Performance Analysis of Multihop Ad hoc and Hybrid Wireless Networks

by

Hrishikesh Venkataraman

A thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

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School of Engineering and Science
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Abstract

Man often becomes what he believes himself to be. If I keep on saying to myself that I cannot do a certain thing, it is possible that I may end by really becoming incapable of doing it. On the contrary, if I shall have the belief that I can do it, I shall surely acquire the capacity to do it, even if I may not have it at the beginning. - M. K. Gandhi

Multihop mobile wireless networks is a subject of intense research interest for next generation wireless systems. As we move towards fourth generation (4G) networks, high data-rates of the order of 100 Mbps can be achieved only over short distances. A multihop network has smaller transmission distance between the transceiving pairs, as compared to an equivalent single-hop network. This enables the radio terminals that are spatially well-separated from each other to reuse the same resources when the resulting interferences are not too severe. An interesting medium access control (MAC) protocol that has great potential for offering high quality of service (QoS) is the spatial reuse time division multiple access (STDMA).

In this dissertation, the multihop network design is studied for two different kinds of systems: multihop ad hoc network and multihop hybrid cellular network. The interference arising from the simultaneous utilization of resources in both multihop cellular and multihop ad hoc networks is controlled by defining an exclusion region around the receiver of every communication pair. No concurrently communicating transmitter, apart from the desired transmitter can communicate in the exclusion region of any receiver. Such an interference-avoidance model is known as a Protocol Model. A restrictive version of the Protocol Model, termed as the restrictive Protocol Model, dictates that not only the undesired transmitter, but also the corresponding receiver of the undesired transmitter should not lie in the exclusion region. Such an interference model has been considered in the graph-based scheduling algorithms and is also considered in certain sections of this research work.

In the first part of the thesis work, a multihop ad hoc network is analyzed in detail and the system capacity is computed. Due to the absence of a central controlling entity, a restrictive Protocol Model is considered for interference control in the multihop ad hoc design, in this research work. Such an interference model results in non-overlapping, unequal exclusion region circles around the coverage area. However, the calculation of optimal resource allocation that would maximize the system capacity under the restrictive Protocol Model is found to be an NP-hard problem. Considering this complexity, a random data hopping technique
has been proposed over a time-slot (TS) partitioned system in order to improve the system capacity of the network. It has been found that the granularity of the TS(s) can be increased by reducing the duration of each TS. Significantly, it has been shown through computer simulations that applying the random data hoping technique over the TS partitioned system results in an increase in the system capacity (31% gain for a traffic load of 30%), without any additional increase in the computational complexity. This random hopping algorithm has also been observed to provide a significant capacity gain (22% gain for a 30% traffic load) when shadowing conditions are taken into account in the system design.

In the second part of the thesis work, a multihop hybrid cellular network is studied. The base station (BS) is located at the center of the cell and all the mobile terminals communicate with the BS in single or multiple hops. Due to the presence of BSs in the multihop network, a Protocol Model is considered for interference management in the system design. It has been found in this research work that for 10% overhead, the system capacity of the multihop cellular network does not increase when the number of multiple hops per link is increased beyond three hops. It is known that optimal resource allocation in a multihop cellular network is again a NP-hard problem. Hence, different heuristic algorithms have been developed over the years that would improve the system performance. A novel cluster-based design is proposed in this work for a 2-hop cellular network, whereby, two pairs communicate simultaneously in every hexagonal cell, at any time instant. This design has been tested under realistic propagation conditions including log-normal shadowing. It has been observed that such a cluster-based 2-hop design provides an increase in the spatial resource reuse and hence results in a much higher system capacity as compared to three standard benchmark algorithms for 2-hop cellular networks. A minimum average gain of 1 bps/Hz/cell has been observed for the cluster-based design as compared to the best performing benchmark algorithm.

Ph.D Defense : 20th July 2007
Author : Hrishikesh Venkataraman
Supervisor : Prof. Dr. Harald Haas
I certify that I have prepared this Ph.D. Thesis by my own without any inadmissible outside help.

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Dedicated to my parents
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This is perhaps the easiest and yet the hardest part of the thesis that I have to write. It will be simple to name all the people who helped me to get this done, but it will be tough to thank them enough. I will nonetheless try my best ...

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my tough times, but also used to constantly challenge me to raise my level and improve my performance.

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“To speak gratitude is courteous and pleasant, to enact gratitude is generous and noble, but to live gratitude is to be divine and touch heaven” - Johannes A. G.
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<td>BMBR</td>
<td>Base driven Multihop Bridge Routing</td>
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<td>BS</td>
<td>Base Station</td>
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<tr>
<td>CDF</td>
<td>Cumulative Distribution Function</td>
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<td>CSMA</td>
<td>Carrier Sense Multiple Access</td>
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<td>DCA</td>
<td>Dynamic Channel Assignment</td>
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<td>GTW</td>
<td>Gateway</td>
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<td>iCAR</td>
<td>integrated Cellular <em>Ad hoc</em> Relay</td>
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<td>LLH</td>
<td>Least Longest Hop</td>
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<td>LMP</td>
<td>Least Maximum Pathloss</td>
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<td>MTP</td>
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<td>NP</td>
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<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
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<td>PDF</td>
<td>Probability Density Function</td>
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<td>PMF</td>
<td>Probability Mass Function</td>
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<td>QoS</td>
<td>Quality of Service</td>
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<td>RDH</td>
<td>Random Data Hopping</td>
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<td>RNC</td>
<td>Radio Network Controller</td>
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<td>RTO</td>
<td>Random Time slot Opposing</td>
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<td>RS</td>
<td>Relay Stations</td>
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<td>SINR</td>
<td>Signal to Interference Noise Ratio</td>
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<td>SIR</td>
<td>Signal to Interference Ratio</td>
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<td>Acronym</td>
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<td>SMRP</td>
<td>Single interface Multihop cellular network Routing Protocol</td>
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<td>SOPRANO</td>
<td>Self Organizing Packet Radio Ad hoc Networks</td>
</tr>
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<td>SRD</td>
<td>Shortest Relaying hop Distance</td>
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<td>STD</td>
<td>Shortest Total Distance</td>
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<td>STDMA</td>
<td>Spatial reuse Time Division Multiple Access</td>
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<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>TS</td>
<td>Time Slot</td>
</tr>
<tr>
<td>TSA</td>
<td>Time Slot Allocation</td>
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<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunication System</td>
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List of Symbols

\( A \) Sum of area covered by the exclusion regions of all the pairs of one end-to-end link

\( A_{mh} \) Area covered by the circular exclusion region in the multihop scenario

\( A_{sh} \) Area covered by the circular exclusion region in the single-hop scenario

\( B \) Area of the exclusion range circle

\( c \) Reuse factor in multihop cellular networks

\( C \) Aggregate system throughput of the network

\( C(.) \) Total number of possible combinations of the distribution of communicating pairs

\( C/I \) Carrier-to-Interference Ratio

\( d \) Transmission distance between any communication pair

\( d_c \) Transmission distance between any transmitter and its desired communication receiver

\( d_{int} \) Transmission distance between any transmitter and the simultaneously communicating unintended receiver

\( d_{min} \) Minimum transmission distance of any communicating pair

\( d_{int_{ij}} \) Distance between the receiver of the \( i \)th communicating pair and the transmitter of the \( j \)th communicating pair

\( E[.] \) Expectation of the variable

\( f(.) \) Auxillary polynomial defined during the calculation of total number of communicating pairs in the system

\( k \) Fraction of the transmit power, \( P_T \), in multihop cellular networks

\( k_1 \) Propagation constant

\( L_M \) Maximum number of simultaneously communicating pairs

\( m \) Number of relay nodes in ad hoc network/ number of BS(s) in cellular network

\( M \) Number of multiple hops per communication link

\( n \) Number of mobile nodes in the system
The number of simultaneous communicating pairs in the system at any time instant, $t$

Number of transmission schemes for a single-hop network with no spatial reuse

Number of transmission schemes for a multihop network with no spatial reuse

Number of transmission schemes for a multihop network with spatial reuse

Source node

cumulative distribution function

Noise power

Received power

Transmit power

Destination node

Radius of the cell

Radius of exclusion range circle

Radius of the coverage area

A time instant

Number of time slots in the frame

Duration of a mini time slot

Duration of a time slot

Variance of the random variable

Total number of communicating pairs in the system over a time frame

Location of mobile node, $i$

Location of mobile node, $j$

Location of mobile node, $r$

Location of mobile node, $s$

Total coverage area of the system

Path loss exponent

Threshold value for signal to interference plus noise ratio

Spatial protection margin, exclusion range

Angle between the lines joining the center of a circle to the point of intersections of the two overlapping circles

Carrier-to-Interference Ratio
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1 Introduction

Wireless communication has been the fastest growing segment of the communications industry. Wireless connectivity is experiencing new horizons with the advent of mobile Internet and global networking. However, this is still a fledgling field wherein the mobile computing is often not truly as convenient as conventional computing [1]. This has led researchers to find effective communication techniques for the next generation wireless systems. The task set before the present system designers is to eliminate the shortcomings of mobile devices so that the inherent convenience of mobility will no longer suffer the burden of inadequate or inappropriate system design.

1.1 Background

1.1.1 Multihop Wireless Networks

A multihop wireless network, by definition is one wherein the source and destination terminals communicate with each other in multiple hops. There are an infinitely large number of dimensions to the design space of multihop wireless networks [1]. Consider for example, whether the range of wireless transmission should be large or small compared to the geographical distribution of the mobile wireless terminals. If all the wireless terminals are within transmission range of each other, no multihop relaying is needed and the wireless network is, by definition, fully connected. The wireless nodes can send directly packets to their destination via single-hop routing as long as the link signal-to-interference-noise ratio (SINR) is above some minimal threshold. The standard technique for long distance wireless communication (in the range of 2-20 kms) that has been prevalent in the last decade has been the single-hop cellular communication with direct transmission between mobile station (MS) and base station (BS), wherein, the BSs are connected by a backbone wired network or a broadband wireless microwave link access. However, such a network frequently encounters problems like dead zones (areas without coverage) and hot spots (congestion of traffic in a particular cell) around the BSs, apart from the limitation of not being able to provide high data rates over long distances, thus causing inefficient spatial reuse of resources and leading to sub-optimal system capacity [2].
In a multihop wireless network, the packets are forwarded from source to destination through intermediate relay nodes. Since path loss causes an exponential decrease in the received power as a function of distance, using intermediate nodes can greatly reduce the transmit power for all the source and relay nodes. This approach reduces the interference experienced by other nodes in the system which in-turn results in an increase in the system capacity.

The next generation wireless system would target a communication environment wherein a wireless terminal can communicate with another terminal through an *ad hoc* network via multihop routing and at the same time establish contact with a gateway to download a file from an Internet server or make contact with another far-off device through cellular networks. However, the fact that the communication design should be sufficiently general to incorporate these cases is a very difficult objective to meet. In particular, the capabilities and limitations that the *physical layer* imposes on the network performance are a matter of great concern. In fact, most of the existing literature focuses on higher layers (such as the network and medium access control (MAC) layers), ‘taking for granted’ that the lower layers, and in particular, *physical layer*, can successfully cope with the channel impairments. This assumption is perfectly valid in networks with very reliable communication links (e.g., fixed optical networks). However, this assumption is much less meaningful in the case of wireless networks, where the radio communication links are very unreliable. This leads to a more severe channel distortion. Hence, it is necessary to take into account the channel characteristics in designing multihop wireless networks. At the same time, the relaying hops put a lot of burden on the overhead requirements and designing an optimum radio resource scheme in the multihop network design. Also, since the same resources are reused for some other communication pair, the performance of the multihop wireless network is sensitive to the quality of all the relaying routes and simultaneously communicating pairs.

On account of all these factors, the design of multihop wireless network calls for many changes in the physical layer design, resource utilization protocols, and also in the system-level design and network protocols.

### 1.1.2 Broad Classification of Multihop Wireless Networks

Multihop wireless networks can be broadly classified into two types: multihop *ad hoc* network and multihop hybrid wireless network. *Ad hoc* networks are, by definition, distributed multihop radio networks. The radio units are distributed and communicate with each other by relaying the messages over one or several intermediate nodes. There is no central coordination between these wireless units. The mobile nodes self-organize to form a network without the need for infrastructure such as BSs or access points. Each mobile node acts as a router, forwarding packets on behalf of other nodes, creating “multihop” paths that allow wireless nodes located beyond direct transmission range of each other to communicate. However,
the nature of the wireless channel, the lack of synchronization, and also the lack of any predetermined topology creates many challenging research topics in the area of ad hoc networks [4]. For example, at the network layer, the main problem is that of routing, which is exacerbated by the time-varying network topology, power constraints and the characteristics of the wireless channel [5]. There has been a lot of research on the MAC layer, routing and transport layers of the networking stack for the multihop ad hoc model. A number of approaches have been proposed for connecting an ad hoc network to the Internet [4, 7, 8, 9]. For example, Maltz et al [6] described an implementation for connecting an ad hoc network (under the the Dynamic Source Routing Protocol (DSR) [10]) to the Internet, using Mobile IP. Their approach allows for roaming of nodes between different ad hoc network clouds and between an ad hoc network cloud and the Internet, and uses subnetting to distinguish between nodes in different ad hoc network clouds. However, issues like scalability, routing, QoS provisioning make it very difficult to implement ad hoc networks in practice. Realistically, ad hoc networks will not in the near future replace cellular networks [11]. However, multihop hybrid wireless networks, i.e., cellular networks with relays represent a very promising technique for future generation wireless systems. Specifically, a cellular system with relays (either fixed relays, or MSs that act as relays) that can store and forward the information between the BS and the users in both uplink and downlink. Hybrid wireless networks are the first step in the cellular system evolution towards ad hoc systems. Multihop hybrid wireless systems are a hybrid combination of cellular systems and multihop ad hoc networks, and they exploit the benefit of both paradigms. The hybrid wireless networks promise a ubiquitous solution for the present day demand of increased data rate and high speed internet connection with the constraint of limited bandwidth [12]. A hybrid network model enhances the overall system capacity and provides greater mobility and interoperability in the system design. In fact, a properly designed system can achieve a cell frequency reuse ratio of one (i.e., the given set of resources for each cell could be reused in every other cell), which is the target for the next generation wireless systems [13].

1.2 Motivation

There are many quality of service (QoS) parameters that dictate the overall performance of the wireless network, viz., system capacity, network delay, effect of mobility, power requirements, data rate per user, etc [14, 15]. System capacity, however, is a very significant parameter that indicates how much gross data can be transmitted through the network over a single unit of bandwidth. This is especially important in a multihop network design, where the given resource could be reused by many users. Hence, the system capacity of the network provides a significant information, viz., how much data could be pushed in the given network over a bandwidth of 1 Hz. Therefore, the primary motivation for this thesis work
has been to study the multihop wireless networks and to analyze the increase in the system capacity that could possibly be obtained by using a multihop design. To the best knowledge of the authors, till date, there has been very few researchers across the globe who have done a concrete system level study on this particular aspect of multihop wireless networks. Analyzing the system design for multihop networks, and studying the impact on the overall system capacity is still a very open area of research. The different works being done in the area of multihop wireless networks would be explained in detail in Chapter 2.

In a distributed multihop network, scheduling and routing are the two most widely researched topics over the last decade [16, 17]. However, there has been relatively very less work done on the resource allocation strategies [18, 19]. Hence, the first part of this thesis aims to study the different time slot (TS) resource allocation strategies for an ad hoc network, with no central controller, and determine the impact of these strategies. Similarly, radio resource allocation for multihop cellular networks is a very nascent field of research [20]. Recently, there has a couple of independent studies on different kinds of algorithms to be used for efficient allocation of resources, and how this causes a reduction in the outage probability, and an increase in the data rate offered to a single user [21, 15]. However, these algorithms are not designed for an optimum resource allocation, and hence, these algorithms do not maximize the system capacity. Hence, the second part of this thesis work integrates multihop design and cellular networks, and aims to find novel resource allocation strategies that would increase the aggregate system capacity of the network.

1.3 Outline of Thesis

The thesis is organized as follows. In Chapter 2, multihop wireless networks are described in detail. The two broad classifications of multihop wireless design, viz., multihop ad hoc networks and multihop hybrid wireless networks are then introduced. The research challenges in these two topics are then addressed and an overview is provided on the related work available in the literature. A multihop ad hoc network is considered in detail in Chapter 3. The system capacity calculation and time slot allocation technique for the multihop ad hoc network is presented in Chapter 3. A novel random data hopping technique is then introduced as a time slot allocation mechanism. Chapter 4 deals with integrating the multihop design with the cellular network architecture. Also, a novel cluster-based design for a 2-hop hybrid cellular network is proposed in Chapter 4. Conclusions are given in Chapter 5 and finally, the limitations of the thesis and future work are explained in Chapter 6.
1.4 Contribution

This research work aims to analyze the different architectures of a multihop wireless network. A multihop design results in better coverage and a reduced power requirement as compared to the single-hop network. It has been found that for higher path-loss exponent values, the multihop design with reduced transmission power at the transmitter significantly reduces the interference, and hence, allows a spatial reuse of resources as compared to the single-hop network. It is shown analytically that if the transmitter power is kept constant, then the multihop design provides an increase in the network performance as compared to the single-hop design.

An equation for aggregate system capacity for multihop ad hoc networks is derived in Chapter 3. The Shannon capacity of a multihop ad hoc network is an open problem. Hence, an aggregate system capacity, even though suboptimal, is considered as a performance measure. Also, a variation in the number of communication pairs with a variation in the time slot (TS) granularity is studied in Chapter 3. Finally, a random data hopping (RDH) technique is proposed as an efficient but a suboptimal spatial reuse time division multiple access (STDMA) schedule for a multihop ad hoc network with high time slot granularity, and is shown to provide a higher system capacity, as compared to a system with low TS granularity.

A time division multiple access (TDMA) based multihop hybrid cellular network is detailed in Chapter 4. It is shown that for a multihop cellular network, the system performance does not increase significantly when the maximum number of hops between the mobile terminal and the BS is increased beyond four, even when no overhead is considered. In addition, for a multihop network with 10% overhead, the maximum increase in the system capacity is achieved for 2-hop and 3-hop networks. In fact, a 2-hop cellular network with a single relay between the MS and BS is shown to significantly improve the system capacity over a single-hop cellular design. A novel cluster-based 2-hop hybrid cellular network, with a frequency reuse of one is then proposed under the interference avoidance protocol. The performance of this novel approach has been mathematically analyzed and verified through computer simulations. The simulation results show that, in terms of system capacity, the cluster-based 2-hop design outperforms three standard benchmark algorithms for 2-hop cellular design.

1.5 Chapter Summary

In this chapter, the concept of the multihop wireless network was introduced along with its two broad types: the multihop ad hoc network and multihop hybrid cellular network. The motivation for this thesis work and the outline of the thesis was then described; and finally, a brief summary of the contribution of this thesis work was provided.
1 Introduction
2 Multihop Wireless Networks

Multihop wireless networks have been studied over the past three decades \cite{22}. However, during the last decade, several new applications of multihop networks have emerged. Community wireless networks are multihop wireless networks that provide “last-mile” access to people’s homes. This approach is an alternative to cable modem and DSL technologies \cite{23}. Similarly, in a large network of sensors, the scale, the environment and the limited capability of the sensors are such that a multihop wireless network is the only means of communication. Recently, over last few years, considerable research effort has focused on multihop wireless networks, in which relaying nodes are in general mobile, and the communication needs are primarily between nodes within the same network \cite{14}.

A fundamental issue in multihop wireless networks is that the system capacity degrades sharply as the number of hops traversed increases. For example, in a network of nodes with identical and omni-directional radio ranges, going from a single-hop to two hops halves the throughput of a flow because wireless interference dictates that only one of the two hops can use a given resource \cite{23}. Similarly, there is another fundamental question that has been the focus of researchers in recent years, “What is the highest achievable system capacity of a multihop wireless network?”. In case of single-hop cellular networks, this question is analyzed on a cell by cell basis, by considering the multiple access channel from the mobile users to the BS (uplink), and the broadcast channel from the BSs to the users (downlink). This area of research has been very active over the last couple of decades and is relatively well understood. The case of multihop wireless networks is more recent, and thus less well understood. The difficulty stems from the fact that in a multihop wireless network, any kind of cooperation between the users is theoretically permissible. Hence, a node in the multihop network has substantially more degrees of freedom than a single-hop cellular network. For example, in a multihop cellular network, all the nodes that communicate to the BS (uplink) in multiple hops would first communicate to the relay node. For this transmission between the mobile and the relay node, the relay would act as a receiver. At the next time instant, the relay node would then act as a transmitter and transmit this signal to the BS. This relay could be a fixed terminal mounted over a roof top or a mobile node that has its own data to transmit to some destination. In a distributed multihop network with no central coordinator, any node in the network can act both as a terminal (sender/receiver of data) and as a relay for other transmission.
Similarly, lack of any centralized control and possible node mobility gives rise to many issues at the network, medium access and physical layers, which have no counterpart in the wired nor in cellular networks. In order to understand in detail the different research problems in the field of multihop wireless networks, the description of the multihop network is divided into two sections: multihop ad hoc network and multihop hybrid wireless network.

2.1 Multihop Ad hoc Network

A multihop ad hoc network is a collection of mobile nodes that self-configure through multihop routing to form a network without the aid of any established infrastructure. Figure 2.1 shows such a multihop ad hoc network. The mobiles handle the necessary control and networking by themselves through the use of distributed control algorithms. Such multihop networks avoid the cost, installation and maintenance of network infrastructure. They can be rapidly deployed and reconfigured and also exhibit great robustness due to their distributed nature, node redundancy and lack of single points-of-failure. Due to the reduced transmission distance on account of multihop transmission, the nodes that are spatially separated can have simultaneous transmissions provided there is no destructive interference of a transmission by others. There has been considerable amount of research done on random access methods [24, 25], transmission scheduling [26] and routing [27, 28, 29]. However, the fundamental question of determining the capacity performance of ad hoc networks remain an open problem [4]. One of the fundamental and most intriguing concepts in information theory is the concept of the capacity of a single communication channel, measured in bits per second per hertz. In the landmark paper of Gupta and Kumar [14], the authors introduced a novel system performance measurement parameter, the transport capacity of the network. The transport capacity is given by the product between the data rate (bits/sec) and the distance (meters) through which the bits can be carried. This is intuitive, since the capacity increases either if the network can transport a few bits for a long range or many bits for a short range. In order to evaluate this theoretical network communication limit, information theorists allow themselves to make some unrealistic assumptions, for example, in terms of routing strategy or MAC protocols. In their seminal paper, Gupta and Kumar also derived an upper and lower bound on the performance of a class of wireless networks in the limit of a large number of nodes, in terms of a single figure of merit, the maximum uniformly achievable communication rate between all nodes and their selected destinations. In this seminal paper, there are two kinds of interference models that are introduced for a successful reception of a transmission pair in an ad hoc network scenario, viz., the Protocol Model and the Physical Model, and is explained later in detail.
2.1 Multihop Ad hoc Network

One of the most challenging problems in multihop ad hoc networks is to guarantee a certain quality of service (QoS). This problem is usually considered in the MAC layer. Traditionally, MAC protocols for ad hoc networks are based on dynamic access methods such as carrier sense multiple access (CSMA), e.g., the IEEE 802.11 standard. Although efforts have been made to guarantee QoS in CSMA based MAC protocols, dynamic methods are inherently inappropriate for providing QoS guarantees [30]. The main reason for this inadequacy is the hidden node/exposed node problem, and exponential back-off schemes, which results in large delays in multihop wireless networks [31]. One of the most important QoS in many applications is delay guarantee, i.e., the upper bound on the time it takes to transmit a message from the source to destination. This is useful when transmitting delay sensitive traffic such as voice or video. One approach where delay bounds can be guaranteed is time division multiple access (TDMA). Unfortunately, this is usually inefficient in sparsely connected networks. However, due to multihop properties, the TSs can often be shared by more than one user without conflicts. Therefore, the given resources can be spatially reused in any TS of a TDMA system, in order
to increase the network capacity. The idea is to let the spatially separated radio
terminals reuse the same TSs when the resulting interference is not severe (Exactly
how much interference could be tolerated by a receiver, so that it can still detect
its desired signal would depend on the carrier signal strength and on the system
specifications). Such a protocol is called spatial reuse TDMA, or STDMA. The
 gain from spatial reuse must, however, outweigh the additional number of trans-
missions required between the source and destination node, in order to achieve an
improvement in the system capacity.

