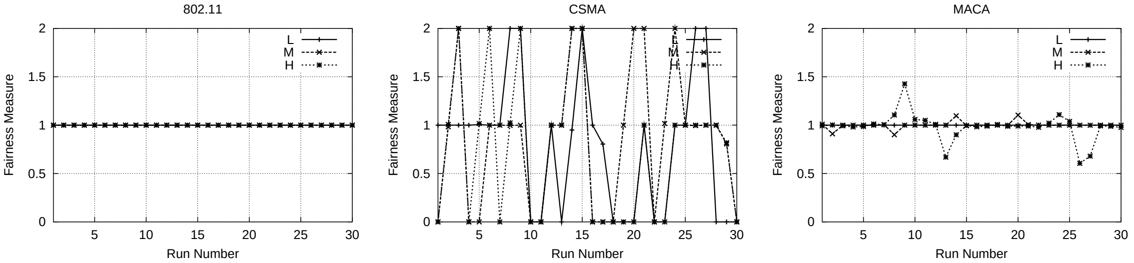


Figure 4.24: Results for scenario in Figure 4.17. Fairness over a set of 30 runs for the three protocols. The $x$-axis shows 10 runs with different simulation seeds. The $y$-axis shows the fairness as a ratio of packets received for connection 1. and 2.

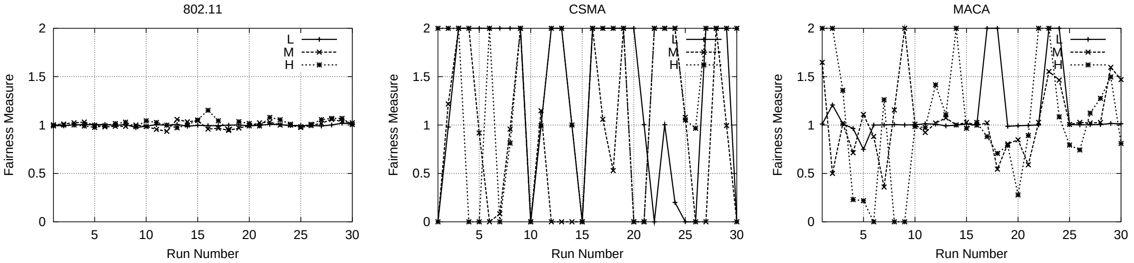


Figure 4.25: Results for scenario in Figure 4.18. Fairness over a set of 30 runs for the three protocols. The $x$-axis shows 10 runs with different simulation seeds. The $y$-axis shows the fairness as a ratio of packets received for connection 1. and 2.

path interaction. This is further worsened by the increasing injection rate. Interestingly, the performance of the protocols on scenarios given in Figures 4.17 and 4.18 is *qualitatively similar.* In both cases, 802.11 and MACA had a drop in performance at high injection rate. In general the performance of the protocols for scenarios in Figures 4.17 and 4.18 is worse than their respective performance for scenario is Figure 4.16.

It is instructive to compare the results for this scenario with the results for the previous scenario (scenario shown in Figure 4.7 and results shown Figures 4.8, 4.9, 4.10). First note that the medium connectivity case in Figure 4.7 is essentially the same as the grid-squared graph shown in Figure 4.16. The main difference is that in one case the connections have crossing paths while in the other case the connections do not have crossing paths. As expected the crossing paths scenario has a slightly worse performance.

**Qualitative Explanations:** The main reasons for the observed behavior of the protocols is again related to (i) the control packets, (ii) the cuts in the graph and the ensuing probability of collision. As can be observed 802.11 sacrifices the packets received to get a better per run fair behavior. CSMA's performance appears quite good on the average but is quite poor when one notes the per run fairness characteristics as depicted in Figures 4.23 through 4.25.

The reason for poorer performance of the protocols for scenarios given in Figures 4.17 and 4.18 as compared to their performance for scenario is Figure 4.16 is quite simple: sparse connectivity and long paths. Both these factors increase the spatial contention for the media.

We finally discuss our results in light of the theoretical results by Nelson, Kleinrock, Takagi and Tobagi [NK83, NK84, TK84, KT75, KT75a, KS78]. The authors obtain analytical bounds on the "best possible degree" of a node when a greedy routing algorithm is used along with a CSMA/ALOHA class of MAC protocol. The results are obtained for a random set of points distributed according to a Poisson point process such that expected number of transceivers per unit area is $\lambda$. The authors also use the notion of *capture* for the radio propagation model. Specifically, the authors pose the question of calculating the optimal power transmission for maximizing the expected progress of a packet towards its destination. The general conclusion is that the expected number of transceivers that should be in the neighborhood of a given transceiver should be between $5$ and $8$. All the topologies considered in Experiments 2 and 3 use fairly uniform graphs (excepting the boundary nodes). Our experimental results show that indeed for cases with low constant degree networks, the performance of protocols is quite good while in cases when the degree of the network is high ($\Omega(n)$) the performance falls significantly. Obtaining exact numerical bounds on the vertex degrees is not very meaningful until we can simulate very large systems. Thus our experiments provide additional insights into the work of [NK83, NK84, TK84, KT75, KT75a, RM+02]. As stated earlier, analytical results for 802.11 have not been carried out to our knowledge.

## 4.5 Conclusions

We experimentally analyzed the performance of three MAC layer protocols: (i) CSMA, (ii) MACA and (iii) 802.11. The performance of the protocols was measured in terms of (i) latency, (ii) throughput, (iii) number of data packets received and (iv) equitable resource assignment. The study was carried out by varying (i) the rate at which packets were injected in the network, (ii) the network topology, (iii) the spatial layout of the connections. The main conclusions are two folds:

1. No protocol dominated the other protocols over all the performance measures **even** for a given combination of all the input parameters (injection rate, topology and spatial location of connections). Although, the conclusion in itself is not surprising, the frequency of its occurrence and the variation displayed by the protocols was certainly surprising. The conclusion is important when service providers are likely to guarantee a given level of quality of service.

2. MACA was by and large dominated over the entire range of combinations by either CSMA or 802.11. Interestingly, it appears that CSMA might indeed be a good protocol for lightly loaded systems (in terms of number of connections). It is also seen from our experiments that the routing layer can affect the performance of the underlying MAC protocols.

As discussed earlier, this motivates a new class of protocols we refer to as **PARADYCE**. Although designing such protocols is non-trivial, the results do suggest key design requirements. They include: (i) ability to shut of the RTS/CTS/ACK mechanism when the traffic streams are non-interfering, (ii) use adaptive back off mechanisms that change with traffic conditions. Both these changes are likely to improve the performance of 802.11 significantly. MACAW designers have also suggested per-channel priority queues. Although this is possible, its overall effect on the network throughput remains to be understood. Additionally, the next generation radio units can likely control their power. This will give rise to interesting questions about simultaneously adjusting power levels for routing and MAC layer for the best utilization of resources.

# Chapter 5

# Interaction of MAC Layer and Routing Layer Protocols

## 5.1 Overall Goal

We aim to empirically characterize the effect of the interaction between the routing layer and the MAC layer in *static* wireless radio networks. Our work is motivated by earlier work by [Ba98, BS+97] which studies the interaction between TCP and the lower levels of the OSI stack. The work builds on the earlier work of [WS+97, NK+99, BD+94], that experimentally analyzes MAC layer protocols and recent results by Royer et al. [DPR00, DP+, RLP00] that note the interplay between Routing and MAC protocols. In [DPR00], the authors conclude by saying – *"This observation also emphasizes the critical need for studying interactions between protocol layers when designing wireless network protocols".* In [RLP00], authors conclude that the MAC protocol selection is a key component in determining the performance of a routing protocol and hence must be considered by any comparative study of routing protocols.

In order to test the issue of *interaction* rigorously, we resort to the popular statistical technique called ANOVA (the Analysis of Variance). ANOVA is commonly used by statisticians to study the sources of variation, importance and interactions among variables. However, to the best of our knowledge, a detailed study aimed towards understanding the effect of interaction between MAC and routing protocols, using formal statistical tools, has not been undertaken prior to this work. Moreover, this is done in settings where the results are interpretable; hence to the extent possible,

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This chapter is a result of joint work with Chris Barrett, Achla Marathe, and Madhav Marathe. See [BD+03a, BD+04a] for reference.

simple instances are chosen to effectively argue about an issue. Apart from routing and MAC protocols, we study the effect of injection rate and network topology on the performance variables. Thus our input variables are:

1. **Routing protocols:** AODV, DSR, LAR1. These are denoted by $R_i,\ 1 \leq i \leq 3$. The set of routing protocols will be denoted by $R$. The routing protocols were chosen keeping in mind the recommendations made by [DPR00, JL+00] after undertaking a detailed experimental study of recent routing protocols.

2. **MAC protocols:** 802.11, CSMA and MACA. These are denoted by $M_k,\ 1 \leq k \leq 3$. The set of MAC protocols will be denoted by $M$. Again the choice of these protocols is based on the study in [RLP00, WS+97].

3. **Injection rates:** low (0.05 second), medium (0.025 second) and high (0.0125 second). The injection rates are denoted by $I_l,\ 1 \leq l \leq 3$. The set of injection rates will be denoted by $I$.

4. **Network topologies:** medium connectivity grid (Figure 5.5(a)(A)), high connectivity grid (Figure 5.5(a)(B)) and 6x6-3x3-6x6 corridor grid (Figure 5.5(b)). The choice of the networks is based upon earlier work in [BD+94, WS+97]

Our evaluation criteria consists of following basic metrics: (i) *Latency:* Average end to end delay for each packet as measured in seconds, and includes all possible delays caused by buffering during route discovery, queuing and backoffs, (ii) Total number of packets received (and in some cases packet delivery fraction) (iii) Long term fairness of the protocols, i.e. the proportional allocation of resources given to each active connection and (iv) *Control Overhead:* The number of control packets used by MAC layer. Each of the input parameters and the performance measures considered here is used in one of the earlier experimental studies [DPR00, DP+, BM+98, KV98, RLP00, RS96].

## 5.2 Specific Results

Specific results obtained include the following:

1. The performance of MAC layer protocols is affected by the routes chosen by the routing layer. Not surprisingly, when two routes share many common nodes, their performance tends to be worse than in scenarios when the routes do not

share many common nodes. More interestingly, MAC layer performance deteriorates even when routes do not intersect but come close enough. This result has an important implication in the context of making the routing protocols adaptive. Specifically, recent routing protocols have attempted to modify the routes after sensing the load on individual links (i.e. they are adaptive). But as we show, in some cases the effect of one path on the other is somewhat indirect. This makes the task of adaptive routing protocols complicated.

2. The worst performer among the three protocols was MACA. At lower injection rates, 802.11 was the best of the three while at higher injection rates CSMA seemed to perform better as long as the interaction among active connections was low. The drop in performance for 802.11 was much more drastic at higher injection rates. This drop is largely due to the increase in RTS/CTS/ACK control packets. Again, routing protocols play a significant role in determining the loads and injection rates at a node.

3. The performance of protocols varies significantly from one run to another with regards to the resources assigned to connections. CSMA (and also other protocols to some extent) tends to inequitably assign resources to the two connections. One of the reasons for this behavior is interaction of the MAC layer protocol with the routing protocol with subsequent impact onto the long term fairness.

4. No single MAC layer protocol could be termed as *dominating* in terms of performance. Moreover, different routing protocols when combined with different MAC layer protocols yielded varying performances. Again there appears to be no single routing protocol/MAC protocol combination that yields best performance as measured over the entire range of parameters and scenarios.

The main conclusions of our results are:

1. The network connectivity, spatial location of connections, injection rate and packet size all play a crucial role in determining the extent of the effect a routing protocol can have on the performance of a media access protocol. To the best of our knowledge such a study has not been carried out in the literature so far.

2. *No single MAC protocol dominated the other protocols across various measures of efficiency.* This motivates the design of a new class of parameterized protocols (PARADYCE) that adapt to changes in the network connectivity and loads.

These include: ability of the routing protocols to dynamically change routes based on the contentions they face. In this regard, a slightly longer path might be more desirable over short but high contention paths. We believe that dynamic routing protocols that adapt to both the function of path length and traffic will also help the lower layer MAC protocols.

3. *No single MAC protocol/routing protocol combination* dominated the other combinations over the entire range of parameters. This implies that future development of protocols for each layer cannot be carried out in isolation of one another. The entire protocol stack has to be treated as a single algorithmic construct and needs to be optimized with this viewpoint.

4. The long term fairness shows a significant amount of variation over independent runs. This is important in providing quality of service guarantees. Moreover, each protocol can be seen as providing a trade-off between fairness and throughput (or latency). But this trade-off is not static, it varies with the network and traffic parameters.

## 5.3 Experimental Setup

Details on the parameters used in this series of experiments are summarized in Figure 5.1

## 5.4 Understanding the effects of Route Interaction

Intuitively, it is clear that the specific routes chosen by the routing protocol affect the performance of the underlying MAC protocols. In this section, we try to understand this effect further. As we have already pointed out the routing paths need not have common nodes, they might be close enough so as to cause MAC protocols at near by transceivers to interact (see Figure 4.15).

**Example 1:** The underlying network is shown in Figure 5.2. We used 35 nodes to produce a grid of 5×7 nodes. The nodes in this experiment were positioned at a distance of 100 meters (i.e. grid unit = 100m) from each other gaining a physical size of the grid of 400× 600 meters. Note that transmission radii from nodes in the very left column are just short of achieving a direct communication with nodes in the very right column, and vice-versa. We have used CSMA as the underlying MAC layer protocol. We had two connections with the end points occupying the grid end points.

1. **Network topologies:** medium connectivity grid (Figure 5.5(a)(A)), high connectivity grid (Figure 5.5(a)(B)) and 6x6-3x3-6x6 corridor grid (Figure 5.5(b)). The choice of the networks is based upon earlier work in [BD+94, WS+97]
2. **Number of connections:** Unless otherwise stated we use two connections.
3. **Routing protocol** : AODV, DSR, LAR scheme 1.
4. **MAC protocol:** IEEE 802.11 DCF, CSMA, MACA.
5. The initial packet size was 512 bytes, the number of packets was 1,000, and the injection interval was 0.1 second. Each time the injection interval was reduced by a factor of 2, we also reduced the packet size by a factor of 2 but increased the number of packets by a factor of 2. For example, if the injection interval was halved to 0.05 seconds then the new packet size was 256 bytes and the new number of packets was 2,000. This allowed us to keep the injection at input nodes constant in terms of bits per second.
6. The bandwidth for each channel was set to 1Mbit. Other radio propagation model details are as follows: (i) Propagation path-loss model: two ray (ii) Channel bandwidth: 1 Mb (iii) Channel frequency: 2.4 GHz (iv) Topography: Line-of-sight (v) Radio type: Accnoise (vi) Network protocol: IP (vii) Connection type: UDP
7. **Simulator used:** GloMoSim.
8. The transmission range of transceiver was 250 meters.
9. Number of independent simulation runs: 10 for each combination of input parameters.
10. The simulation time was 100 seconds.
11. Hardware used in all cases was a Linux PC with 512MB of RAM memory, and Pentium III 500MHz microprocessor.
12. The following information was collected to measure the performance: (i) Average end to end delay for each packet as measured in seconds (latency), (ii) Total number of packets received, (iii) Throughput in bits/second and (iv) Total number of control packets at the MAC layer level.

Figure 5.1: Parameters used in the Experiments.

The end points of the two connections were placed in such a way that if the routing protocol chooses the shortest (geographical) path there would be no interference between the x-y connection and the z-w connection, see Figure 5.2. If the routing protocol chooses a less than optimal routing, interference between connections will arise.

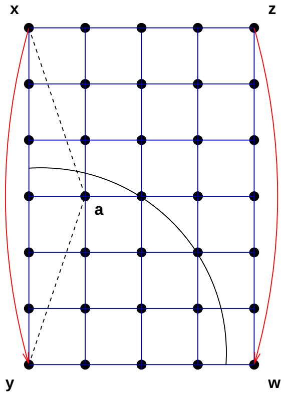

Figure 5.2: MAC protocol – routing protocol interaction. The quarter circle depicts the radio radius that the nodes are using. x–y and w–z depicts an optimal packet path fly with no interactions; x–a–y depicts a path that causes an interaction between the MAC and routing protocol.

Several modes of operations were observed. One of them occurred when the routing protocol found the shortest path for the connections. In this case, the number of received packets at sinks was 1,000, i.e., 100%. In the other case, the routing protocol did not find the shortest path for one of the connections. This caused interference between the two connections and resulted in delivering only one packet for the connection. The four basic modes of operation from 15 different runs are summarized here. Different modes were counted as follows:

1. We considered 1,000 received packets for connection 1, and 0 received packets for connection 2 the same as 0 for connection 1 and 1,000 for connection 2, i.e., in general, we regarded symmetric results to be the same for the two connections.
2. If the number of packets received for a connection was e.g. 995 we counted it as 1,000, i.e., in general, we discarded small fluctuations and regarded such results as identical.

Let us use the notation $(x, y, z)$ to denote that in $z$ runs the number of packets received were $x$ and $y$ from connection 1 and 2 respectively. The experiments showed the following four modes: $(1000, 0, 6)$, $(1000, 500, 5)$, $(500, 500, 3)$, $(1000, 1000, 1)$. The ratio of packets delivered by the two connections was 1000 to 0 in six out of 15 runs, 1000 to 500 in five runs, 500 to 500 in 3 runs and 1000 to 1000 in 1 run. We see that the routing protocol (AODV) [1] managed to find the shortest path only in one case.

**Example 2** As another example, we consider how the path lengths and the location of connections affect the MAC protocol performance. For this experiment we consider two different topologies. In the first case, we fix the grid ($12 \times 7$ nodes, 1 grid unit = 100m). For each value of injection rate do the following: (i) First collect results for a single connection. This is shown by the thick line between $x$ and $y$ in Figure 5.3(a). (ii) Run the experiment for 2 connections that are very far away. This is shown as connections $t - u$ and $r - s$ in Figure 5.3(a). Cases (i) and (ii) provide us with the base cases. The first tells us the basic variation introduced due to the simulator while the second case yields a base case in terms of how much effect a routing protocol has with no interaction between connections. (iii) Run the experiment when the two connections are very close as shown by $x - y$ and $w - z$. (iv) Finally, run it for connections that are slightly further off. This is also shown in Figure 5.3(a). For each value of injection rate, we measured latency, the number of packets received and the throughput of each of the three MAC protocols.