Spatial reuse in TDMA based multihop packet radio networks was first studied
more than two decades back in [32, 33], and was introduced as a collision free access
scheme for multihop ad hoc networks. The concept of a spatial reuse channel ac-
cess schedule for multihop radio networks was formalized by Nelson and Kleinrock
[34]. A STDMA scheduler describes the transmission rights for each TS. In the
literature, various algorithms for generating reuse schedules have been proposed.
Centralized algorithms [35, 36] as well as distributed algorithms [33, 37] have been
proposed for multihop ad hoc networks. Most of the early work in the literature
have in common that the reuse schedule is designed from a graph-model of the
network, wherein the radio terminals that are located beyond a certain distance
could communicate simultaneously. The graph-scheduling technique is therefore
based on the same principle as the interference-avoidance Protocol Model. Zander
[38] proposed an alternative interference model where the signal-to-interference
ratio (SIR) is used to describe the interferences in the network. The schedule was
defined to be conflict-free if the SIR does not fall below a certain threshold [39].
Further, [40] shows that under complete knowledge of the interference envi-
ronment, interference-based scheduling can improve the network performance by up
to one third, as compared to the graph-based scheduling. Recently, Sinanovic et.
al. [41] derived the conditions when the spatial reuse of resources would result in
higher spectral efficiency for a simple 2-link ad hoc network. However, the main
disadvantage of interference-based STDMA scheduling is the increased network
complexity and the control overhead, as the interference has to be calculated at
the receiver of every potential communication pair. The graph-based scheduling
and interference-based scheduling are described in more detail in Chapter 3. Also,
the relaying of traffic causes a considerable variation in the traffic of the commu-
nicating pairs in the network. This results in “bottle-neck” effects at busy nodes
which in turn results in long packet delays. In fact, it is shown in [42] that for
an ad hoc network with a large number of wireless terminals, it is an NP-hard
problem to determine the optimum STDMA scheduling.

2.1.2 Interference Model

The interference model for this research work is primarily derived from the seminal
paper of Gupta and Kumar [14]. Consider a multihop wireless network with \( n \)
nodes in the system. Let \( X_i \) and \( X_j \) denote the location of the two wireless nodes,
Suppose node $X_i$ transmits over a particular subchannel to node $X_j$. The distance between the two nodes would be given by $|X_i - X_j|$. Let there be $n_t$ concurrent transmitters over the same subchannel, all of them transmitting with the same power level, $P_T$.

1. **Protocol Model** [14]: The transmission from node, $X_i$, is successfully received by node, $X_j$, if

\[ |X_s - X_j| \geq (1 + \Delta)|X_i - X_j| \tag{2.1}\]

for every other node, $X_s$, ($X_s; s \neq j, s \in n_t$), simultaneously transmitting over the same subchannel. The quantity, $1 + \Delta$, models situations where a circular exclusion region (or a guard zone) around the receiver of a communicating pair is specified by the protocol to prevent a neighboring node from transmitting on the same subchannel at the same time. The exclusion range ratio, $\Delta \geq 0$, indicates the ratio of the exclusion range distance to the transmission distance of the communicating pair. In the literature, as well as in this thesis, the exclusion range ratio is also sometimes described as spatial protection margin. It should be noted that under the Protocol Model, a node cannot send and receive at the same time nor transmit to more than one other node at the same time. Also, it is to be noted that this model differs from the popular 802.11 MAC in an important way - the protocol Model only requires the receiver to be free of interference, instead of requiring that both the sender and the receiver be free of interference, as in the IEEE 802.11 MAC protocol. This is because, a duplex link is usually considered in the system design, and hence, the sender would become the receiver, when the direction of the link is changed.

2. **Physical Model** [14]: The transmission from a node, $X_i$, is successfully received by node, $X_j$, if

\[ \frac{P_T |X_i - X_j|^\alpha}{P_N + \sum_{s=1, s \neq i}^{n_t} P_T |X_s - X_j|^\alpha} \geq \beta \tag{2.2}\]

Here, $\beta$ is the minimum signal-to-interference-noise ratio required at the receiver for successful reception of the signal, $P_N$ is the ambient noise power level and $\alpha$ is the propagation loss coefficient.

It can be observed that the constraints defined by the Protocol Model are local. They only require certain localities of transmitters to be free of receivers. On the other hand, the Physical Model considers the cumulative interference due to all the nodes in the network. Thus, intuitively it appears that the Physical Model is a much more restrictive model, and would entail lower capacity. However, it has been shown in Theorem 4.1 in [18] that the exclusion range concept of the Protocol...
Figure 2.2: Simultaneous communication of two pairs under the interference-avoidance Protocol Model

Figure 2.3: Two pairs cannot communicate simultaneously even if the interference-avoidance condition is satisfied by one of them

Model (also known as interference avoidance model) that has been introduced in the landmark paper of Gupta and Kumar [14] results in a more restrictive bound on the system throughput in comparison to the Physical Model. Also, in a multi-hop design, especially in multihop ad hoc networks, it is very difficult in practice to calculate the total interference across each of the communicating pairs, and then select a new simultaneously communicating pair, based on the interference across the receiver of each pair. On account of this, an interference-avoidance Protocol Model is considered in this research work.

Restrictive Interference-Avoidance Protocol Model

The interference-avoidance Protocol Model defined by Gupta and Kumar does not state anything about the presence of any other communicating receiver in the
2.1 Multihop Ad hoc Network

Exclusion region. Figure 2.2 and Figure 2.3 show two cases of the interference-avoidance model where the interfering transmitter, \( X_{s_1} \) and \( X_{s_2} \), is beyond the exclusion region of the receiver, \( X_j \), of the communicating pair, \( X_i \rightarrow X_j \). In Figure 2.2, the receiver node, \( X_{r_1} \) of the communicating pair \( X_{s_1} \rightarrow X_{r_1} \) is located such that the transmitter \( X_i \) is beyond the exclusion region of the node, \( X_{r_1} \). Hence, both the pairs, \( X_i \rightarrow X_j \) and \( X_{s_1} \rightarrow X_{r_1} \) can communicate simultaneously. However, in Figure 2.3, even though the transmitter node, \( X_{s_2} \) is located beyond the exclusion region of \( X_j \), the pair \( X_{s_2} \rightarrow X_{r_2} \) cannot communicate concurrently with \( X_i \rightarrow X_j \), since the transmitter, \( X_i \) is within the exclusion region of the pair, \( X_{s_2} \rightarrow X_{r_2} \). Therefore, the conditions for selecting the concurrent pairs are not reciprocal, i.e., the presence of a 2nd concurrently communicating pair would be acceptable to the 1st pair, but in reality, the 2nd pair might not be able to communicate because of the presence of the 1st communicating pair. Hence, in order to avoid this complexity involved in computing the conditions for each concurrently communicating pairs, especially in a multihop ad hoc network, a restricted version of the interference-avoidance Protocol Model is considered in the research work carried out in Chapter 3. In this design, apart from the condition given by eqn. 2.1, an additional condition is taken into consideration, and is given by:

\[
|X_r - X_j| \geq (1 + \Delta)|X_i - X_j|
\]

where \( X_r \) is the receiver of the communicating pair \( X_s \rightarrow X_r \) that communicates concurrently with \( X_i \rightarrow X_j \).

It should be noted that as per this restricted version of the interference-avoidance model, the exclusion region of the simultaneously communicating pairs would not overlap with each other, as shown in Figure 2.4. A simple example of a multihop ad hoc network and an equivalent single-hop network is shown in Figure 2.5. It can be observed from the figure that there is a much greater exclusion region around the single-hop link as compared to the multihop link, and hence, the multihop system has a lower interference region, and therefore, results in a better system performance as compared to the single-hop network. A detailed analysis of the improvement in the system capacity that could be obtained from a multihop link as compared to an equivalent single-hop link, (even without considering spatial reuse of resources) is shown in Appendix A.1.

A simple multihop link between a source node, \( P \), and destination node, \( Q \), is shown in Figure 2.5a. There are three nodes between \( P \) and \( Q \) that act as relays.

2.1.3 Capacity Scaling

In the landmark paper of Gupta and Kumar [13], it has been shown that for a randomly distributed wireless network with \( n \) nodes, the capacity per node scales as \( \left( \frac{1}{\sqrt{n \log n}} \right) \) bits per second under the interference avoidance Protocol Model. Thus, the aggregate capacity of all the nodes in the networks scales as \( \left( \frac{n}{\sqrt{n \log n}} \right) \). The nodes are assumed to be uniformly distributed. Also, the destination for each
node is independently chosen as the node nearest to a randomly located point. At the same time, the nodes are assumed to be homogeneous, i.e., all transmissions employ the same transmission range or power. The above mentioned results also indicate that the upper bound for the system capacity is inversely proportional to the common transmission range. It is to be noted that as per the definition given in [14], the transport capacity is defined as the total bit-distance product per second that can be transported by the network. On the other hand, link capacity (capacity per node) is defined as the maximum common throughput that can be provided to each node in the network with a randomly chosen destination. In [43], Gupta and Kumar studied the capacity of a random three dimensional wireless ad hoc network and showed that the aggregate throughput capacity scales as \((\frac{n}{\log n})^{\frac{2}{3}}\).

In [19], Grossglauser and Tse introduced mobility into the model presented in [14]. They showed that the average long-term capacity per source-destination pair can be kept constant even as the number of nodes per unit area increases, provided, sufficient delay period is allowed for the data to reach the destination. This is achieved by exploiting mobility to keep data transfers local, and transmitting only when the transmitter and receiver are close to each other, at a distance of \(\Theta(\frac{1}{\sqrt{n}})\), thereby reducing total resource usage and interference. The authors also showed that by allowing only one-hop relaying, the scheme achieves an aggregated system capacity of \(\Theta(n)\) at the cost of unbounded buffer and delay requirement.
2.1 Multihop Ad hoc Network

Figure 2.5: Single-hop and multiple hop transmission between source, $P$, and destination, $Q$

Case a: Multihop communication between $P$ and $Q$

Case b: Equivalent single-hop communication between $P$ and $Q
Li, Blake et al. extended the pioneering work of Gupta and Kumar by considering the impact of different traffic pattern on the scalability of per-node capacity. They point out that a random traffic pattern represents the worst case, from the view point of per-node capacity. They also show that for traffic patterns with power law distance distributions, the per-node capacity stays nearly constant as the network size grows, provided, the distance distribution decays more rapidly than the square of the distance. In a similar manner, Jain et al. computed the capacity bounds for a given wireless network and traffic load. However, they use a conflict graph to model the constraints imposed by wireless interference. Similarly, Yang and Vaidya use the notion of conflict graph for priority scheduling in wireless ad hoc networks. However, the conflict graph is defined on flows rather than actual communication pairs, and is only used to show that the 802.11 MAC causes flows with a high degree of conflict to suffer disproportionately as compared to flows with low degree of conflict. The recent work of De Couto et al. based on two experiments in a 802.11b-based multihop wireless testbeds shows that minimizing the hop count of an end-to-end link is not sufficient for achieving good performance. The reason they point out is that link quality can vary widely and that the long hops that may be included in “short” paths may incur a high packet error rate. Toumpis and Goldsmith investigated the capacity regions for finite ad hoc wireless networks. A capacity region characterizes the set of achievable rate combinations involving all source-destination pairs in the network. A very small ad hoc network with only five nodes is considered in their system model. They show that in the absence of spatial reuse, the slice that determines the boundary of capacity regions for both single-hop and multihop networks is a straight line. However, in the presence of spatial reuse, the slice is no longer a straight line, as in this case, the network can spatially reuse the resources in order to maintain multiple active transmissions, and at any time instant more than one stream may be serviced (directly or along a multihop route).

2.1.4 Mobile Clustering

Over the last decade, there has been an intense research on the design of a cluster-oriented hierarchical architecture for achieving a basic performance guarantee in a large scale mobile ad hoc network (MANET). In a clustering scheme, the mobile nodes in the mobile ad hoc network are divided into different virtual groups and the nodes that are geographically adjacent to each other are allocated the same cluster according to some rules and specifications. A cluster-based structure, as an effective topology control means, provides three main benefits. First, a cluster network facilitates the spatial reuse of resources to increase the system capacity. With the non-overlapping multi-cluster structure, two clusters may deploy the same frequency or use the same time resource if they are not neighboring clusters and if they are substantially separated from each other. Also, a cluster can better coordinate its transmission events with the help of
2.1 Multihop Ad hoc Network

A special mobile node such as a cluster-head or a relay node. The importance of relays in ad hoc network is explained in 2.1.5. The second benefit is in routing, where the set of cluster-heads and cluster-gateways form a virtual backbone for inter-cluster routing 54, 55, 56. Thus, the generation and spreading of routing information can be restricted to the set of nodes that are in the same cluster 57, 58. Lastly, a cluster structure makes a multihop ad hoc network appear smaller and more stable from the mobile terminal perspective. When a mobile node changes its attaching cluster, only those nodes residing in the corresponding clusters need to change their information 59, 60. However, to maintain a cluster structure in a dynamically changing scenario often requires explicit message exchange between mobile node pairs. When the underlying network topology changes quickly and involves many mobile nodes, the clustering related information exchange increases drastically 61. Frequent information exchange may consume considerable bandwidth and drain mobile nodes’ energy quickly. Also, some clustering schemes may cause the cluster design to be completely rebuilt over the whole network when some local events like movement of a mobile node takes place. This is called the ripple effect of clustering 62. A comprehensive survey on different clustering schemes for multihop mobile ad hoc networks has been presented in 63 wherein the state-of-the-art clustering algorithms have been classified based on their main objectives and their performances have been analyzed. A cluster-based design for the multihop wireless network is analyzed and explained in detail in Chapter 4 of this thesis.

2.1.5 Relays in Multihop Network

Gastpar and Vetterli 64 extended the work of Gupta and Kumar 14 in a different direction. Instead of the simple point-to-point coding assumption of 14, which treats each transmitter-receiver pair to be independent of other pairs, they consider a network coding model where nodes could cooperate in arbitrary ways. In this scheme, there is only one source-destination pair while all others act as relays that assist the transmission between the source and destination. The optimum system capacity under these conditions is \( \Theta(\log n) \). In the landmark paper by Gupta and Kumar 14, they also point out that, if \( m \) additional homogeneous nodes are deployed as pure relays in random positions, with no independent traffic of their own, then the capacity that can be furnished to each of the \( n \) sources is 

\[
\Theta \left( \frac{n^2}{n^2 + 1} \right) \ln(n^2 + m). \]

There is however a severe cost of providing this increase in capacity. The number of additional relay nodes that need to be deployed to gain an appreciable increase in the capacity for the source nodes may be very large. The addition of \( m \) relay nodes provide less than \( \sqrt{\frac{n^2}{n} + 1} \)-fold increase in capacity. Also, the lack of any centralized control and possible node mobility gives rise to many issues at the network, medium access and physical layers, which have no counterpart in wired networks like Internet, or in the cellular networks. This
gives rise to one of its most serious drawbacks, the limitation in providing global connectivity. This is the reason why few real world applications of mobile ad hoc networks have been developed or deployed outside the military environment. As a result, no traces of actual node movement in a real ad hoc network have been available for ad hoc network routing protocol simulation studies. In all practical and realistic applications that have been designed so far, an infrastructure based network is considered in the backbone of the multihop ad hoc networks. An “anytime - anywhere” connectivity between two mobile devices is obtained by having the multihop ad hoc network combined with infrastructure-based cellular networks (or any other centralized control) and is known as “multihop hybrid wireless networks”.

2.2 Multihop Hybrid Wireless Network

A multihop hybrid wireless network model overcomes the limitation posed by the ad hoc networks and the single hop cellular networks. Since wireless units are typically energy constrained and ad hoc networks have limited communication capacity, the addition of infrastructure or BS nodes is a natural approach of reducing the energy and traffic burden on ad hoc nodes while possibly increasing the system throughput. For example, one can envisage a hybrid ad hoc wireless network as a means to enable sharing of information between mobile sensor nodes or gathering of sensed information toward query points on a wireline network [65]. Alternatively, one can view multihop cellular network model as a means to extend the communication coverage of wireless cellular infrastructure. Such a hybrid network model aims at providing global connectivity and at the same time, seeks to suppress the interference and maximize the throughput capacity of the network, in order to achieve a cell frequency reuse ratio of one which is the target being aimed for the development of 4th generation orthogonal frequency division multiplexing (OFDM) based TDMA/TDD cellular mobile communication network. Note that, in contrast to a single-hop cellular network, the traffic in a multihop hybrid wireless network need not be always mediated through the BS. The wireless nodes that wish to communicate with each other might do so directly. Thus, as shown in Figure [2.6] there are two “types” of traffic in such networks: that which is eventually mediated through the infrastructure nodes and that which is relayed in a purely ad hoc manner [65].

2.2.1 Architecture Classification

There are several different kinds of multihop hybrid wireless architectures available in the literature In this section, some of the prominent multihop hybrid wireless network architectures are listed, based on a efficient spectrum reuse, high data rate capability especially at the fringes of the cell, support for large user volumes, etc.
Figure 2.6: A multihop hybrid transmission: A link communicates in either *ad hoc* mode or in cellular mode
1. **Multihop cellular networks (MCN):** MCN, [66], is a novel cellular architecture where a connection between the source and destination is established over a multihop path. However, like in a traditional single-hop cellular network, the end-to-end communication is always between the MS and BS. MCN suggests that the transmission power of the mobile node and the BS over the data channel be reduced to a fraction $\frac{1}{c}$ (where $c$ is referred to as the reuse factor) of the cell radius, $R$, as shown in Figure 2.7. This means that more than one node can transmit simultaneously on the same channel. The node density expected in MCN is quite high, and hence, the chances of a network partition are quite small. There have been lots of research work on multihop cellular networks in recent years [2], [67]. Manoj and Siva Ram Murthy have done research in this direction and have suggested different routing techniques for multihop cellular networks, viz., base assisted *ad hoc* routing (BAAR) [68], base-driven multihop bridge routing (BMBP) [69], [70], single-interface multihop cellular network routing protocol (SMRP) [71], for different kinds of traffic patterns. These techniques effectively utilize the *ad hoc* relaying in presence of fixed infrastructure in order to achieve enhanced network capacity. Chapter 4 of this research work introduces a special case of multihop cellular network, a novel cluster-based design for a 2-hop cellular network.

2. **Mobile Assisted Data Forwarding (MADF):** The MADF is a hybrid architecture in which a multihop relaying system is overlaid on the existing cellular networks [72]. The main objective of this system is to dynamically divert the traffic load from a *hot cell* (highly loaded cell) to *cooler cells* (lightly loaded) in its neighborhood. The mobile terminals use multihop relaying to transfer a part of the traffic load from the *hot cell* to neighboring cells. For this purpose, a small number of designated channels called *forwarding channels* are used to establish multihop paths.

3. **Integrated Cellular *ad hoc* Relay system, (iCAR):** iCAR, [15], is a next generation wireless architecture that can easily evolve from the existing cellular infrastructure. In particular, it enables a cellular network to achieve a throughput closer to its theoretical capacity by dynamically balancing the load among different cells. In a normal single-hop cellular network, even if the network load does not reach the network capacity, several calls may be blocked or dropped because of isolated instances of congestion in the system. To counter this, iCAR uses fixed relays over and above the infrastructure-based cellular system that dynamically routes the traffic. This architecture eliminates the problem of hot spots by employing different kinds of routing (primary routing, secondary routing and tertiary routing) and by allowing high data rates to be transmitted over long distances with the help of multiple hops between the source and destination.

4. **Self Organizing Packet Radio *ad hoc* Networks (SOPRANO):** SO-
Figure 2.7: A multihop cellular transmission where the mobile node communicates to the BS in multiple hops
PRANO, [73], is a slotted packet CDMA system with dedicated relay stations (also referred to as repeaters or routers) where the repeaters form a hexagon or a random shape. SOPRANO assumes the use of asynchronous CDMA with a large number of spreading sequences. A channel assignment process is used to inform every node about the channel to be used by that node. SOPRANO aims at providing high data-rate Internet access by using inexpensive relay stations.

5. Multihop Hybrid Cellular Network: A multihop hybrid cellular network with both BSs and dedicated relays have been considered in [74]. The dedicated relay stations are used to store and forward data from the BS to the wireless terminals and vice-versa. Like in the case of multihop ad hoc network, the relays in the multihop hybrid wireless network rely on the wireless transmission to communicate to either the MS or the BS. Deploying relays and employing multihop transmission in the cellular architecture results in simultaneous transmission by both the BS and the relays. This would, therefore, clearly improve the performance of the system as compared to a multihop ad hoc network or the standard single-hop cellular network.

Routing in the traditional single-hop cellular networks is fairly simple and does not extend to multihop hybrid wireless networks due to multihop transmission and high routing overhead. There has been a lot of research work done with regard to routing in ad hoc networks and extending the same to multihop hybrid wireless architectures. It is observed that routing efficiency is higher in iCAR and SOPRANO as compared to other hybrid wireless architectures [15, 73]. This is because, iCAR uses a seed-growing algorithm which places the seed relay stations at the boundary between two cells, whereas, the SOPRANO architecture places the relay stations in layers, forming a co-centric hexagonal pattern inside the cell. The hybrid wireless network design has shown significant capacity improvement over the single-hop cellular network and the ad hoc network model, and is explained in detail in the next subsection.

2.2.2 Capacity Scaling

Following the research work in the capacity scaling of ad hoc networks, there has been a couple of research groups who have worked in the direction of capacity scaling for multihop hybrid wireless networks. It was shown in [75] that having the infrastructure based BS component within the multihop ad hoc network drastically increases the connectivity of the network. For a multihop hybrid cellular network with $n$ nodes and $m$ BSs, the results in [76] show that if $m$ grows asymptotically slower than $\sqrt{n}$, the benefit of adding BSs on capacity is insignificant. However, if $m$ grows faster than $\sqrt{n}$, the throughput capacity increases linearly with the number of BSs providing an effective improvement over the multihop adhoc network. Therefore, in order to achieve non-negligible capacity gain, the
investment in the wired infrastructure should be high enough. In fact, the authors in [76] consider two different routing strategies to obtain the analytical expression of the throughput capacity. A multicell scenario is considered for the multihop hybrid cellular network. In the first routing strategy, a node sends data through the infrastructure if the destination is outside of the cell where the source is located. Otherwise the data is forwarded in the multihop ad hoc fashion. Under this strategy, if $m$ grows asymptotically slower than $\sqrt{n}$, the maximum system capacity is $\Theta\left(\sqrt{\frac{n}{\log m}}\right)$. In this case, the benefit of adding BSs is insignificant. However, in the case where the BSs are added at a speed faster than $\sqrt{n}$, the maximum capacity is $\Theta(m)$, which increases linearly with the number of BSs. Similar results are obtained from the probabilistic routing strategy where a node chooses to send data through the infrastructure according to some probability. Under this routing strategy, if $m$ grows than $\sqrt{\frac{n}{\log n}}$ the maximum system capacity has the same asymptotic behavior as the pure ad hoc network. There is no point in using infrastructure in this case. However, if $m$ grows faster than $\sqrt{\frac{n}{\log n}}$, then the capacity scales linearly with the number of BSs.

2.3 Chapter Summary

In this chapter, the two broad types of multihop network, viz., multihop ad hoc and multihop hybrid wireless network were described in detail. Two kinds of interference model: Protocol Model and Physical Model were explained and the restrictive version of the Protocol Model was introduced. The benefits of spatial reuse in multihop design, and the improvement in system capacity of multihop ad hoc network due to the presence of relays were then explained. Finally, a description of the multihop hybrid wireless network, its different architectures and the scaling of the system capacity as a function of the number of BSs was provided.
Multihop Wireless Networks
3 Time Slot Allocation in a Multihop Ad hoc Network

Media access control is an integral part of multihop ad hoc communication and has obtained intense research attention over the last decade. Recently, the concept of multi-channel MAC has been studied by several research groups with the objective of achieving high system capacity. A large number of multi-channel MAC protocols and TDMA scheduling algorithms have been proposed in the literature [77, 78, 79, 80]. In a multihop packet radio environment with TDMA channel access, the time slot allocation (TSA) problem basically deals with assigning the time slots to the packet radio units in some optimal, efficient and equitable fashion [16]. This topic has received considerable attention from the research community and is also known as communication scheduling, resource allocation, time slot assignment, link activation, TDMA cycle allocation, etc.

The authors in [81] compare the scheduling technique based on the Protocol Model with the scheduling technique based on the Physical Model, on the basis of attainable system capacity. The throughput for the Protocol Model, denoted as the protocol throughput, is defined as the average number of simultaneous transmissions per slot. They show that the protocol throughput increases with an increase in the traffic load (packet generation rate). However, this is not true in reality. This is correctly pointed out by the authors in [81], by considering a scheduling technique based on Physical interference Model and by calculating the physical throughput. They show that there exists an optimum number of simultaneous communication pairs which results in a maximal throughput. This is because, for a low number of simultaneously communicating pairs, the interference experienced by each receiver is less, and hence, the C/I at any receiver node is high, which results in a high number of bits that could be transmitted per communicating pair. Similarly, with a very high number of simultaneous communicating pairs, there is an increase in the interference experienced by every communicating pair, which reduces the C/I at the receiver and hence the system capacity. Hence, the throughput calculation based on the Physical interference Model is a more accurate representation of the system behavior, than the throughput calculation based on the Physical interference Model. But, the biggest drawback in the calculation of throughput, and hence, the system capacity under the Physical interference
Model is that, for a large network, it is not possible to calculate the interference at every receiver node and then decide whether a given pair can communicate at a particular time slot. The two main reasons being, the system complexity and network delay. Hence, there needs to be a concise mechanism that can accurately reflect the system capacity.

In this thesis work, the system capacity is not measured in terms of number of concurrent transmissions per time slot (as is done in [81] for the Protocol Throughput). But the system capacity is measured using the Shannon equation which takes the $C/I$ into account, as will be shown in section 3.1. It should be however noted that the $C/I$ calculation done at the receiver for calculating the system capacity does not affect the selection of simultaneous communication pairs (unlike the Physical Model where each pair is selected for communication only if the $C/I$ is above a certain threshold). It should also be noted at this stage that the Shannon capacity of the multihop ad hoc network is still an open problem [4]. At the same time, the transport capacity introduced in [14] and explained in Chapter 2 is not sufficient to describe the overall performance and dynamics of the ad hoc network. While the transport capacity (bit rate × distance) is a meaningful metric for overall performance in ad hoc wireless networks, this parameter does not tell us anything about the connectivity properties of the network (e.g., the average number of hops per link and the average number of simultaneously active links). Hence, the performance measure is based on Shannon capacity equation. In addition, an ideal coding and modulation scheme is considered in this research. Hence, in case of the multihop ad hoc network design, the aggregate system capacity is taken as the performance measuring quantity. Proceeding further, due to the Protocol Model considered in this thesis for controlling the interference, the system capacity of the multihop ad hoc network depends on the spatial protection margin across the receivers. In the next section, the equation for system capacity is derived and the optimum value of the spatial protection margin that maximizes the system capacity is calculated.

### 3.1 System Capacity of a General Multihop System

#### 3.1.1 General Multihop Network

A general schematic of a multihop link between the source node, $P$, and the destination node, $Q$ is shown in Figure 3.1. The transmission from source $P$ to destination $Q$ takes place using multiple hops, represented as $M$ hops ($M = 7$) in Figure 3.1. The circles drawn around the receiver of every communicating pair represent the transmission range circle and the radius of the circle represent the transmission distance, $d_c$. The transmission distance, $d_c$, of every communication pair would, in general, be different, and hence, could be written as $d_{ci}$, $i \in \{1, 2, ..., M = 7\}$. An exclusion region circle is drawn around the receiver
such that no other transmitter except the desired one transmits in that region. Figure 3.1 shows the exclusion region only around the destination node, $Q$, given by the area, $B$. The radius, $r_{ei}$, of any exclusion region circle is $\Delta$ times the transmission distance, i.e.,

$$r_{ei} = d_{ei}(1 + \Delta),$$  \hfill (3.1)

where $\Delta$ is a factor that determines the spatial protection margin added to the transmission distance. If the area of the exclusion region around the receiver of the communicating pair, $i$ is represented as $B_i$, $i \in \{1, 2, ..., M\}$, then the exclusion range area could be written as, $B_i = \pi d_{ei}^2 (1 + \Delta)^2$.

Figure 3.1: A multiple hop transmission between the source, $P$, and destination, $Q$

### 3.1.2 Calculation of Aggregate System Capacity

A finite coverage area, $Z$, is considered in the system design of multihop wireless networks. The MSs are assumed to be uniformly distributed in the given
coverage area. For any TS, the instantaneous number of simultaneously communicating pairs in the system, \( n_t \), is a random variable that depends on the location of the communicating pairs. The upper bound on the number of simultaneously communicating pairs for any TS, \( L_M \), depends on the coverage area, and most importantly, on the area of the exclusion range circles of all simultaneously communicating pairs. In a practical scenario, the condition for the number of simultaneously communicating pairs for any TS is \( 1 \leq n_t \leq L_M \). For any transceiver pair, separated by a distance, \( d_c \), the power at the receiver is found from a generic pathloss model as:

\[
P_R = P_T - (k_1 + 10\alpha \log_{10}(d_c)) \text{ dB} \tag{3.2}
\]

where \( P_T \) is the transmit power, \( \alpha \) is the pathloss exponent and \( k_1 \) is a propagation constant. A constant transmit power is assumed for all the nodes in the system. For each of the \( n_t \) simultaneously communicating pairs at any time slot, \( t \), the remaining \( n_t - 1 \) simultaneous communicating pairs act as interferers. Therefore the carrier-to-interference ratio, \( \gamma_{it} \), of the \( i \)th communicating pair at \( t \)th TS is given by

\[
\gamma_{it} = \frac{10^{P_T/10} 10^{-(k_1 + 10\alpha \log_{10}(d_c))/10}}{\sum_{j=1,j \neq i}^{n_t} 10^{P_T/10} 10^{-(k_1 + 10\alpha \log_{10}(d_{int_{ij}}))/10}}
\]

which simplifies to

\[
\gamma_{it} = \frac{d_c^{-\alpha}}{\sum_{j=1,j \neq i}^{n_t} d_{int_{ij}}^{-\alpha}} \tag{3.3}
\]

where \( d_{int_{ij}} \) is the distance between the receiver of the \( i \)th communicating pair and the transmitter of the \( j \)th communicating pair. The distance between a desired receiver and an unintentional transmitting entity is given by \( d_{int_{ij}} \geq (1 + \Delta)d_c \). The expression for \( \gamma_{it} \) can be further simplified by assuming that all the interfering nodes are at the circumference of the exclusion region itself. In this case, all the interfering transmitters would be at the closest possible distance from the intended receiver. Hence, this would model the worst-case interference scenario. For such a scenario, the distance of all the transmitting interferers from the receiver of the \( i \)th communicating pair would be given by \( d_{int_{ij}} = (1 + \Delta)d_c \). The carrier-to-interference ratio, \( \gamma_{it} \), eqn. (3.3), can therefore be lower bounded as follows:

\[
\gamma_{it} \geq \frac{(1 + \Delta)^\alpha}{n_t - 1} \forall \ i \in \{1, 2, ..., n_t\} \tag{3.4}
\]

The average system capacity for the wireless network is calculated from the expected values of \( \gamma_{it} \) and \( n_t \).

**Calculation of System Capacity:**

The Shannon equation for system capacity is used to derive the equation for aggregate system capacity. For a continuous transmission by a communication pair, the Shannon capacity of the system is given by:
\[ C_s = \log_2(1 + C/I) \text{ bps/Hz} \quad (3.5) \]

where \( C_s \) indicates the Shannon capacity of the communication link, and \( C/I \) is the carrier-to-interference ratio. However, the performance measure in this thesis for the multihop ad hoc network is the aggregate system capacity of the network.

In a multihop system, there are several communication pairs per link, as shown in Figure 3.1. Each of these pairs would communicate for only one of the \( T \) TSs. Hence, each of the pairs would contribute to the capacity for only one of the \( T \) TSs. Hence, the eqn. \((3.5)\) is divided by the factor \( T \). Since the TDMA frame has \( T \) TSs, the calculation for system capacity is performed for all \( T \) TSs. In addition, for each of the \( T \) TSs, there are \( n_t \) simultaneous communication pairs. Hence, while calculating the aggregate system capacity, the capacity has to be calculated for each of the \( n_t \) concurrently communicating pairs.

It is to be noted that the total area occupied by the exclusion regions of all the communicating pairs for any time instant, \( t \), is given by

\[ A = \sum_{i=1}^{n_t} B_i \quad (3.6) \]

However, since \( 1 \leq n_t \leq L_M \) (where \( L_M \) is the upper bound on the number of concurrent transmissions), the area, \( A \), given by eqn. \((3.6)\) would always be less than the coverage area, \( Z \), considered in the system, i.e., \( A \leq Z \). Hence, in order to calculate the aggregate system capacity for a given coverage area, the equation for the system capacity is scaled by the factor, \( Z \). It should be noted that scaling by the term \( Z \) is more appropriate than scaling by the factor, \( A \). This is because, scaling by the factor, \( Z \), takes the whole coverage area of the system into account, whereas, \( A \) only indicates the total area occupied by the exclusion region circles.

Hence, the equation for aggregate system capacity is written as follows:

\[ C = \frac{1}{ZT} \sum_{t=1}^{T} \sum_{i=1}^{n_t} \log_2(\gamma_{it} + 1) \text{ bps/Hz/km}^2 \quad (3.7) \]

where \( \gamma_{it} \) is the carrier to interference ratio of the \( i^{th} \) communicating pair at the \( t^{th} \) TS.

A unit coverage area is considered throughout in the system design for the multihop ad hoc network. Hence, \( Z = 1 \), and therefore, the above equation for the system capacity would be modified as follows:

\[ C = \frac{1}{T} \sum_{t=1}^{T} \sum_{i=1}^{n_t} \log_2(\gamma_{it} + 1) \text{ bps/Hz/km}^2 \quad (3.8) \]

In the calculation of eqn. \((3.8)\), it is assumed that all the nodes have sufficiently long buffer. Hence, all the pairs of a communicating link would communicate, either in the given time frame or in subsequent time frames. Therefore, all the communicating pairs contribute to the system capacity.
3.1.3 Optimum Spatial Protection Margin

In the interference-avoidance Protocol Model, the value of $\Delta$ is a very significant parameter that affects the system capacity calculation of multihop wireless networks. Hence, before studying the different scheduling techniques, the variation of capacity with the spatial protection margin is evaluated. The aim of this subsection is twofold:

1. To determine the optimum spatial protection margin for the given system that would maximize the system capacity.

2. To determine a relation between the optimum spatial protection margin and other system parameters.

Simulation Model and Results for Optimum $\Delta$

A multihop wireless network with 500 uniformly distributed MSs is considered in a square-shaped coverage area of $Z \text{ km}^2$. The coverage area considered for the wireless network is a square and is given by $Z = s^2$ where $s$ is the side length. For any value of the maximum number of multiple hops per link, a MS located at the edge of the coverage area would employ a maximum of $M$ hops per link to communicate to its destination. As a result, the maximum transmission distance for any hop is given by the diagonal of the square that is normalized by the number of multiple hops per link, i.e., $d_c = 1.414s/M$. The value of $C/I$ is estimated for each MS from the carrier strength of the desired Rx and from the interference arising from all the MSs that are communicating simultaneously.

With an increase in the radius of the exclusion region around the receiver, the interference coming from other MSs decreases, and hence, there is an increase in $C/I$ for every communicating pair. But at the same time, the number of simultaneously communicating pairs decreases for a given coverage area, which in turn reduces the overall system capacity. Hence, the obtainable system capacity is not a monotonically increasing function of $\Delta$; instead it observes a bell-shaped performance. Figure 3.2 shows the numerically obtained results while Figure 3.3 shows the simulation results for two different values of pathloss exponent. An indoor pathloss model values [82], with $k_1 = 37$, and $\alpha = 3$ and also $\alpha = 4$ have been considered in the simulations.

Analytical Framework for Calculating Optimum $\Delta$

A simple multihop ad hoc network is considered in order to develop an analytical framework. It has been shown in [23] and explained in detail in the next section, that for a general multihop ad hoc network under the Protocol interference Model, it is not only a non-deterministic polynomial time hard (NP-hard) problem
to determine the optimum system capacity, but also, it is NP-hard to approximate the conditions for optimal throughput. However, in order to analytically validate the results of optimum $\Delta$ obtained through computer simulations, a simple and a deterministic model of a multihop ad hoc design is considered. The aim of this analysis is to find an optimum value of $\Delta$ that would maximize the system capacity and to study the dependence of $\Delta$ on other system parameters. The following assumptions are made in order to develop the simplified analytical model.

1. A constant number of multiple hops per link, $M$, is considered in the multihop design. The transmission distance, $d_c$ is however different for different communication pairs.

2. A constant $\Delta$ is assumed for all the communicating pairs. Hence, the radius of the exclusion region circles drawn around each of the receivers depends only on the transmission distance. This reduces the problem of ‘finding the number of concurrent transmissions per time slot’ to an ‘maximum unequal-circle packing’ problem.

3. A dense packing of circles is considered in the coverage area. This dense packing condition of the unequally sized circles simplifies the understanding of the problem. At this stage, it should be noted that the optimal packing of unequal circles is an NP-hard problem and there exists no general solution in the literature [83]. The optimal packing problem and the non-optimal packing scenarios are shown in Appendix A.2.

Given that an optimal packing of circles is considered, the number of exclusion range circles that can be placed in the coverage area depends on the radius of the circle, which in turn depends on the exclusion range factor, $\Delta$. When $\Delta = 0$, the radius of the exclusion region circle is $d_c$, and correspondingly, the number of circles in the area is, $N = N_{\text{max}}$, where $N_{\text{max}}$ is the maximum number of non-overlapping circles that can be placed in the coverage area. An increase in the ratio, $\Delta$, would result in a reduction in the maximum number of possible circles. Therefore, the optimum number of circles in the coverage area, $N$, depends on $M$ and $\Delta$. For any fixed value of $M$ (given a coverage area), $N$ depends entirely on $\Delta$; i.e., $N = f(\Delta)$ and is written as $N_{\Delta}$. In the absence of a general equation for calculating the precise value of $N_{\Delta}$ [83], the different values of $\Delta$ and the corresponding number of circles, $N_{\Delta}$, is obtained numerically using the “billiards” simulation algorithm as done in [84]. Table 3.1 shows the value of $\Delta$ for certain selected values of $N_{\Delta}$. As seen in Table 3.1, the maximum value of $\Delta$ for which the multiple number of pairs can be supported in the system increases with increasing $M$. For a given $M$, the aggregate system capacity does not increase linearly with

Table 3.1: Optimum Values of $\Delta$ for Various Numbers of Circles.
Figure 3.2: Variation of system capacity (numerically obtained results) for different values of exclusion range ratio, $\Delta$, for a bounded system

$\Delta$, but reaches a peak when $\Delta$ is between 1.0 and 1.2, and then starts decreasing. The variation of $\Delta$ with $\alpha$ and $M$ that maximizes the system capacity is shown in Table 3.2 which shows the numerically obtained analytical results and the simulation results. It could be seen that as the value of $\alpha$ or $M$ increases, the value of $\Delta$ for the maximum capacity also increases marginally. The exact value of $\Delta$ where the aggregate system capacity reaches its peak depends on $M$ and $\alpha$.

A noteworthy observation that could be made from Figure 3.2 is that for each different value of $M$, there exists a specific value of $\Delta$ above which the numerically obtained capacity results are not plotted. This is because an increase in the value

<table>
<thead>
<tr>
<th>$N_\Delta$</th>
<th>30</th>
<th>25</th>
<th>20</th>
<th>16</th>
<th>12</th>
<th>9</th>
<th>8</th>
<th>6</th>
<th>4</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M = 3$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.0</td>
<td>0.126</td>
<td>0.5</td>
<td>0.73</td>
<td>1.02</td>
</tr>
<tr>
<td>$M = 4$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.0</td>
<td>0.072</td>
<td>0.7</td>
<td>0.8</td>
<td>0.95</td>
<td>1.043</td>
</tr>
<tr>
<td>$M = 5$</td>
<td>-</td>
<td>0.0</td>
<td>0.114</td>
<td>0.25</td>
<td>0.482</td>
<td>0.878</td>
<td>1.07</td>
<td>1.16</td>
<td>1.27</td>
<td>1.54</td>
</tr>
<tr>
<td>$M = 6$</td>
<td>0.08</td>
<td>0.2</td>
<td>0.336</td>
<td>0.5</td>
<td>0.68</td>
<td>1.0</td>
<td>1.047</td>
<td>1.2523</td>
<td>2.0</td>
<td>2.515</td>
</tr>
</tbody>
</table>

Table 3.1: Values of exclusion range ratio, $\Delta$, for varying number of maximum pairs, $N_\Delta$ and different values of $M$
3.1 System Capacity of a General Multihop System

Variation of System Capacity with $M$ and $\Delta$ when $\alpha = 3$

![Graph showing variation of system capacity with $M$ and $\Delta$ when $\alpha = 3$.]

Figure 3.3: Variation of system capacity (simulation) for different values of exclusion range ratio, $\Delta$, for a bounded system

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
<th>3.5</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M = 3$</td>
<td>0.76</td>
<td>0.84</td>
<td>0.94</td>
<td>1.04</td>
<td>1.1</td>
</tr>
<tr>
<td>$M = 4$</td>
<td>0.84</td>
<td>0.92</td>
<td>1.0</td>
<td>1.08</td>
<td>1.2</td>
</tr>
<tr>
<td>$M = 5$</td>
<td>0.92</td>
<td>1.0</td>
<td>1.1</td>
<td>1.2</td>
<td>1.26</td>
</tr>
<tr>
<td>$M = 6$</td>
<td>1.0</td>
<td>1.08</td>
<td>1.2</td>
<td>1.28</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Numerically obtained analytical results

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
<th>3.5</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M = 3$</td>
<td>0.76</td>
<td>0.84</td>
<td>0.94</td>
<td>1.04</td>
<td>1.12</td>
</tr>
<tr>
<td>$M = 4$</td>
<td>0.83</td>
<td>0.92</td>
<td>1.0</td>
<td>1.08</td>
<td>1.2</td>
</tr>
<tr>
<td>$M = 5$</td>
<td>0.92</td>
<td>1.02</td>
<td>1.12</td>
<td>1.2</td>
<td>1.26</td>
</tr>
<tr>
<td>$M = 6$</td>
<td>0.99</td>
<td>1.08</td>
<td>1.2</td>
<td>1.26</td>
<td>1.32</td>
</tr>
</tbody>
</table>

Simulation results

Table 3.2: Values of spatial protection margin, $\Delta$, for achieving maximal system capacity
of $\Delta$ results in a scenario where there is only one exclusion region circle in the given area, i.e., there is only one communicating receiver at any time instant. There is no interfering entity for such a situation. The main aim of this analysis has been to study the behavior of $\Delta$ under the interference limited communication, i.e., when there is more than one pair utilizing the given resource, and observe its effect on the system capacity. Hence, the results for system capacity is not plotted in the absence of any interfering entity. Also, the effect of noise is not considered as it is outside the scope of this work. Figure 3.3 shows the simulation results for a pathloss exponent of $\alpha = 3$. It can be seen from Figure 3.2 and Figure 3.3 that there is a difference in the absolute value of the system capacity attained in the analytical and simulation results. This arises from the fact that in the numerical model, a dense packing of the unequal circles is considered according to the “billiards simulation” algorithm; whereas in the simulations, the circles are placed with the receiving node as the center of the circle. Hence, in practice, the placement of circles is governed by the distribution of the mobile terminals and the number of MSs in the coverage area. However, as can be seen by comparing the optimum $\Delta$ values from Figure 3.2 and Figure 3.3, this does not affect the general findings for the variation in $\Delta$.

In the remaining parts of this thesis, a constant spatial protection margin of $\Delta = 1.0$ is considered. This will not necessarily give an optimum system capacity, as the optimum value depends on the exact number of multiple hops per link. However, a constant value of $\Delta = 1.0$ will yield a throughput close to the optimum value, irrespective of the number of multiple hops per link.

### 3.2 Transmission Scheduling Algorithms

In this section, the different scheduling techniques are analyzed for a multihop design, with the objective of maximizing the system capacity. The optimum scheduling technique and the complexity involved in its calculation is shown in subsection 3.2.1. The different suboptimal algorithms based on the graph-based scheduling technique (restrictive Protocol Model) and the interference-based scheduling technique (Physical Model) are explained in subsection 3.2.2. Section 3.3 then introduces a simple, yet an efficient heuristic algorithm, named random data hopping (RDH) technique, as an TDMA scheduling mechanism, under the restrictive Protocol Model and explains how such a randomized algorithm could provide an increase in the system capacity.

#### 3.2.1 Complexity In Finding Optimum Transmission Schedule

A channel access spatial reuse TDMA for multihop packet radio networks was first formalized in [34]. In a significant contribution made by Toumpis and Goldsmith [4] towards spatial reuse in multihop radio networks, they derived a mathematical expression for calculating the number of distinct transmission schemes possible in
3.2 Transmission Scheduling Algorithms

an ad hoc network with multihop routing and spatial reuse. The distinct transmission schemes in the multihop ad hoc network indicates the number of possible distinct communicating pairs in the system (between source and relay, relay and destination, or between source and destination itself). For an ad hoc network with \( n \) nodes in the system, the number of transmission schemes for a single-hop network with no spatial reuse, \( N_a \), is given by

\[
N_a = n(n - 1)
\]

In a multihop network with no spatial reuse, for each of the \( n \) nodes in the system, there are \( n - 1 \) different possible receivers and \( n \) possible nodes to forward data for (including itself and the receiver). Therefore, the number of possible transmission schemes is written as:

\[
N_b = n^2(n - 1)
\]

In case of a multihop network with spatial reuse, the possible transmission schemes, \( N_c \), in a network of \( n \) nodes would be calculated as:

\[
N_c = \sum_{i=1}^{\lfloor n/2 \rfloor} \frac{n(n - 1) \ldots (n - 2i + 1)}{i!} n^i
\]

where the \( i^{th} \) term in the above sum is the total number of schemes having \( i \) transmit-receive pairs. There are \( n(n - 1) \ldots (n - 2i + 1) \) distinct choices for the \( 2i \) nodes that are involved; however, this number must be divided by \( i! \) to account for the fact that pair orderings are unimportant. The total number of pair combinations is multiplied by \( n^i \) to account for the different possibilities in the choice of information sources, for each of the pairs. Figure 3.4 plots the number of possible transmission schemes for single hop and multihop routing, with no spatial reuse and for increasing values of nodes in the system, and Figure 3.5 shows the plot for a multihop routing system in the presence of spatial reuse. It can be seen that even for a network with 50 nodes in the system, the number of possible combinations for the transmission schemes for a multihop system with spatial reuse is in the order of \( 10^{80} \). Hence, as the number of nodes in the system increases, finding the optimal transmission scheme among all possible combinations becomes extremely complex. In fact, for a system with large number of nodes, the problem of determining the optimal selection of transmission schemes is an NP-hard problem [12]. In a recent result, it has been shown in [23] that for a given network and a set of source and destination nodes, it is not only NP-hard to find the optimal throughput under the protocol interference model, but also it is NP-hard to approximate the optimal throughput. This implies that there exists no polynomial time algorithm for determining the optimal transmission scheme or even approximating the optimal transmission scheme that would maximize the network performance. The restrictive version of the Protocol Model was introduced in this research work as an alternative to the Protocol Model. As explained in detail in
3.2.2 Suboptimal Algorithms

A number of algorithms have been proposed in the literature to generate the STDMA schedules [89, 90, 91, 92, 93]. The algorithms are classified into two main types:

1. **Graph-based scheduling**: In the graph-based scheduling method, the
3.2 Transmission Scheduling Algorithms

Figure 3.5: Different possible transmission schemes for multihop system in the presence of spatial reuse

wireless terminals are represented by nodes and the communication between the wireless terminals are represented by edges. The graph-based scheduling technique is described by defining different coloring methodologies. All the pairs that can communicate simultaneously are represented by the same color. There is an exclusion region defined around every communicating pair, as per the interference-avoidance Protocol Model. Only those edges that are located beyond the exclusion region can have the same color. Hence, as per the graph-based scheduling technique, the performance of the system increases linearly with an increase in the number of simultaneously communicating pairs. However, in reality, this is not the case. The graph-based scheduling technique does not take into account the aggregate effect of the interferences at the receiver of any communicating pair. The simulation results show that [94] the reuse schedules obtained from the graph-based approach result in serious interferences and hence reduction in the signal-to-interference-noise ratio at the individual receivers, resulting in a dramatic deterioration in the network performance.

2. Interference-based scheduling: In this method, any two pairs can communicate simultaneously only if the carrier-to-interference ratio at every receiver is greater than a certain threshold. In case the interference at a particular receiver is very high, because of other interfering transmitters, then the particular pair cannot communicate in that time instant. This interference-
### Table 3.3: Summary of System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage Area</td>
<td>1 km²</td>
</tr>
<tr>
<td>No. of MSs</td>
<td>500</td>
</tr>
<tr>
<td>Duration of time frame</td>
<td>100ms</td>
</tr>
<tr>
<td>Minimum no. of TSs per frame</td>
<td>5</td>
</tr>
<tr>
<td>Maximum no. of partitions per TS</td>
<td>20</td>
</tr>
</tbody>
</table>

A graph-based technique is exactly the same as the Physical interference Model. The algorithms presented in [20, 32] assign the transmission rights to nodes, whereas the algorithms presented in [33] assign the transmission rights to communication pairs, in which case both the transmitters and receivers are determined in advance. Furthermore, in [95], assignment algorithms based on both node and communication pairs are described. However, these algorithms are suitable for small networks, where it is not difficult to minimize the delays and update the schedules in a distributed fashion. For a multihop ad hoc network with large number of nodes, the complexity of these algorithms increases. Hence, for a multihop ad hoc network with hundreds of nodes, a graph-based scheduling technique with a Protocol interference Model serves as a very practical and a preferred method.

### 3.3 Time Slot Granularity Variation and Random Data Hopping

It has been explained in section 3.2.1 about the complexity involved in computing the optimum transmission schedule for a multihop ad hoc network, that would maximize the system capacity. Before going into the working principle of the random data hopping technique, the variation of the number of simultaneously communicating pairs and its effect on the optimum system capacity is first analyzed in the next subsection.