In the second sub-experiment we used three line graphs of varying length to reason about the influence of the length of route used in transportation of packets from source to destination. The length of line graphs were 7, 15, and 30 nodes. The rationale was to show that length of route has an effect on latency of packets and also to quantify this latency. The minimum connectivity for start and end nodes was two and maximum connectivity was five. The setup is depicted in Figure 5.3(b).

Figure 5.4 shows the average fairness, latency and throughput for *Non-interfering* and *Very-Close* connections for the three MAC protocols. $L$ and $H$ extensions refer to low and high injection rates respectively. In case of non-interfering connections, all MAC protocols behave equally well in terms of average fairness, latency and throughput except for MACA at high injection rate. MACA-H appears more unfair, have higher latency and lower throughput. However, when the connections are very close and interfering, 802.11 and MACA at high injection rate, are more unfair, have higher latency and lower throughput compared to CSMA. Although, 802.11 at low injection rate, is the most fair with least latency and best throughput among all the MAC protocols. The graphs for *partially-interfering* connections and *single* connection are omitted

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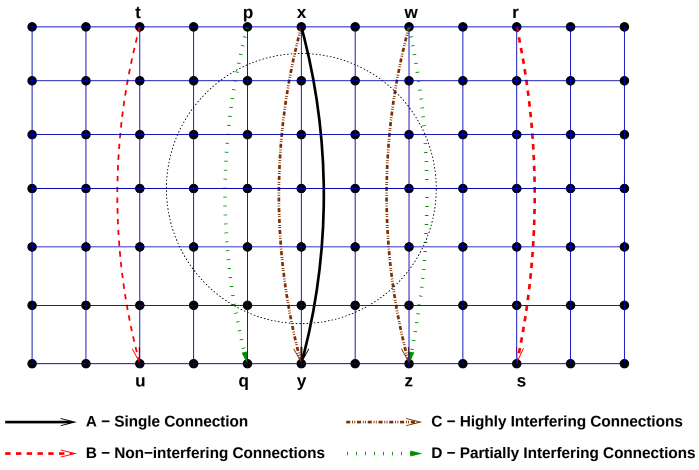
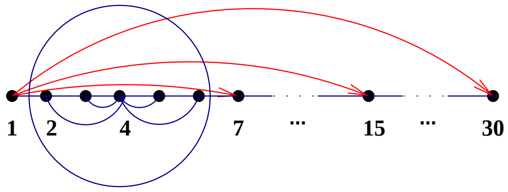
[1] We have run this experiment also with DSR. In that case the routing performance was worse then that of AODV.



(a)



(b)

Figure 5.3: Set up for 2nd experiment. (a) This experiment started with base cases consisting of connections that were far away and then progressively got them closer. (b) Effect of Path lengths. The figure shows three different line-squared graphs with length of 7, 15, and 30 nodes. The source and destinations for each of the three cases are shown by the arrows.

here to avoid repetition. However, the following conclusions summarize the results for the entire experiment.

1. 802.11 and CSMA show almost identical behavior when we compare the single connection and two connections that are far apart. In case of MACA there was a difference between the two cases which may have been caused by the interaction between MACA and the routing protocol, AODV. Suboptimal routing increased interaction between the two connections and the lack of carrier sensing in MACA became a factor.

2. Allocation of resources in the case of the two connections that are very close and

slightly apart is characterized by worse performance of CSMA at all injection rates, and 802.11 at high injection rate. In case of CSMA this is caused by the simplicity of the protocol, and in case of 802.11 this is caused by interference of control packets at high injection rate.

3. Even from this simple setting we can see that no MAC layer protocol dominates.

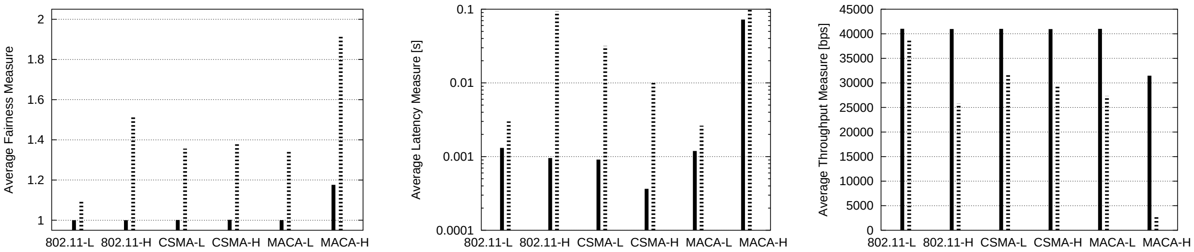


Figure 5.4: Average (Un)Fairness, Latency and Throughput of the three MAC protocols under low and high injection rates when we have for (a) Non-interfering connections (full line), and (b) Very close connections (dashed line).

In the second set of experiments we show relation between the length of route and basic performance parameters such as latency and packets received. The setup is shown in Figure 5.3(b). The basic conclusions from this set of experiment are:

1. Latency and number of control packets increase with the length of the line graph, and the number of packets received decreases with the length of the line graph.

2. In simple settings with low interaction, CSMA performs much better than the more advanced 802.11 or MACA. For MAC layer protocols with advanced RTS/CTS control packet mechanisms, deterioration comes at lower injection rate due to increased interaction between data and control packets.

## 5.5 Characterizing Interaction Using Statistical Methods

We set up an experiment which evaluates the performance of the following four factors; the MAC protocol, routing protocol, network topology and the injection rate. Each of these four factors (variables) have three levels (values the variables take) as described in Section 5.1.

This experiment generates $3^4 = 81$ distinct scenarios by using different combinations of MAC, router, network and injection rate. For each scenario, we generate 20 replicates/samples for the analysis. Our performance matrix for this experiment consists of three measures i.e. latency, number of packets received and the fairness.

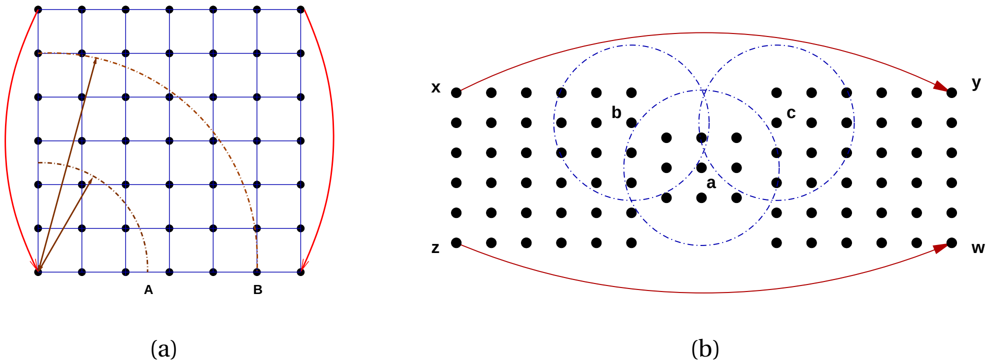


Figure 5.5: (a) Medium and high connectivity grid of $7 \times 7$ nodes. (A) medium connectivity, and (B) high connectivity. (b) Corridor grid. Two $6 \times 6$ grid connected with a $3 \times 3$ grid.

Using statistical methods we study whether these four factors interact with each other in a significant way. In the presence of interaction, the mean differences between the levels of one factor are not constant across levels of the other factor. A general way to express all interactions is to say that the effect of one factor can be modified by another factor in a significant way. In our analysis, we analyze, if the above four factors, interact in their effect on the performance measure. We perform three different analysis, one for each performance measure to observe the interaction among factors.

**Approach**: We first construct a matrix of 4 dummy variables. For each factor we create a dummy variable. This variable takes a value 1, 2 and 3 depending upon which level of the factor is switched on during the calculation of the performance measure. For example, the dummy variable for MAC protocol, would take a value 1 whenever 802.11 is being used to calculate the performance matrix, value 2 whenever CSMA protocol is being used and value 3 whenever MACA is being used to calculate the performance matrix. Similarly, for the router variable, the dummy takes a value of 1 whenever AODV protocol is being used and value 2 whenever DSR is being used and value 3 whenever LAR1 is being used to calculate the performance matrix. To calculate interactions between the factors, we use a statistical technique known as *analysis* *of variance* (ANOVA). It is a useful technique for explaining the cause of variation in response variable when different factors are used. The statistical details discussed below are routine and are provided for the convenience of the reader. For more details on the techniques used in this analysis, refer to [GH96, Ch90]. Given that we have four factors, we use a four factor ANOVA.

**Mathematical Model:** The appropriate mathematical model for a four factor ANOVA is as follows:

$$
\begin{gathered}
y_{ijklm} = \mu + \alpha_i + \beta_j + \gamma_k + \delta_l + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\alpha\delta)_{il} + \\
+ (\beta\gamma)_{jk} + (\beta\delta)_{jl} + (\gamma\delta)_{kl} + (\alpha\beta\gamma)_{ijk} + (\alpha\beta\delta)_{ijl} + \\
+ (\alpha\gamma\delta)_{ikl} + (\beta\gamma\delta)_{jkl} + (\alpha\beta\gamma\delta)_{ijkl} + \varepsilon_{ijklm}
\end{gathered}
$$

where $y_{ijklm}$ is the measurement of the performance variable (e.g. latency) for the *i*th network, *j*th router, *k*th MAC and *l*th injection rate. $m$ is the number of replicates which is 20 in our experiment. $\alpha_i$ is the effect of network topology, $\beta_j$ is the effect of the routing protocol, $\gamma_k$ is the effect of the MAC protocol and $\delta_l$ is the effect of the injection rate on the performance measures. The two way interaction terms are $(\alpha\beta)_{ij}$, which captures the interaction present between the network topology and the routing protocols; $(\alpha\gamma)_{ik}$, which measures the interaction present between the network topology and the MAC protocols; $(\alpha\delta)_{il}$, measures the interaction between the network topology and the injection rates. Similarly, $(\beta\gamma)_{jk}$, measures the interaction between the router and the MAC protocol. $(\beta\delta)_{jl}$, the interaction between the router and injection rates; $(\gamma\delta)_{kl}$, the interaction between the MAC protocols and the injection rates. The three way interaction terms are $(\alpha\beta\gamma)_{ijk}$ which captures the interaction present between the network, router and MAC protocols; $(\alpha\beta\delta)_{ijl}$, the interaction present between the network, router and injection rates; $(\alpha\gamma\delta)_{ikl}$, the interaction present between the network, MAC and injection rates; $(\beta\gamma\delta)_{jkl}$, the interaction present between the router, MAC and injection rates. Finally the four way interaction is measured by $(\alpha\beta\gamma\delta)_{ijkl}$ which includes all the four factors. $\varepsilon_{ijklm}$ is the random error.

**Model Selection and Interpretation**: The model selection method considered here is called the *stepwise method.* This method assumes an initial model and then adds or deletes terms based on their significance to arrive at the final model. *Forward selection* is a technique in which terms are added to an initial small model and *backward elimination* is a technique in which terms are deleted from an initial large model. Our analysis is based on the method of *backward elimination* where each term is checked for significance and eliminated if found to be insignificant. Our initial model is the largest possible model which contains all the four factor effects. We then eliminate terms from the initial model to eventually find the smallest model that fits the data. The reason for trying to find the smallest possible model is to eliminate factors and terms that are not important in explaining the response variable. After eliminating redundant factors, it becomes simpler to explain the response variable with the remaining factors. The smaller models can normally provide more powerful interpretations

To test four way interaction between the MAC, routing protocol, network and injection rates in effecting the response variable, we perform the four factor ANOVA using the above mathematical model. This is also called the *full/saturated* model since it contains all 1-way, 2-way, 3-way and 4-way interactions. After running this model, we calculate the residual sum of squares[2] and refer it by $SS(14)$, which stands for residual sum of squares for model number 14. The degrees of freedom is referred by $DF(14)$. Now we drop the 4-way interaction term i.e. $(\alpha\beta\gamma\delta)_{ijkl}$ and rerun the ANOVA model. The resultant model has now only have 1-way, 2-way and 3-way interaction terms. From this model, we can calculate the residual sum of squares for model 13, i.e. $SS(13)$ and degrees of freedom for model 13, $DF(13)$. We now compare model 14 with model 13 to find out if the 4-way interaction is significant. If the $F$-statistic turns out to be insignificant, we can say that 3-way interaction model i.e. model number 13 can explain the response variable as well as model 14. This implies that model 14 can be dropped off without loosing any information. Next we test for each term in model 13 and check which ones are significant. Any term that is not important in affecting the response variable can then be dropped off. This is achieved by dropping each 3-way term one at a time and then comparing the resulting model with model 13. In our tables, model 9 to 12 are being compared with model number 13. If the $F$-statistic is significant after dropping off the term, it implies that the term that was dropped off played a significant role and hence should not have been dropped. After checking 3-way interactions, we compare *all 2-way* interaction model (model 8) with *all 3-way* interaction model to see if there is a smaller model that can fit the data as well as the 3-way interaction model. Just like the 3-way model, we then drop off one term at a time from model 8 and compare the new models with model 8 to find out which of the 2-way interactions are most significant; in the table, models 2 to 7 are

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[2] For a regression model, $Y_i = \alpha + \beta X_i + e_i$, the residual are $e_i = Y_i - \alpha - \beta X_i$ and the residual sum of squares is $\sum_i (e_i)^2 = \sum_i (Y_i - \alpha - \beta X_i)^2$

being compared with model 8. We continue with the elimination process till we find the smallest possible model that explains the data.

The sum of squares, degrees of freedom and the $F$-*test* value for each of the models is shown in the Table 5.1. Interaction column shows which interactions are included in the model. Finally the $F$-*test* is calculated using the following statistic:

$$F = \frac{SS(a) - SS(b)/DF(a) - DF(b)}{SS_{full}/DF_{full}}$$

where $SS(a)$ is the sum of squares residuals for model $a$ and $SS(b)$ is the sum of squares residuals for model $b$. Similarly $DF(a)$ is the degrees of freedom for model $a$ and $DF(b)$ is the degrees of freedom for model $b$. The $SS_{full}$ is the sum of squares residuals for the full model (largest model) i.e. the model with all the four interaction terms. $DF_{full}$ is the degrees of freedom for the full model.

**Performance measure-Latency:** Table 5.1 shows the ANOVA results. Columns 4-6 show the results for the response variable *latency*. We start with an initial model with all the 4-way interactions and compare it with all 3-way interactions model. Model 14 is being compared with model 13. The $F$-test, $0.67$, shows that the model 13 fits the data as well as model 14 so the four way interaction is not significant. Similarly, we try to find which 3-way interactions are significant and try to find the most important combination by dropping each 3-way term one at a time. Looking at the $F$-test results of model numbers 9 to 12, we find model 9 to be the most significant and model 12 to be marginally significant. From that we conclude that the router, MAC and injection rates interact most significantly. Also, the network, router and the MAC interact significantly in 3-way interaction. Note that these were the combinations that were dropped off in models 9 and 12.

To find out if there is a smaller model i.e. model with 2-way interactions that can fit the data as well as the 3-way interaction model, we further look at the 2-way interaction models. We start by looking at a complete 2-way interaction model, i.e. model number 8 and then drop off one term at a time. The $F$-test values conclude that the most of the 2-way interactions are significant. The only exception is the interaction between router and injection rate. Now we create a model with only the 2-way significant interaction terms and compare it with a model containing only the 3-way significant terms to find that the smallest model that fits the data. If the $F$-test for these two models turns out to be significant, we conclude that the smallest model includes $[NRM][RMI]$, which means that these 3-way interactions cannot be explained by the 2-way model and hence cannot be dropped off. Our results find that to be true implying that indeed $[NRM][RMI]$ is the smallest possible model.

| Response Variable | | | Latency | | | Num. of Packets Recd. | | | Fairness | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Interaction | Source | $SS$ | $DF$ | $F$-**test** | $SS$ | $DF$ | $F$-**test** | $SS$ | $DF$ | $F$-**test** |
| 1 | All 1-way | $[N][R][M][I]$ | 18733.78 | 1611 | $12.61^*$ | 1875199 | 1611 | $21.92^*$ | $3.86 \times 10^9$ | 801 | $5.48^*$ |
| 2 | 2-way | $[NR][NM][NI][RM][RI]$ | 16429.57 | 1591 | $15.22^*$ | 1535050 | 1591 | $31.77^*$ | $3.33 \times 10^9$ | 781 | 1.38 |
| 3 | 2-way | $[NR][NM][NI][RM][MI]$ | 15882.91 | 1591 | 0.88 | 1433837 | 1591 | 2.08 | $3.31 \times 10^9$ | 781 | 0.59 |
| 4 | 2-way | $[NR][NM][NI][RI][MI]$ | 16434.59 | 1591 | $15.35^*$ | 1454324 | 1591 | $8.09^*$ | $3.71 \times 10^9$ | 781 | $24.21^*$ |
| 5 | 2-way | $[NR][NM][RM][RI][MI]$ | 15998.74 | 1591 | $3.91^*$ | 1465026 | 1591 | $11.23^*$ | $3.32 \times 10^9$ | 781 | 0.81 |
| 6 | 2-way | $[NR][NI][RM][RI][MI]$ | 17168.48 | 1591 | $34.60^*$ | 1682018 | 1591 | $74.88^*$ | $3.36 \times 10^9$ | 781 | $3.6^*$ |
| 7 | 2-way | $[NM][NI][RM][RI][MI]$ | 16069.16 | 1591 | $5.77^*$ | 1438545 | 1591 | $3.46^*$ | $3.34 \times 10^9$ | 781 | 2.3 |
| 8 | All 2-way | $[NR][NM][NI][RM][RI][MI]$ | 15849.33 | 1587 | $3.5^*$ | 1426720 | 1587 | $3.71^*$ | $3.30 \times 10^9$ | 777 | 0.77 |
| 9 | 3-way | $[NRM][NRI][NMI]$ | 15346.48 | 1563 | $7.5^*$ | 1393866 | 1563 | $10.05^*$ | $3.182 \times 10^9$ | 753 | 0.89 |
| 10 | 3-way | $[NRM][NRI][RMI]$ | 14908.73 | 1563 | 1.76 | 1331645 | 1563 | 0.93 | $3.188 \times 10^9$ | 753 | 1.07 |
| 11 | 3-way | $[NRM][NMI][RMI]$ | 14919.62 | 1563 | 1.91 | 1329497 | 1563 | 0.61 | $3.181 \times 10^9$ | 753 | 0.88 |
| 12 | 3-way | $[NRI][NMI][RMI]$ | 14999.95 | 1563 | $2.9^*$ | 1347649 | 1563 | $3.27^*$ | $3.21 \times 10^9$ | 753 | 1.75 |
| 13 | All 3-way | $[NRM][NRI][NMI][RMI]$ | 14774 | 1555 | 0.67 | 1325312 | 1555 | 0.99 | $3.15 \times 10^9$ | 745 | 1.15 |
| 14 | All 4-way | $[NRMI]$ | 14672.34 | 1539 | | 1311724 | 1539 | | $3.07 \times 10^9$ | 729 | |

Table 5.1: **Results of Four-Factor ANOVA:** This table shows results of four-factor ANOVA where the factors are network topology, routing protocol, MAC protocol and the injection rate. The *response variable or the performance measures are the* latency, number of packets received and fairness. $*$ shows that the $F$-test is significant at 99% confidence level.

**Performance measure-Number of packets received:** Columns 7, 8 and 9 in Table 5.1 show the ANOVA results for the response variable “packets received”. The interpretation of the results is similar to the response variable “latency”. The interaction results are also very similar to the latency results. Again we find that the four factor interaction is not significant. Among the 3-way interactions, $F$-test shows that the network, MAC and injection rates interact most significantly. The network, router and the MAC also interact significantly in 3-way interaction. Among the 2-way interaction terms, the router and injection rates are the only ones that show insignificant interaction, all other 2-way interactions turned out to be significant. As before, we find that the router and injection rate have very significant interaction in affecting the number of packets received. In this case also, the smallest model has only $[NRM][RMI]$ 3-way interaction terms.

**Performance measure: Fairness** The last three columns of Table 5.1 shows the ANOVA results for various models using long term fairness as the performance measure. The initial setup for a four way interaction effect of the factors on the fairness measure is done as explained before. The only exception is that now we have 10 runs instead of 20 for each of the 81 scenarios mentioned above.[3] The results show that both 4-way and 3-way interactions are insignificant in affecting the fairness. Looking at the results of 2-way interactions between the factors, we find that the router and MAC protocol interact in the most significant way in affecting the fairness. The interaction between the network and MAC is also significant but not to the extent of router and MAC interaction. In this case, the smallest model has only $[RM][NM]$ 2-way interaction terms.

## 5.6 Explaining the Statistical Results

We try to give some more insight into the statistical results presented in Section 5.5. We carried out additional investigation on the spatial distribution of MAC layer control packets generated in our simulations. The MAC layer usually plays an important role in forming various kinds of interactions. We can see that from the results in the previous section where the MAC layer interacted with almost any other input parameter. In this particular experiment setup the interactions were either 2-way or 3-way. To demonstrate these results we focus on grid squared network with medium connectivity with two parallel connections shown in Figure 5.5(a)(A). The experiment setup

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[3] This is due to the fact that fairness measure is calculated by taking a ratio of the number of packets received for the two connections.

| Medium Connectivity Grid: Performance Range from High to Low Injection Rate | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 802.11 | | | CSMA | | | MACA | | |
| | AODV | DSR | LAR1 | AODV | DSR | LAR1 | AODV | DSR | LAR1 |
| Latency | 0.009-0.02 | 0.01-0.02 | 0.01-0.02 | 0.02-0.01 | 2-3 | 0.02-0.04 | 2-0.02 | 1-0.05 | 1-0.04 |
| %Pkts. | 100-100 | 100-100 | 100-100 | 90-98 | 75-64 | 92-97 | 62-88 | 62-83 | 72-98 |
| High Connectivity Grid: Performance Range from High to Low Injection Rate | | | | | | | | | |
| | 802.11 | | | CSMA | | | MACA | | |
| | AODV | DSR | LAR1 | AODV | DSR | LAR1 | AODV | DSR | LAR1 |
| Latency | 0.01-0.01 | 0.01-0.01 | 0.01-0.02 | 0.02-.05 | 1-4 | 0.01-1 | 10-0.01 | 4-0.06 | 9-1 |
| %Pkts. | 100-100 | 100-100 | 100-100 | 53-58 | 36-25 | 38-23 | 8-80 | 10-75 | 23-72 |
| Corridor Grid: Performance Range from High to Low Injection Rate | | | | | | | | | |
| | 802.11 | | | CSMA | | | MACA | | |
| | AODV | DSR | LAR1 | AODV | DSR | LAR1 | AODV | DSR | LAR1 |
| Latency | 2-0.02 | 6-0.06 | 3-2 | 0.01-0.03 | 3-3 | 0.01-0.06 | 2-0.02 | 3-0.09 | 2-0.04 |
| %Pkts. | 10-88 | 18-85 | 20-62 | 48-50 | 38-40 | 58-56 | 20-76 | 18-52 | 18-68 |

Table 5.2: This table shows the latency and number of packets received (%) for low and high injection rates for the three grid considered i.e. medium connectivity, high connectivity and corridor grid.

was identical to the setup in the previous section. Results about the numbers of MAC layer control packets are shown in Figure 5.6, 5.7, 5.8 . We only show graphical results for the 802.11 protocol.

Important observations made about the identified interaction terms are:

1. The routing protocols failed to find the theoretical shortest path in most cases. We can see that bars representing the number of MAC layer control packets emitted by a given (grid) node are off the shortest paths (0,6) to (0,0) and (6,6) to (6,0) (see Figures 5.6 to 5.8). It is no surprise then that MAC layer and routing layer are part of the 2-way and 3-way interaction terms.
2. Interaction depends on topology. It is obvious that sparser networks produce less interaction. This is mainly result of largely eliminated interference between the routing and MAC layer. Note that two of the three topologies can be classified as dense – high connectivity grid and corridor grid.
3. The influence of injection rate is comparable to the influence of topology. Medium injection rate tends to produce the highest number of MAC layer data packets. The reason is that at low injection rate there is less need for medium access negotiation (collisions are less often) and at high injection rate there are many data packets drops.
4. Our results show that in case of fairness injection rate is not significant. Long term fairness disregards latency and ratio of data packets received. Only relative ratio of data packets received between connections is important. This is especially true in cases such as our when we have only two connections with equal amount of traffic.
5. To determine interaction terms without resorting to a statistical method such as ANOVA can be very complicated. This can be seen if we try to inspect the data produced by a multitude of simulation runs. This data needs to get analyzed and that can be very challenging task in case of e.g. highly mobile ad hoc networks or networks with time dependent amount of traffic.

## 5.7 Concluding Remarks

In this chapter we undertook a detailed study to quantify the effects of ad-hoc routing protocols on MAC protocols. The study extends the earlier simulation based experi-

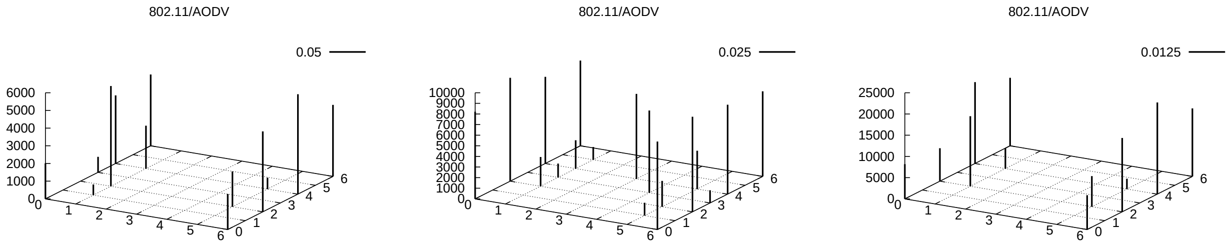

Figure 5.6: MAC control packets for (802.11,AODV) combination for three different injection rates (.05, .025, .0125). The figure shows the average number of MAC layer control packets for a given node over 10 simulation runs. For a specific run the number of MAC layer control packets was computed as the number of control packets emitted by a given node, i.e. the sum of RTS, CTS and ACK packets sent out.

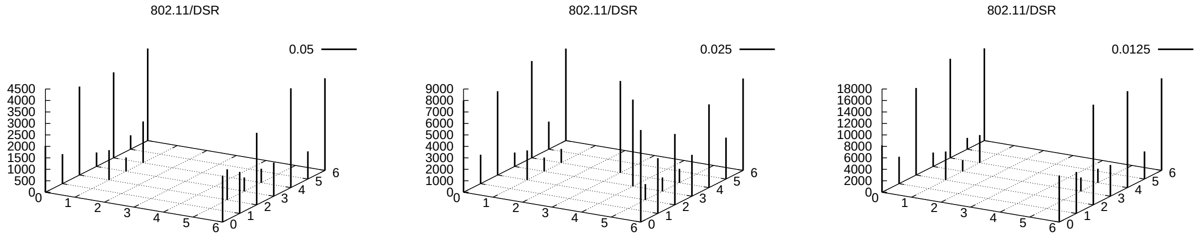

Figure 5.7: MAC control packets for (802.11,DSR) combination for three different injection rates (.05, .025, .0125). The figure shows the average number of MAC layer control packets for a given node over 10 simulation runs.

mental studies in [DPR00, DP+, BM+98, KV98, RLP00, RS96]. Intuitively it is clear that different levels in the protocol stack should affect each other in most cases. This issue needs to be investigated in greater detail; our results point out some of the subtleties involved.

They show that the paths chosen by routing protocol can significantly affect the MAC layer protocol especially with regards to inequitable assignment of channel resources. Combined with the results of [KKB00, RLP00], our results show that discussion about the performance of a MAC layer cannot typically be carried out without putting it in context of the other protocols in the stack. Specifically, we show that the performance of MAC protocols depends on what paths are chosen by the routing protocols to send packets. Intuitively, it is obvious that if the virtual paths corresponding to two connections intersect then they should yield different dynamics than when the paths do not. This is exactly what happens; moreover, given the randomized nature

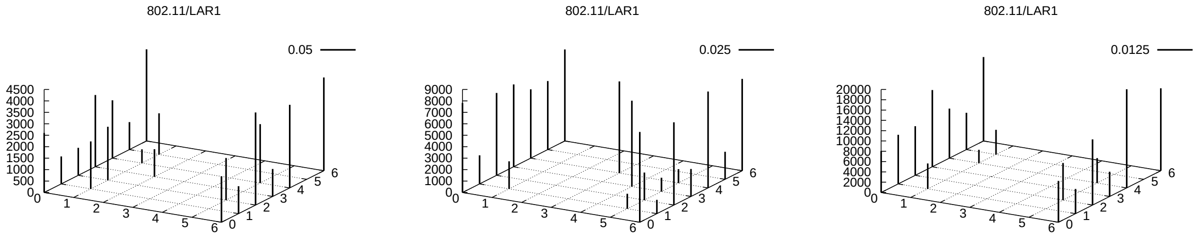

Figure 5.8: MAC control packets for (802.11,LAR1) combination for three different injection rates (.05, .025, .0125). The figure shows the average number of MAC layer control packets for a given node over 10 simulation runs.

of the protocols, it is hard to predict exactly the paths the routing protocols are going to choose. As a result all the MAC protocols exhibit varying levels of performance.

An important implication of our results and those in [BS+97, RLP00] suggest that optimizing the performance of the communication network by optimizing the performance of individual layers is not likely to work beyond a certain point. We need to treat the entire stack as a single algorithmic construct in order to improve the performance. Specifically, optimizing a particular layer might improve the performance of that layer locally but might produce non-intuitive side effects that will degrade the overall system performance. The issue is likely to become more important in ad hoc networks where the topology is changing constantly and hence it is not even easy to discern what shortest paths mean.

# Chapter 6

# Mobility and Quality of Service

## 6.1 Our Contributions

In this chapter we present a comprehensive simulation based experimental analysis to characterize the interaction between MAC and routing protocols in *mobile* ad-hoc networks. The need to study this sort of interactions has been underlined in the earlier work by Balakrishnan et al. [BS+97, KKB00] and by the recent results by Royer et al. [DPR00, DP+, RLP00].

We employ three different mobility models: (i) grid mobility model that simulates movement of nodes in a town with grid architecture, (ii) the random waypoint mobility model that approximates mobility in square area but the directionality and duration is random, and (iii) the exponentially correlated random mobility model [RS98] that approximates movement of groups of nodes in a square area. The models are all qualitatively different. At one extreme is the random waypoint movement model with no predictable movement, while on the other extreme is the ECR model where points form clusters and these clusters move in fairly deterministic fashion. The grid mobility model is somewhere in the middle.

Apart from mobility patterns, we study the effect of speeds and injection rates of packets on the system performance. Thus our input variables are:

1. **Routing protocols:** AODV, DSR, LAR1. These are denoted by $R_i,\ 1 \leq i \leq 3$. The set of routing protocols will be denoted by $R$. The routing protocols were chosen keeping in mind the recommendations made by [DPR00, JL+00] after undertaking a detailed experimental study of recent routing protocols.

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This chapter is a result of joint work with Chris Barrett, Achla Marathe, and Madhav Marathe. See [BD+02b, BD+03b] for reference.

2. **Speed of Nodes:** 10m/s, 20m/s and 40m/s.[1] These are denoted by $S_j,\ 1 \leq j \leq 3$. The set of all speeds will be denoted by $S$.
3. **MAC protocols:** 802.11, CSMA and MACA. These are denoted by $M_k,\ 1 \leq k \leq 3$. The set of MAC protocols will be denoted by $M$. Again the choice of these protocols is based on the study in [RLP00, WS+97].
4. **Injection rates:** low (0.05 second), medium (0.025 second) and high (0.0125 second). The injection rates are denoted by $I_l,\ 1 \leq l \leq 3$. The set of injection rates will be denoted by $I$.

Our evaluation criteria consists of following basic metrics: (i) *Latency:* Average end to end delay for each packet as measured in seconds, and includes all possible delays caused by buffering during route discovery, latency, queuing and backoffs, (ii) Total number of packets received (and in some cases packet delivery fraction) (iii) Long term fairness of the protocols, i.e. the proportional allocation of resources given to each active connection and (iv) *Control Overhead:* The number of control packets used by MAC and routing layers. Each of the input parameters and the performance measures considered here is used in one of the earlier experimental studies [DPR00, DP+, BM+98, KV98, RLP00, RS98]. We briefly comment on the parameters chosen in [DPR00, RLP00] since the two studies are closest to the one in this thesis. The authors consider two parameters that we have not varied in this simulation: (i) Pause time in movement models and (ii) total number of connections. In our case the pause time is always 0 and the number of connections have always been kept constant. On the other hand, we vary (i) the injection rate, (ii) the movement models and (iii) speeds. These parameters are kept constant in [DPR00, RLP00]. Based on the discussion in [DPR00], a pause time of zero and our injection rates which start at .05 second and up imply that our scenarios might be considered “stressful”. Most of our results agree with their general findings in this regime.

Each combination of the input variable corresponds to a *scenario*. The total number of scenarios considered is $3^4 = 81$. We ran each scenario 10 times to get a reasonable sample size for statistical analysis. This resulted in 810 runs. We constructed 3 basic experiments: each corresponding to one of the mobility models. For each of these mobility models, we have 81 scenarios and 810 runs. In our experiments, we make two important observations. (i) All parameters considered here are *important* and cannot be *ignored*. Specifically, the results show that two and three way interactions are quite common; also, the interacting variables differ for different response

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[1] m/s stands for meters per second.

variables (performance measure). Thus omitting any of these parameters is not likely to yield meaningful conclusions. (ii) The variation in parameters represents realistic possibilities. Other closely related studies have also considered similar parameters. See [RLP00, DPR00, DP+].

Given the large number of variables involved i.e. MAC, router, injection rate, nodes' speed, mobility and several levels of each variables, it is hard to derive any meaningful conclusions by merely studying plots and tables.

In order to effectively deal with the combinatorial explosion, and to draw conclusions with certain level of precision and confidence, we resort to well known techniques in statistics that can simultaneously and effectively handle such data sets. We setup a *factorial experimental design* and measure the response of 3 important response variables (output metrics). We again use analysis of variance (ANOVA) to perform statistical analysis. A methodological contribution of this thesis is to use *statistical methods* to characterize the interaction between the *protocols, injection rates* and *speed.*[2] Even though it is widely believed that these parameters interact in affecting the performance measure, to our knowledge a formal study such as the one undertaken in this thesis has not been previously done. The simple statistical methods used here for analysis of network/protocol performance modeling are of independent interest and can be used in several other contexts.

While intuitively it is clear that different levels in the protocol stack should affect each other in most cases; to the best of our knowledge a thorough understanding of this interaction is lacking. The only related references in this direction that we are aware of are [BS+97, KKB00, RLP00, DPR00, DP+]. In [KKB00], the authors were specifically considering TCP/IP protocol and have devised an elegant snoop protocol that conceptually sits between the transport layer and the network layer to overcome this problem. It also point out how short term fairness of the MAC can affect the TCP/IP performance which in turn can affect the overall performance of the communication system. In [RLP00] the authors considered performance of routing and the effect of MAC layers on routing protocols. Our results can be viewed as furthering the study initiated in [RLP00][3] in the following ways:

1. In [RLP00], the authors consider a multitude of routing and MAC protocols as considered here. But the authors did not consider simultaneously the effect of injection rates, spatial location of connections and mobility models in charac-

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[2] The statistical techniques used in this thesis are well known and routine; but to our knowledge have not been previously applied in our setting.

[3] We are not aware of other such studies in the literature.

terizing the interaction. As our results show each of these parameters play a significant role in characterizing interaction.

2. Statistical methods to characterize and quantify interactions between protocols have not been considered prior to this thesis. Moreover, we characterize the interaction not only between the MAC and Routing protocols but also between other input parameters and show that in many cases are significant.
3. In [RLP00], the authors *leave open the question of characterizing the interplay between On Demand Routing protocols and MAC protocols.* This thesis takes the first step in this direction and considers AODV and DSR (both of which are on demand routing protocols). Our findings show that these protocols exhibit different levels of variations due to MAC protocols.
4. Finally, the thesis not only aims to study the effects of MAC layer on routing layer but also studies the effect of routing layer on the MAC layer. The results show that the interaction is both ways: routing layers affect MAC layers and MAC layers affect routing layers.

### 6.1.1 Summary of Experiment Specific Results

We first summarize results specific to each experiment.

***Experiment 1: Grid mobility model.*** CSMA and MACA did not perform well. For MACA, this was accompanied with an extreme increase in MAC layer control packets generated. Interaction between MAC and routing layer protocols is quite apparent. Control packets at the routing layer in many cases failed to deliver the route to the source. This was especially apparent at higher speeds and agrees with the earlier experimental studies [DPR00, DP+, BM+98, KV98, RLP00, RS98]. This caused the data packets to spend inordinate amounts of time in the node buffers and their subsequent removal due to time-outs. Number of control packets for 802.11 was also extremely high and varied under different routing protocols. Yet it is fair to say that it performed substantially better than CSMA and MACA at low speeds. As for the routing protocols, AODV performed better than DSR, or LAR scheme 1 – demonstrating an advantage of distributed routing (AODV) information handling over centralized (DSR).