#### 3.3.1 Motivation for Introducing a Random Technique

In a multihop ad hoc network enabling spatial reuse of resources, the number of pairs that can communicate in a given coverage area at any time instant is a function of the position of the selected nodes. It was shown in [83], that for any coverage area, there exists an optimum pattern for placing the exclusion region circle around the receiver, in the restrictive Protocol Model, that would result in maximal number of circles being packed in a given boundary. In order to further explain the effect of placement of nodes on the number of communicating pairs in the coverage area, the system model as described in the analytical section and
summarized in Table 3.3 is considered here again. Figure 3.6 (a-b) shows two cases where an exclusion region circle is defined around every communicating receiver. The radius of every exclusion region circle is twice the transmission distance. However, the transmission distance of every communicating pair is different, and hence, the radius of all the exclusion range circles are different. Figure 3.7 shows the behavior of system capacity and its variation when the average transmission distance between the communicating pairs is varied. The location of the mobile terminals and the number of communicating wireless nodes are both kept constant. It can be seen from Figure 3.7 that the number of simultaneous communication pairs per time slot, that result in optimum system capacity is not a constant, but is a variable, that depends on the transmission distance of the communicating pairs. In fact, it is observed from Figure 3.8 that with a simple change in the user density, (with no change in the average transmission distance), the optimum value for number of parallel transmissions that would maximize the system capacity is varied. A similar result has been reported in [81], where, for a multihop network with 30 nodes in the system, it has been proved that maximizing the cardinality of the independent sets, i.e., maximizing the number of parallel transmissions per time slot does not necessarily increase the capacity of the network. This is a very significant result that points to the inherent complexities involved in finding an exact relation between the different system parameters that would optimize the system capacity. At this stage, it is imperative to categorize that the calculation of optimal system capacity depends mainly on three parameters.

1. The distribution of the mobile terminals
2. The user density
3. The transmission distance \((d_{c1}, d_{c2}, ..., d_{cn})\) of all the \(n_t\) simultaneously communicating pairs.

At the same time, it needs to be emphasized that the absolute values indicated in Figure 3.7 or in [81] cannot be taken as a benchmark for determining the exact number of simultaneous communicating pairs that would optimize the system capacity. However, the simulation results do provide a deeper insight into the mathematical complexity involved in finding an analytical expression for optimum system capacity, in a multihop ad hoc network with hundreds of nodes in the system.

### 3.3.2 System Model for Multihop Ad hoc Network

Before explaining the underlying principle of the random data hopping technique, a system model of a simple multihop ad hoc network is considered. As explained in section 3.1, the mobile units in the multihop ad hoc network are uniformly distributed. The end-to-end communication between the source node and destination
Figure 3.6: Different number of simultaneously communicating pairs in a given coverage area for a multihop ad hoc network under interference avoidance model.

Figure 3.7: The system capacity attains its peak for different values of simultaneously communicating pairs, $n_t$, depending on the average transmission distance between any communicating pair.
3.3 Time Slot Granularity Variation and Random Data Hopping

![Graph showing variation of system capacity for different user density](image)

- **Figure 3.8:** Behavior of system capacity in a multihop *ad hoc* network with a variation in the user density.

A node is termed as a ‘link’, and any transmitter and receiver that communicate with each other over a single time slot is termed a ‘pair’. With this definition, a transmitter and receiver may communicate using multiple ‘pairs’. This means that multiple TSs might be used for communication between a given transmitter and receiver. A simple example of a multihop *ad hoc* network is shown in Figure 3.9 wherein there are eight nodes \( n_1, ..., n_8 \) that are randomly distributed. In the case of communication over link \( n_1 - n_4 \), the data is sent across three pairs \( n_1 - n_2, n_2 - n_3, \) and \( n_3 - n_4 \). Another multihop scenario would be that the same packet could be sent over \( n_1 - n_3 \) and \( n_3 - n_4 \), which would then consist of only two communicating pairs. The equivalent single hop scenario would be a direct transmission across \( n_1 - n_4 \). In order to combat the interference coming from other simultaneously communicating node pairs, a guard zone (or an exclusion region) is defined around every communicating receiver. As shown in Figure 3.9, an exclusion region circle is defined around the receiver \( n_3 \) for the communicating pair \( n_2 - n_3 \). In a precursor result [96], the critical range for connectivity of networks formed by randomly located nodes has been determined. For a unit coverage area, the lower bound on the transmission distance that would keep the network connected with a probability of one is given by \( d_{\text{min}} = \sqrt{\frac{\log_e(n)}{\pi n}} \). Hence, \( d_{\text{min}} \) is taken as the minimum transmission distance of any communicating pair. However, if there is no suitable relay MS at this distance, the transmission distance is increased in order to find the relaying MS.
A TDMA system with $K$ slots per frame is shown in Figure 3.10 case 1. The number of TSs in the frame is increased by partitioning the TSs, as shown in case 2 of Figure 3.10. The total duration of the time frame remains constant. With an increase in the number of time slots, the duration of each TS in the frame is reduced accordingly. Assuming that the data is still transmitted with the same modulation technique, the amount of data transmitted per TS reduces with an increase in the number of TSs. This however provides an additional degree of freedom in the selection of simultaneously communicating pairs. Before explaining the underlying principle of random data hopping technique, the effect of TS partitioning and the subsequent increase in the number of communicating pairs in the system is explained in the next two sections.

### 3.3.3 Effect of Time Slot Partitioning

The number of TSs in the time frame is increased by partitioning the TSs and thereby reducing the duration of each TS. With an increase in the number of TSs per frame, the total number of communicating pairs in a given frame is increased. It is assumed that every TS can serve at least one pair and that the number of users are uniformly distributed in space. As a consequence, the probability mass function (PMF) of the number of communicating pairs that can be served by one TS is uniform, provided that the service area is limited. The number of
3.3 Time Slot Granularity Variation and Random Data Hopping

\[ t_{sl} = \frac{t_{frame}}{K} \]

Case 1: Number of time slots: \( T = K \)

\[ t_{sl} = \frac{t_{frame}}{2K} \]

Case 2: Number of time slots: \( T = 2K \)

Figure 3.10: TDMA frame with different TSs in a multihop system

pairs that can be served depends on the actual distance between the MSs and on the exclusion range distance. The variance of the rectangular function obtained from the uniform distribution (Figure 3.11) is finite. In addition, to begin with, the number of TSs in the frame is taken as 5 TSs. Hence, for a minimal TS partitioning technique, where every TS is divided into 2 TSs, there would be 10 TSs per frame. For higher number of TS partitions, the number of TSs per frame would be even higher. Therefore, the central limit theorem can be applied and the total number of communication pairs that can be served under the condition, \( \sum_{t=1}^{T} n_t = x \), and subject to constraint, \( 1 \leq n_t \leq L_M \), can be approximated by a Gaussian PMF [87]. The mean and the variance for the number of communicating pairs in \( T \) TSs is given by,

\[
E[x] = \frac{T(L_M + 1)}{2} \tag{3.12}
\]

and

\[
\text{Var}[x] = \frac{T(L_M^2 - 1)}{12} \tag{3.13}
\]

It can be seen from eqn. (3.12) and eqn. (3.13) that the expected value as well as the variance of the PMF increases linearly with the number of TSs in the time frame. In this context, the most noticeable result that can be seen in eqn. (3.13) and in Figure 3.12 is the increase of the variance which can be interpreted as a measure for the reusability of a TS. Moreover, the slope of the graphs in Figure 3.12 rise with a reduction in the value of the exclusion range. For example, reducing
the exclusion range from 1.6 times the transmission range to 1.3 times enables a 30% increase in the communicating pairs at 60 TSs. Figure 3.2 also provides a comparison between the analytical calculation of mean and variance and the simulation. As can be seen from Figure 3.2, the analytical results matches very closely with that obtained from the simulations.

3.3.4 CDF Derivation for Number of Communication Pairs

For a TDMA system with $T$ TSs per frame, the cumulative distribution function (CDF) for the total number of communicating pairs, $x$, that can be served under the condition, $\sum_{t=1}^{T} n_t = x$, and subject to constraint, $1 \leq n_t \leq L_M$, is given by:

$$P(X \leq x) = \frac{1}{L_M^T} C(x)$$

(3.14)

$L_M$ is the maximum number of possible communication pairs for any TS. Hence, $L_M^T$ in the denominator of eqn. (3.14) indicates the maximum possible number of communication pairs over $T$ TSs. The numerator, $C(x)$ is the number of all possible combinations of the distribution of communicating pairs. It is mathematically derived, starting from the above mentioned two conditions. For this purpose, an auxiliary polynomial function $f(t)$ is introduced, that satisfies the above two criteria. The coefficients of the auxiliary polynomial, $f(t)$ would give the value for $C(x)$, i.e., the general expression of the coefficients of $f(t)$ gives the number of possible combinations for the distribution of communication pairs. The polynomial function, $f(t)$, is written as follows:

$$f(t) = \frac{(1 + t + t^2 + \ldots + t^{L_M-1})^T}{1 - t}$$

(3.15)
In order to find the coefficients, $C(x)$, the eqn. (3.15) is further simplified as follows:

\[
f(t) = \left( \frac{1 - t^{LM}}{1 - t} \right)^T \times \frac{1}{1 - t} \\
= (1 - t^{LM})^T \times (1 - t)^{-T-1} \\
= \sum_{j=0}^{T} (-1)^j \binom{T}{j} t^{LM} \times \sum_{n=0}^{\infty} \binom{T + n}{T} t^n \\
= \sum_{j=0}^{T} \sum_{n=0}^{\infty} (-1)^j \binom{T}{j} \binom{T + n}{T} t^{n+jLM}
\]

The function $C(x)$ is the coefficient of the polynomial term, $t^x$. This could be obtained by substituting $x$ for $n + jLM$ and reducing the double summation to a single sum. Given the fact that for any TS, there is at least one communicating pair (i.e., no spatial reuse), it holds that $x \geq T$. Hence, the coefficient $C(x)$ could be written in a generalized form as

\[
C(x) = \sum_{j=0}^{\left\lfloor \frac{x}{LM} \right\rfloor} (-1)^j \binom{T}{j} \binom{x - jLM}{T}
\]  

(3.16)
3.3.5 Network Parameters for Time Slot Partitioned System

A deeper insight into the system model is obtained by assuming a unit coverage area of \(1\text{km}^2\) with 500 uniformly distributed MSs across the coverage area. For an exclusion range ratio of two (i.e., \(\Delta = 1.0\)), the area of the exclusion region circle is \(B = 4\pi d_c^2\). The minimum transmission distance, \(d_{\text{min}}\), for this scenario would be 62.8m. The exclusion range circle would then have a radius of \(r_c = 2d_c = 2 \times 62.8 = 125.6\)m. The upper bound on the number of communicating pairs for any TS is \(L_M = 18\), subject to the condition, \(d_c = d_{\text{min}}\). A fixed TDMA frame of duration 100 ms is considered in the system. The time slot granularity is varied from 5 TSs per frame, each with a duration of 20 ms to a maximum of 100 TSs per frame each with a duration of 1 ms. The cumulative distribution function (CDF) of the total number of communicating pairs given in eqn. (3.16) is plotted in Figure 3.13. As seen in Figure 3.13, the number of communicating pairs increases with the number of TSs in the time frame. This is because, with increasing number of TSs the duration of each TS is reduced. Hence, as shown in Figure 3.10, in order to transmit the same amount of data, the communication between the transmitter and receiver has to take place over increased number of TSs. Therefore, from a system design point of view, the communication has to take place across greater number of pairs in order to transmit the same amount of data in the given time frame. As explained in detail in the next section, an increased number of communicating pairs provides a basis for introducing a random component while selecting the simultaneously communicating pairs in the time slot partitioned...
3.3 Time Slot Granularity Variation and Random Data Hopping

3.3.6 Underlying Concept of Random Data Hopping Technique

In order to explain the concept of random data hopping, consider a simple multi-hop ad hoc system with two communication links as shown in Figure 3.9. For the ease of understanding, a TDMA frame with two slots is considered. Suppose at the 1st TS the transmission pair \( n_1 - n_2 \) is selected for communication. In accordance with the interference avoidance model, the exclusion region around node \( n_2 \) does not include any of the three communicating pairs, \( n_5 - n_6, n_6 - n_7 \) and \( n_7 - n_8 \). Therefore, either of the three communicating pairs can communicate along with \( n_1 - n_2 \). An arbitrary selection of the pair, \( n_6 - n_7 \), that would communicate with \( n_1 - n_2 \) in the 1st TS is shown in Figure 3.14-a. The pair \( n_2 - n_3 \) communicates in the 2nd TS. However, apart from \( n_2 - n_3 \), there is no other pair that communicates in the 2nd TS. This is because, the exclusion region circle around the receiver node \( n_3 \) does not allow any other pair except \( n_6 - n_7 \) to communicate at the same time instant. However, \( n_6 - n_7 \) has already communicated in the previous TS. Hence, only three pairs communicate in two TSs. At this stage, consider a variation in the time slot granularity obtained by partitioning each TS into two TSs. There are now four TSs in the frame \( (T = 4) \). In order to transfer the same amount of data, all three pairs: viz. \( n_1 - n_2, n_2 - n_3 \) and \( n_6 - n_7 \) should communicate for two TSs each. An arbitrary assignment of the communicating pairs, employing the random data hopping technique is shown in Figure 3.14-b. The pair \( n_6 - n_7 \) communicates with \( n_1 - n_2 \) in the 1st TS and with \( n_2 - n_3 \) in the 3rd TS. In addition, the pair \( n_5 - n_6 \) communicates in the 2nd TS along with \( n_1 - n_2 \). This results in an increase in the system resource reuse and hence an increase in the system capacity. At the same time, it should be noted that Figure 3.14-b is still not an optimum allocation technique. An optimum selection of the communicating pairs for the schematic of Figure 3.9 is shown in Figure 3.14-c.

By definition, a random data hopping technique, is a new approach for allocating TS resources, whereby, all the communicating pairs that are outside the exclusion region of each other are selected randomly for concurrent communication. This random assignment is preceded by time slot partitioning, wherein, each TS is divided into several mini TSs (TSs of smaller duration). The random hopping technique is applied over each of the smaller-duration TSs. Hence, the different pairs that communicate concurrently vary randomly over each of these smaller-duration TSs. In practical situations, such a random hopping technique could be implemented over a distributed multihop network in two ways. First, a central entity, like a radio network controller (RNC), could be used over the ad hoc network that would carry out the scheduling tasks for all the MSs in the system. Such an entity would basically act as a controller, and the random data
Case (a). A 2-TS scenario wherein 3 pairs communicate

Case (b). An equivalent 4 TS scenario with a random data hopping technique

Case (c). A 4 TS scenario with an optimum technique for selection of communicating pairs

Figure 3.14: Random data hopping technique in the multihop ad hoc network
hopping algorithm would be implemented at this RNC. The second method is to use a pseudo-random code generator at one or few MSs and the pseudo-random code could be then sent to all other nodes during the set-up phase. It is assumed that all the nodes in the system know the locations of all other communicating pairs. Hence, each node, and thereby, the transmitters and receivers of each communicating pair has complete knowledge (stored in its memory, through a lookup table) of all transmission pairs that can concurrently communicate with the intended pair. In addition, due to the pseudo-random code generation, all the MSs in the system would know exactly, over which TS it has to communicate.

It should be noted that the random data hopping technique follows the same principle that is used in the frequency domain by the concept of frequency hopping. The basic idea behind frequency hopping is the periodic change of transmission frequencies carried out in a pseudo-random fashion over a set of carrier frequencies [97]. In a similar manner, the random data hopping scheme randomly changes the time slot over which the data is transmitted. Such a random hopping technique has been previously proposed as a novel dynamic channel assignment (DCA) algorithm for cellular networks [98]. It has been shown [99, 100] that for a cellular network, a random TS opposing techniques provides interference diversity, and hence, reduces the total interference from the neighboring cells. In this chapter, however, the random hopping technique is developed as a TS allocation technique for a distributed multihop network. Comprehensive system level simulation has been conducted under different traffic demands in order to assess the performance of the random data hopping scheme for a time slot partitioned multihop wireless system.

### 3.3.7 Simulation Results

The simulation parameters are the same as described in the section 3.3.5. The number of MSs that have data to transmit determine the traffic demand. A 100% traffic load indicates that half the total number of MSs in the system act as source nodes, and the other half act as destination nodes. Hence, for a system with 500 nodes, a 100% traffic load would indicate that there are 250 communication links. The source node communicates to its intended receiver in multiple hops, wherein the MSs located between the source and destination act as relays. These relay MSs may have their own data to transmit depending on their traffic pattern. It should be noted that at any node, the data is transmitted to the immediate receiver after employing the random data hopping technique. The simulation model gives the expected values of the number of simultaneously communicating pairs and the carrier-to-interference ratio at the receiver of each of these communicating pairs. The average system capacity is calculated from these parameters using eqn. (3.8). The simulation result plotted in Figure 3.15 illustrates that due to TS partitioning, with an increase in the number of TSs per frame from 5 to 100, the
The number of TSs per frame is increased by partitioning the TSs. For a higher number of TSs per frame, the random data hopping technique produces an inherent randomness across each of the TSs, in the selection of concurrently communicating pairs. This results in an increased number of occasions when a high number of communicating pairs could be established in any TS. This increase results from a better spatial reuse for the given TS, and hence, results in an increase in the average system capacity.

The simulation results also show that for low traffic load, the obtainable system capacity is higher than the case for high traffic load. This is because, for less traffic, the total interference experienced by any communicating receiver is less as compared to the high traffic scenario. Hence, the $C/I$ experienced at any receiver is higher. This results in an increase in the average system capacity for a multihop network with a low traffic load, compared to a multihop design with a high traffic load. Figure 3.15 shows that for a system with a 100% traffic load, a maximum increase in the average system capacity that could be obtained by employing the random data hopping technique would be around 16%. When the traffic load is less, the improvement obtained by the random data hopping scheme is higher. For e.g., at 30% traffic, a increase of around 31% is observed at 100 TSs per time.
3.3 Time Slot Granularity Variation and Random Data Hopping

![Graph](image)

Figure 3.16: Variation of system capacity with traffic loads for different TSs frame. It can also be observed from Figure 3.15 that for high traffic load (80% and 100% traffic in Figure 3.15), the system capacity saturates at around 100 TSs per frame, compared to low traffic load (30% and 40% traffic) where the throughput does not saturate at even 100 TSs per frame. In order to further study the effect of traffic load, the variation of system capacity with the traffic load is observed for different values of TS partitions and is shown in Figure 3.16. It can be seen that, irrespective of the number of TSs per frame, the variation of system capacity observes a similar pattern. Initially, the capacity increases with increasing traffic and attains a peak for a certain value of traffic load (around 25% - 30%), after which the system capacity decreases. This indicates that there exists an optimum value of traffic load (i.e., an optimum ratio between the communicating nodes and the relay nodes where the system capacity is maximized.

In order to study the performance of the random data hopping technique under realistic pathloss conditions, a lognormal shadowing with a standard deviation of 4 dB is considered. In the presence of lognormal shadowing, the received power, $P_R$, and the carrier-to-interference ratio, $C/I$, given in eqn. (3.2) and eqn. (3.3) would be modified as follows:

$$P_R = P_T - (k_1 + 10\alpha \log_{10}(d_c)) + \zeta \text{ dB}$$

(3.17)
Figure 3.17: Variation of system capacity with traffic loads for different TSs in the presence of log-normal shadowing.
\[ \gamma_{it} = \frac{10^{P_r/10} \cdot 10^{-\left(k_1+10\alpha \log_{10}(d_{it})+\zeta_i\right)/10}}{\sum_{j=1, j\neq i}^{\eta_t} 10^{P_r/10} \cdot 10^{-\left(k_1+10\alpha \log_{10}(d_{int})+\zeta_j\right)/10}} \]

which simplifies to

\[ \gamma_{it} = \frac{d_{it}^{-\alpha}/\zeta'_i}{\sum_{j=1, j\neq i}^{\eta_t} \left(\frac{d_{int}^{-\alpha}}{\zeta'_j}\right)} \]  

(3.18)

where \( \zeta'_i \) and \( \zeta'_j \) are the absolute values of the shadowing term of the transmission path and the interfering path respectively, and is given by, \( \zeta' = 10^{0.1\zeta} \).

The equation for system capacity, \( C \), remains the same as given in eqn. (3.8).

The simulation results for the lognormal shadowing scenario are plotted in Figure 3.17. It can be observed that, even in the presence of lognormal component, the RDH technique shows an improvement in the performance. For 30% traffic load, a maximum improvement of 21% is observed as compared to the 31% improvement in the absence of log-normal component. This is because, the interference experienced by any receiver node due to an interfering transmitter located at a much far-off distance could be higher due to the lognormal component, which in turn deteriorates the performance of the RDH algorithm.

### 3.4 Chapter Summary

In this chapter, a multihop *ad hoc* network was considered and the scheduling techniques for such a network was analyzed, with the main objective of maximizing the system capacity. The aggregate system capacity was defined to be the quantity which measured the system performance. It was shown that an optimum spatial protection margin value, \( \Delta \), that maximizes the system capacity is a function of the number of multiple hops per link. The complexity involved in finding the optimum transmission schedule for a multihop *ad hoc* network was then analyzed. A novel random data hopping technique was then introduced and applied to a system with a variable number of TSs. The randomness was produced by first partitioning the TSs, and thereby varying the number of TSs per frame. The time slot over which the transmission pairs communicate was then randomly varied over every time slot. This randomness resulted in a better reuse of the system resources, and hence, resulted in an increase in the network performance. The amount of increase in the system capacity depended on the number of TSs in the time frame and the traffic load in the system.
3 Time Slot Allocation in a Multihop Ad hoc Network
4 Radio Resource Management in Multihop Hybrid Cellular Networks

One of the key areas in research today is to design a wireless system that would not only provide data rate of the order of several Mbps, but also provide a network architecture that would efficiently utilize the available spectrum resources. In today’s era of high capacity and increased data-rate communication, single-hop cellular networks as a stand-alone technology would be handicapped by numerous limitations, viz., inability to cover *dead zones*, high attenuation of signals, deep shadowing, etc. Multihop hybrid cellular networks present a trade-off between traditional cellular networks and pure *ad hoc* networks. The signals could be transmitted in either single or multiple hops, and also the data might be communicated through the infrastructure or only through the *ad hoc* mode without involving the central entity.

In this chapter, a multihop cellular network (MCN) model is considered, as explained in Chapter 2. All communication between the source and destination nodes are routed through the BS. Hence, in any cell, all the MSs communicate with its corresponding BS. This communication between the MS and the BS takes place in either single-hop or multiple hops. An interference avoidance Protocol Model is considered in the system design. It has been shown [70] that for a cellular network with *n* wireless nodes, the number of BSs must scale as at least $O(\sqrt{n})$ to achieve better scaling of capacity than pure *ad hoc* networks. It has been shown through outage analysis in [15] that an integration of cellular and multihop communication models results in better relaying and avoids traffic congestion. Deploying relays can clearly help improve the performance of the users near the edges of the cell and has the potential to solve the coverage problems for high data rates in macro-cells [101]. Since it is possible to have simultaneous transmission by both, BSs and relays, capacity gains can also be achieved. However, it requires extra radio resources for relaying hops and is sensitive to the quality of relaying routes. Therefore, multihop cellular networks require a well-designed radio resource allocation strategy in order to secure performance gains.
4.1 Multihop Cellular Network

4.1.1 System Model

A mobile coverage area comprising a hexagonal cellular structure is considered here, as shown in Figure 4.1. The coverage area is a constant, \( Z = 1 \text{km}^2 \), and has a radius, \( R \), while each of the hexagonal cells has a side length, \( r \). 1000 MSs are assumed to be uniformly distributed in the coverage area. An interference avoidance Protocol Model, as explained in section 2.1.2 is considered for a hybrid cellular design, such that no MS except the desired transmitter can transmit within that circular region. The area of one exclusion range circle is given by \( B = \pi((1 + \Delta)d_c)^2 \), where \( d_c \) is the transmission distance between the transmitter and receiver and \( \Delta \) is the exclusion range ratio/spatial protection margin added to the transmission distance. In the single-hop model, there are no relays, and all MSs communicate with the BS in single-hops. In case of a multihop model, the
mobile terminal located between the source and destination is selected as the relay node, such that, the total end-to-end transmission distance between the source and destination node is minimized. This relay selection mechanism is known as shortest total distance (STD) selection scheme. If there are \( n \in N \) possible routes for a \( M \)-hop communication between the source and destination node, and \( d_{c_{a1}}, d_{c_{a2}}...d_{c_{aM}}, \) are the distances of the \( M \) hops of the \( n^{th} \) route, then the selected route, \( r_s, \) as per the STD selection scheme is given by,

\[
r_s = \min_{\forall n \in N} \sum_{i=1}^{M} ((d_{c_{ni}}))
\]

A typical example for a multihop cellular communication model is shown in Figure 4.2 and Figure 4.3. In Figure 4.2, the MS communicates with the BS in 2 hops, with a single relay between the source and destination, whereas, in Figure 4.3 there are two relays between the MS and BS. It can be observed that the relays are not on the same line as the source and destination node. But, out of the all possible routes, the selected route has the shortest total distance between the source and destination. At this stage, the STD algorithm is considered throughout the analysis, for all \( M \)-hop cellular model. There are, however, better schemes available in the literature for selecting the relays, and are considered later in this chapter, for a specific case of 2-hop cellular networks. In the next subsection, the performance of multihop cellular networks is studied for a different number of multiple hops per link, and for a different number of BSs in the system.