***Experiment 2: Random waypoint model.*** This experiment illustrated the difference as measured by response variables between models in which movement of nodes is correlated in some way versus models in which the node movement is by and large random. The temporal variance of individual node degrees and connectivity is quite high. As a result, the performance parameters exhibit the worst behavior under this movement model as compared to other movement models. CSMA and MACA performed poorly. Performance of 802.11 depended on the routing protocol used, and performed best with AODV.

***Experiment 3: Exponentially correlated random model.*** ECRM represents a mobility model that keeps relative distances of nodes within a group roughly constant. Moreover, the nodal degree and connectivity characteristics of nodes within a group stay roughly the same and this feature positively influences performance. Performance of 802.11 with this model is very good, and performance of MACA shows significant improvement over the random waypoint model. Performance of CSMA is again very poor. The correlated movement of nodes within a group facilitated routing and decreased the number of control packets at the MAC as well as the routing layer.

### 6.1.2 Broad Conclusions and Implications

1. The performance of the network varies widely with varying mobility models, packet injection rates and speeds; and can in fact be characterized as fair to poor depending on the specific situation. No single MAC or routing protocol, as well as, no single MAC/routing protocol combination dominated the other protocols in their respective class across various measures of performance. Nevertheless, in general, it appears that the combination of AODV and 802.11 is typically better than other combination of routing and MAC protocols. This is in agreement with the results of [DPR00, RLP00].

2. MAC layer protocols *interact* with routing layer protocols. This concept which is formalized in Section 6.2 and 6.4 implies that in general it is not meaningful to speak about a MAC or a routing protocol in isolation. See Figure 6.1 for a summary of results on interactions. Such interactions lead to trade-offs between the amount of control packets generated by each layer. More interestingly, the results raise the possibility of improving the performance of a particular MAC layer protocol by using a cleverly designed routing protocol or vice-versa.

3. Routing protocols with distributed knowledge about routes are more suitable for networks with mobility. This is seen by comparing the performance of AODV with DSR or LAR scheme 1. In DSR and LAR scheme 1, information about a computed path is being stored in the route query control packet.

1. **Grid Mobility Model**
    (a) **Latency:** Significant 3 way interaction – Routing protocols, Transceiver (node) speeds and the MAC protocols interact significantly.
    (b) **Number of packets received:** Significant 4-way interaction – Routing protocols, Transceiver (node) speed, Injection rate and the MAC protocols interact significantly.
    (c) **Long term Fairness:** 2 kinds of 2-way interactions – Routing protocol/MAC-protocol and MAC-protocol/Injection Rate are significant.
2. **ECR Mobility Model**
    (a) **Latency:** Significant 3 way interaction – Routing protocols, Transceiver (node) speeds and the MAC protocols interact significantly.
    (b) **Number of packets received:** All 2-way interactions *except* Routing protocol/Injection rate and Routing Protocol/Transceiver Speed are significant.
    (c) **Long term Fairness:** Only Routing protocols and MAC protocols interact. All other interactions are completely insignificant.
3. **Random Waypoint Mobility Model**
    (a) **Latency:** Unlike the first two mobility models, there is no 3-way interaction when latency is used as the response measure. Among 2-way interactions, the only significant ones are MAC protocols/injection rate, Routing protocols/Transceiver speed and Routing protocols/MAC-protocol.
    (b) **Number of packets received: All** 2-way interactions are significant.
    (c) **Long term Fairness:** The only 2-way interactions that are significant are MAC protocol/Injection rate and Routing protocol/MAC protocols.

Figure 6.1: Brief Summary of Statistical Results on Interactions Between Various Input Variables.

4. MAC layer protocols have varying performance with varying mobility models. It is not only speed that influences the performance but also node degree and connectivity of the dynamic network that affects the protocol performance.

## 6.2 Characterizing Interaction

An important research question we study is whether the four factors i.e. routing protocol, nodes' speed, MAC protocol and injection rate interact with each other in a significant way. Of particular interest is to characterize the interaction between the MAC and the routing protocols.

**Example 1:**[4] Figure 6.2 (a) shows a simple grid. We have two connections, both running from left to right. One connection is at the top of the grid and the other connection is at the bottom of the grid. (A) An example of a situation when the routing protocol found the shortest path. Thus, there was no interaction between the two paths shown with the actual hops. The MAC layer transmitted 1,000 packets per connection and the latency was 0.017s. (B) Illustrates a situation when the routing protocol found a route that is really bad. The packets received were 2 for the upper connection and 993 for the lower connection. The latency was 0.17s for the upper connection and 0.014s for the lower connection. (C) This shows situation that lies in between the previous two situations. Packets received for the upper and lower connections were 425 and 983 respectively. The latency for the upper connection was 0.028 seconds and for the lower connection 0.0175 seconds.

**Example 2:** We show the interaction between MAC and routing layer. The interaction is measured by the variation in the number of control packets generated by each layer. We used two routing protocols: AODV and DSR. The MAC protocols used were MACA and 802.11. Interestingly, quantifying CSMA interaction is somewhat harder to measure since it does not generate any control packets per se. We could have used the number of back-offs as a proxy variable though. For illustrative purposes, the experiments were done on a *static grid.* This is done since it allows us to show a spatial distribution of control packets and thus argue about long range interactions. The network is shown in Figure 6.2(b). There is a transmitter at each grid point and each transmitter has the same range. Figure shows the range for one of the transmitter via a dotted quarter circle. There are two connections. The first connection starts at node $(1, 0)$ and ends at node $(1, 6)$. The second connection starts at node $(5, 0)$ and ends at node $(5, 6)$. We consider four combinations obtained by using MACA and 802.11 as MAC protocols and AODV and DSR as routing protocols. Figure 6.3 shows two different types of plots one for each combination (8 plots in total). The quantities plotted are: (i) distribution of MAC overhead packets and (ii) distribution of Routing overhead packets. From the figures it is clear that the different combination yield different levels of overhead. This phenomenon becomes more pronounced in the presence of mobility; the aim of the example is to explain the basic idea. We have also plotted a spatial distribution of these control packets depicting the control packets produced at each node. Figure 6.4 shows examples of MAC/routing overhead for three different

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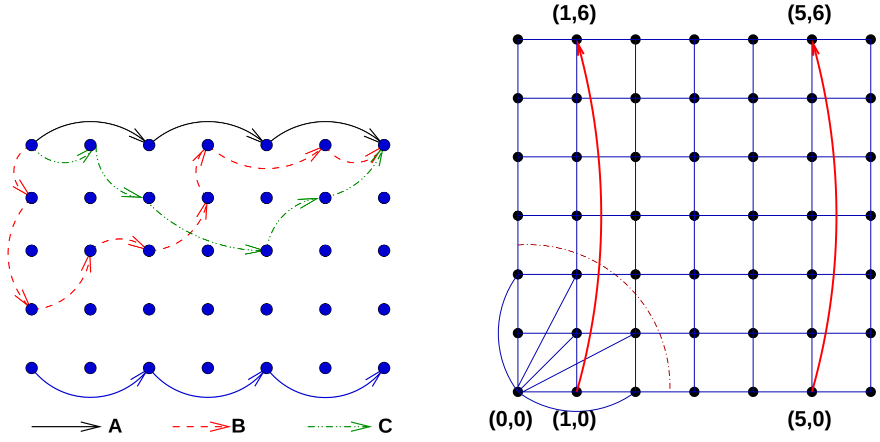
[4] The setup for Examples 1 and 2 is: two connections, each with 1,000 data packets injected over 100 second simulations time; injection rate 0.1 second; MAC protocol 802.11 for Example 1, 802.11 and MACA for Example 2; routing protocol: AODV for Example 1, AODV and DSR for Example 2.

(MAC, Routing) protocol combination. The square grid is represented in the $(X, Y)$-plane and the the height of the bars denotes the average number of MAC/Routing control packets generated over 10 runs at each transceiver. Interestingly, as the figures show, the routing protocol tries to discover non-interfering paths. The results clearly demonstrate protocol level interaction. They also show that the spatial distribution of the overhead packets vary; this aspect is harder to demonstrate for dynamic networks. This includes the number of overhead packets and the paths used to move the packets.



(a) (b)

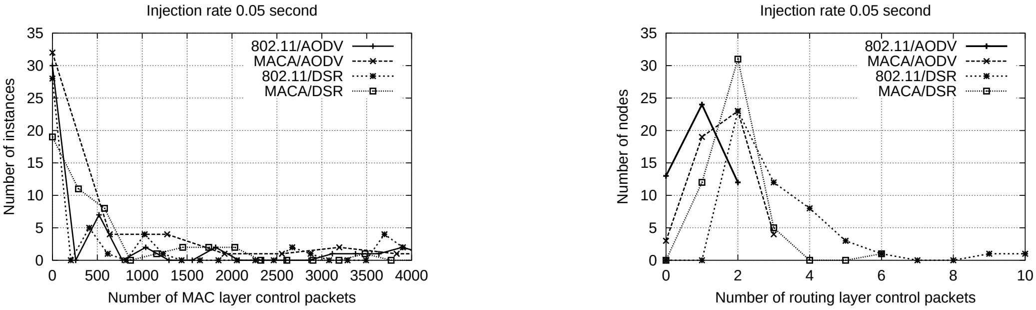
Figure 6.2: (a) Illustration of Example 1. (a) Figure illustrating the different paths used by a routing protocol. (b) Set up for Experiment 2. The figure schematically illustrates the connectivity of the graph. For clarity only the edges incident on the node $(0,0)$ are shown. The dotted arc shows the transceiver's radio range.

## 6.3 Experimental Setup

The overview of the parameters can be found in Figure 6.5.

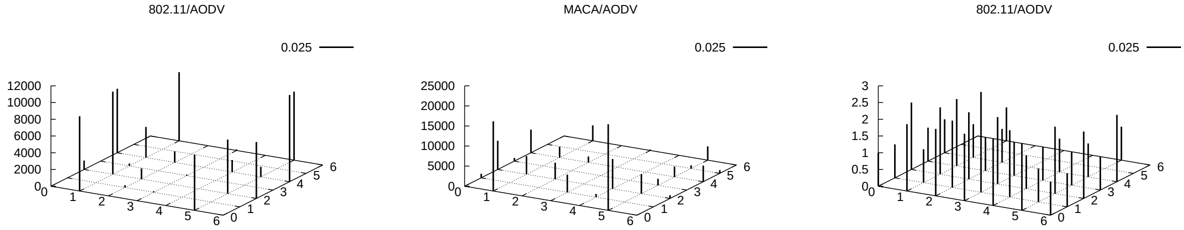
### 6.3.1 Mobility Models

The results show that the routing protocol can significantly affect the MAC layer protocols and vice-versa. The paths taken by the routing protocol, induce a virtual network by exciting the MAC protocols at particular nodes. Conversely, contention at the MAC layer can cause a routing protocol to respond by initiating new route queries and



(a) (b)

Figure 6.3: Figure showing the MAC and routing overhead packet distribution for Example 2. The network is as shown in Figure 6.2(b). Each figure consists of four plots: one for each MAC/routing protocol combination. (a) The left plot shows the MAC overhead packet distribution. (b) The right plot shows the routing overhead packet distribution. Example: from the right hand figure we can see that for the combination 802.11 and AODV there were 24 nodes with just a single routing control packet emitted, and 13 nodes with no routing control packets emitted.



(a) (b) (c)

Figure 6.4: Figure showing the spatial distribution of the control overhead for Example 2. The network is as shown in Figure 6.2(b). All the plots are for injection rate of 0.025 seconds. (a) Left: Results for MAC layer overhead for (802.11,AODV). (b) Center: Results for MAC layer overhead for (MACA,AODV) combination. Although the number of MAC overhead packets appears low, it is because the percentage of packets delivered using this combination is substantially lower than what is delivered using (802.11,AODV) combination. (c) Right: Results for Routing layer overhead for (802.11, AODV) combination. The number of control packets was computed as average number of control packets emitted by a given node over 10 simulation runs, i.e. in case of MAC layer control packets it was a sum of RTS, CTS and ACK packets, and in case of routing layer control packets it was a sum of RREQ, RREP packets.

1. **Network Topology:** We describe the experiment specific topologies in respective sections.
2. **Number of connections:** We use two connections.
3. **Routing protocols** : AODV, DSR, LAR scheme 1.
4. **MAC protocol:** IEEE 802.11 DCF, CSMA, MACA.
5. The size of physical area simulated was $600 \times 600$ meters.
6. Movement of nodes at 10 m/s, 20 m/s, 40 m/s.
7. The initial packet size was 256 bytes, the initial number of packets was 2,000, and the initial injection interval was 0.05 second. Each time the injection interval was reduced by a factor of 2, we also reduced the packet size by a factor of 2 but increased the number of packets by a factor of 2. For example, if the injection interval was halved to 0.025 seconds then the new packet size was 128 bytes and the new number of packets was 4,000. This allowed us to keep the injection at input nodes constant in terms of bits per second.
8. The bandwidth for each channel was set to 1Mbit. Other radio propagation model details are as follows: (i) Propagation path-loss model: two ray (ii) Channel bandwidth: 1 Mb (iii) Channel frequency: 2.4 GHz (iv) Topography: Line-of-sight (v) Radio type: Accnoise (vi) Network protocol: IP (vii) Connection type: UDP
9. **Simulator used:** GloMoSim.
10. The transmission range of transceiver was 250 meters.
11. Number of simulation runs: 10 for each combination of input parameters.
12. The simulation time was 100 seconds.
13. Hardware used in all cases was a Linux PC with 512MB of RAM memory, and Pentium III 500MHz microprocessor.

Figure 6.5: Parameters used in the Experiments.

routing table updates. Combined with the results of [KKB00, RLP00], our results show that discussion about the performance of a MAC or a routing layer cannot typically be carried out without putting it in context of the other protocols in the stack. Moreover given the randomized nature of the protocols and constant movement of transceivers in an ad-hoc environment makes the problem of engineering these protocols significantly harder.

**Grid Mobility Model:** The setup of this experiment is a grid network of $7 \times 7$ nodes. The grid unit is 100 meters. There are 49 nodes that are positioned on the grid. See Figure 6.6(a). The mobility model follows movement in an area with grid architecture, i.e., nodes at $(i, j)$ move only to one of the 4 adjacent grid sites. If a node reaches a boundary, it is reflected back and continues to move with the same speed. Let the node IDs range from $0$ to $48$; the IDs are assigned row wise starting from the top and from left to right.

The movement of the nodes is described quite simply. Let $0 \leq k \leq 48$. Nodes belonging to the equivalence class $0 \equiv k (\bmod 4)$ start moving to the South, nodes belonging to the class $1 \equiv k (\bmod 4)$ start moving to the North, nodes belonging to the class $2 \equiv k (\bmod 4)$ start moving to the East and nodes belonging to the class $3 \equiv k (\bmod 4)$ start moving to the West. When a node reaches the end of the grid, movement of the node is reversed. This is essentially reflecting the boundary condition as opposed to periodic boundary condition used in many other contexts. We run the simulation with three different node speeds: 10 m/s, 20 m/s, 40 m/s.

**Random Waypoint model:** The setup of this experiment is again a grid network of $7 \times 7$ nodes. The grid unit is 100 meters. There are 49 nodes (numbered 0 to 48) that are positioned on the grid. In this model nodes move from the current position to a new randomly generated position at a predetermined speed. After reaching the new destination a new random position is computed. There are no stop-overs, i.e., nodes start moving immediately to a new destination. This setup is depicted in Figure 6.6(b).

**ECR Model:** The setup of this experiment is an area of $600 \times 600$ meters onto which we uniformly randomly position $49$ nodes. Let the nodes be numbered from $0$ to $48$ in the order they are positioned onto the grid. We divide the nodes into four groups. Nodes belonging to the class $0 \equiv k \pmod 4$ form the first group, nodes belonging to the class $1 \equiv k \pmod 4$ form the second group, nodes belonging to the class $2 \equiv k \pmod 4$ form the third group, and nodes belonging to the class $3 \equiv k \pmod 4$ form the fourth group. The setup is shown in Figure 6.6(c). The four groups follow the exponentially correlated random model described by an equation of the form $\mathbf{x}(t+1) = \mathbf{x}(t)e^{(-1/\tau)} + s \cdot \sigma \cdot r \cdot \sqrt{1 - e^{(-2/\tau)}}$ where: (i) $\mathbf{x}(t)$ is the position $(r, \alpha)$ of a group at time $t$, (ii) $\tau$ is a time constant that regulates the rate of change, (iii) $\sigma$ is the variance that regulates the variance of change, (iv) $s$ is the velocity of the group, and (v) $r$ is Gaussian random variable. Let $\gamma_i$ be the orientation of the velocity vector $s$ for the $i$-th group. The orientation is assigned as follows: the first group - south, the second group - north, the third group - east, the fourth group - west. Should a node reach boundaries of the area its orientation is reversed. After all nodes' orientation is reversed, the group starts moving to the opposite direction.

## 6.4 Statistical Analysis

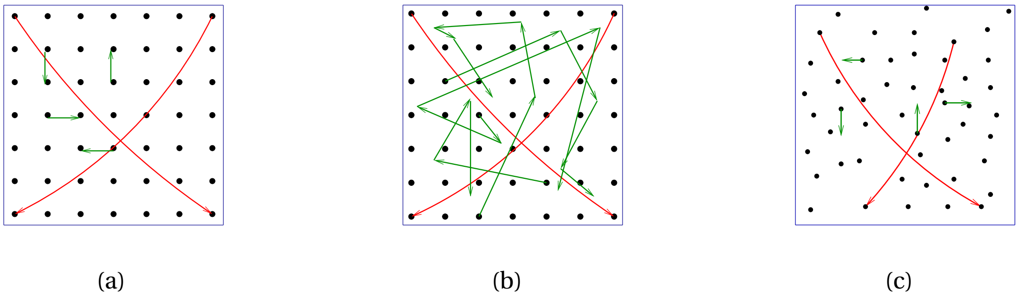

(a) (b) (c)

Figure 6.6: (a) Grid mobility and (b) Random Waypoint Models. We position 49 nodes onto a $7 \times 7$ grid. The nodes are numbered from the top left corner in rowwise order. The figure gives an example for four chosen nodes. Movement for other nodes is not shown. There are two connections: the first one from the top left corner to the bottom right corner, and the second one from the top right corner to the bottom left corner. (c) Exponential correlated random mobility. We position 49 nodes uniformly onto a $600 \times 600$ meters area. The nodes are numbered in the order their random position is computed. The start movement depends on assignment of the four groups.

We set up a statistical experiment to evaluate the performance of the following four factors; the MAC protocol, routing protocol, the injection rate and the speed at which the nodes are moving in the network. Each of these four factors (variables) have three levels (values the variables take). The variables and their levels are given in Section 6.1.

In our analysis, we analyze, if the four factors, interact in their effect on the performance measure. We perform three different analysis, one for each performance measure to observe the interaction among factors. We perform a different set of experiments for each of the mobility models. Our general implications are summarized in Figure 6.1.

### 6.4.1 Experimental Setup for the Statistical Analysis

Each set of experiment utilizes three different combinations of MAC, router, injection rate and the speed; thus yielding $3^4 = 81$ different scenarios. Our performance matrix consists of three measures i.e. latency, number of packets received and the long term fairness.

**Approach**: We first construct a matrix of 4 dummy variables. For each factor we create a dummy variable. This variable takes a value 1, 2 and 3 for the three levels of the factor. For example, the dummy variable for MAC protocol, takes a value 1 whenever 802.11 is being used to calculate the performance matrix, value 2 whenever CSMA protocol is being used and value 3 whenever MACA is being used to calculate the performance matrix. For the router variable, the dummy takes a value of 1 whenever AODV protocol is being used and value 2 whenever DSR is being used and value 3 whenever LAR1 is being used to calculate the performance matrix. Similar dummies are created for the injection rate and the speed variables. Similarly to the previous chapter, to detect interactions between the factors, we use a statistical technique known as the *analysis of variance* (ANOVA). ANOVA is used to study the sources of variation, importance of different factors and their interrelations. The statistical details discussed below are routine and are provided for the convenience of the reader. Given that we have four factors, we use a four factor ANOVA.

**Mathematical Model:** The appropriate mathematical model for a four factor ANOVA is as follows:

$$y_{ijklm} = \mu + \alpha_i + \beta_j + \gamma_k + \delta_l + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\alpha\delta)_{il} + (\beta\gamma)_{jk} + (\beta\delta)_{jl} + (\gamma\delta)_{kl} +$$

$$+ (\alpha\beta\gamma)_{ijk} + (\alpha\beta\delta)_{ijl} + (\alpha\gamma\delta)_{ikl} + (\beta\gamma\delta)_{jkl} + (\alpha\beta\gamma\delta)_{ijkl} + \varepsilon_{ijklm}$$

where

1. $y_{ijklm}$ is the measurement of the performance variable (e.g. latency) for the $i^{th}$ routing protocol, $j^{th}$ speed, $k^{th}$ MAC protocol and $l^{th}$ injection rate.
2. $m$ is the number of samples which is 20 (10 runs) in our experiment.
3. $\alpha_i$ is the effect of routing protocol, $\beta_j$ is the effect of the speed of nodes, $\gamma_k$ is the effect of the MAC protocol and $\delta_l$ is the effect of the injection rate on the performance measures.
4. The **two way interaction terms** measure the interaction present between pairs of variables $(x, y)$ and are as follows:
   (a) $(\alpha\beta)_{ij}$: (routing protocol, speed of the nodes);
   (b) $(\alpha\gamma)_{ik}$: (routing protocol, MAC protocol);
   (c) $(\alpha\delta)_{il}$: (routing protocol, injection rates);
   (d) $(\beta\gamma)_{jk}$, (nodes' speed, MAC protocol);
   (e) $(\beta\delta)_{jl}$: (nodes' speed, injection rates);

   (f) $(\gamma\delta)_{kl}$, (MAC protocols, injection rate).

5. The **three way interaction terms** measure the interaction present between triples of variables $(x, y, z)$ and are as follows:
   (a) $(\alpha\beta\gamma)_{ijk}$: (routing protocol, nodes' speed, MAC protocol);
   (b) $(\alpha\beta\delta)_{ijl}$: (routing protocol, nodes' speed, injection rates);
   (c) $(\alpha\gamma\delta)_{ikl}$: (routing protocol, MAC protocol, injection rates);
   (d) $(\beta\gamma\delta)_{jkl}$: (nodes' speed, MAC protocol, injection rates).
6. The **four way interaction term** $(\alpha\beta\gamma\delta)_{ijkl}$ measures the four way interaction: (routing protocol, nodes' speed, MAC protocol, injection rate).
7. Finally, $\varepsilon_{ijklm}$ is the random error.

A scenario is a particular combination of MAC protocol, routing protocol, nodes' speed and injection rate. For example, CSMA, AODV, 10m/s and low injection rate would form one scenario. For each scenario we generate 20 samples for the analysis.

**Model Selection and Interpretation**: Similarly to the previous chapter we have used the stepwise method with backward elimination to exclude insignificant terms. We refer the reader to section 5.5 for details on this method. The sum of squares, degrees of freedom and the *F-test* value for the three experiments are in Table 6.1, 6.2, and 6.3.

### 6.4.2 Grid Mobility Model Results (Experiment 1)

*Performance measure: Latency.* In Table 6.1, we show the results for the Grid Mobility model using latency as the performance measure. We start with an initial model with all the 4-way interactions and compare it with all 3-way interactions model. Model 14 is being compared with model 13. The $F$-statistic of $0.65$ shows that the model 13 fits the data as well as model 14 so the four way interaction is not significant in affecting the latency measure. Similarly, we try to find all significant 3-way interactions by dropping each 3-way term one at a time. Looking at the $F$-test results of model numbers 9 to 12, we find model 12 to be the most significant. From that we conclude that the router, nodes' speed and the MAC protocol interact most significantly. Note that this was the combination that was dropped off from model 12. To find out if there is a smaller model that can fit the data as well as the 3-way interaction model, we further look at the 2-way interaction models. The $F$-test values conclude that the most

| Response Variable | | | Latency | | | Num. of Packets Recd. | | | Fairness | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Interaction | Source | $SS$ | $DF$ | $F$-**test** | $SS$ | $DF$ | $F$-**test** | $SS$ | $DF$ | $F$-**test** |
| 1 | All 1-way | $[R][S][M][I]$ | 87879 | 1611 | $7.01^*$ | 354609 | 1611 | $92.28^*$ | $7.3 \times 10^7$ | 801 | $3.35^*$ |
| 2 | 2-way | $[RS][RM][RI][SM][SI]$ | 80071 | 1591 | 2.9 | 283870 | 1591 | $347.24^*$ | $6.8 \times 10^7$ | 781 | $4.63^*$ |
| 3 | 2-way | $[RS][RM][RI][SM][MI]$ | 79705 | 1591 | 1.07 | 166571 | 1591 | $4.87^*$ | $6.7 \times 10^7$ | 781 | 2.47 |
| 4 | 2-way | $[RS][RM][RI][SI][MI]$ | 82480 | 1591 | $14.98^*$ | 189797 | 1591 | $72.66^*$ | $6.7 \times 10^7$ | 781 | 2.34 |
| 5 | 2-way | $[RS][RM][SM][SI][MI]$ | 79541 | 1591 | 0.24 | 172840 | 1591 | $23.16^*$ | $6.6 \times 10^7$ | 781 | 0.60 |
| 6 | 2-way | $[RS][RI][SM][SI][MI]$ | 83689 | 1591 | $21.05^*$ | 199212 | 1591 | $100.14^*$ | $6.9 \times 10^7$ | 781 | $8.80^*$ |
| 7 | 2-way | $[RM][RI][SM][SI][MI]$ | 79857 | 1591 | 1.83 | 166835 | 1591 | $5.64^*$ | $6.6 \times 10^7$ | 781 | 1.29 |
| 8 | All 2-way | $[RS][RM][RI][SM][SI][MI]$ | 79492 | 1587 | 1.41 | 164903 | 1587 | $9.69^*$ | $6.6 \times 10^7$ | 777 | 1.06 |
| 9 | 3-way | $[RSM][RSI][RMI]$ | 77310 | 1563 | 0.17 | 156619 | 1563 | $26.67^*$ | $6.3 \times 10^7$ | 753 | 0.62 |
| 10 | 3-way | $[RSM][RSI][SMI]$ | 77512 | 1563 | 0.68 | 140957 | 1563 | $3.81^*$ | $6.3 \times 10^7$ | 753 | 0.64 |
| 11 | 3-way | $[RSM][RMI][SMI]$ | 77377 | 1563 | 0.34 | 141359 | 1563 | $4.40^*$ | $6.4 \times 10^7$ | 753 | 1.06 |
| 12 | 3-way | $[RSI][RMI][SMI]$ | 79012 | 1563 | $4.44^*$ | 140992 | 1563 | $3.86^*$ | $6.4 \times 10^7$ | 753 | 1.93 |
| 13 | All 3-way | $[RSM][RSI][RMI][SMI]$ | 77240 | 1555 | 0.65 | 138342 | 1555 | $4.76^*$ | $6.3 \times 10^7$ | 745 | 0.80 |
| 14 | All 4-way | $[RSMI]$ | 76718 | 1539 | | 131816 | 1539 | | $6.2 \times 10^7$ | 729 | |

Table 6.1: ***(Experiment 1), Grid Mobility Model:*** This table shows results of four-factor ANOVA where the factors are the routing protocol, nodes' speed, MAC protocol and the injection rate. The *response variables or the performance measures are the* latency, number of packets received and long term fairness. Note that the degrees of freedom for the fairness measure is smaller than the other two measures. This is due to the fact that the long term fairness is calculated by taking the ratio of packets received for the two connections. Hence 20 samples lead to only 10 actual measurements for fairness. $*$ shows that the $F$-test is significant at 99% confidence level.

significant interaction is between the router and MAC. The other most significant 2-way interaction is between nodes' speed and MAC. The rest are all insignificant. This shows that the 3-way interaction between the router, nodes' speed and the MAC are due to the 2-way interaction between router-MAC and speed-MAC. There is no interaction between router and nodes' speed as far as the effect on latency is concerned. Now we create a model with only the 2-way significant interaction terms and compare it with a model containing only the 3-way significant terms to find the smallest model that fits the data. If the $F$-test for these two models turns out to be significant, we conclude that these 3-way interactions cannot be explained by the 2-way model and hence cannot be dropped off. Our results find that to be true, implying that indeed the smallest possible model, is the 3-way [RSM] model.

*Performance measure: Number of packets received.* Columns 7, 8 and 9 in Table 6.1 show the ANOVA results for the response variable "packets received". The interpretation of the results is similar to the response variable "latency". The interaction results show significant 4-way interaction between the router, nodes' speed, MAC and the injection rate in explaining the number of packets received. The 4-way interaction automatically implies that there must be significant 2-way and 3-way interactions present too, although it does not imply that all smaller models will be significant. A closer look in our case, however shows that all smaller models with 3-way and 2-way interaction are significant. Among the 2-way interactions, $F$-test shows that the MAC and injection rate interact most significantly. The router and the MAC also interact very significantly. In 3-way interaction, it is the router, MAC and injection rate that interact most significantly. The 3-way interaction results are consistent with the 2-way results because they all point to interaction between router, speed and the injection rate in affecting the number of packets received. In this case, the smallest model has all four factors $[RSMI]$ interacting significantly.

*Performance measure: Long Term Fairness.* The last three columns of Table 6.1 shows the ANOVA results for various models using long term fairness as the performance measure. The initial setup for a four way interaction effect of the factors on the fairness measure is done as explained before. The only exception is that now we have 10 samples instead of 20 for each of the 81 scenarios mentioned above.[5] The results show that both 4-way and 3-way interactions are insignificant in affecting the fairness. Looking at the results of 2-way interactions between the factors, we find that the router and MAC protocol interact in the most significant way in affecting the fair-

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[5] This is due to the fact that fairness measure is calculated by taking a ratio of the number of packets received for the two connections.

ness. The interaction between the MAC and injection rate is also significant but not to the extent of router and MAC interaction. In this case, the smallest model has only $[RM][MI]$ 2-way interaction terms.

### 6.4.3 ECR Mobility Model Results (Experiment 2)

*Performance measure: Latency.* Table 6.2 shows the ANOVA results for the ECR mobility model using latency as the response variable. The analysis done here is similar to the grid mobility model case. The results show that there is significant 3 way interaction between Routing protocols, Transceiver (node) speeds and the MAC protocols. Models 6 and 7 reconfirm that interaction. Model 6 shows that router and MAC interact significantly and model 7 shows that router and speed interaction is important.

*Performance measure: Number of packets received.* Table 6.2 shows results for the number of packets as the performance measure. Unlike in the grid mobility model, here we do not find any significant 4-way or even a 3-way interaction between the variables. All 2-way interactions *except* Routing protocol/Injection rate and Routing Protocol/Transceiver Speed are significant.

*Performance measure: Fairness.* Table 6.2 shows that only MAC and router interact in affecting the fairness. Note that so far all selected models have had MAC and router interacting significantly. This was true for grid mobility models also.

### 6.4.4 Random Waypoint Mobility Model Results (Experiment 3)

*Performance measure: Latency.* Table 6.3 shows results for random waypoint mobility model. Unlike the first two mobility models, there is no 3-way interaction when latency is used as the response measure. Among 2-way interactions, the significant ones are MAC protocols/injection rate, Routing protocols/Transceiver speed and Routing protocols/MAC-protocol.

*Performance measure: Number of packets received.* Table 6.3 shows that **All** 2-way interactions are significant.

*Performance measure: Fairness.* Table 6.3 shows that there is no 3-way or 4-way interactions present in affecting the fairness. The only 2-way interactions that are significant are MAC protocol/Injection rate and Routing protocol/MAC protocols. Again, note that MAC/router interactions are the most robust of all.

| Response Variable | | | Latency | | | Num. of Packets Recd. | | | Fairness | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Interaction | Source | $SS$ | $DF$ | $F$**-test** | $SS$ | $DF$ | $F$**-test** | $SS$ | $DF$ | $F$**-test** |
| 1 | main effect | $[R][S][M][I]$ | 59078 | 1611 | $3.54^*$ | 971992 | 1611 | $8.51^*$ | 91650121 | 801 | 1.96 |
| 2 | 2-way | $[RS][RM][RI][SM][SI]$ | 56565 | 1591 | 3.05 | 875080 | 1591 | $6.39^*$ | 87802691 | 781 | 3.17 |
| 3 | 2-way | $[RS][RM][RI][SM][MI]$ | 56295 | 1591 | 1.08 | 869226 | 1591 | $3.69^*$ | 86833820 | 781 | 0.99 |
| 4 | 2-way | $[RS][RM][RI][SI][MI]$ | 56314 | 1591 | 1.22 | 882616 | 1591 | $9.86^*$ | 86900548 | 781 | 1.14 |
| 5 | 2-way | $[RS][RM][SM][SI][MI]$ | 56377 | 1591 | 1.68 | 866640 | 1591 | 2.49 | 86471784 | 781 | 0.18 |
| 6 | 2-way | $[RS][RI][SM][SI][MI]$ | 57568 | 1591 | $10.32^*$ | 919267 | 1591 | $26.77^*$ | 88986111 | 781 | $5.82^*$ |
| 7 | 2-way | $[RM][RI][SM][SI][MI]$ | 56686 | 1591 | $3.92^*$ | 865304 | 1591 | 1.88 | 86595981 | 781 | 0.46 |
| 8 | All 2-way | $[RS][RM][RI][SM][SI][MI]$ | 56145 | 1587 | 1.85 | 861228 | 1587 | 1.08 | 86388163 | 777 | 0.94 |
| 9 | 3-way | $[RSM][RSI][RMI]$ | 54520 | 1563 | 1.51 | 846792 | 1563 | 1.01 | 84725467 | 753 | 1.89 |
| 10 | 3-way | $[RSM][RSI][SMI]$ | 54490 | 1563 | 1.40 | 846206 | 1563 | 0.88 | 83596135 | 753 | 0.62 |
| 11 | 3-way | $[RSM][RMI][SMI]$ | 54365 | 1563 | 0.95 | 850800 | 1563 | 1.94 | 83440690 | 753 | 0.45 |
| 12 | 3-way | $[RSI][RMI][SMI]$ | 55082 | 1563 | $3.55^*$ | 844576 | 1563 | 0.50 | 83739425 | 753 | 0.78 |
| 13 | All 3-way | $[RSM][RSI][RMI][SMI]$ | 54103 | 1555 | 1.98 | 842382 | 1555 | 0.92 | 83037851 | 745 | 0.99 |
| 14 | All 4-way | $[RSMI]$ | 53012 | 1539 | | 834026 | 1539 | | 81273633 | 729 | |

Table 6.2: ***(Experiment 2), ECR Model:*** This table shows results of four-factor ANOVA where the factors are the routing protocol, nodes' speed, MAC protocol and the injection rate. The *response variables or the performance measures are the* latency, number of packets received and long term fairness. Note that the degrees of freedom for the fairness measure is smaller than the other two measures. This is due to the fact that the long term fairness is calculated by taking the ratio of packets received for the two connections. Hence 20 samples lead to only 10 actual measurements for fairness. $*$ shows that the $F$-test is significant at $99\%$ confidence level.

| Response Variable | | | Latency | | | Num. of Packets Recd. | | | Fairness | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Interaction | Source | $SS$ | $DF$ | $F$-**test** | $SS$ | $DF$ | $F$-**test** | $SS$ | $DF$ | $F$-**test** |
| 1 | main effect | $[R][S][M][I]$ | 10607 | 1611 | $3.79^*$ | 464087 | 1611 | $26.84^*$ | 68018661 | 801 | 2.60 |
| 2 | 2-way | $[RS][RM][RI][SM][SI]$ | 10290 | 1591 | $10.34^*$ | 391646 | 1591 | $73.13^*$ | 65649520 | 781 | $8.40^*$ |
| 3 | 2-way | $[RS][RM][RI][SM][MI]$ | 10049 | 1591 | 0.90 | 335409 | 1591 | $4.85^*$ | 63071889 | 781 | 0.61 |
| 4 | 2-way | $[RS][RM][RI][SI][MI]$ | 10089 | 1591 | 2.46 | 358047 | 1591 | $32.34^*$ | 63210850 | 781 | 1.03 |
| 5 | 2-way | $[RS][RM][SM][SI][MI]$ | 10045 | 1591 | 0.74 | 334379 | 1591 | $3.60^*$ | 62892626 | 781 | 0.07 |
| 6 | 2-way | $[RS][RI][SM][SI][MI]$ | 10131 | 1591 | $4.11^*$ | 368572 | 1591 | $45.11^*$ | 64076723 | 781 | $3.65^*$ |
| 7 | 2-way | $[RM][RI][SM][SI][MI]$ | 10136 | 1591 | $4.31^*$ | 333074 | 1591 | 2.02 | 63453354 | 781 | 1.77 |
| 8 | All 2-way | $[RS][RM][RI][SM][SI][MI]$ | 10026 | 1587 | 0.74 | 331408 | 1587 | 2.00 | 62867260 | 777 | 0.65 |
| 9 | 3-way | $[RSM][RSI][RMI]$ | 9893 | 1563 | 0.37 | 322958 | 1563 | 2.87 | 61319722 | 753 | 0.27 |
| 10 | 3-way | $[RSM][RSI][SMI]$ | 9901 | 1563 | 0.53 | 323667 | 1563 | $3.30^*$ | 61517964 | 753 | 0.57 |
| 11 | 3-way | $[RSM][RMI][SMI]$ | 9912 | 1563 | 0.74 | 319065 | 1563 | 0.51 | 61691607 | 753 | 0.83 |
| 12 | 3-way | $[RSI][RMI][SMI]$ | 9945 | 1563 | 1.39 | 320379 | 1563 | 1.31 | 61757483 | 753 | 0.93 |
| 13 | All 3-way | $[RSM][RSI][RMI][SMI]$ | 9874 | 1555 | 0.45 | 318220 | 1555 | 0.39 | 61139838 | 745 | 0.59 |
| 14 | All 4-way | $[RSMI]$ | 9828 | 1539 | | 316922 | 1539 | | 60357510 | 729 | |

Table 6.3: ***(Experiment 3), Random Waypoint Model:*** This table shows results of four-factor ANOVA where the factors are the routing protocol, nodes' speed, MAC protocol and the injection rate. The *response variables or the performance measures are the* latency, number of packets received and long term fairness. Note that the degrees of freedom for the fairness measure is smaller than the other two measures. This is due to the fact that the long term fairness is calculated by taking the ratio of packets received for the two connections. Hence 20 samples lead to only 10 actual measurements for fairness. $*$ shows that the $F$-test is significant at $99\%$ confidence level.