\subsection*{4.1.2 System Capacity Variation}

In order to determine the system performance of multihop cellular networks, the variation of system capacity with the number of hops per link is studied for different number of BSs in the coverage area. A constant coverage area is considered and the performance of the multihop cellular network is analyzed for varying number of BSs. In the initial stages, two different scenarios are considered in detail in the system design, depending on the relation between the radius of the hexagonal cell, \( r, \) and the radius of the coverage area, \( R. \)

1. The radius of the hexagonal cell, \( r, \) is \( 1/4^{th} \) of the radius of the coverage area, \( R, \) i.e., \( r = R/4. \) This results in 19 hexagonal cells in the system with a center cell surrounded by 2 tiers of 6 and 12 cells respectively.

2. \( r = R/5. \) This would result in 30 hexagonal cells in the system.

Figure 4.4 and Figure 4.5 show the plot of variation in the system capacity with different number of multiple hops per link when the number of BSs in the
Figure 4.2: Relay selection mechanism for a 2-hop cellular network using the shortest total distance method
4.1 Multihop Cellular Network

Figure 4.3: Relay selection mechanism for a 3-hop cellular network using the shortest total distance method
Figure 4.4: System capacity variation for different number of multiple hops per link and for different values of pathloss exponent, $\alpha$, for a system with 19 BSs in the coverage area.

Figure 4.5: System capacity variation for different number of multiple hops per link and for different values of pathloss exponent, $\alpha$, for a system with 30 BSs in the coverage area.
system are 19 and 30 respectively. Both the figures indicate that, irrespective of
the path loss exponent, $\alpha$, the system capacity increases with an increase in the
number of multiple hops per link. This is because, with an increase in the number
of multiple hops per link, the transmission distance of each communicating pair
reduces which in turn reduces the exclusion region around every communicating
pair. This in-effect increases the spatial reuse of resources which results in an
increase in the system capacity. However, it should be noted that the increase in
capacity is not linear. With an increase in the number of multiple hops, the system
capacity saturates. This is because, as the number of multiple hops per link is
linearly increased, the improvement in spatial reuse efficiency reaches a constant
which in-turn saturates the system capacity. In fact, it is observed in Figure 4.4
that for 19 cells in the coverage area, the average system throughput for a single-
hop system is 1.1 bps/Hz, whereas for a system with 4-hop per link, the system
throughput is 2.2 bps/Hz, which is twice the increase over a single-hop system. If
the number of hops per link is increased to 10 hops, the system capacity saturates
to 2.8 bps/Hz, an increase of only 27\% over the 4-hop per link system, and that is
without considering any loss of capacity due to additional overhead signals. Figure 4.6 shows the capacity gain obtained from a multihop cellular network when
a 10\% overhead is considered for each of the multiple hops of the communication
link. It can be observed from Figure 4.6 that the capacity gain is highest when
the maximum number of multiple hops between the MS and the BS is either two
or three hops. For higher number of multiple hops, the total amount of overhead
signal required also increases which reduces the increase in the system capacity.
Hence, in a practical system, it is not practical to have more than 3 to 4 hops
per link. In addition, as the number of multiple hops per link is increased, the
end-to-end delay between the source and destination also increases. The effect of
delay is however not considered in this research work. Also, in practise, it is very
difficult to maintain co-operation between the communication pairs, as the num-
ber of hops per link is increased. It has been recently shown in [67] that optimum
resource allocation in multihop cellular network with the objective of throughput
maximization (TM-RRA) is an NP-hard problem. In fact, the well-known multi-
ple choice knapsack problem, (MCKP), which was proven to be NP-hard [102], is
shown to be a restricted version of TM-RRA [67]. Hence, researchers across the
scientific community have limited their focus to a 2-hop cellular network and have
worked towards designing suboptimal but efficient heuristic algorithms.

In the remaining part of the chapter, the focus is on 2-hop links where the
maximum number of hops between any mobile terminal and the BS is only 2
hops. However, instead of deriving heuristic algorithms for 2-hop cellular network,
the focus of this chapter is on designing a new architecture for a 2-hop cellular
system. In the next section, a novel cluster-based architecture is introduced for a
2-hop model, under an interference-avoidance Protocol Model. The system details
of this architecture are then explained and its performance is compared against
standard benchmark designs for 2-hop cellular networks. Before that, a simple 2-hop cellular network is considered and the variation in the system capacity is analyzed for different number of BSs within the coverage area.

### 4.1.3 Variation in the number of BSs for 2-hop Cellular Network

The performance of of 2-hop cellular network is analyzed for different number of BSs in the coverage area, and compared with an equivalent single-hop network. The MSs located beyond half the cell radius communicate to the BS in 2-hops. The selection of the relay mobile is not constrained by any condition, i.e., the mobile node that is selected as a relay for a particular end-to-end link could be equidistant from the source and destination, or it could be very close to the source or destination. This flexibility in the selection of relay provides a wide range of choice as to which a mobile terminal could be selected as a relay. A deeper study in the selection of relays will be described later in the chapter, while developing the cluster-based architecture. The main aim of this subsection is to evaluate the performance of a 2-hop cellular network with different numbers of BSs in the system. It can be observed from Figure 4.7 that as the number of BSs in the given coverage area is increased, the system capacity increases for both single-hop and 2-hop cellular network. However, the rate of capacity increase is much higher.

![Figure 4.6: Capacity gain for a multihop multi-cellular system (19 BSs in the coverage area) with 10% overhead for each of the multiple hops](image-url)
for single-hop network than for 2-hop design. With an increase in the number of BSs from 18 to 180, the capacity of single-hop cellular network increases from 1.38 bps/Hz to 1.87 bps/Hz, an increase of 35.5%. However, for the 2-hop cellular design, this increase is only 14.6%, (2.4 bps/Hz to 2.81 bps/Hz). This is because, for a 2-hop design, the relays help in balancing the traffic. In case a relay node is over-loaded, the wireless terminals communicate through another relay node that has less traffic. This is implemented by checking the buffer of each possible relay node, before selecting the particular wireless terminal as the relay node. The node that has the least number of packets in its buffer to be transmitted, and the node which is in the direction of the destination node is selected as the relay node, for a given communication link. Hence, the rate of increase of the system capacity is much lower for the 2-hop design. In the cluster-based design explained in the next section, 19 BSs are considered in the coverage area throughout the analysis. These 19 BSs are arranged such that a center cell is surrounded by 6 cells in the 1st tier and 12 cells in the 2nd tier.
4.2 Cluster-Based 2-Hop Cellular Network

4.2.1 System Model

The proposed cluster-based design is based on the formation of multiple clusters in every cell. Each cell is initially divided into two layers, viz., inner layer and outer layer.

1. **Inner Layer**: This is the circular area contiguous to the BS, and the MS in this zone communicate to the BS directly using a single-hop. The distance between the MS and BS in the inner layer is less than or equal to half the cell edge length, i.e., $r/2$.

2. **Outer Layer**: This circular region is located around the inner zone and the MSs located in this region communicate to the BS in 2 hops. This area is further divided into several clusters. The MSs within any of the clusters would communicate to the BS via a cluster-head node, called the gateway (GTW). The GTWs are located on the boundary adjoining the inner and outer layer, i.e., at a distance of $r/2$ from the BS. Hence, the maximum transmission distance between BS and GTW, or between MS and GTW is $r/2$.

The MSs located in the outer layer are grouped into several clusters. A single cell scenario depicting the cluster-based 2-hop cellular architecture is shown in Figure 4.8. There are 6 circular clusters in each cell. For each of the clusters, a wireless terminal located at the boundary of the inner and outer layer of the cell is selected as a cluster-head node, alternatively known as GTWs. There are 6 GTWs/cell, each of them located at a distance of $r/2$ from the BS. Cluster-heads GTW$_{1a}$ and GTW$_{1b}$ are diametrically opposite to each other and are separated by a distance of $r$, i.e., twice the transmission distance, $r/2$. The same holds for the cluster-heads GTW$_{2a}$ and GTW$_{2b}$, and for GTW$_{3a}$ and GTW$_{3b}$. In practice, the GTWs could be fixed relay stations (RSs), located on the street lamps/roof tops, or, MSs/wireless terminals with its own traffic. If the MSs are selected as relays, then the exact location of the relay node would depend on the distribution and the density of the mobile terminals. In the deterministic cluster-based design considered in the semi-analytical model, later in this paper, the 6 GTWs in the cell are assumed to be equidistant with each other, and also, assumed to be located exactly at a distance of half the cell radius from the BS. However, in the simulation model in this work, the GTWs are not equidistant and are not located exactly at a distance of $r/2$ from the BS. As would be shown later in section 4.6, this difference in the location of GTW nodes, and the subsequent difference in the transmission distance of the communicating pairs, does not result in a significant
4.2 Cluster-Based 2-Hop Cellular Network

Figure 4.8: Schematic model of a cluster based 2-hop cellular network (downlink). There are 6 clusters/cell located at a distance of half the cell radius, \( r/2 \). Cluster-heads GTW_{1a} and GTW_{1b} are diametrically opposite to each other and are separated by a distance of \( r \), i.e., twice the maximum transmission distance, \( r/2 \). The same holds for the cluster-heads GTW_{2a} and GTW_{2b} and for GTW_{3a} and GTW_{3b}.
difference in the system capacity.

In order to understand the working mechanism, a conceptual model of the cluster-based 2-hop cellular network, and the underlying principle of the synchronized resource reuse technique is described as follows:

1. As shown in Figure 4.8, \( SH_0 \) is the inner-layer (single-hop region) and \( MH_{1a}, MH_{1b}, ..., MH_{3b} \) are the 2-hop clusters in the outer layer. In addition, \( GTW_{1a}, GTW_{1b}, ..., GTW_{3b} \) are the respective cluster-heads for \( MH_{1a}, MH_{1b}, ..., MH_{3b} \). Each cluster contains a number of MSs. In case of downlink communication between BS and a wireless terminal located in any of the clusters, the BS would communicate to the cluster-head GTW in the 1st hop, and in the 2nd hop, the GTW would communicate to the MSs associated with the corresponding clusters. Similarly, in the uplink, the MSs in any of the clusters communicate with the BS in 2 hops, wherein, the MS communicates to the GTW in the 1st hop, and the GTW communicates to the BS in the 2nd hop.

2. A TDD/TDMA scheme is considered for the cluster-based 2-hop network. For a multihop system with number of hops per link, \( M \geq 1 \), the signal for any hop can be transmitted only for \( T/M \) time slot duration, where \( T \) is the TS period. Hence, the TS is divided into 2 minislots for the 2-hop links. However, for a wireless node located in the inner layer (\( SH_0 \)), the communication between the wireless terminal and the BS would take place in single-hop.

3. The reusability of the resources is increased by allowing two multihop clusters in any cell to occupy the same TS at the same frequency. As shown in Figure 4.8, the clusters \( MH_{1a} \) and \( MH_{1b} \) are located at diametrically opposite sides of the BS. The synchronized TDD frame structure for both uplink and downlink is shown in Figure 4.9. In the downlink, \( GTW_{1a} \) can download to the MS in its cluster in a particular time slot. At the same time instant, the BS located at a distance of \( r \) from \( GTW_{1a} \), could download to \( GTW_{1b} \) in the opposite cluster of the same multihop cell. Similarly, in the next time slot, the \( GTW_{1b} \rightarrow MS \) and \( BS \rightarrow GW_{1a} \) communication takes place simultaneously.

4. In the uplink, the transmitters and receivers of the cluster-based model are reversed, as seen in Figure 4.9, but the governing principle of the resource reuse technique remains the same. It can be therefore noted that the reuse of the resources can be done independently for both uplink and downlink.
using the synchronized resource reuse technique. Hence, this cluster-based design remains valid even for asymmetric traffic, as long as it remains the same for all the cells.

5. The given TS resource is also allotted to each of the hexagonal cells, i.e., in all the cells in the system, there are two simultaneously communicating pairs located in the diametrically opposite clusters of the cell that communicates using the same TS resource. As shown in Figure 4.10, for both uplink and downlink, the transmitters of all the concurrently communicating pairs in the adjacent cells are beyond the exclusion region of the desired receiver in the intended cell.

6. Even though the MSs located in the outer layer of the cell require 2 hops to communicate with the BS, the synchronized resource reuse technique ensures that there are two concurrently communicating pairs for any TS. Also, the transmission distance of any communicating pair is restricted to $r/2$ in this cluster-based design. Hence, due to the synchronized resource reuse technique that reduces both the intra-cell and the inter-cell interference, the same TS resource could be allotted to all the adjacent cells. Hence, as shown in Figure 4.12, a given TS resource is not only used by two simultaneously communicating pairs in any cell, but also, the same TS resource is reused in every cell, thus giving rise to a frequency reuse factor of one, in a multi-cell environment.

7. In a realistic scenario for the cluster-based design, the GTWs can be considered to be equidistant and located at exactly $r/2$ from the BS, only if they are fixed terminals. However, if the GTWs are not fixed, and are selected from the distributed MSs, then, the transmission distance between any communicating pair in the cell is not restricted to $r/2$. Since the MSs are uniformly distributed across any cell, the selection of the GTW node would depend on the distribution of the MSs and the network density. In case of non-availability of a wireless terminal at the boundary adjoining the inner and outer layer, a wireless terminal located closest to half the cell radius (either in the inner-layer or in the outer-layer) is selected as a GTW. Irrespective of whether the selected GTW is in the inner layer or outer layer, the transmission distance of the communicating pair between the BS and GTW would be then different from $r/2$. Correspondingly, the transmission distance of the GTW - MS pair would also vary. For such cases, the value of $\Delta$ is then altered for the particular communication pair, in order to satisfy the Protocol Model, and at the same time, enable concurrent communication of 2 transmission pairs in the cell.
8. While analyzing a multihop wireless network under the Protocol Model, it is observed in [103] that when the value of $\Delta$ is varied from 0.8 to 1.3, the achievable system capacity is always above 90% of the maximum value. Hence, when the selected GTW in the cluster-based design is located in the inner layer or the outer layer of the cell, the operational value for the exclusion range, $d_{\text{exc}}$, for the communication pair involving the particular GTW is varied between $1.8d_c \leq d_{\text{exc}} \leq 2.3d_c$. The aim of varying the value of $\Delta$ is to allow two simultaneously communicating pairs in the cell, even when the GTW is not exactly at $r/2$ from the BS.

4.3 Capacity Calculation

All the wireless terminals in any cell are assumed to transmit its signal with the same power, $P_T$. If $d_c$ is the transmission distance between any communicating pair, then the power received, $P_R$, using a general propagation model, is given by:

$$P_R = P_T - (k_1 + 10\alpha \log_{10}(d_c) + \zeta_c) \ [\text{dB}] \quad (4.2)$$

where $k_1$ is a constant that depends on the propagation environment (indoor/urban/suburban), $\alpha$ is the pathloss exponent and $\zeta_c$ is the shadowing factor across the transceiving pair. It should be noted that, as per the cluster-based design, the distance between a transmitter and its corresponding desired receiver is, $d_c = r/2$. In a multi-cell scenario, the given radio resource is utilized by all the cells in the system. The transmitters of all simultaneously communicating pairs in the 7-cell scenario are marked and shown in Figure 4.12. For any communicating pair, the inter-cell interference only across 6 adjacent cells, i.e., the 1st tier of cells are considered. The transmitting interferers from the 2nd tier of cells are very far from the intended receiver, and hence, the interference generated from these transmitters are assumed to be negligible. Therefore, for any communicating pair in this cluster-based model, there is 1 interferer from own cell and 2 interferers from each of the adjacent cells. The $C/I$ is therefore calculated as follows:

$$\gamma = \frac{10^{-[k_1+10\alpha \log_{10}(d_c)+\zeta_c]}}{\sum_{i=1}^{N_I} 10^{-[k_1+10\alpha \log_{10}(d_i)+\zeta_i]}} \quad (4.3)$$

where $d_i$ is the distance of the desired receiver from the $i^{th}$ interfering entity and $N_I$ is the total number of interfering entities for any receiver in a cluster-based model. $\zeta_i$ accounts for shadowing between the desired receiver and the $i^{th}$ interfering transmitter. The capacity in bps/Hz/cell is calculated by finding the system capacity independently over 7 cells (center cell and 6 cells in the 1st tier), as shown in Figure 4.12 and averaging over them. Each cell in the 1st tier is surrounded by 6 cells out of which 3 cells belong to the 2nd tier. The traffic in the 12 cells of the 2nd tier only contribute for the inter-cell interference calculation.
Figure 4.9: Synchronized resource reuse mechanism for a TDD/ TDMA cluster based 2-hop cellular network
Figure 4.10: Interference reduction mechanism for cluster based 2-hop cellular network using synchronized resource reuse technique.
for the 1\textsuperscript{st} tier of cells. This 2\textsuperscript{nd} tier of cells is necessary to remove the boundary effects while calculating the $C/I$ for the 1\textsuperscript{st} tier of cells, and hence, the Shannon capacity is not calculated for the 12 cells in the 2\textsuperscript{nd} tier. As shown in Figure 4.9, the data across each communicating pair is transmitted for only half the time slot period in a 2-hop system. Hence, the Shannon capacity equation for each communicating pair is reduced by a factor, $1/2$. Also, in each of the 7 cells, there are two simultaneously communicating pairs, and depending on the distance of the interfering transmitters the receivers of these 2 communicating pairs would have different $C/I$. Therefore, the system capacity is calculated from the Shannon equation as:

\begin{equation}
C = \frac{1}{2N_c} \sum_{i=1}^{N_c} \sum_{j=1}^{N_l} \log_2(\gamma_{ij} + 1) \text{ bps/Hz/Cell} \quad (4.4)
\end{equation}

where $\gamma_{ij}$ is the $C/I$ of the $j^{th}$ communicating pair in the $i^{th}$ cell. $N_l$ is the number of concurrently communicating pairs in the outer layer that use the same radio resource, in any single cell. For a cluster-based design, 2 pairs located diametrically opposite to each other communicate simultaneously, i.e., $N_l = 2$. $N_c = 7$ is the number of cells over which the system capacity is calculated. In order to calculate the average per-cell system capacity, the Shannon capacity equation in eqn. (4.4) is summed up over all $N_c$ cells and averaged over them.

### 4.4 Semi-Analytical Model

In order to assess the performance of the synchronized resource reuse technique for the cluster-based design, a semi-analytical model is developed for a deterministic cluster-based 2-hop network. In this deterministic cluster-based model, the GTWs are always located exactly at a distance of $r/2$ from the BS. Also, the GTWs are equidistant from each other. Hence, the 6 GTWs in the cell form the 6 vertices of a regular hexagon, with a side length of $r/2$. In addition, the MSs in the outer layer are assumed to be always located at a distance of $r/2$ from their respective GTWs. Also, the MSs are assumed to be uniformly distributed between $[0^\circ, 360^\circ]$ across the outer layer of the cell. Hence, the distance of both the GTWs, and the MSs are fixed with respect to its BS. The precise location of the GTW is determined from the angle made by the BS - GTW pair with the reference line. Similarly, the precise location of any MS is determined by the angle made by the line joining the MS and its corresponding GTW with the reference line. Therefore, the 2-dimensional variation of the location of GTWs and MSs is now reduced to a 1-dimensional variation problem. It should be noted that for this 1-dimensional variation problem, the exact location of the GTWs and the MSs in the deterministic scenario depend only on the angle it makes with the reference line. This simplifies the analysis for numerically calculating the Shannon capacity of the cluster-based 2-hop network. At the same time, in the deterministic
cluster-based model, the transmission distance is always the maximum possible value, $r/2$. This results in high interference from the transmitters of the simultaneously communicating pairs belonging to the neighboring cells.

In the result section, the capacity results obtained from the deterministic cluster-based model is compared with the simulation model. For both uplink and downlink, this semi-analytical model first calculates the distance of the intended receiver from all simultaneously communicating unintended transmitters. A downlink schematic for a 7-cell cluster-based 2-hop model is shown in Figure 4.12. It should be noted from Figure 4.12 that only the locations of the BSs are fixed. The distance between 2 BSs is $\sqrt{3}r$. Since the transmission distance, $d_c = r/2$, for the cluster-based model, the distance between 2 BSs is also written as $2\sqrt{3}d_c$. In Figure 4.12, all the transmitters in the 7 cells are shaded with gray background. The black circle in the center cell marks one of the desired receivers which would experience interference from other unintended transmitters. The distance between the black circle (desired receiver) and all the gray colored circles (interfering transmitters from the own cell and all the adjacent cells) marks the distance of the different interfering entities. Hence, as shown in Figure 4.12, the total interference experienced by a receiver depends on the relative distance between this receiver and all its interfering transmitters.

### 4.4.1 C/I calculation for downlink:

In the downlink, the communication takes place from BS $\rightarrow$ GTW and from GTW $\rightarrow$ MS. Figure 4.11 (both, case a and case b) shows the simultaneously communicating pairs in cell 0 and cell 1 in the downlink scenario. As seen in Figure 4.11 there are 2 simultaneously communicating pairs per cell, i.e., the BS $\rightarrow$ GTW pair and GTW $\rightarrow$ MS pair. The receivers of cell 0 would experience interference not only from its own cell, but also from the simultaneously communicating pairs from other cells. The interference experienced by the communicating pairs in cell 0 are calculated as follows:

**BS $\rightarrow$ GTW communication in the intended cell**

When the gateway in the intended cell is the desired receiver (say, GTW 1a in cell 0 in Fig 4.11), the distance between this gateway and the interfering transmitters of the adjacent cell are calculated as shown in Figure 4.11. There are 2 cells, cell 0 and cell 1, shown in Figure 4.11. Using basic trigonometry, the distance of the communicating receiver in cell 0 from the interfering transmitters in cell 1 is computed. As shown in Figure 4.11a, the distance of receiving gateway at cell 0, GTW 1a, from the BS of cell 1 is given by:

$$d_{BSi} = \sqrt{(2\sqrt{3}d_c - d_c \cos(q_{11}))^2 + (d_c \sin(q_{11}))^2}$$  \hspace{1cm} (4.5)
whereas the distance of the unintended transmitting gateway of the cell 1, GTW 2b, to the desired gateway receiver in cell 0 is given by:

$$d_{GTW_1} = \sqrt{(2\sqrt{3}d_c + d_c \cos(x_{12}) - d_c \cos(q_{11}))^2 + (d_c \sin(x_{12}) - d_c \sin(q_{11}))^2}$$

(4.6)

The angle, $q_{11}$, is formed between the line joining the communicating pairs, BS $\rightarrow$ GTW 1a in cell 0 with the reference line of cell 1. Similarly, $x_{12}$ is the angle between the line joining the communicating pairs, GTW 2b $\rightarrow$ MS in cell 1, with the reference line of cell 1. The above equations, eqn. (4.5) and eqn. (4.6) could be generalized to calculate the interference coming from the transmitters of all the 6 adjacent cells into the desired receiver, i.e., the GTW of the intended cell. By changing the reference line for each of the 6 adjacent cells, the distance of the interfering transmitters from the $i^{th}$ cell can be calculated as follows:

$$d_{BS_i} = \sqrt{(2\sqrt{3}d_c - d_c \cos(\theta_{i1}))^2 + (d_c \sin(\theta_{i1}))^2}$$

(4.7)

$$d_{GTW_i} = \sqrt{(2\sqrt{3}d_c + d_c \cos(\phi_{i2}) - d_c \cos(\theta_{i1}))^2 + (d_c \sin(\phi_{i2}) - d_c \sin(\theta_{i1}))^2}$$

(4.9)

whereas the distance of the unintended transmitting GTW to the desired GTW receiver is given by:

$$d_{owncell} = 2d_c$$

The $C/I$ at the receiver of any communication pair is therefore given by:

$$\gamma = \frac{d_c^\alpha}{(2d_c^\alpha + \sum_{i=1}^{6}(d_{GTW_i})^\alpha + \sum_{i=1}^{6}(d_{BS_i})^\alpha}$$

(4.12)

Dividing the numerator and denominator by $d_c^\alpha$ results in:

$$\gamma = \frac{1}{2^\alpha + \sum_{i=1}^{6}(\beta_{GTW_i})^\alpha + \sum_{i=1}^{6}(\beta_{BS_i})^\alpha}$$

(4.13)
where

\[ \beta_{(BS)}_i = \sqrt{13 - 4\sqrt{3}\cos(\theta_{i1})} \] (4.14)
\[ \beta_{(GTW)}_i = \sqrt{14 + 4\sqrt{3}(\cos(\phi_{i2}) - \cos(\theta_{i1})) - 2\cos(\phi_{i2} - \theta_{i1})} \] (4.15)

**GTW → MS communication pair in the intended cell**

For the 2\(^{nd}\) active communication pair, GTW → MS, in the downlink of cell 0, the maximum distance of the intended receiver, i.e., the MS of the GTW → MS pair, from the BS is twice the transmission distance. Therefore, as seen in Figure 4.11, the MS in cell 0 is located at a distance of \(d = 2d_c = r\) from the BS, and is distributed uniformly from \([0^\circ, 360^\circ]\). The distance of the interfering BS and the interfering GTW from the cell 1 is calculated from basic trigonometry as:

\[ d_{BS} = \sqrt{(2\sqrt{3}d_c - 2d_c \cos(q_{12}))^2 + (2d_c \sin(q_{12}))^2} \] (4.16)
\[ d_{GTW} = \sqrt{(2\sqrt{3}d_c + d_c \cos(x_{12}) - 2d_c \cos(\theta_{12}))^2 + (d_c \sin(x_{12}) - 2d_c \sin(\theta_{12}))^2} \]

This equation for calculating the distances of the interfering transmitters from other cells could be written in a generalized form as follows:

\[ d_{BS} = \sqrt{(2\sqrt{3}d_c - 2d_c \cos(\theta_{i2}))^2 + (2d_c \sin(\theta_{i2}))^2} \] (4.17)
\[ d_{GTW} = \sqrt{(2\sqrt{3}d_c + d_c \cos(\phi_{i2}) - 2d_c \cos(\theta_{i2}))^2 + (d_c \sin(\phi_{i2}) - 2d_c \sin(\theta_{i2}))^2} \]

where, \(\theta_{i2} = q_{i2} + 60(i - 1)\) is the angle made by the GTW → MS pair in the intended cell with the reference line of the \(i^{th}\) cell (Figure 4.11b shows the angle \(q_{i2}\) between the communicating pair, GTW 1b → MS with the reference line of cell 1).