## 6.5 Experimental Performance Results

In this section we briefly explain specific results for the three mobility models. We omitted most figures for some results and we present only those for the speed of 20 m/s and injection rate (interval) of 0.025 second. Latency and number of packets received are presented for various injection rates. The results are depicted in Figures 6.7 to 6.12.

The ECR model represents a mobility model that keeps the relative distances of nodes within a group roughly constant. Let $G_i$ be the $i$-th group in our setting, and let $S_i$ be the set of nodes that belong to the group $G_i$. Then any two nodes $a, b \in S_i$ that have a common edge $(a, b)$ at time $t$ will also have a common edge with high probability, at time $t+k$, $k = (0, ST\rangle$, $ST$ is the simulation time. This fact facilitates routing and there are lower requirements on the MAC layer protocols as well. Interaction among the four groups influences the behavior to a much bigger extent.

The random waypoint model represents a movement pattern that is hard to predict. Note that we do not insert any pauses into the model, i.e., pauses were 0 second. On the other hand, the grid mobility model has a very deterministic movement pattern that is easy to predict.

We make the following observations. Many of these observations tend to agree with the conclusions in [DPR00, RLP00] qualitatively.

- CSMA and MACA do not perform well at all for any of the three mobility models. Both CSMA and MACA are able to deliver no more than 20% of the total packets, the percentage drops with increased speeds and injection rates. In addition, MACA also produces huge number of MAC level control packets. They range between 70,000 and 100,000. This makes the behavior of MACA much less acceptable than CSMA. One of the reasons behind the poor performance of these two protocols is also the fact that GloMoSim does not implement broken link notification from the two MAC layer protocols to routing protocols. Thus, routing protocols have no means to learn about broken links and any Hello messages system is not implemented by default. This notification is however implemented for 802.11.

- Our results show that in general the performance of the system falls significantly with increased speed for all MAC protocols. However (802.11,AODV) is still able to deliver 50% of the packets at high speeds (40 m/s) and injection rates (0.0125s).

- Figure 6.7 depicts the distribution of node degrees at three distinct times in the simulation. Intuitively, such distributions and their temporal properties are a good measure of geographical reconfiguration change over time. Networks with higher mobility have different temporal properties than networks with low mobility or static. Less fluctuational distributions allow routing and MAC protocols to perform much better. In our case we can see some variation among the mobility models. The grid mobility model has the most strict movement pattern. There are only four major cliques observable at simulation time 0 second for this model. Nodes for the other two models were positioned randomly so the distributions looks more even.

- Figures 6.8 to 6.10 show the performance of protocols in terms of three response variables; Fairness, Latency, and percentage of packets received, respectively. The results make an interesting point: in contrast to recent efforts to improve the fairness of MAC protocols [LNB98], the results show that routing layer can make a considerable impact on the fairness characteristics of these protocols.

- Figures 6.11 and 6.12 show the distributions of MAC and Routing level control packets for three different combinations. Due to the discussion above, the MAC layer protocol considered is always 802.11. The routing layer protocols used are AODV, DSR and LAR1 respectively. We can that the ECR model produced the least number of MAC layer control packets. This corresponds with our assertion that this model puts the least pressure on the protocols stack.

- Performance for other injection rates and speeds look similar to those shown. The difference in performance is proportional to increased or decreased injection rate, or speed.

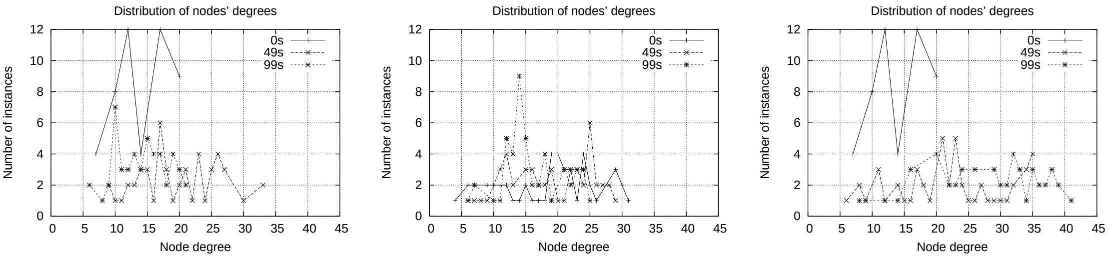
- For high mobility of nodes the creation of hidden and exposed terminal problems becomes even more intriguing than in case of static networks. The used MAC layer protocols help very little in predicting these problems. At high speeds new hidden terminals are simply created by movement of nodes during transmission of other nodes. Since these nodes were outside of the RTS-CTS or carrier sensing mechanism for a given data transmission, they are not aware of the radio environment around. After establishing themselves in an area they many times leave almost immediately. This feature is very common to random waypoint model, and less to the grid mobility model. For ECRM nodes are always established within their respective groups.

- The difference in performance between DSR and AODV is also due to different handling of broken links. We note that the version of DSR implemented in GloMoSim uses salvaging. In DSR if there is a broken link the forwarding node tries to salvage packets waiting in send buffer by trying to search the Route Cache for an alternative route. If this procedure fails a route error is sent to the source and the source tries to resend the packet. In AODV local repair is possible. If a node detects link failure it send a route request to the destination affected. The version of AODV in GloMoSim does not implement route error packets. However, an unsolicited route reply packet is sent upstream to notify all active sources. Other differences between AODV and DSR pertinent to our reasoning is the fact that DSR encodes complete routes into route request, route reply, and data packets. This contributes to slightly higher consumption of bandwidth compared to AODV. This mechanism looks to be less effective in a highly mobile setting than the distributed handling of routes by forwarding nodes. In AODV each node only has the next hop information for each active destination. This makes dynamic repair of routes easier.

- We note that speed of 40 m/s for both source and destination can easily mean that the destination is moving at 80 m/s relative to the source or vice-versa. Speed of 40 m/s corresponds to 144 km/h, and accordingly 80 m/s corresponds to 288 km/h. A node at speed of 40 m/s can be a fast moving car on a highway. Thus at latency for data packets nearing or exceeding 1 second the topology changes can be staggering. As we said before this problem is partly eliminated for ECRM where movement of nodes within a group is correlated.

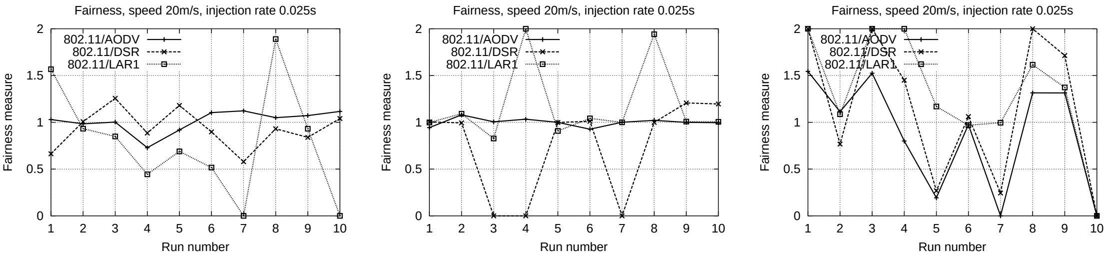
- Performance with less nodes or bigger underlying area becomes in our setting almost unmeasurable. Other researchers (see [Ro01+]) alleviated the problem constituted by high mobility by inserting pauses in nodes' movement. These small pauses help nodes to get reestablished after they kept moving for a while. Our observations correspond roughly with conclusions made in [Ro01+] where authors show that node degrees as high as 15-20 are necessary for decent performance in a mobile setting. Our results extend their performance results for higher injection rates and speeds.

- We consider the capability of MAC/routing layer protocols to predict movement as a viable way to better overall performance. It is obvious that for mobility patters such as the random waypoint this can be very challenging. However, the good performance for ECRM suggests that well established mobile nodes help in this matter. In this case the nodes were established indirectly without any help from the MAC or routing protocols. Intuitively, well predictable movement of mobile nodes is equivalent to their easy establishment into any radio environment that is new to them after a substantial change or coordinates. Mechanism of LAR scheme 1 helped little in this respect as in our setting request zones in many cases coincided with the total area.



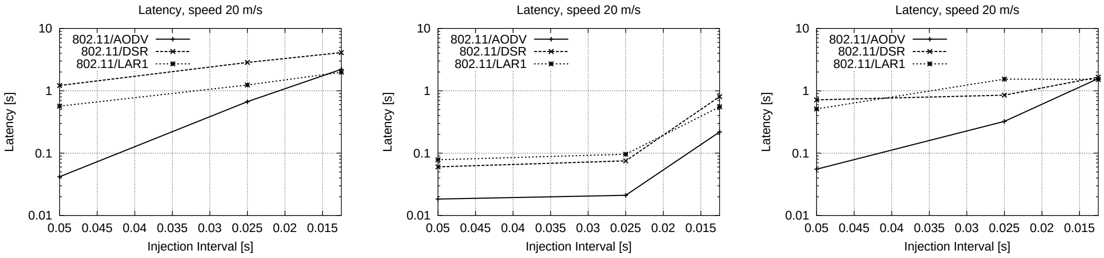
(a) (b) (c)

Figure 6.7: Distribution of node degrees at three different simulation times for the three mobility models. From left: (a) Grid mobility model, (b) ECRM, (c) Random waypoint mobility model.



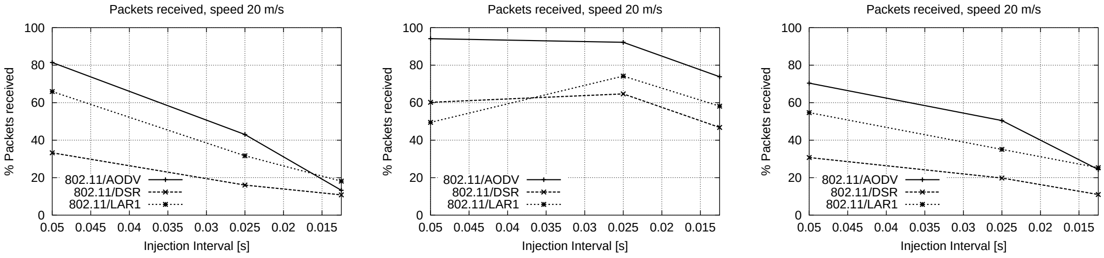
(a) (b) (c)

Figure 6.8: Long term fairness for the three mobility models. From left: (a) Grid mobility model, (b) ECRM, (c) Random waypoint mobility model.



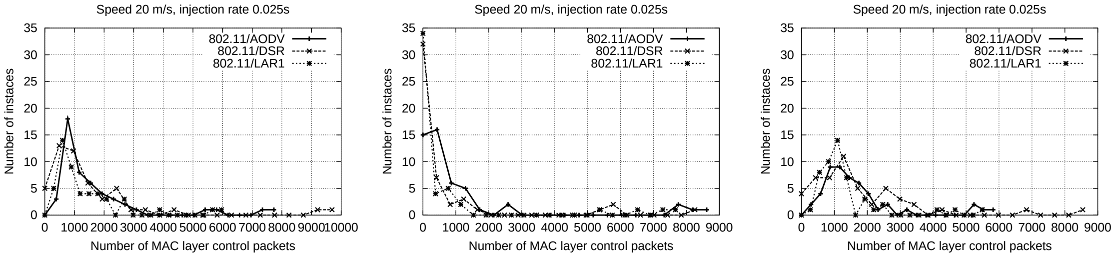
(a) (b) (c)

Figure 6.9: Latency for the three mobility models. From left: (a) Grid mobility model, (b) ECRM, (c) Random waypoint mobility model.



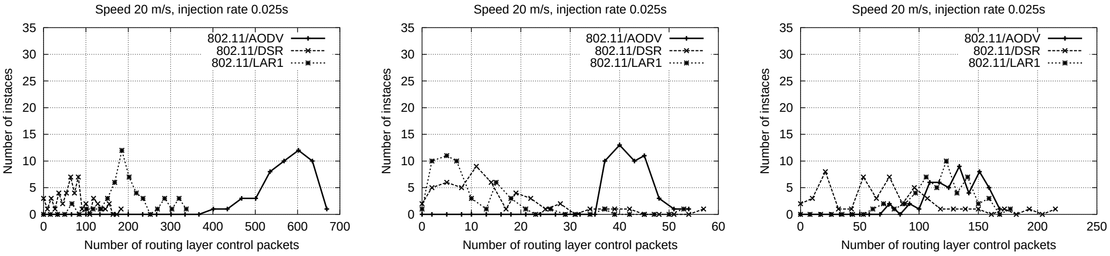
(a) (b) (c)

Figure 6.10: Packets received for the three mobility models. From left: (a) Grid mobility model, (b) ECRM, (c) Random waypoint mobility model.



(a) (b) (c)

Figure 6.11: MAC layer control packets distribution for the three mobility models. From left: (a) Grid mobility model, (b) ECRM, (c) Random waypoint mobility model.



(a) (b) (c)

Figure 6.12: Routing layer control packets distribution for the three mobility models. From left: (a) Grid mobility model, (b) ECRM, (c) Random waypoint mobility model.

## 6.6 Number of Connections and Average Transceiver Density

So far we only considered the effect of two connections on the overall performance of ad-hoc networks. In this section we study the sensitivity of our results to increasing the number of connections and decreasing the area of simulation. This on an average increases the node density during the course of our simulations. Note that both these variables were kept fixed in our setup described in Section 6.3. The differences in the experimental setups with respect to experiments described in Section 6.3 are summarized in Figure 6.13.

In view of the results reported in the preceding section, we did a small focused experiment. Specifically, we used only 802.11 and CSMA as MAC layer protocols, and AODV and DSR as routing layer protocols. The injection rate was designed to keep the number of data packet injections constant at 8,000 packets over the simulation time. Some of the previously reported studies kept the per connection injection rate constant with the increasing number of connections. This approach does not allow one to distinguish the possible reasons behind the drop in performance. We have used a single node speed of 15m/s and a single mobility model which was the Random waypoint model.

**Mixed Effects Model.** One reason for not including number of connections in the earlier ANOVA based analysis was that the design space becomes very large, especially when one considers the levels that this variable can take in a full design. Indeed, in general, for an $n$ node system, the total number of possible connections in a system can be $O(n^2)$ (assuming no more than one connection per node). To handle this situation, we use a mixed effect model. A combination of fixed and random effect

1. **Network topology:** The topology was given by 49 mobile nodes initially uniformly distributed over an area of $600 \times 600$ meters ($1000 \times 1000$ meters) and the radio range of 250 meters. Later, the topology behaved accordingly to the Random waypoint model with pauses set to 0 seconds and the speed of nodes set to 15m/s.
2. **Number of connections:** We use 2, 4, or 8 connections. The sink and source connection pair was chosen randomly for each simulation run. Connections are denoted by $C_i$, $1 \leq i \leq 3$.
3. **Routing protocols** : AODV, DSR.
4. **MAC protocols**: IEEE 802.11 DCF, CSMA.
5. **Speed of nodes**: A single speed: 15m/s.
6. **Injection rates:** We have kept the total number of packets injected during the 100-second simulation time constant at 8,000 packets. That determined the related injection rates and the numbers of packets injected in case of 2, 4, or 8 connections. For 2 connections we have injected 4,000 data packets per connection and the injection rate (interval) was 0.025 second; for 4 connections we have injected 2,000 data packets per connection and the injection rate was 0.05 second, and finally, for 8 connections we have injected 1,000 data packets per connection and the injection rate was 0.1 second.
7. **Simulation runs:** 30 simulation runs for each combination of input parameters.
8. Other parameters were identical to those in Figure 6.5.

Figure 6.13: Differences in parameters used in the experiment on the effect of increasing number of connections and other experiments from Section 6.3.

model is called the mixed effects model. Mixed effects model consists of at least one random and one fixed effect factor. In our analysis we use MAC and routing protocols as fixed factors and number of connections as the random factor. In a fixed effect model, the levels of a factor considered are fixed (e.g. 802.11, CSMA as MAC protocols) and the inference is made only for the levels considered in the study. The inference derived for a fixed factor cannot be generalized to other levels of the factor which are excluded from the study. In contrast, in a random effect model, the levels of the factor are viewed as a random sample from an infinite population of normally distributed levels which can vary across different replications of the same experiment. One might perform the study using one set of levels but the inference can be generalized to other levels of that factor.

In order to address the issue of interaction between MAC and routing protocols when different number of connections are used, we consider the number of connections as a random factor. This allows us to use a few connections to perform the study and yet the conclusions would hold for the entire population of number of connections. We set up a three factor experiment to test whether MAC and routing protocols interact for different number of connections. MAC and routing protocols are assumed to be the fixed factors and the number of connections is the random factor. The two levels of the MAC protocol considered are 802.11 and CSMA; and the two levels of the routing protocol considered are AODV and DSR. The number of connections used are 2, 4 and 8. The response variables used to measure the performance of different factors are latency, the number of packets received and fairness. The experiments were carried out for two different areas as noted in Figure 6.13. The following conclusions were obtained, more details on the tests are omitted here but can be requested from the authors.

- The results show that for a $1000 \times 1000$ simulation area, all response variables i.e. latency, the number of packets received and fairness, there is significant interaction between MAC and routing protocols at $95\%$ confidence level. Given that the number of connections is a random factor, we can conclude from the results that for any number of connections, MAC and routing protocols show significant level of interaction.
- Essentially identical results hold even when the simulation area was changed to $600 \times 600$.

Thus, we can conclude that the results in preceding sections are robust to changes in number of connections and node density.

## 6.7 Concluding Remarks and Future Directions

We characterized the performance and interaction of well known Routing and MAC protocols in an ad-hoc network setting. Our results and those in [BS+97] on the design of snoop protocols suggest that optimizing the performance of the communication network by optimizing the performance of individual layers is not likely to work beyond a certain point. We need to *treat the entire stack as a single algorithmic construct* in order to improve the performance. The statistical analysis method used in this thesis suggests an engineering approach to choose the right protocol combination for a given situation. Specifically, the analysis combined with the concept of recommendation systems can be used as an automated method for tuning and choosing a protocol combination if the network and traffic characteristics are known in advance. We are currently in the process of building such a kernel.

Another implication of the work is to design new dynamically adaptive protocols that can adapt to changing network and traffic characteristics in order to efficiently deliver information. Moreover, evaluation of such protocols as discussed above needs to be done in totality. For instance when we say overhead it should include both MAC and routing overhead (in fact should also include transport layer overhead but is beyond the scope of the thesis). Also, in order to draw meaningful and robust conclusions from the results of such complex experiments, it is almost essential to use statistical tools which are used extensively by other researchers in similar situations. As a next step, we plan to undertake a more comprehensive experimental study involving in addition to the MAC and routing protocols, various Transport protocols.

# Chapter 7

# Robustness of Ad Hoc Wireless Networks

## 7.1 Introduction and Motivation

Recently there has been considerable interest in characterizing the structural properties of social networks from a graph theoretic viewpoint. The primary motivation for such studies is that by suitable abstraction, very different aspects of social networks can be viewed as transport networks. For example, transmission of an infectious disease takes place via social contacts between individuals. Similarly, wireline and wireless networks act as transport networks for digital data in the form of packets. The intent is to relate the structural properties of such transport networks to their performance and robustness. This research includes the following three interwoven efforts: (i) explaining how such networks are formed, (ii) designing such networks for optimal performance and (iii) understanding intrinsic vulnerabilities of such networks and obtaining methods derived from structural analysis for mitigating these vulnerabilities. Albert and Barabasi [AB02] have highlighted the fact that "real world" graphs have a fundamentally different structure than traditional random graphs.[1] More importantly, structural properties can often be used to explain several characteristics of such networks.

Motivated by this line of research, here we undertake a similar vulnerability study of sensor networks formed by a group of individual sensors communicating through

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This chapter is a result of joint work with Chris Barrett, Charlie Engelhart, Anil Kumar, Madhav Marathe, Monique Morin, S.S.Ravi, and Jim Smith. See [BD+03d] for reference.

[1] We refer here to the type of random graphs often called Erdös-Rényi random graphs which are defined with a number of nodes ($n$) and a probability ($p$) for the existence of each edge [Bo]. The existence of an edge is independent of the other edges.

the wireless medium. There is a natural way to construct the interference graph induced by a collection of communicating sensors. Each sensor is associated with a disk of a certain radius which models the broadcast range of the sensor node. There is an edge from a node $u$ to a node $v$ if the latter is contained in the disk around $u$. In this chapter, we make two assumptions: (i) All sensors have the same broadcast range. (ii) The decay in power levels is insignificant inside the disk and falls to zero outside the disk. Under these assumptions, this graph theoretic model associates a **unit disk graph** with a group of sensors. Although this is a fairly simplistic model, it captures the essence of the communication among the sensors. Various modifications are possible and we refer the reader to [Ra96] for a further discussion.

## 7.2 Summary of Results

We study structural properties of sensor networks. We focus on those properties that have a significant influence on robustness of such networks. These range from local properties such as degree distribution and clustering coefficient to more global properties such as the size of induced matchings that are related to the capacity of the media access layer. The main contributions are summarized below.

1. Our results help in obtaining a qualitative understanding of the effect of spatial distributions of sensors. We use two different distributions. The first, called the Random Waypoint model (see Section 7.4.1) is obtained by initially placing nodes randomly in the plane and then allowing them to move around randomly. This distribution has been studied extensively and serves as a benchmark for our comparisons. We also study another class of spatial distributions obtained by placing sensors in an urban environment, namely along the roadway system in the city of Portland, OR (see Section 7.4.2). Placing sensors along a roadway is useful in measuring traffic conditions. Such a placement may also model the placement of sensors on electric utility lines which typically run along the road network. The particular choice of sensor placement is somewhat arbitrary; our primary goal was to demonstrate the importance of using realistic distributions whenever possible. The results also yield insights into the possible structures of sensor networks in an urban environment.

2. We use structural analysis to argue about robustness of sensor networks. As a first illustration, we produce a base case to establish a benchmark behavior and to point out difference between performance of the two different distributions.

> As a second illustration, we study the robustness of sensor networks under node/edge failures. This study is important in the context of sensor networks wherein one expects nodes to fail routinely due various natural or system dependent reasons. This study is carried out in two steps. In the first step, we study the graph theoretic properties of a sequence of induced networks as nodes/edges fail (equivalently, as nodes/edges are removed from the network). We then use a network simulator to see if the variation in the values of graph parameters correlates with the degradation in protocol performance. The results show that indeed the impact of node/edge failures on the performance can be predicted to a certain degree using graph theoretic tools.

Sensor networks are being increasingly deployed in urban environments. Our interest comes from the use of sensor networks in detecting chemical/biological releases and in measuring traffic conditions in an urban environment.

## 7.3 Related Work

In general, it is rather difficult to analyze ad hoc communication networks consisting of a large number of nodes. One factor that contributes to this difficulty is the interaction among the various levels in the network protocol stack and the varied performance of the protocols. A significant volume of research focuses on designing good protocols for different network layers. Since these protocols are hard to analyze theoretically, most of their evaluation is done empirically. While studying mobile ad hoc networks, researchers use simple mobility models (e.g. points moving randomly in the plane) to generate the underlying interference graphs, which they then use as test beds for their protocols. Protocols that might work well in such situations may behave very differently in real settings. Our thesis is that a study of the structural measures as undertaken in this chapter is a good way to get a rough estimate of the performance of protocols. In addition, as discussed in previous chapters, cross layer protocol interaction is more significant than previously suspected in determining protocol performance. Therefore, we study the performance of protocols using a combination of protocols for different layers.

The work presented here is also related to earlier work on geometric random graphs and percolation theory. Several authors have investigated the structural properties of geometric random graphs and percolation theory based results for sensor networks; see [LW+03, DC02, MR96, Pe99, SSS02] and the references therein. All these papers are interested in proving probabilistic results showing that a certain graph property is likely to be true for geometric random graphs with high probability beyond certain values of broadcast range. Similarly, in percolation theory and its application to sensor networks, researchers are interested in proving that the graph continues to have a certain desired property until a certain threshold for node/edge failures. Our work differs with the earlier work in the following ways. First, earlier results are not applicable to structured sensor distributions, the results presented here show that the structural properties of sensor networks depend crucially on the spatial distribution of sensors. Second, the goal here is to connect the structural analysis of sensor networks to network protocol performance and network robustness. Our results show that graph theoretic measures although useful have to be necessarily coupled with network simulation to understand the problem in realistic setting. See Sections 7.5, 7.6 for additional details.

## 7.4 Preliminaries

### 7.4.1 Random Way Point Induced Spatial Distribution

As mentioned earlier, we considered two different spatial distributions of sensors in our experiments. The generation of random placements is discussed below. Our method for generating spatial distributions in an urban setting is discussed in the next subsection.

The Random Way Point (RW) model [BM+98] is widely used by the mobile networking research community. The model can be described as follows. Given a grid of size $X \times Y$ and the number $N$ of sensor nodes, the starting locations for these nodes are chosen uniformly randomly within the grid. Destinations for each node are also chosen randomly from the grid and each node travels to its destination at a speed chosen from a uniform distribution over the range *MinSpeed* to *MaxSpeed*. Once the trip is complete, the node may pause at its destination for a certain number of seconds, and then proceed to a new randomly chosen destination. We generated random spatial distributions by taking snapshots of the positions of nodes at various time instants.

### 7.4.2 Distributions in an Urban Environment

To generate spatial distributions in an urban setting, we used a section of downtown Portland, OR, measuring $2900m \times 2950m$. The particular area of Portland chosen for our study is shown in Figure 7.1(a); an enlarged view of the area is shown in Figure 7.1(b). Spatial distributions of sensors are obtained by placing them along a roadway system. The specific distance between consecutive sensors was simply obtained by running a traffic simulation program (TRANSIMS) developed at the Los Alamos National Laboratory and measuring the average distance between cars at different time instants. A few sensors were also placed around buildings. This was done by attaching sensors to pedestrians and then taking (as in the case of cars) a series of snapshots of their locations. The reason for doing this is two fold. First, it gives us a method for constructing non-uniform distributions in an urban setting. Second, the study can be naturally extended to ad-hoc networks where the nodes are mobile instead of being stationary; see [BD+04b, BD+03c]. For our experiments, the system has approximately $1520$ sensors along the roadway and $757$ sensors in blocks between roads.

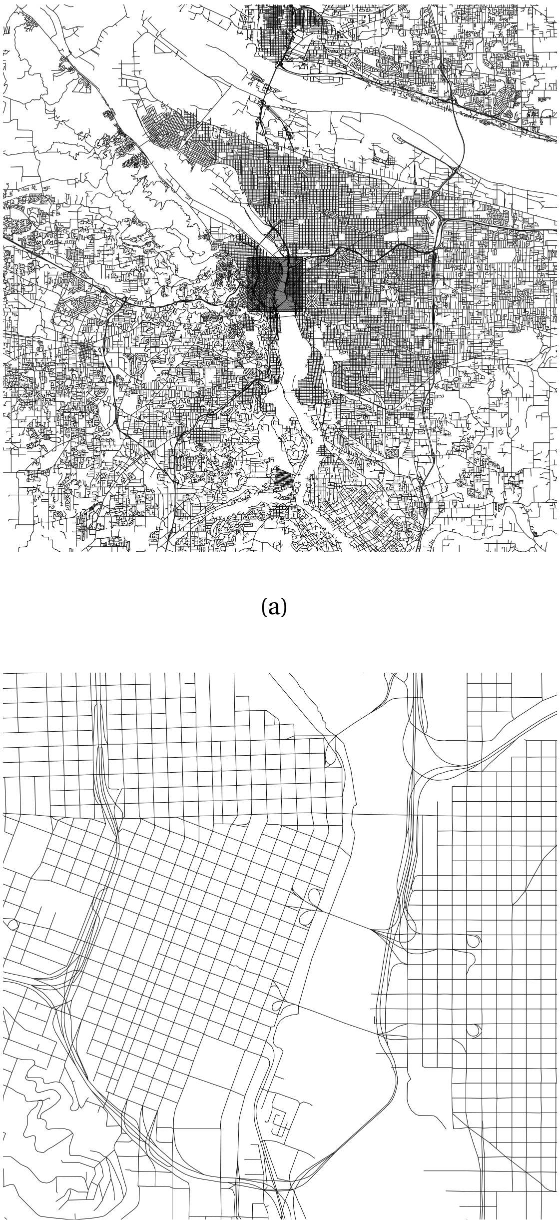
To make a fair comparison between the two classes of spatial distributions, the grid size for random distribution is fixed at $2900m \times 2950m$, and the number of nodes is kept the same in both classes of distributions. Further, the two distributions have roughly the same average node degree. As will be seen in Section 7.6, it turns out that the average node degree in the two classes of distributions remains roughly equal even when nodes are removed randomly in the robustness experiment.

For the remainder of the chapter, we use the term *random distribution* to mean sensor nodes distributed in space using snapshots of locations produced by the random way point model. Similarly, we use the term *structured distribution* to mean that the sensor nodes are distributed in an urban environment as discussed above. Sometimes we use the terms *random sensor networks* and *structured sensor networks* to mean sensor networks induced by random distributions and those induced by structured distributions respectively.

## 7.5 Protocol Performance for Random and Structured Networks

In this section, we simulated some real protocols on the GloMoSim simulator to study measures like fairness, latency and the number of MAC and Routing control packets, as the radius (power level) varies. The motivation was to provide the reader with a strong base case that can be compared to results in Section 7.6 in order to capture the effect of nodes and edges deletions on performance. The simulation setup is summarized in Figure 7.2.

Figure 7.3 shows the results of our simulation. Each figure shows the variation of a



(a)

(b)

Figure 7.1: Area of Portland where sensors were placed. (a) Portland road network with the area of interest marked by a square. (b) A zoomed-in view of the area of interest.

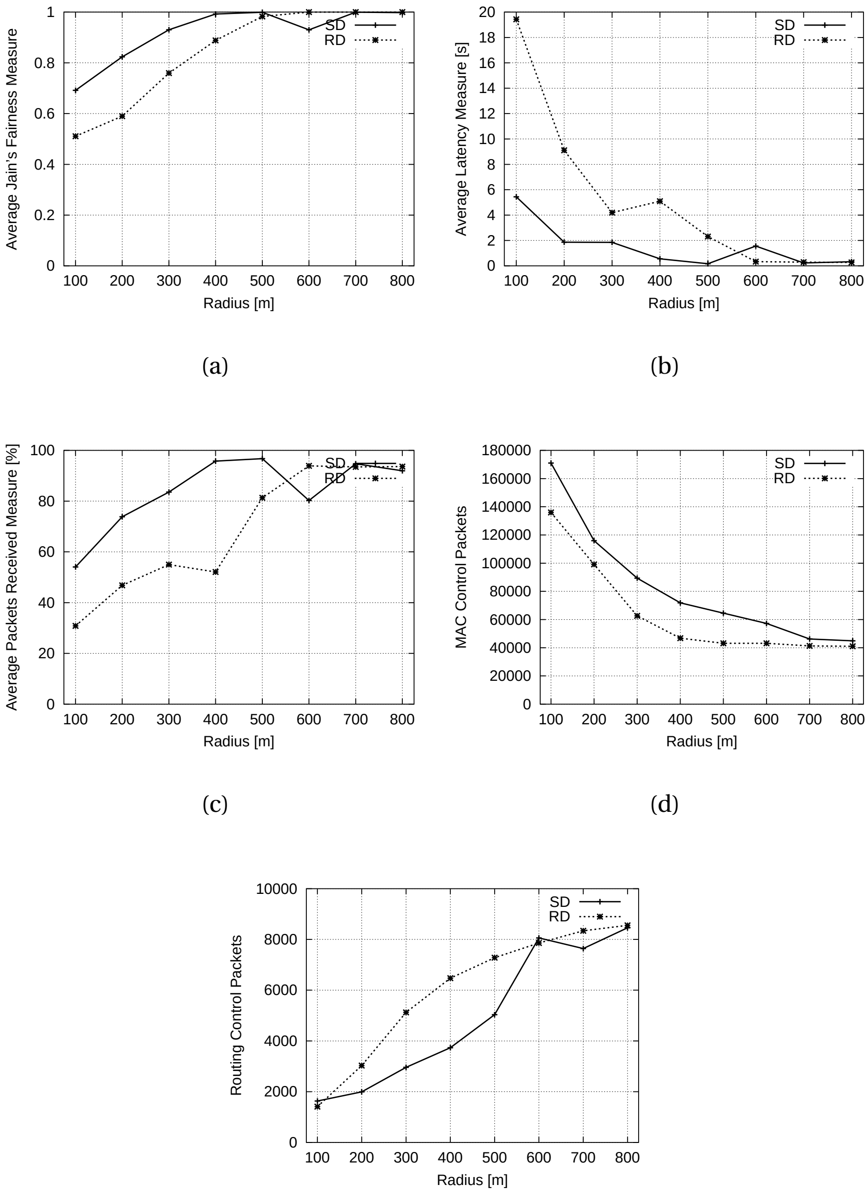
1. **Network Topology:** Snapshots from the structured (SD) and random (RD) distributions.
2. **Number of connections:** 10 connections.
3. **Protocols:** IEEE 802.11 DCF at the MAC layer and DSR at the Routing layer.
4. **Traffic:** 4,000 packets injected per connection over the simulation time. Packet size was 128 bytes, and injection rate was 0.025 second. The simulation time was 100 seconds.
5. **Radio propagation model**: (i) Propagation path-loss model: two ray, (ii) Channel bandwidth: 2 Mb, (iii) Channel frequency: 2.4 GHz, (iv) Topography: Line-of-sight, (v) Radio type: Accnoise, (vi) Network protocol: IP, (vii) Connection type: UDP, (viii) In-band data and control, i.e., a single channel for both data and control packets. (ix) Transmission range chosen from $[100, 800]$ meters.
6. **Simulator used:** GloMoSim 2.03.
7. Simulation runs: **5** with independent simulation seeds for any combination of input parameters.
8. Hardware used in all cases was a PC running Linux (SuSE).
9. **Performance Measures** The following information was collected to measure the performance: (i) Average end to end delay for each packet as measured in seconds (latency), (ii) Total number of packets received, (iii) Throughput in bits/second, (iv) Total number of control packets at the MAC and routing layer level.

Figure 7.2: Summary of Simulation Setup

performance measure with the transmission radius for the two models. Figure 7.3(a) shows the Jain's fairness measure as the radius changes, for the two models. Figure 7.3(b) shows the average latency measure for the two models, as the radius varies. Figure 7.3(c) shows the average number of packets received as the radius varies. Figures 7.3(d),(e) show the number of MAC and routing control packets, respectively, send for the connections, as the radius varies.

## 7.6 Network Robustness

In this analysis section, we study the robustness of the sensor networks to random edge and node failures. The basic experimental setup is as follows. In the node deletion experiment, we delete each node independently with a probability $p$. We then measure the structural properties of the modified sensor network as a function of



(a)

(b)

(c)

(d)

(e)

Figure 7.3: (a) A comparison of the Jain's fairness measure, (b) A comparison of the latency measure, (c) A comparison of the average number of packets received (d) The number of control packets for MAC layer, (e) The number of control packets for Routing layer

increasing the $p$ value. We study: (i) average degree, (ii) average size of distance-2 matching and (ii) average diameter. Figure 7.4 shows the results for these quantities for random and structured distributions.