Eqn. (4.17) is simplified and the corresponding equations for \(\beta_{(BS)}\) and \(\beta_{(GTW)}\) are given as:

\[ \beta_{(BS)}_i = \sqrt{16 - 8\sqrt{3}\cos(\theta_{i2})} \] (4.18)
\[ \beta_{(GTW)}_i = \sqrt{17 + 4\sqrt{3}(2\cos(\theta_{i2}) - \cos(\phi_{i2})) - 4\cos(\phi_{i2} - \theta_{i2})} \] (4.19)

Note that the equation for \(\gamma\) remains the same as given in eqn. (4.13).
4.4 Semi-Analytical Model

The angle made by the 2 communicating pairs in the cell 0 with the reference line of cell 1 are given by $q_{11}$ and $q_{12}$.

The angle made by the 2 communicating pairs in the cell 1 with the reference line of cell 1 are given by $x_{11}$ and $x_{12}$.

Case a: Distance calculation at the receiver of BS - GTW pair in cell 0.

Case b: Distance calculation at the receiver of GTW - MS pair in cell 0.

1. $q_{11}$ indicates the angle made by the 1st communication pair, BS $\rightarrow$ GTW, in the intended cell (cell 0 in this case) with the reference line of cell 1.

2. $q_{12}$ indicates the angle made by the 2nd communication pair, GTW $\rightarrow$ MS, in the intended cell (cell 0 in this case) with the reference line of cell 1.

3. Similarly, $x_{11}$ and $x_{12}$ indicates the angles made by the 1st interfering communication pair, BS $\rightarrow$ GTW, and the 2nd interfering communication pair, GTW $\rightarrow$ MS, (both) in cell 1 with the reference line of cell 1.

Figure 4.11: Calculation of distance at the receivers of BS $\rightarrow$ GTW and GTW $\rightarrow$ MS pairs (downlink) from the two interfering transmitters of $i$th cell.
The figure shows the interference calculation at the receiver gateway (i.e., the receiver of BS $\rightarrow$ GTW pair) of the center cell (cell 0).

1. The black colored thick ray from BS $\rightarrow$ GTW and GTW $\rightarrow$ MS in all the cells, represent the simultaneous communicating pairs.

2. A reference line (dotted line in the figure) is considered that connects the BS of cell 0, cell 1 and cell 4.

3. The dashed lines from the transmitting BSs and GTWs of cell 2 and cell 3, to the RX GTW in the center cell indicates the distance of the RX GTW from other interfering transmitters in cell 2 and cell 3.

4. In all, the RX GTW in cell 0 would experience interference from 13 interferers: 2 interferers from each of the 6 adjacent cells and 1 transmitting GTW (of GTW $\rightarrow$ MS pair) from cell 0.
4.5 Simulation Model

4.4.2 \( C/I \) calculation for uplink:

In the case of an uplink as well, there exist 2 simultaneously communicating pairs in the cluster-based model: the MS → GTW and the GTW → BS pairs located at the diametrically opposite clusters. In the case of an uplink, both the transmitters in the cluster-based design: the GTW and the MS, are not fixed, whereas, the receiver of one of the communicating pairs, GTW → BS is located in a fixed position.

**MS → GTW communication pair in the intended cell**

For the MS → GTW pair communication, the expression for \( \beta \) is given by:

\[
\beta_{(MS)_i} = \sqrt{17 + 4\sqrt{3}(2 \cos(\phi_{i2}) - \cos(\theta_{i2})) - 4 \cos(\phi_{i2} - \theta_{i2})} \quad (4.20)
\]

\[
\beta_{(GTW)_i} = \sqrt{14 + 4\sqrt{3}(\cos(\phi_{i1}) - \cos(\theta_{i2})) - 4 \cos(\phi_{i1} - \theta_{i2})} \quad (4.21)
\]

where \( \phi_{i1} = x_{i1} + 60(i - 1) \), is the GTW → BS communicating pair in the \( i^{th} \) cell with the reference line of the \( i^{th} \) cell.

**GTW → BS communication pair in the intended cell**

Similarly, for the GTW → BS communication in the intended cell, the corresponding \( \beta \) values are:

\[
\beta_{(MS)_i} = \sqrt{16 + 8\sqrt{3}\cos(\phi_{i2})} \quad (4.22)
\]

\[
\beta_{(GTW)_i} = \sqrt{13 + 4\sqrt{3}\cos(\phi_{i1})} \quad (4.23)
\]

4.5 Simulation Model

A simulation model for the cluster-based 2-hop cellular network is built in Matlab. An airport or a campus environment, with a total coverage area of 1 km\(^2\) is considered in the system design. There are 19 cells within a coverage area of 1 km\(^2\). Hence, the distance from the centrally located BS to the edge of the cell, \( r \), is around 130 meters and the average transmission distance between any receiver and its desired transmitter for such a scenario is, \( r/2 = 65 \) m. An indoor propagation model with \( k_1 = 37 \) and \( \alpha = 3 \) has been considered in the simulation model. 1000 MSs are uniformly distributed around this network coverage area and each cell is designed to have 6 clusters. All the MSs that are located in the outer layer of the cell are assigned to any one of the 6 clusters. This assignment is done depending on the closest distance (lowest pathloss, in the presence of lognormal shadowing) of the respective MS to the 6 GTWs in the cell. This results in a system where there are, on an average, 8 MSs per cluster. The GTWs are selected from among the MSs. The MSs selected as GTWs are located at nearly half the
cell radius. The exact position of the GTW depends on the distribution of the MSs. A TDMA time frame with 16 TS(s) has been considered in the simulator design. The simulation model calculates the $C/I$ and the system capacity for 7 cells independently and then takes an average over these 7 cells. The network is simulated for two different scenarios. In the 1st case, it is assumed that there is no shadowing. Hence, for this case, $\zeta = 0$ in eqn. (4.2). In the 2nd case, a lognormal shadowing with a zero mean and a standard deviation of 4 dB is considered [104].

For different locations of the GTWs and the MSs (with respect to the reference line), the distance of the desired receiver from the interfering transmitters would vary which in-turn would vary the $C/I$ experienced at the receiver of the communicating pair. The synchronized resource reuse technique ensures that all the interfering transmitters are spatially well-separated in distance. The exact value of $C/I$, and thereby the system capacity value, however, depends on the relative distance between the receiver and other transmitting GTWs and MSs. Hence, the system capacity is plotted as cumulative distribution function (CDF) in Figure 4.13 and Figure 4.16. In addition, while running the simulations, a symmetric traffic is considered between the uplink and downlink. Hence, the system capacity plots shown in the results are for 1:1 traffic, obtained by averaging the system capacity over the uplink and downlink. The study of the system capacity for the cluster-based design is left for future work. Also, the system capacity results obtained from the cluster-based 2-hop cellular architecture is compared with the following systems:

1. **A single-hop cellular network with no relaying:**
   There are no relays in this design. In every hexagonal cell, the BS and the MS communicate with each other in single hop, irrespective of whether the MS is located in the inner layer or outer layer.

2. **A benchmark relaying algorithm for a 2-hop cellular network:**
   The benchmark algorithms for the 2-hop cellular design, introduced in [105], provides three efficient methods for finding the wireless terminals that could act as relays in order to maximize the system capacity. These benchmark algorithms could be either distance-based or pathloss-based, as explained below. The pathloss based algorithms take the random effects, arising due to shadowing, into account. Hence, in the presence of lognormal shadowing, the pathloss based algorithms are superior to distance-based algorithms.

**Distance-based Benchmark Algorithm**

In the 2-hop design based on benchmark algorithms, the MSs located in the outer layer of the cell communicate to the BS in 2 hops, as is the case with the cluster-based model. The GTWs/relay nodes are selected from the
4.5 Simulation Model

mobile nodes available in the network. Suppose, there are \( N \) possible 2-hop routes, between the BS and the MS in the outer layer. Then, the selected route, \( r_s \), is determined, depending on the transmission distance between the BS and the relay node, \( d_{c_{n1}} \), and between the relay node and the MS, \( d_{c_{n2}} \), for each of the \( n \in N \) routes. The three selection schemes of the standard benchmark algorithm for 2-hop network \([105]\) are given as follows:

(a) shortest total distance (STD) selection scheme:
\[
    r_s = \min_{\forall n \in N} (d_{c_{n1}} + d_{c_{n2}})
\]

(b) least longest hop (LLH) selection:
\[
    r_s = \min_{\forall n \in N} \max(d_{c_{n1}}, d_{c_{n2}}) \quad \text{and}
\]

(c) shortest relaying hop distance (SRD) selection:
\[
    r_s = \min_{\forall n \in N} (d_{c_{n2}})
\]

### Pathloss-based Benchmark Algorithm

In addition to the distance-based benchmark algorithms, \([105]\) also introduced the pathloss-based benchmark algorithms. Let \( P_{L_{n1}} \) and \( P_{L_{n2}} \) denote the path losses in dB associated with the first hop (BS and relay node), and second hop (relay node and MS of the outer layer) respectively, along the \( n^{th} \) route where \( n \in N \). Then, the selected route is determined as follows:

(a) minimum total pathloss (MTP) selection scheme:
\[
    r_s = \min_{\forall n \in N} (P_{L_{n1}} + P_{L_{n2}})
\]

(b) least maximum pathloss (LMP) selection:
\[
    r_s = \min_{\forall n \in N} \max(P_{L_{n1}}, P_{L_{n2}}) \quad \text{and}
\]

(c) minimum relaying hop pathloss (MRP) selection:
\[
    r_s = \min_{\forall n \in N} (P_{L_{n2}})
\]

In order to have a fair comparison, the source MSs in case of uplink (or the destination MSs in case of downlink) remain the same in all the methods, viz., the cluster-based 2-hop design, the three standard benchmark 2-hop schemes, and the single-hop non-relaying technique. Also, an interference avoidance model, with an optimum spatial protection margin of \( \Delta = 1.0 \), is considered for all the different methods. In addition, it should be noted that, in the simulation model, the increase in the overhead due to additional signaling is not considered in any of the 2-hop cellular designs. This increase in the overhead in the 2-hop design would cause some reduction in the capacity gain with respect to the single-hop cellular network. However, comparing the performance of the 2-hop schemes with the single-hop design is not the main focus of this work. Also, it is expected that, the cluster-based architecture with an intelligent resource allocation technique, would
4.6 Results

Figure 4.13 shows the CDF of the system capacity for all the different methods, in the absence of any lognormal shadowing. The CDF’s of the cluster-based design, obtained from both semi-analytical model and simulation results, show a good match. The expected value obtained from the semi-analytical model and the simulation results are 5.7 bps/Hz/cell and 5.53 bps/Hz/cell respectively. However, there is a considerable difference in the values over the higher and lower end of the CDF’s. For example, for the system capacity of 6 bps/Hz/cell, the CDF value obtained from the semi-analytical model is 0.7, whereas, the CDF value obtained from the simulations is 0.8. This is because, in the semi-analytical model, the GTW’s are always assumed to be located at exactly half the cell radius, $r/2$, whereas in the simulation, the GTWs are distributed around $r/2$, as shown in Figure 4.14. Also, in the semi-analytical model, the MSs in the outer layer are require less or same amount of overhead signaling as compared to the benchmark algorithms, for the 2-hop cellular network. Hence, the capacity results obtained in this work for the 2-hop networks, viz., the cluster-based design and the three benchmark algorithms are directly comparable.
always assumed to be located at a maximum transmission distance of \( r/2 \), from the GTWs. However, in the simulation model, the GTWs are selected from among the MSs, and hence, the transmission distance between GTW and MS could be either less, or more, than \( r/2 \). Also, Fig 4.14 shows the probability density function (PDF) of the location of the GTW node, when the GTW is selected from among the MSs. In the absence of lognormal shadowing, the distribution of the GTW is almost symmetric with a mean value of 0.55. However, in the presence of lognormal shadowing, the pathloss experienced by the wireless terminals vary depending on the shadowing factor. Hence, the PDF of the GTW selection in the presence of lognormal shadowing exhibits a long tail, resulting in an expected value of 0.58r.

Reverting back to Figure 4.13, it is observed that for the 2-hop cluster-based design, the system capacity is nearly double that obtained from the single-hop cellular system with no relaying. More significantly, the cluster-based design shows a superior performance over all three standard benchmark techniques for 2-hop cellular network. The throughput behavior of the STD and SRD schemes are nearly similar to each other and their expected values are 4.19 bps/Hz/cell and 4.37 bps/Hz/cell respectively. The cluster-based design therefore provides an improvement of 21% and 25% over the STD and SRD algorithms. The LLH technique provides the best performance out of the three standard benchmark techniques.
The expected value of the system capacity for the LLH method is 4.83 bps/Hz/cell, which is higher than the expected value of the capacity obtained from the STD and SRD schemes, but less than the expected value obtained for the cluster-based technique by 0.7 bps/Hz/cell. In the LLH method, the node that has the least longest hop (both between, MS and GTW node, and GTW node and BS) among all possible relay nodes is selected as a relay. Hence, a node located in the vicinity of half the cell radius is selected as a relay, which results in more than one pair utilizing the given resource simultaneously, in any cell. A greater insight into the performance of the benchmark algorithms could be obtained from Figure 4.15, that plots the PDF of all three standard benchmark algorithms along with the cluster-based design, in the absence of lognormal shadowing. It can be observed from Figure 4.15 that the PDF of the STD algorithm is almost a straight line, in the range from 0.3 to 0.7. The SRD algorithm selects the relay that is more towards the cell edge, than at the center of the cell. Hence, the PDF of the SRD method has a non-zero value only after 0.38. A significant observation that can be made from Figure 4.15 is that, in case of the LLH method, the mean of the PDF is at 0.5, same as that of the cluster-based design. Hence, the LLH method outperforms STD and SRD benchmark algorithms. However, the variance of the LLH method is 0.28, which is twice more than that of the cluster-based design, which has a variance of 0.13. Depending on the location of the MS and the relay node, the LLH selection scheme allows another MS located within the same cell but outside the exclusion region to communicate simultaneously and utilize the same radio resource. It should be noted that this is similar to the cluster-based design introduced in this paper. However, the significant improvement observed in the cluster-based design is due to the synchronized resource reuse technique proposed in this work that ensures a reuse of the radio resource in every cell. Hence, it is observed that the cluster-based 2-hop model, with resource reuse in every cell, gives the best performance in terms of system capacity, as compared to the single-hop non-relaying scenario and the benchmark algorithms for the 2-hop cellular network.

The performance of the cluster-based design is then compared with the pathloss-based benchmark algorithms, in the presence of lognormal shadowing. A lognormal shadowing with a zero mean and a standard deviation of 4 dB is considered in the simulations, for both the cluster-based design and the benchmark algorithms. It is observed in Figure 4.16 that, even in the presence of lognormal shadowing, the performance of the cluster-based 2-hop network is superior to all the three techniques of the benchmark method. For example, the expected value of the system capacity for the cluster-based design is 5.36 bps/Hz/cell, and is 0.41 bps/Hz/cell better than LMP (the best performing algorithm among all three benchmark algorithms, and has an expected value of 4.95 bps/Hz/cell). It should however be noted that, in spite of this difference of 0.41 bps/Hz/cell, the performance of the LMP scheme comes close to the performance of the cluster-
4.6 Results

Figure 4.15: PDF of the location of GTW node for standard benchmark algorithms and the cluster-based design, in the absence of lognormal shadowing.

Figure 4.16: CDF of throughput capacity in the presence of log normal shadowing.
4 Radio Resource Management in Multihop Hybrid Cellular Networks

Based design. This is because, the relays are selected not on the basis of distance measurement, but on the basis of pathloss measurement, which vary with lognormal shadowing. The presence of lognormal shadowing results in MSs that are far from half the cell radius, $r/2$, to be selected as GTWs. As seen from the PDF of the GTW location in Figure 4.14, in the presence of lognormal shadowing, there is a non-zero probability for a node located beyond $0.8r$, to be selected as a GTW. This results in a situation in the cluster-based design, where the exclusion region of a communicating pair in one cell extends to the other cell, and hence, prevents the simultaneous communication of another pair in the adjacent cell. This, in turn, results in a reduction in the system capacity for the cluster-based design, and can be observed from the capacity plots shown in Figure 4.13 and Figure 4.16. In the presence of lognormal shadowing, the mean value of the capacity for the cluster-based design is 5.36 bps/Hz/cell, which is less than the expected value of 5.53 bps/Hz/cell when there is no lognormal shadowing. Hence, there is a marginal decrease in the performance due to the presence of lognormal shadowing.

4.7 Chapter Summary

In this chapter, a multihop hybrid cellular network was analyzed in detail. It was observed that the throughput capacity of the system increases with an increase in the number of multiple hops per link. However, there was not much significant increase beyond three/four hops per link. The maximum increase in the capacity was observed when a transition is made from single-hop to 2-hop design. A 2-hop cellular network was then analyzed and a novel cluster-based architecture is proposed for the 2-hop model. It was observed that that under the interference avoidance Protocol Model, with an exclusion range factor, $\Delta = 1.0$, two pairs can always communicate simultaneously in a cell. This system was compared against three benchmark techniques available for 2-hop design. The cluster-based design was found to deliver a much better performance than the three benchmark algorithms.
5 Conclusions

Multihop wireless networks is a fledgling area of research. There are several dimensions to this research field, and innumerable open research issues. There are two main categories in the design of multihop networks, viz., multihop ad hoc networks, and multihop cellular networks. It has been found in the literature [67], that for a multihop network under an interference avoidance model, it is an NP-hard problem to optimally allocate the radio resources that would maximize the system capacity. Hence, this thesis looked into different heuristic techniques for radio resource allocation, for both kinds of multihop networks and studies the impact on the aggregate system capacity.

In a distributed multihop network, there is no central controller that could efficiently assign the resources to the communicating users. Hence, in this part of research work, a restrictive version of the Protocol Model has been considered for interference avoidance in the system design. Therefore, the exclusion region circles around the receivers of the simultaneously communicating pairs do not overlap with each other. In order to efficiently assign the resources in a decentralized manner, a simple random algorithm has been introduced in this work as an efficient resource allocation technique. In this technique, the TS granularity of the TDMA frame is first increased by reducing the duration of each TS. This has been shown to provide an increase in the reusability of resources. A random data hopping scheme, is then implemented, whereby, the TS over which the transmission pair communicates is varied randomly. It has been found that such a random assignment of TSs, enabled by TS partitioning, results in a higher system capacity as compared to a system with no TS partitioning. Hence, such blind techniques could be used as efficient resource allocation algorithms that would increase the system capacity with no increase in computational complexity.

In a multihop hybrid ad hoc cellular network, the BS, as a central control entity, plays a pivotal role in assigning the radio resources in every cell. However, optimal resource allocation is still an NP-hard problem. Hence, the focus of research has been restricted to 2-hop cellular networks. A novel cluster-based design has been proposed and studied for a 2-hop cellular network. In this design, each hexagonal cell is divided into two layers. The MSs located in the inner layer communicate with the BS in single-hop, whereas, the MSs that are located in the outer layer
are grouped into several clusters and communicate with the BS in two hops. The significant feature of this design is that it enables simultaneous transmission of two communicating pairs, in every cell. This results in an increase in the reusability of resources which in-turn results in an increase in the system capacity. In fact, it has been observed that the cluster-based architecture provides an improvement of 0.4-1.2 bps/Hz/cell in the system capacity as compared to standard benchmark techniques 2-hop cellular network.
6 Limitations and Future Work

6.1 Limitations

Any and every research work is based on certain assumptions. These assumptions help in understanding the system and also help in developing a theoretical model and obtaining simulation results. However, at certain times, these assumptions themselves are likely to be the main source of limitations of the research work. The interference model considered in this research work also forms a major limitation of this thesis work.

In this research work, the multihop wireless network has been designed and analyzed under the Protocol Model and the restrictive Protocol Model. These are simple interference mechanisms that ensure that there is a minimum distance between two concurrently communicating pairs in the system. A major disadvantage of these methods is that they do not take into account the cumulative effect of the interferences from all other simultaneously communicating pairs. Therefore, in certain situations, due to a large number of concurrently transmitting pairs, the aggregated interference at the receiver of a communicating pair will be very high; and hence, such interference models are not sufficient to guarantee that the assignment is conflict-free, in terms of $C/I$. An obvious argument in favor of the Protocol Model could be that the effect of aggregate interference could be reduced by increasing the value of the exclusion range ratio, $\Delta$, in the definition of the Protocol Model. But the main drawback of such technique is that it often over-estimates the interference caused by neighboring nodes, thereby assigning fewer number of communication pairs to a given TS than would otherwise be possible. A better alternative for realistic interference considerations that would give superior performance is to opt for a Physical Model. This requires calculation of interference at the receiver of every communicating pair whenever a new pair is to be added to the set of concurrently communicating pairs. Such an interference-based technique gives a more accurate representation of the system. However, this increases the complexity of the system and more specifically, the complexity on the user equipment, which is not acceptable, especially in the distributed ad hoc networks where there is no central entity to monitor the entire system.

Recently, there have been a few research works which use the Physical interfer-
ence Model. But mostly they are suited for cellular networks where there is a base station at the center of the cell. Development of a distributed multihop network under the Physical interference Model is still a subject of open research.

6.2 Future Work

The area of multihop wireless networks is still a nascent field of research, and hence, there are several possible directions in which this research work could be extended in the future. There are, however, four prominent design aspects in which the current research work on multihop wireless networks could be extended.

1. Improvement over the random data hopping algorithm for multihop ad hoc network:

In this research work, the random data hopping algorithm has been applied over the time slot partitioned system. A further improvement in the performance could be obtained by designing a more structured algorithm that would iteratively improve the performance of the proposed heuristic algorithm. An interesting method would be to start with a random solution and use information about the previous solutions in order to derive the solution at the next iteration. In the genetic heuristic algorithms, a ‘population’ of initial solutions is randomly generated and each solution, encoded into a series of numbers or ‘strings’ is evaluated using a measure of effectiveness. Based on the performance of each string, a random process is used to ‘mate’ the strings with each other to produce other strings, or ‘offspring’. The population tends to contain better and better strings as the algorithm progresses because the better strings are chosen as beacons for the next iteration. The main advantage of the genetic algorithm is that it allows for a very wide search in the large and complex solution spaces inherent in packing problems in a systematic and efficient way and iteratively progresses towards the optimal solution [106]. An interesting observation made in [107] with respect to unequal circle packing problem is that, while ‘random’ algorithms have one of the lowest average deviation from its mean performance, ‘genetic’ heuristic algorithms not only have better mean values but also it has the lowest maximum deviation, which perhaps, indicates that it is the most reliable method.

2. Extension of the time slot partitioning to a multihop hybrid cellular network:

The time slot partitioning technique considered for the multihop ad hoc network could be extended to the multihop hybrid cellular network. In the
6.2 Future Work

In an ad hoc scenario, there was no central entity and hence a random assignment of TSs was considered as a distributed algorithm in the system design. In the multihop cellular network, due to the presence of BS, a dynamic time slot partitioning (DTSP) algorithm could be applied for a TDMA system, based on the principle of statistical multiplexing (SM).

In a multihop cellular network, the TS allocation based on synchronous TDM is not efficient for packet-oriented services, especially for packets of varying length. This is primarily because, in synchronous TDM, all the TSs are of same duration - hence different data traffic with variable packet sizes cannot be served sequentially without any loss of TS resources. A novel and efficient technique for transmitting such data is by employing dynamic time slot partitioning. The key advantage of using DTSP technique is that it is expected to yield a system which can flexibly adapt to different quality of service (QoS) requirements. This particularly holds if it is combined with adaptive modulation. For example, links with very high SINR could either be given longer or shorter TSs, depending on the state of transmission buffer and particular QoS constraints such as delay, priority and fairness.