We also studied two other classical quantities studied earlier in percolation theory: (i) the probability that the graph is disconnected after deleting nodes with probability $p$ and (ii) the average number of components that the node deletions yield. To calculate these quantities, we ran each experiment with 1000 different random node deletions for a fixed value of $p$ and took the average. Figures 7.4(a),(c) show the results for this experiment for the node deletion process and Figure 7.4(b) shows the results for edge deletion. While the probability of getting disconnected under random deletions varies quite continuously in Figure 7.4(a), there seems to be a threshold like phenomenon in the case of random edge deletions.

The experimental simulation setup that we used to argue about robustness of sensor networks is similar to setup in Section 7.5 with the following differences:[2] (i) we had 20 connections instead of 10 since this allowed us to better see the effect of network breaking into more than one connected component (see Figure 7.5), (ii) we set the bandwidth to 11 Mb/s, (iii) we decreased the injection rate to 0.1 second thus injecting only 1,000 data packets over the 100-second simulation time, data packet size was the same: 128 bytes, (iv) there were 10 simulation runs instead of 5, (v) we used transmission radii of 200, 250, 300 meters. Nodes or edges were removed randomly and independently for each simulation run. Corresponding simulation results are shown in Figure 7.6.

The experiments were set up with two basic goals: (i) to investigate how the performance of protocols deteriorates with increasing node/edge failures, and (ii) investigate this as a function of varying broadcast range. Intuitively one expects the following behavior. The overall network performance will degrade slowly till a certain threshold point, after which there would be a rapid drop in its performance. Our results appear to be the first of its kind where the structural theory of percolation is integrated with a simulator level study in the context of communication networks. The important observations and possible insights and explanations are summarized below.

1. The average degree of random distribution and structured distributions were quite close throughout the process of removing nodes. The distributions were

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[2] The differences are of legacy origin. Also, it is usually not an easy task to propose simulation parameters that would fit a broad range of scenarios.

set up so that the average degrees were close to begin with, but it was a bit surprising to see them so close as we removed nodes from the graphs.

2. The average size of the distance-2 matching were also very close in the case of random and structured distributions throughout the node deletion process (Figure 7.4(d)). The result is a bit surprising at first. But the result can be explained at least intuitively as follows: to begin with the size of the d2-matching for both distributions was close. Every time a node is deleted, the matching size can decrease by at most 1, since only one of the incident edges can be in the optimum matching. We thus see a steady decrease in the ratio of matching size by the number of nodes. Note also that the best value of ratio can be .5 since each matching edge consumes two nodes. The result says that initially roughly .15 which is the number of matched nodes are roughly 1/6 of the total number of nodes and finally around 1/10 or so. Note though that we are computing an approximately optimum matching and thus there the numbers can be off by a constant factor (approximately 4).

3. The average number of components and probability of graph being disconnected show clear differences between random and structured distributions. Random distributions are much more uniform and thus exhibit a greater level of robustness than structured distributions. Note that for particular instances, it is not a problem if one gets disconnected components, so far as the source sink pairs are in the same component and their are at least a few pathways between the source and destination. In fact breaking the system into disconnected components can sometimes be useful, as is appears in Figure 7.6. The intuitive reason is that this reduces MAC layer interference. The performance of the protocols is a complicated combination of these factors. It also depends on the amount of traffic and the spatial distribution of the source sink pairs.

4. Simulations done in conjunction with graph theoretic analysis yield potentially interesting insights (see Figure 7.6). The graph theory results suggest that one should expect performance degradation as nodes/edges are removed. But the precise point appears to be hard to predict. The main reason is that protocol performance is a function of multiple variables. Specifically, graph theoretic analysis shows that diameter of the system increases and the matching size decreases with increasing node failure, suggesting that the performance should steadily worsen. But, note that the graph theoretic parameters are properties of the entire network while simulations allow us to study these deletion effects on

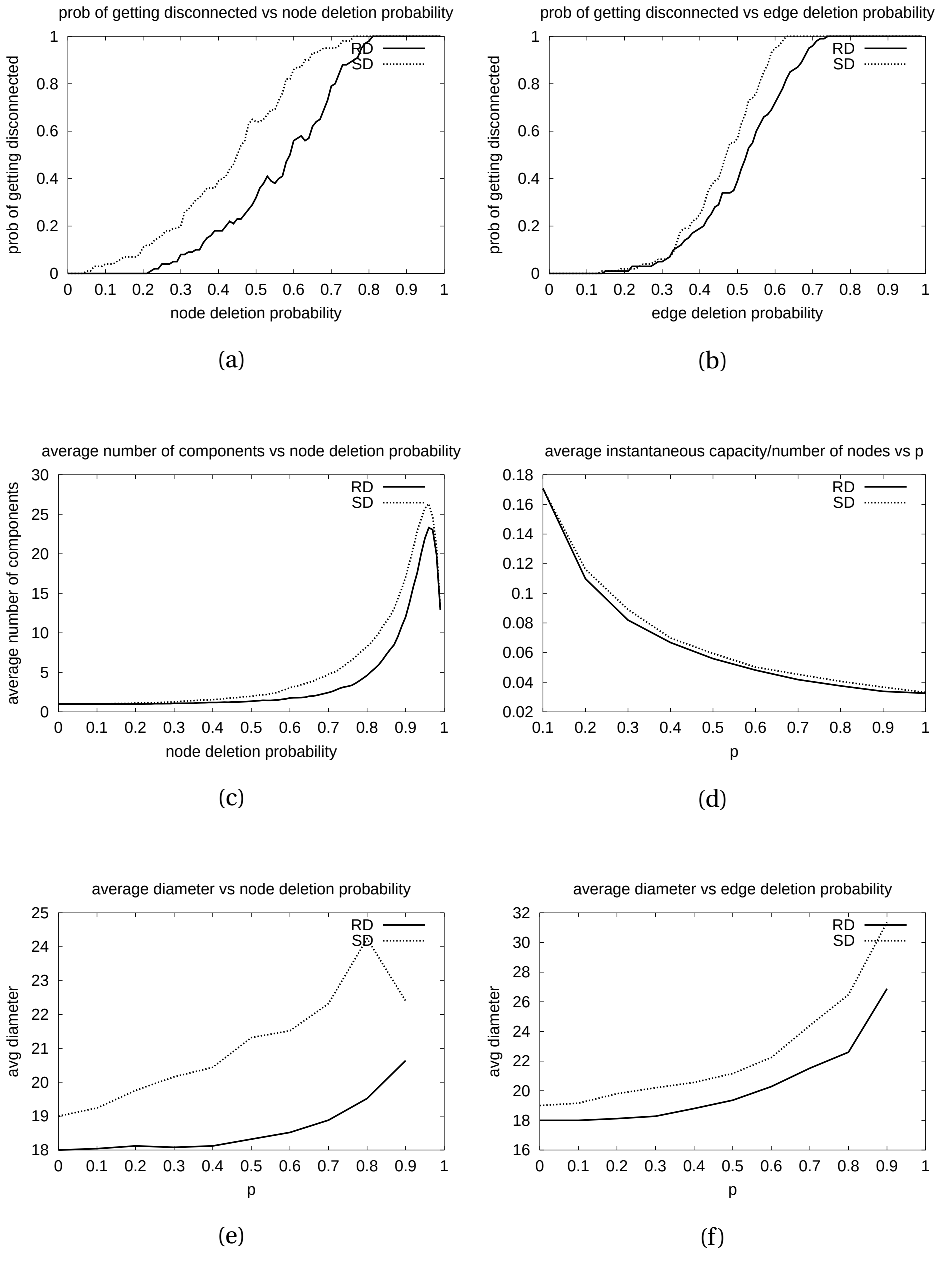
each connection.

The results show that sensor networks as considered here are structurally very different than many other infrastructure networks that were shown to be scale-free networks. An important implication of this distinction as discussed in the literature has to do with robustness of such systems. Scale-free networks are quite robust to random failures but are sensitive to deliberate attacks. Sensor networks are on the other hand appear to be robust for both such attacks. The robustness of sensor networks implies that they can indeed be deployed in realistic urban settings.

## 7.7 Concluding Remarks

We analyzed the structural properties of sensor networks formed by random placement of sensors as well sensors placed in an urban infrastructure. Our results show that certain performance measures are possible to predict from the graph theoretic properties. However, it is only possible at qualitative level; exact point when performance changes due to change in corresponding graph theoretic measure is hard to predict. Nevertheless, our end-to-end analysis on network robustness is new and demonstrates the usefulness of structural analysis combined with simulations.

The current analysis does not take into account occlusions; a subsequent study will take this important parameter into consideration. The process of edge deletion is a first step towards understanding effects of occlusions. Another direction for future work includes study of mobile sensors in an urban environment and allowing for non-uniform radio ranges of sensors.



(a) (b)

(c) (d)

(e) (f)

Figure 7.4: (a),(b) Probability of the graph becoming disconnected under random node and edge deletions, vs node/edge deletion probability ($p$). (c) Average number of components in the case of random node deletions, vs node/edge deletion probability. (d) Average instantaneous capacity (size of distance-2 matching/number of nodes) vs node deletion probability. (e),(f) Variation of average diameter under node and edge deletions vs node/edge deletion probability.

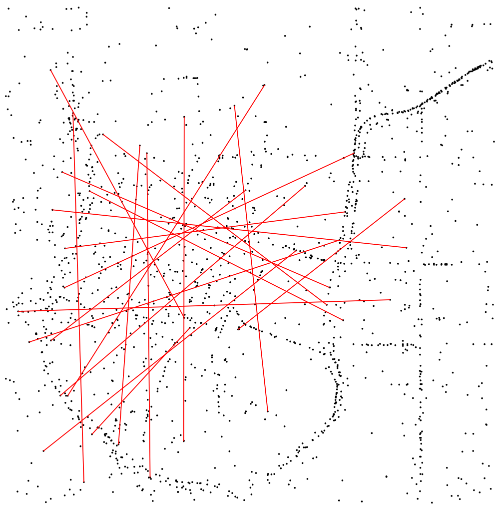
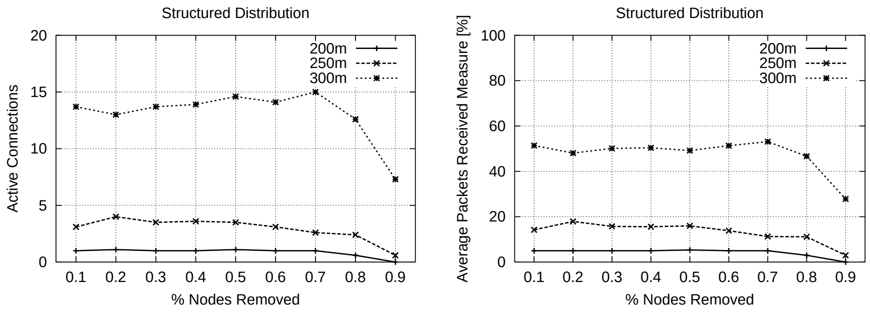


Figure 7.5: The spatial distributions of sensors used in our robustness study. The solid lines indicate the source destination pairings used in our experiment.



(a) (b)

Figure 7.6: Variation in performance as nodes are deleted. (a) Average number of active connections, (b) Average number of packets received. An active connection is such that there has been at least a sigle data packet received at the sink node.

# Chapter 8

# Conclusions and Future Work

The *central result* of this thesis states that protocol and variable interactions are present in wireless ad hoc network; higher order interactions are often the case, and additionally these interactions are frequently a result of intriguing relationships within a given ad hoc network. These relationships would be hard to detect without a suitable methodology. This result immediately motivates design of protocols that would integrate functionality from different levels of the OSI stack. Such integrated protocols are usually called cross-layer design, or mega protocols.

The motivation for the research was that issues such as whether a protocol interaction is present, how much it impacts the over-all performance, and what is the quality of the protocol interaction, are considered in the community of mobile wireless networking an important open problem. This has been demonstrated by a recent IRTF draft titled *"Interlayer Interactions and Performance in Wireless Ad Hoc Network"* [LSR01] that discusses exactly this area.

Table 8.1 summarizes results of our experimental analysis of ad hoc wireless net-

| Resp. Variable | Static Case | Grid Mobility Model | ECRM | Random Waypoint Model |
|---|---|---|---|---|
| Latency | $[NRM][RMI]$ | $[RSM]$ | $[RSM]$ | $[MI][RS][RM]$ |
| Packets Rcvd. | $[NRM][RMI]$ | $[RSMI]$ | All 2-way except $[RI][RS]$ | All 2-way |
| Fairness | $[RM][NM]$ | $[RM][MI]$ | $[RM]$ | $[MI][RM]$ |

Table 8.1: Summary of the results within the area of protocol and variable interactions.

works coupled with ANOVA, Analysis of Variance. Higher order interaction terms in the table point out that the issue of interactions within ad hoc networks is more complex than usually intuitively perceived. A very notable is the presence of MAC and routing protocols in each of the interactions terms. Therefore, we can conclude that it is indeed the case that protocol interaction is an important feature with considerable influence on over-all performance. As the reader could see, the analysis has been done on a set of respected mobility models, and on a set of instances of static networks, as well. The topology of the static networks has been motivated by basic graph theoretic measures, alongside with such concepts as the hidden terminal phenomenon. In this analysis we have restricted ourselves to rather smaller networks. This is due to our effort to lower the impact of spatial non-uniformity of input parameters, thus making the interpretability of results more straightforward. However, a basic assessment of the impact of the number of connections, and the number of participating nodes has been done. We have shown that these two parameters cannot substantially change the over-all picture, and that our results are robust in this direction.

The emphasis of this thesis is on *interpretability* of simulation based experiments. This is an important fact that discerns the results presented in this thesis from similar results that attempted to evaluate interactions. Previous results were often too restricted on protocol interactions, not capturing effects of other input parameters, or approaching the issue in a non-systematic way. As a consequence, conclusions of general value could not have been formed. Therefore we have used a rigorous method based on statistical analysis of experimental data that simplifies reasoning about the influence of a given interaction term, and at the same time, minimizes a possibility of human bias or error. This method has allowed us to reason about sources of both variable and algorithmic (protocol) interaction at a given level of significance.

In order to evaluate performance of large scale ad hoc networks we have designed a framework for modeling, and simulating of realistic mobility scenarios. This framework is based on TRANSIMS, a tool for microscopic simulation of vehicular, and pedestrian traffic. This tool has been previously successfully applied to a number of studies ranging from equity analyses of transportation system improvements through detailed studies of response strategies for chemical and biological attack. We have taken an advantage from existing data that model the area of the city of Portland, Oregon at a very microscopic level. This data set is, to our best knowledge, the only set that contains this level of preciseness, and at the same time consists of millions of travelers.

With the help of the above described framework, we have computed basic graph theoretic measures for an instance of a realistic topology. Our motivation with respect to this research was to develop a capability of rough assessment of ad hoc networks' robustness against transceiver and link failures based on these measures. The results point out that such an assessment is possible, however, only at a qualitative level. We do not expect that this approach could easily lead to a point where quantity of any QoS measure could be easily predicted. However, methods based on graph theoretic measures should not be underestimated. We have shown that certain issues such as capacity, or robustness can be suitably expressed through these measures. They offer a comfortable way for automated generating of networks that match topology of a realistic scenario. This is an important concept for any large scale simulation.

The general motivation of the effort presented in this thesis was to develop means for easy performance evaluation, testing, benchmarking, and inter-comparability of large scale ad hoc networks. In the above paragraphs we have described how we coped with such issues as protocol, or variable interaction, or generation of large scale scenarios for large scale simulations. The important limiting factor for this thesis was performance of the currently available simulation tools. We have successfully coupled our TRANSIMS based framework with GloMoSim, and ns2. The main discrepancy in this approach is that our framework is able to produce scenarios in the order of millions of travelers, whereas, GloMoSim or ns2 are able to simulate only scenarios in the order of 100s or 1000s of travelers. This is also an important limiting factor in our ANOVA based approach. Even a small number of input parameters with a modest number of levels, and a reasonable number of independent simulation runs for each combinations of input parameters, led to a very complex simulation experiment. In order to obtain enough experimental data for statistical analysis thousands of simulations runs were necessary. We hope that once a more powerful computational platforms become available we will be able to improve on expressiveness of our results. The reader should not underestimate the computational aspects under no circumstances. When real time for a set of experiments runs in days, or even weeks, the feedback necessary in order to tune experiments can become accompanied with a large turn-over delay.

In the future, we plan to concentrate more on issues connected with large scale simulation of ad hoc networks. Large scale simulation is necessary in order to estimate the impact of data packet overload, to evaluate suitability of ad hoc networks for various broadcasting and newscasting operations, to assess necessity of data integration or fusion in order to improve performance, to discuss attainability of a fullyfledged uni-cast communication, and other issues. We would like to improve our statistics based methodology in order to be able to characterize ad hoc networks better, perhaps to propose an approach for "succinct" characterization of ad hoc networks. Any efficient characterization would be of enormous impact for testing, and benchmarking of future ad hoc networks. Additionally, at present we are no close to believe that current communication protocols such as IEEE 802.11, HiperLAN2, AODV, DSR, or other protocols at any level of the OSI stack can scale up well with the number of portable devices, and thus to get us any closer to the global goal of ad hoc networks. This global goal is wireless connectivity, at any time, at any place, and without fixed infrastructure in form of base stations, or access point.

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# Index

# Résumé

Martin Drozda holds an Ing. (eq. to MSc.) degree from the Slovak University of Technology in Bratislava, Dept. of Electrical Engineering and Information Systems where he graduated in 1995. In 1998 he was a visiting scholar at BRICS (Basic Research in Computer Science) at Århus Universitet, Denmark on a scholarship awarded by the Danish Research Academy. From 1997 to 2002 he was affiliated with the Slovak Academy of Sciences, Institute of Informatics. From 1999 to 2002 he was a research assistant/visiting scientist at Los Alamos National Laboratory, Basic and Applied Simulation Science (CCS-5) group. He participated on projects in areas of high performance computing, theory and application of simulation sciences, decentralized electric power market, and mobile computing (ad hoc wireless networks). These projects were sponsored by the US Dept. of Energy, US Dept. of Defense (DARPA), Motorola and other institutions. Since 2003 he is a research affiliate with the Simulation and Modeling group at Universität Hannover. Currently, his research focus is within the area of ad hoc wireless networks.