With such a DTSP algorithm, any TS could be partitioned dynamically into several mini-slots which could also be given to different users. This is done by sensing the SINR of all the channels; in case a particular user has a good channel and hence a high SINR, a higher modulation technique could be used and all the data in the buffer of that user could be transmitted within a fractional TS period (integer number of mini-slots). This information about the required TS duration could then be calculated for all the users and broadcasted before the start of data transmission. Hence, every user in the networks would then precisely know the time instant when it has to start its transmission and how many TSs it would need to transmit the data in its buffer.

3. A generalized cluster-based design for multihop hybrid cellular networks:

In this thesis, a cluster-based design was introduced for a specific model of 2-hop cellular networks, wherein, all the MSs in the cell communicate with the BS in either one or two hops. It has been shown in Chapter 4 that a multihop cellular network provides a significant improvement in performance when the number of multiple hops per link is restricted to around four hops. Hence, the cluster-based design could be extended to a 3-hop as well as to a 4-hop cellular network scheme. In such a scenario, the number of concurrently communicating pairs per cell would also increase (3 concurrent pairs for 3-
hop cellular network and 4 simultaneously communicating pairs for a 4-hop cellular design). However, the complexity of such a system would also be very high and it would require a very efficient architecture design in order to offset the increased overhead and additional interference, and provide an increase in the throughput performance.

Another challenge while designing the cluster-based model is that, all MSs need not communicate to the BS. It has been shown in [108] that the greatest level of interference, and hence, the relaying bottleneck, is generally found to be at the last hop, in the vicinity of the BS. Hence, in order to overcome this shortcoming, the cluster-based design for the multihop hybrid cellular network could be extended such that, if the source and destination MS are in the same cell, or in the adjacent cells, then the traffic could be routed through the gateways, by-passing the BS itself. A multihop design that by-passes the BS has been well researched in the literature, as was explained in Chapter 2, but it would be not only be very interesting but also very challenging to design a cluster-based model for such a hybrid cellular network.
A Appendix

A.1 Comparison between Single-Hop and Multihop Transmission

A.1.1 Capacity equation for single-hop and multihop transmission

Single-hop transmission between source and destination

Consider an end-to-end link communication between node, $P$, and node, $Q$, taking place at a constant data rate for a time period of $T_s$ seconds.

In case of a single-hop communication, as shown in Figure [A.1-a], the entire $T_s$ seconds is given to link $P \rightarrow Q$. Let $\gamma$ be the SNR experienced at the receiver node, $Q$. A TDMA system is considered and hence there is no spatial reuse of resources. Using the Shannon equation, the capacity of the system calculated during these $T_s$ seconds would be given by:

$$C_1 = \log_2(1 + 10^{0.1\gamma}) \quad (A.1)$$

where

$$\gamma = P_R - N_O \quad dB \quad (A.2)$$

$$P_R = P_T - L_{P_1} \quad dB \quad (A.3)$$

and

$$L_{P_1} = k_1 + 10\alpha \log_{10}(d) \quad dB \quad (A.4)$$

In the above equations, $P_T$ represents the transmit power, $P_R$ is the received power, $N_O$ is the noise power, $L_{P_1}$ is the path-loss value, $k_1$ is a propagation constant, $d$ is the transmission distance between nodes $P$ and $Q$, and $\alpha$ is the
path-loss exponent.

\[ \gamma_2 = P_T - N_O - (k_1 + 10\alpha \log_{10}(d/2)) \]
\[ = P_T - N_O - (k_1 + 10\alpha \log_{10}(d)) + 10\alpha \log_{10}(2) \]
\[ = \gamma + 3\alpha \]

**2-Hop Scenario**

Now suppose, instead of a single-hop link, a 2-hop scenario is considered between the link \( P \rightarrow Q \), with the node, \( Z \), lying exactly between \( P \) and \( Q \). Such a transmission scenario is shown in Figure A.1b. The transmission \( P \rightarrow Z \) and \( Z \rightarrow Q \) both takes place for only \( T_s/2 \) seconds each. Since the path loss is assumed to be only distance-dependent, the path loss between node \( P \) and \( Z \) or between \( Z \) and \( Q \) remain the same and is given by:

\[ L_{P2} = k_1 + 10\alpha \log_{10}(d/2) = k_1 + 10\alpha \log_{10}(d) - 10\alpha \log_{10}(2) = L_{P1} - 3\alpha \quad (A.5) \]

The SINR equation for the 2-hop scenario is given by:

\[ \begin{align*}
\gamma_2 & = P_T - N_O - (k_1 + 10\alpha \log_{10}(d/2)) \\
& = P_T - N_O - (k_1 + 10\alpha \log_{10}(d)) + 10\alpha \log_{10}(2) \\
& = \gamma + 3\alpha
\end{align*} \quad (A.6) \]
A.1 Comparison between Single-Hop and Multihop Transmission

In case of a 2-hop link, even though the time slot duration is reduced by half, the transmit power for each of the transmitting MS(s) remain the same. Hence, the signal-to-interference-noise ratio at the receiver of any pair would be given by $\gamma_2 = \gamma + 3\alpha$, where $\gamma_2$ is the SINR of each pair of the 2-hop link. Therefore, the capacity of the system during the time interval of $T_s$ would be given by:

$$C_2 = \frac{1}{2} \log_2 (1 + 10^{0.1(\gamma+3\alpha)}) \quad (A.9)$$

*M-hop Scenario*

Similarly, for a general $M$-hop link scenario where node, $P$, and node, $Q$, communicates in $M$-hops, each hop having same distance, the SINR at the receiver of each communicating pair would be given by $\gamma_M = \gamma + (\alpha \times 10 \log_{10}(M))$. Therefore, the capacity of the system in the $T_s$ interval would be given by:

$$C_M = \frac{1}{M} \log_2 (1 + 10^{0.1(\gamma+(10\alpha \log_{10}(M)))}) \quad (A.10)$$

**Performance Measure in terms of Shannon Capacity**

A real-time example is taken into consideration for performance comparison. The receiver node, $Q$, of the single-hop link, $P \rightarrow Q$, is assumed to experience a SINR of 6 dB. The resulting capacity of the link is calculated from the Shannon equation and is equal to 2.316 bps/Hz. Table A.1 shows the system capacity for different multihop link scenarios and for different values of the path-loss exponent, $\alpha$. It should be observed that at a path-loss exponent of $\alpha = 3$, the system capacity of the 2-hop scenario is higher than the single-hop case by 8.5%. In case of higher attenuation factor, for example at $\alpha = 4$, it could be seen that the capacity of the 2-hop link is higher than the capacity of the single-hop link by 30%. This is because, for higher attenuation factors, the interference is less which in turn results in a higher system capacity. In another significant result, as the number of multiple hops per link is increased, the capacity of the $M$-hop link becomes less than the single-hop scenario, especially for low path-loss exponent values. For example, the capacity of the 3-hop link is less than the single-hop link when $\alpha = 3$, but as the path-loss exponent value is increased, for example, at $\alpha = 3.5$, or at $\alpha = 4$, the capacity of the 3-hop link becomes higher than the single-hop scenario. Also, for a 5-hop link, there is always a capacity reduction as compared to the single-hop network, for any value of path-loss exponent between $\alpha = 3$ and $\alpha = 4$. It should be noted at this stage that for this simple example, the increase in capacity is only due to the reduced transmission distance resulting from the multihop transmission. The spatial reuse of resources that could further improve the system performance is not taken into consideration in this calculation.
Table A.1: Shannon capacity for different multihop scenario, when the SINR of the single-hop link is 6 dB

<table>
<thead>
<tr>
<th>Number of hops per link, $M$</th>
<th>$\alpha = 3$</th>
<th>$\alpha = 3.5$</th>
<th>$\alpha = 4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M = 2$</td>
<td>2.52</td>
<td>2.76</td>
<td>3.01</td>
</tr>
<tr>
<td>$M = 3$</td>
<td>2.25</td>
<td>2.52</td>
<td>2.78</td>
</tr>
<tr>
<td>$M = 4$</td>
<td>1.99</td>
<td>2.243</td>
<td>2.491</td>
</tr>
<tr>
<td>$M = 5$</td>
<td>1.79</td>
<td>2.02</td>
<td>2.26</td>
</tr>
</tbody>
</table>

A.1.2 Power reduction due to multihop transmission

The aim of this section is to analyze the power reduction that could be possible in a multihop design in order to achieve the same system capacity as the single-hop network.

If the transmission power of the single-hop link is $P_T$, then let the transmit power required for the multihop design be $kP_T$, where $k$ is any fraction of the single-hop transmission power, $P_T$. A value of $k < 1$ would indicate a reduction in the power requirement. Similarly, $k > 1$ would indicate that a power higher than $P_T$ would be required in order to achieve the same capacity as the single-hop design.

2-Hop Transmission

The SINR equation for the 2-hop transmission when the transmit power is different than $P_T$, is given by:

$$
\gamma'_2 = (P_T + 10 \log_{10}(k)) - N_0 - (k_1 + 10\alpha \log_{10}(d)) + 10\alpha \log_{10}(2) (A.11)
$$

$$
\gamma'_2 = \gamma + 10 \log_{10}(k) + 3\alpha \quad (A.12)
$$

$$
\gamma'_2 = \gamma + k' + 3\alpha \quad (A.13)
$$

where $k' = 10 \log_{10}(k)$. The capacity of this 2-hop network is given by:

$$
C'_2 = \frac{1}{2} \log_2(1 + 10^{0.1(\gamma + 3\alpha + k')}) \quad (A.14)
$$

The power reduction obtained from the 2-hop transmission is calculated by equating (A.14) with the equation for the single-hop network, given by (A.1). Therefore, the expression for the reduction of power is obtained by equating (A.1) and (A.14) as follows:

$$
\log_2(1 + 10^{0.1\gamma}) = \frac{1}{2} \log_2(1 + 10^{0.1(\gamma + 3\alpha + k')}) \quad (A.15)
$$

This could be simplified as follows:

$$
(1 + 10^{0.1\gamma})^2 = (1 + 10^{0.1(\gamma + 3\alpha + k')}) \quad (A.16)
$$
A.1 Comparison between Single-Hop and Multihop Transmission

Expanding the left side of eqn. (A.16), and substituting for $k'$

$$(10^{0.1\gamma})^2 + 2(10^{0.1\gamma}) = (10^{0.1(\gamma+3\alpha+10\log_{10}(k'))})$$  

(A.17)

As derived in A.10, in case of a general $M$-hop link, the capacity equation would be written as:

$$C_M' = \frac{1}{M} \log_2\left(1 + 10^{0.1(\gamma+10\alpha\log_{10}M+k')}\right)$$  

(A.18)

The capacity for the $M$-hop link would be same as that of the single-hop link when the following condition is satisfied:

$$(1 + 10^{0.1\gamma})^M = 1 + 10^{0.1(\gamma+10\alpha\log_{10}M+k')}$$  

(A.19)

The left hand side is the capacity equation for the single-hop link, whereas, the right hand side is the capacity equation for a general $M$-hop link.

It should be noted from (A.19), that for higher number of multiple hops per link, the order of the equation would increase. Hence, it becomes very difficult to simplify the analytical expression for a general $M$-hop link.

Performance Measure in terms of Power Requirement

A SINR value of $\gamma = 6$dB is considered for the single-hop network, which results in a single-hop link capacity of 2.316 bps/Hz. The same value of capacity could be obtained for the 2-hop design when the transmit power is only 0.75 times the single-hop transmit power, $P_T$, when $\alpha = 3$. It could be seen from Figure A.2 that as the value of $\alpha$ is increased, the power required for the 2-hop network reduces drastically in order to have the same capacity as that of the single-hop network, even when there is no spatial reuse of resources considered due to the multihop design. Figure A.2 also shows the power requirement for a 3-hop link and a 4-hop link. It could be seen from Figure A.2 that for higher number of multiple hops per link ($M = 3, 4$), there is an increase in the power requirement at lower values of $\alpha$. However, when the value of $\alpha$ is increased, the power required is quite less in order to achieve the same capacity as that of the single-hop link. This shows the power benefit obtained from the multihop design.
Figure A.2: Power requirement for a multihop scenario for different values of the path-loss exponent, $\alpha$, when the capacity is same as that obtained from an equivalent single-hop network. A SINR of 6dB is considered for the single-hop design in this figure.
A.2 Optimal Packing of Unequal Circles

The number of simultaneously communicating pairs in a finite coverage area is calculated by noting that the exclusion region circles of the simultaneously communicating entities should not overlap with each other. Figure A.3 (a-c) shows 3 cases where the exclusion region circles are distributed within the bounded coverage area. Case (a) represents a scenario where more number of pairs could communicate in the given coverage area but there are no more transmission pairs to make any communication. In case (b), the placement of the communicating pair of nodes are such that no more MS(s) could transmit data in the particular time instant. Figure A.3 shows a dense packing of unequal circles, but it should be noted that the packing scenario shown in Figure A.3-c is not necessarily optimal.

Assume that there are $n_t$ circles (radius of the circles given by $r_1, r_2, ..., r_{n_t}$) that can be placed in the coverage area (a square of side length, $s$). If $x_i$ and $y_i$ indicate the X and Y co-ordinates of the center of the circle $i$, $i \in 1, 2, ..., n_t$, then the optimum packing problem of unequal circles can be formulated as follows:
\[ \max(n_t) \text{ subject to} \]
\[
r_i \leq x_i \leq s - r_i \quad \text{for } i \in \{1, 2, ..., n_t\} \quad (A.20) \\
r_i \leq y_i \leq s - r_i \quad \text{for } i \in \{1, 2, ..., n_t\} \quad (A.21) \\
\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \geq r_i + r_j \text{ for } i \neq j \quad (A.22) \\
r_{\min} < r_i \leq s/2 \quad (A.23) \\
0 < r_{\min} < s/2 \quad (A.24) \\
0 < s \leq +\infty \quad (A.25) \\
\]

It should be noted that the conditions (A.20) and (A.21) ensure that none of any part of each circle is outside the coverage area whereas condition (A.22) ensures that there is no overlapping of exclusion region circles. Condition (A.23) stipulates that there is a minimum non-zero value for the radius of the exclusion range circle. Condition (A.23), therefore, implies that the transmission range between any communicating pair is a non-zero value, and that, it cannot be infinitesimally small. There are usually many different packing configurations which give the same objective function value, and the feasible solutions differ only in the pattern in which the circles are placed [88]. It is shown in [85] that for this class of packing problem, it is not only NP-hard to determine the optimal packing, but also, it is prohibitively complex to approximate the optimal packing problem, even for small values of \( n_t \).
B Publications

B.1 Accepted Papers


B.2 Submitted Papers


Performance Analysis for Hybrid Wireless Networks

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Abstract—A hybrid cellular and ad hoc network for high data rate wireless access is considered. An air-interface which uses TDD in combination with time division multiple access (TDMA) is assumed. Interference and resource reuse are important issues in hybrid networks. For this purpose analytical models for the reuse efficiency and a capacity bound of such a network are developed. These models are based on an exclusion range concept which is introduced to keep interference at an acceptable level. It is found that with this interference limiting measure, multi hop networks can benefit from a multi hop reuse gain compared to single hop networks. However, it is further found that this gain does not significantly increase for more than 5 hops. Furthermore, the pre-requisite for being able to exploit the multi hop reuse gain is a certain TS granularity. It was observed that with an increasing number of TS per frame, the mean and the variance of the number of supported hops increased almost linearly.

Keywords: Ad hoc networks, exclusion range, reuse efficiency, Base Station (BS), Mobile Station (MS), time slot (TS), signal-to-noise ratio (SNR), Time Division Duplexing (TDD), Time Division Multiple Access (TDMA).

I. INTRODUCTION

A great interest has been observed towards ad hoc networks for next generation wireless systems. An ad hoc topology enables building and deployment of wireless nodes to form a communication network with no central control. Such networks are both dynamic and temporary since the network topology changes as devices move in space, as new devices join the region, others leave and as devices turn on and off. In today’s era of global connectivity, where a particular mobile device would like to communicate to some other wireless terminal located anywhere in the world, ad hoc networks as a stand alone technology would be handicapped by numerous limitations [1]. The main drawback of an ad hoc network is its limitation in providing global connectivity. Long distance communication, achievable through cellular networks has the disadvantage of encountering dead zones (areas without coverage). In addition, because of power limitations high transmission rates are only feasible for short range wireless communication. Hybrid wireless networks which are comprised of both, an infrastructure as well as an ad hoc component are envisaged to provide an ideal solution for the drawbacks encountered in the single network architectures. Hybrid networks promise an ubiquitous solution for the present day demand of increased data rate and high speed Internet connection with the constraint of limited bandwidth [2].

Fig. 1. Distribution of hexagonal cells, base stations and mobile stations around the coverage area of 1 km²

An integrated cellular network with fixed ad hoc relays has been considered in recent years [3] to improve the performance of the system by distributing the load equally among different neighboring BS(s). The aim has been to avoid congestion among individual BS(s) while keeping the total system capacity at a constant level. A hybrid network model with full mobility for the wireless terminals in the ad hoc mode has generated great interest in the field of research. In recent studies, [4] [5], the authors considered the different routing strategies and studied the scaling behavior of the throughput capacity of a hybrid network.

In this paper, the short range and long range communication of the system are considered and the system performance is analyzed. Section II introduces the hybrid wireless network model and explains in detail the mathematical analysis for the reuse efficiency and the traffic served with regard to the exclusion range distance. Section III explains the simulation setup; the range selection of the key parameters involved and then evaluates the served traffic of the hybrid network. Concluding remarks are in Section IV.

II. HYBRID WIRELESS NETWORK

A. Network model

A Hybrid wireless network is composed of two components. First, an ad hoc network containing the mobile stations (MS(s)) and second, a network of base stations BS(s). The MS(s) are assumed to be uniformly distributed in the given area. A common wireless channel is being shared by all the...
MS(s) and BS(s) for MS - MS, MS - BS and BS - MS communication. Fig. 1 shows the distribution of BS(s), 14 hexagonal cells and 100 MS(s) over the given area. The figure indicates the mechanism of ad hoc cellular communication between two pairs of communicating MS(s). The mode of communication between two MS(s) is selected based on their separation distance. Data transmission over the wireless channel takes place using TDMA and TDD. A node cannot transmit and receive data simultaneously and also, it can receive data from only one of the other MS(s) at any time.

In order to combat the interference coming from other node pairs, an exclusion range around each receiver is defined. Any potential transmitter of another link should be prevented from transmitting on the same channel (i.e., TS) at the same time within the exclusion range. Usually, the exclusion range is set to be greater than the maximum transmission range which should ensure that the carrier-to-interference ratio at the channel is greater than some pre-defined, QoS-dependent value. In [9], a media access control (MAC) protocol is proposed which realizes this exclusion range mechanism for an arbitrary propagation scenario by exploiting the channel reciprocity in TDD.

A generalized multi hop scenario for the ad hoc mode is shown in Fig. 2 where the number of hops between the source, P', and destination, Q, is M. Fig. 2 also shows a single hop connection between P and Q along with the exclusion range (dark grey area) defined around the receiving node. The transmission range (light grey area) is given by d in the multi hop case and d' = Md in the single hop case. In both cases, the distance between the transmitting and the receiving node is d'. The exclusion range ratio is k and defined as the percentage of which the transmission ranges exceeds the exclusion range. In the following subsection it is aimed at calculating the reuse efficiency in such a multi hop system, and as a consequence a factor defined as the multi hop reuse gain will be introduced.

B. System Analysis

1) Deterministic model: Multi hop networks aim to maximize the reuse efficiency. The reuse factor for any time slot is determined by the exclusion range around the receiver. In the multi hop scenario (case 1 in Fig. 2) a TS of duration, t_{TS}, is subdivided into M subslots each of which is used for one of the M hops. Thereby, orthogonality in the data transmission from P to Q is maintained. Since a pure TDMA air-interface is considered the capacity per link is proportional to the time duration used for transmission. The capacity per hop in the multi hop case is reduced by a factor M, but each subslot can be reused more often than one entire TS in the case of the single hop scenario (case 2 in Fig. 2). This results in a trade-off to be calculated in the following. For this purpose a traffic density parameter is defined as the ratio of the time duration used for data transmission per hop t_{TS} to the area of the exclusion range, B per hop. For the multi hop (mh) scenario (case 1), this results in, δ_{mh} = \frac{t_{TS}}{B M (1+k)}, and for the single hop (sh) scenario (case 2) this results in, δ_{sh} = \frac{t_{TS}}{B d' (1+k)}.

A measure for the channel reuse efficiency can be defined as the ratio of the traffic density to the area 'occupied' for data transmission from P to Q. For the multi hop scenario, the total area 'occupied' for transmission can be approximated by a rectangle (see Fig. 2). The corresponding reuse efficiency can be calculated as follows,

\[ \eta_{mh} = \frac{M \pi d'^2 (1+k)^2}{t_{TS} d'(2d(1+k) + (M-2)d) / 2d(1+k)} \]

(1)

For the single hop scenario, the area 'occupied' for the transmission is equivalent to the area defined by the exclusion range, hence \( \eta_{sh} = \frac{1}{\delta_{sh}} \). A direct comparison of the reuse efficiency of the single hop and the multi hop scenario yields:

\[ \eta = \frac{\eta_{mh}}{\eta_{sh}} = \frac{1}{\frac{t_{TS}}{B M d'} + \frac{2(M-2)d}{2d(1+k)}} \]

(2)

(3)

Thus, it can be seen that the presence of a multi hop component in the system increases the reuse efficiency. A calculation of the limit for an infinite number of hops results in:

\[ \lim_{M \to \infty} \eta(M) = \frac{\pi(1+k)}{2} \]

(4)

From the above equations, it can be seen that the multi hop reuse gain increases with an increase in the exclusion range. This is a significant result in the light of the following. It generally holds that the larger the exclusion range, the higher

\[ \lim_{M \to \infty} \eta(M) = \frac{\pi(1+k)}{2} \]

(4)
the expected SNR at the receiver. This means that in the cases where a high SNR is required, primarily high data rate packet services, the multi hop scenario clearly works in favor of achieving high spectral efficiencies. Fig. 3 plots the reuse efficiency obtained for varying number of hops and also the upper bound as is derived in eqn. (4). It can be observed from Fig. 3 that for different exclusion ranges, the multi hop reuse gain obtained with 4 hops is nearly 90% of that obtained with an infinite number of hops, hence it is more efficient to use a multi hop network with a maximum of 5 hops for a hybrid ad hoc cellular structure.

From the simple deterministic model, it has been found that the multi hop mode can utilize a multi hop reuse gain. However, in order to be able to exploit this gain, a certain TS granularity is required. In the next subsection, a statistical model is developed to calculate the number of supported hops when increasing the number of TS(s) in the system.

2) Statistical model: The complementary cdf (cumulative distribution function) for X, the number of simultaneous hops that can be served by a single TS when applying the exclusion range concept can be found as,

\[
p(X > x) = \frac{|A - xB(1 + \tau)|}{A}
\]  

This can also be written as:

\[
p(X > x) = 1 - xF,
\]  

with,

\[
F = B(1 + \tau)/A,
\]

where A is the total coverage area, B is the area with radius being the exclusion range and \( \tau \) is the overlapping factor between two exclusion range areas (because of assuming a full duplex link). F represents the fraction of a normalized area which is required, due to the interference constraint, for a single communication hop. The calculation of the area of an ellipse (because of overlapping of areas between the two circles formed by the exclusion ranges) gives the overlapping factor \( \tau \).

\[
\tau = \frac{(\pi/4) (2kr[r + 2kr] - (2kr)^2)}{(\pi/4) (2kr)^2}
\]  

\[
= \frac{1}{2k},
\]

where \( r \) is the transmission range equal to the cell radius. It is assumed that the MS(s) in the multi hop mode are at the maximum possible distance of the transmission range equal to cell radius \( r \) [6]. With this assumption a lower bound of the number of served links is obtained given that the separation distance between multi hop MS(s) is always less than the maximum possible transmission range. Hence, the maximum number of links that can be served in any TS is \( L_M = \left\lfloor \frac{1}{F} \right\rfloor \), provided that the maximum transmission range is always used. From eqn. (6) it can be found that the number of hops served per TS is uniformly distributed. It is assumed that every TS can serve at least one hop. This results in a probability density (pdf) given by Fig. 4. Moreover, TS(s) can be used independently from each other. Therefore, the number of hops for, \( T \), TS(s) are independent identically distributed (i.i.d.). For multiple number of TS(s), \( T \), per frame the cdf for the total number of hops that can be served can be found as:

\[
P(X \leq x) = \frac{1}{L_M} C(x),
\]

where \( C(x) \) is the number of all possible combinations of the distribution of hops with the condition, \( \sum_{x=1}^{\infty} n_x = x \), subject to constraint, \( n_x \leq L_M \), where \( n_x \) is the instantaneous number of hops per single TS, \( x \). The closed form expression for \( C(x) \) is mathematically derived, starting from the above mentioned two conditions. For this purpose, an auxiliary polynomial function \( f(t) \) is introduced. The polynomial function \( f(t) \) is obtained as:

\[
f(t) = \frac{1 + t + t^2 + \ldots + t^{L_M-1}}{1-t}
\]  

\[
= \frac{1-t^{L_M}}{1-t} \times \frac{1}{1-t}
\]  

\[
= \sum_{j=0}^{\infty} (-1)^j \left( \begin{array}{c} T \\ j \end{array} \right) t^{\frac{j}{L_M}} \sum_{n=0}^{\infty} \left( \begin{array}{c} T + n \\ T \end{array} \right) t^n
\]  

\[
= \sum_{j=0}^{L_M} \sum_{n=0}^{\infty} (-1)^j \left( \begin{array}{c} T \\ j \end{array} \right) \left( \begin{array}{c} T + n \\ T \end{array} \right) t^{\frac{j}{L_M} + n}
\]

The function \( C(x) \) is the coefficient of the polynomial term \( t^x \). This could be obtained by substituting \( x = n + \frac{j}{L_M} \) and reducing the double summation to a single sum. Given the fact that for any TS, there is at least one communicating hop, it holds that \( x \geq T \). Hence, the coefficient \( C(x) \) could be written in a generalized form as

\[
C(x) = \sum_{j=0}^{L_M} (-1)^j \left( \begin{array}{c} T \\ j \end{array} \right) \left( x - \frac{j}{L_M} \right)
\]
This closed form solution is further validated by an approximation. It is assumed that every TS can serve at least one hop and that the number of users are uniformly distributed in space. As a consequence, the pdf of the number of links that can be served by one TS is uniform provided that the service area is limited. The number of links that can be served depends on the actual distance between the MS(s) and on the exclusion range distance. The variance of the rectangular function obtained from the uniform distribution (Fig. 4) is finite and, in general, more than 10 TS per frame are considered. Therefore, the central limit theorem can be used to simplify eqn. (9). With this simplification, the total number of served hops (summation over all TS(s) per frame) can be approximated by a Gaussian pdf [7]. The mean and the variance for, $T$, TS(s) is given by,

$$E[X] = \frac{T(L_M + 1)}{2} \text{,} \quad (12)$$

and

$$\text{Var}[X] = \frac{T(L_M - 1)^2}{12} \text{.} \quad (13)$$

It can be seen from eqn. (12) and eqn. (13) that the expected value as well as the variance increases linearly with the number of TS(s) available.

### III. PERFORMANCE ANALYSIS

In this paper, a hexagonal cellular structure with a coverage area of 1 km² is considered such that the distance between BS(s) = 300m resulting in 14 BS(s) within the considered area. The number of communication links which want to exchange data is fixed and the maximum distance between two link nodes is assigned to be equal to cell radius, $r = 173.2$ m. A perfect scheduling algorithm is considered such that the locations of all nodes and all traffic demands are known [8]. The nodes are assumed to be stationary over the time frame considered. The system model is simulated and number of successful communication links (complete transmission chain from source to destination) is used as a performance measure. Note that, if it is assumed that the packet duration equals the TS duration, the results can also be interpreted as the total throughput capacity (in packets) of the system.

In Fig. 5, results are presented for the case where the exclusion range is twice the transmission range and for different TS(s) allotted. The number of links is assumed to be 50. As the number of TS(s) is increased, more number of node pairs can communicate in a given frame and hence at the high end of the TS(s), the Gaussian function attains a peak value indicating that nearly all the node pairs are able to communicate. From Fig. 6 it can be seen that, as expected, the mean and the variance of the pdf(s) increases nearly in a linear fashion with an increase in the TS(s) allotted. In this context, the most noticeable result is the increase of the variance which can be interpreted as a measure for the reusability of a TS. Moreover, the slope of the graphs in Fig. 6 rise with a reduction in the value of the exclusion range, i.e. reducing the exclusion range from 1.6 times the transmission range to 1.3 times, this approximately enables a 30 % increase in the communicating links assuming, for example, 60 TS(s). Fig. 6 also provides a comparison between the analytical calculation of mean and variance and the simulation. As can be seen from Fig. 6, the analytical results matches very closely with that obtained from the simulations.

Fig. 7 and Fig. 8 give the cumulative distribution function (cdf) of the number of hops for varying TS(s). As can be seen, the cdf’s obtained from the analysis serve as a lower bound as compared to those obtained from simulations. As
discussed earlier, this is because, in the analysis, it is assumed that the multi hop MS(s) are always located at the maximum transmission range equal to the cell radius, \( r \), which restricts the maximum number of communicating links per TS to \( \frac{1}{r} \).

In practical scenarios, the multi hop mobiles are uniformly distributed and are always at a certain distance less than the cell radius, \( r \). This results into an greater number of total hops in the system than obtained from the analysis. It is, therefore, clear that as the number of TS(s) increase, the difference between the results from the analytical model and results from simulation increases. This effect could be clearly observed in Fig. 7 for TS=50 and also for TS=60 and TS=70 where the exclusion range is 1.6 times the transmission range. However, for a lower exclusion range (1.3 times the transmission range, as shown in Fig. 8), this effect though observed at TS=50 is not significant for TS=60 and TS=70 because in the simulation the likelihood rises that all communication links (50) are served with the increasing number of resources in the system. This saturation effect results in the convergence of the simulation results and analysis results for a high number of TS(s). Notice that the validity of the lower bound calculation remains untouched by this observation.

IV. CONCLUSION

A hybrid cellular and ad hoc network has been analyzed in which interference is controlled by an exclusion range concept. In this paper, it has been found that the ad hoc component can benefit from a multi hop reuse gain as compared to a single hop transmission which corresponds to an increased spectral efficiency. An asymptotic limit of this gain factor is reached as the number of hops is increased to infinity. However, it can be found that beyond 5 hops the relative gain is only marginal. This suggests a reduction of the number of hops in a hybrid network. Links which would require more than 5 hops, for example, could easily be diverted to the cellular mode. In order to be able to exploit the multi hop reuse gain a certain number of TS(s) are required. It was found that with an increasing number of TS(s) the mean and the variance of the pdf of the number of hops increased almost linearly. In particular, the linear increase of the variance is an important result as it can be interpreted as a measure for the reusability of a TS which might be exploited by intelligent resource allocation algorithms. In addition, a lower bound of the number of supported hops in the network – which for certain conditions is equivalent to the number of packets transmitted – is calculated. Lastly, the analytical results and the simulation results showed a good match.

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REFERENCES


Throughput Capacity for 2-Hop Hybrid Cellular Networks

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Abstract—Multi-hop wireless networks have gained considerable importance in recent years because of their ability to eliminate dead zones, to provide increased capacity and high peak-to-average data rate as compared to an infrastructure based pure cellular network. In this paper, the capacity of 2-hop hybrid wireless network is analyzed and compared to a single hop design. A mathematical model for the capacity of a general multihop cellular network is initially developed and the benefits obtained from a 2-hop system are then studied. This is then re-modeled to form a cluster based 2-hop hybrid wireless network. It has been observed that this cluster based architecture provides a superior performance over the general 2-hop cellular design. Moreover, the capacity gain for the 2-hop network (calculated with respect to the single hop system), scales with the number of BS(s). The gain for the cluster based model is maximum for a sparse network of BS(s) (2.1 for a network with 7 BS(s)) and decreases with increasing number of BS(s) (1.85 for 150 BS(s)). Hence, in a wireless network with a sparse-to-medium number of BS(s), the cluster based 2-hop hybrid network with the MS as relays is best suited to improve the capacity performance of the network.

I. INTRODUCTION

The field of multihop ad hoc networking is evolving amidst an explosive growth in the magnitude and diversity of wireless communications. As compared to the cellular networks, multihop ad hoc networking is a relatively new field and there exists a large number of dimensions to the design space of multihop networks. Such networks are dynamic in nature, since the network topology changes as devices move in space, as new devices join the region, others leave and as devices turn on and off. In today’s era of high capacity and increased data rate communication, single-hop cellular networks as a stand alone technology would be handicapped by numerous limitations viz: inability to cover dead zones and to serve hotspots; high attenuation of signals, etc. [1]. A multihop network model with full mobility for the wireless terminals in the ad hoc mode has generated great interest in the field of research. In recent years, there has been intensive studies [2], [3] on the scaling behavior of the throughput capacity for a multihop network model. A significant result reported by Gupta and Kumar in [2] is that in a point to point network with a uniform distribution of traffic, the aggregated capacity of an ad hoc system with r nodes scales as $O(1/\sqrt{r})$. The authors in [3] apply the same physical model including the exclusion range concept introduced in [2] to a hybrid wireless network wherein the base station (BS) based infrastructure mode and ad hoc mode exist simultaneously. In [4], capacity is studied under a different traffic pattern and the authors presented specific criteria and key parameters on which the capacity would scale. It has been shown in [5] that for any practical application, the obtainable reuse efficiency does not gain significantly when the number of multiple hops is greater than five. In [6], the authors proposed a scheme that takes advantage of the mobility of the nodes. By allowing only two hop relaying, the scheme achieves a high aggregated capacity but at the cost of unbounded buffer and delay requirement. But till now, and to the best knowledge of the authors, there has been no comprehensive work on the obtainable system capacity for a specific 2-hop hybrid cellular model.

In this paper, the capacity analysis for a general multi-hop cellular system is carried out and the dependence of system capacity on the number of multiple hops per link, $M$, is studied. The capacity gain obtained from a 2-hop design over a single hop cellular model is analyzed and compared with that obtained when a higher order multihop architecture ($M > 2$) is used. A specific cluster based architecture for a 2-hop hybrid cellular network is then introduced and the benefits of such a model are then described. The organization of the paper is as follows. The description of the multi-hop network model and the complete capacity analysis are carried out in Section II. Section III explains the cluster based architecture for the 2-hop hybrid cellular model and presents the simulation results. Concluding remarks are found in Section IV.

II. MULTI-HOP NETWORK MODEL

A. System Model

A mobile coverage area comprising of hexagonal cellular structure is considered, as shown in Fig. 1. The coverage area is constant and has a radius, $R_r$ while each of the hexagonal cells has a radius, $r$. While analyzing the system model, the area is wrapped around in order to eliminate cell boundary effects. Fig. 2 and Fig. 3 shows a general intra-cell and an inter-cell multihop wireless model. Each node has a randomly chosen destination with which it wishes to communicate. If the source and destination nodes are within the same cell or in adjacent cells, they communicate with each other in an ad hoc mode, without transmitting the data through the
This general multihop model reduces the traffic in the BS and hence results in a superior performance as compared to the scenario where the communication between source and destination nodes always takes place via BS [7]. All the nodes are assumed to be homogeneous, i.e. all transmissions employ the same power. The number of base stations, $s$, in the system is proportional to the size of the hexagonal tessellation. For an hexagonal cell of radius $r$, the area of a single cell is given by $A_{\text{cell}} = \sqrt{3}r^2$. The number of BS(s) in the system is therefore given by $s = \pi R^2 / A_{\text{cell}}$. The distribution of the MS is given by the function: $p(r) = 2rR^2$. The distance between the desired transmitting and receiving entity is given by $d_{\text{int}}$ and the distance between a desired receiver and an unintentional transmitting entity is written as $d_{\text{dist}}$. The maximum distance of an interfering source is the radius, $R$, of the coverage area. The mean distance of an interfering source is the radius, $R$, of the coverage area. The mean interfering distance for any MS is given by $I_{\text{dist}}$, and $k$ is the exclusion range factor, defined as the radius of the exclusion range circle to the transmission range circle. The area of one exclusion range circle is given by $B = \pi (kd_c)^2$. Therefore the number of communicating hops, $N_k$, for any instant of time is defined as the ratio of the total coverage area to the area occupied by one exclusion range circle; i.e., $N_k = A / B = (R/(kd_c))^2$. For a $M$-hop system, the number of communicating links is given by $N = N_k / M$.

In this paper, an exclusion range of twice the transmission range, i.e. $k = 2$ is considered, as is done in [5]. This would result in simultaneous communication of alternate hops for any link in a multihop system. Hence, the number of simultaneously communicating hops per link is $M/2$. Therefore, for a TDMA scheme, the TS (timeslot) is divided into only 2 minislots. A general multihop communication model (between source node, $P$ and destination node, $Q$) for $k = 2$ and the corresponding TDMA frame (for the multihop network with $M$ hops per link) is shown in Fig. 4. For a single hop system, the data is transmitted from $P$ to $Q$ over the entire TS period, but for a multihop system with an exclusion range factor of $k = 2$, each of the multiple hops transmits for only half the TS period. Hence the effective bandwidth for a multihop system is reduced by a factor 2 which also reflects in the system capacity. The capacity is then calculated using Shannon’s capacity equation which relates the system capacity to the carrier to interference ratio ($C/I$) and the number of links, $N$.

For a single hop system,

$$C_{\text{ap}} = N \log_2(C/I + 1) \text{ bps/Hz} \quad (1)$$

whereas for a multihop system with $k = 2$, this would be

$$C_{\text{ap}} = N/2 \log_2(C/I + 1) \text{ bps/Hz} \quad (2)$$

### B. Capacity Analysis for a General Multi Hop System

The mean distance of an interferer is calculated as:

$$I_{\text{dist}} = E[d_{\text{dist}}] = \int_{kd_c}^{R} r p(r)dr = \int_{kd_c}^{R} 2r \left( \frac{2r}{R^2} \right) dr \quad (3)$$

This results in,

$$I_{\text{dist}} = \frac{2}{3R^2} \left( R^3 - (2kd_c)^3 \right) \quad (4)$$
The received carrier and interference powers for any receiving MS is found using a general path loss model,

\[
P_{r\text{car}} = P_r - (\xi + 10\alpha \log_{10}(d_c)) \text{dB} \quad (6)
\]

\[
P_{r\text{int}} = P_r - (\xi + 10\alpha \log_{10}(d_{int})) \text{dB} \quad (7)
\]

where \(\xi\) is a constant, \(P_r\) is the transmit power and \(\alpha\) is the pathloss exponent. Therefore the carrier-to-interference ratio, \(C/\Gamma\), is given by

\[
\frac{C}{\Gamma} = \frac{10P_r}{10^{\xi + 10\alpha \log_{10}(d_c)/10}}
\]

Substitution of values for \(E_N\) and \(I_{\text{dist}}\) results in the following equation for \(C/\Gamma\).

\[
\frac{C}{\Gamma} = 2 \left( \frac{2N}{M^2N} \left[ R^3 - (kR^3)^2 \right] \right)^{\alpha} \quad (9)
\]

A general scenario where the radius of the hexagonal cell is an arbitrary fraction, \(m\), of the radius of the coverage area \((r = R/m)\) where \(m\) is any value greater than 1 is very difficult to analyze mathematically. The derivation of the capacity equation for such a general situation is subject to future work. In the corresponding section, two specific scenarios for the radius of the hexagonal cell \(r = R/3\) and \(r = R/4\) are considered and the capacity equations are derived accordingly. For \(r = R/3\), the total number of cells in the coverage area are, \(s = 34\) BS(s). For a general multihop system with \(M\) hops per link, the transmission distance, \(d_c\), is a fractional value of the hexagonal cell radius, \(r\). This function is expressed in a general form as: transmission distance, \(d_c = fR/3\) where \(f\) could be also be termed as the fractional distance factor of the transmission range and is equal to the reciprocal of the number of multiple hops in the cellular structure \((f = 1/M)\). For mathematical convenience, the capacity equations are derived in terms of \(f\). Substituting eqn. (9) into eqn. (2), the capacity obtained for the multihop system \((M > 1)\) is written as

\[
C_{\text{ap}} = \frac{1}{2} \times \frac{3}{4} \frac{1}{f^2} \log_2 \left( \frac{\left(2/f \left(1-(2f/3)^2\right)^{\alpha} \right)^2 f^2 + 1}{9} \right) \quad (10)
\]

For a single hop system, \(f = 1\). Also, there would be no factor \(\frac{1}{8}\) in the eqn. (10). The \(C/\Gamma\) and capacity equations are plotted in Fig. 5 and Fig. 6 respectively for various number of hops per link, between the transmitter and receiver for different values of path loss exponent \(\alpha\). The results show that the capacity increases with increasing number of hops per link. This is primarily because of the reduced transmission distance in a multihop cellular network. Consequently the exclusion range distance is also reduced and hence more number of MS(s) could communicate at any time instant. At the same time, the increase in capacity from 1-hop to 2-hop is significantly higher as compared to the increase from 2 to a higher number of hops \((M > 2)\); i.e., the increase in slope for the capacity reduces with increasing number of hops. As seen in Fig. 6, for a path loss exponent of \(\alpha = 4\), the capacity obtained for a single hop cellular system is 1.7 bps/Hz which increases to 2.35 bps/Hz for a 2-hop hybrid cellular network; i.e., 50\% increase in the capacity is obtained for the 2-hop architecture. Then the slope for the capacity increase starts saturating and for a 10-hop system, a theoretical capacity gain of 4.75 bps/Hz is attained. However in a practical system such a realization would result in an excessive buffer requirement for each of the relay nodes and an unbounded delay between the source and destination.

In order to study the change in system behavior because of a variation in the number of BS(s) in the system, a different scenario is considered where the relation between the radius of the hexagonal cell and the radius of the coverage area is given by \(r = R/4\). The number of BS(s) for this realization would be \(s = 62\). A similar analysis as above for the \(C/\Gamma\) and the capacity for a multihop system \((M > 1)\) would result in the following:

\[
C_{\text{ap}} = \frac{1}{2} \times \frac{4}{3} \frac{4}{f^2} \log_2 \left( \frac{\left(\left(4/3f \left(1-(2f/3)^2\right)^{\alpha} \right)^2 f^2 + 1\right)}{8} \right) \quad (11)
\]

Note that there would be no factor \(\frac{1}{8}\) in the relation for the single hop case. Eqn. (11) is plotted in Fig. 7. For \(\alpha = 4\), the capacity attained for the single-hop scenario is 1.9 bps/Hz.
whereas this increases to 2.7 bps/Hz for a 2-hop cellular network; i.e., a 42% increase for the 2-hop cellular model over the single-hop architecture. The capacity achieved for a corresponding 10-hop system is only 5.15 bps/Hz; i.e., less than double the capacity attained for the 2-hop model.

A comparison of Fig. 6 and Fig. 7 for the two cases of $s = 34$ and $s = 62$ reveals that, irrespective of the path loss exponent, the capacity for a single hop and the 2-hop cellular architecture increases with an increase in the number of BS(s). This is clearly seen in Fig. 8 where the simulation results for the system capacity is plotted for different number of BS(s). However, the rate of increase for the 2-hop cellular model is not as high as the rate for the single hop cellular network. This results in a scenario where the capacity gain for a 2-hop cellular model over the single hop architecture decreases noticeably with an increase in the number of BS(s). This result is depicted in Fig. 10 where the capacity gain for a general 2-hop hybrid architecture over a single hop cellular network is plotted for different number of BS(s). This could be explained from the fact that with an increase in the number of BS(s), the capacity of the single hop cellular network increases prominently as is also pointed out in [3]. However, in the case of a 2-hop network, the relay MS is selected on the basis of a link which has the least path loss. Hence, the presence of relay nodes reduces the significance of the increase in BS(s) in the 2-hop cellular model. In the next section, a cluster based architecture for a 2-hop hybrid cellular network is introduced and explained in detail. Also, the performance benefits of this cluster based design over the general 2-hop cellular network in terms of the system throughput and the effect of the number of BS(s) in the system is studied.

III. CLUSTER BASED 2-HOP HYBRID CELLULAR NETWORK

In this section, a new design concept is introduced which is termed as a cluster based model for a 2-hop hybrid cellular network. In this scheme, all MS(s) communicate to their BS in either 1 or 2 hops. A single cell scenario depicting the design concept of
this 2-hop hybrid cellular architecture is shown in Fig. 9. A selected number of MS(s) (6 as in the case of Fig. 9), located at the distance of half the cell radius and having least path loss from the BS are selected as gateways (GTW). The MS located beyond half the cell radius form a cluster with the nearest GTW as the cluster head. All the MS(s) within the cluster communicate to the BS in two hops. In the 1st hop, the MS communicates to the cluster head MS (i.e., the GTW) and in the 2nd hop, the GTW communicates to the BS. In the case when the MS is located within a distance of half the cell radius from the BS, it communicates to the BS directly in 1 hop. As can be seen from Fig. 9, having \( k = 2 \) always results in the same resource to be used twice (diametrically opposite locations with regard to the BS(s)) within the same cell. This improves the re-usability of the resources for this model and is a very significant result in case of a multi cell scenario when the interference from other cells are quite high. Monte-Carlo simulations are carried out and the capacity gain results for such a cluster based 2-hop hybrid architecture are plotted in Fig. 10. These results are then compared with the gain obtained from a general 2-hop cellular network. The cluster based 2-hop cellular network provides a capacity gain of 2.0 over the single hop cellular design, when the number of BS(s) are 28. But the gain obtained with a general 2-hop cellular model over the same single-hop design for the same number of BS(s) is only 1.6. Hence, the capacity gain for the cluster based 2-hop model explained in this section provides an improved performance over the general 2-hop cellular network model. Also, as is the case for a general 2-hop model, the capacity gain for the cluster based 2-hop architecture decreases with an increasing number of BS(s).

IV. CONCLUSIONS

The capacity analysis for a general multihop system shows an increase in capacity over a single hop network model. An increase in capacity gain of up to 65% is observed for a 2-hop cellular model over the single hop design. But this capacity gain saturates for increasing number of hops. A cluster based model for a 2-hop hybrid cellular network is introduced where the MS(s) located beyond the cell radius form a cluster and communicate to the BS in 2-hops through a GTW. Initial results show that such a cluster based 2-hop hybrid design results in an improved performance over the general 2-hop model. Another intuitive, but significant result is that, a 2-hop hybrid network design is more efficient in an environment with a sparse network of BS(s). With an ever increasing demand for high throughput capacity and with more and more users joining the system, it is very costly to have a dense network of BS(s). A 2-hop cellular model provides a highly efficient solution for high data rates and increased throughput capacity. Future work will focus on the development of an analytical capacity model of the cluster based 2-hop architecture.

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Time Slot Partitioning and Random Data Hopping for TDD based Multihop Wireless Networks

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Abstract—A multihop ad hoc wireless network with an interference avoidance model is analyzed for a time division duplex (TDD) air-interface. In accordance with the non-interference protocol, an exclusion region is defined around every communicating receiver wherein no other node except the desired transmitter can transmit. In a network comprising finite coverage area, the position of the communicating nodes determine the number of simultaneous communicating pairs and hence the overall system throughput. A novel random data hopping technique for a time slot (TS) partitioned system is proposed in this paper.

In this technique, the number of TS(s) in the TDMA frame is increased by reducing the granularity of each TS, and the time instant over which the transmission pairs of the end-to-end link communicate is varied randomly over these TS(s). This randomness in the selection of communicating pairs, in a system with high number of TS(s) per frame, results in an increased system throughput when compared to a multihop network with no time slot partitioning.

Keywords: multihop ad hoc wireless network, interference avoidance model, exclusion region, time slot partitioning, random data hopping.

I. INTRODUCTION

The field of multihop ad hoc networking is evolving amid an explosive growth in the magnitude and diversity of wireless communications. As compared to the cellular networks, multihop ad hoc networking is a relatively new field and there exists a large number of dimensions to the design space of multihop networks. The nature of the wireless channel, the lack of predetermined topology and mainly the lack of a centralized server like a base station, as in the cellular network creates many challenging research topics in the area of multihop ad hoc networks [1]. In recent years, there has been intensive studies [2, 3] on the scaling behavior of the throughput capacity for a multihop network model. The problem of finding the optimal system capacity for a given set of source and destination nodes in a multihop wireless network under the interference avoidance model is found to be NP-hard [4]. It has been shown in [5] that the exclusion range concept of the interference avoidance model that has been introduced in the landmark paper of Gupta and Kumar [2] results in a more restrictive bound on the system throughput in comparison to the Physical Model that is based on the signal-to-interference ratio calculations. Hence, the interference avoidance protocol model is considered in the analysis and system design throughout this paper.

There are several key parameters in the design of multihop wireless ad hoc network that affect the behavior of the system throughputs, for e.g., the routing protocols and algorithms, link adaptation, time slot allocation, node distribution, etc. Lately, there has been several studies on the time slot allocation (TSA) for the TDD mode [6–8], in a cellular network. It has been recently shown in [8] that a region-based partitioning of the time slot minimizes the co-channel interference in case of a multi-cellular environment. In this study, however, the focus has been to analyze the effect of a general variation of the TS granularity on the average system throughput for a time slot partitioned system for a multihop wireless ad hoc network. The total number of TS(s) per frame, and the corresponding analytical method for the time slot partitioned system is explained in Section III along with the simulation results. Concluding remarks are found in Section IV.

II. MULTIHOP WIRELESS NETWORK

A. System Model

The wireless network consists of $N$ ad hoc mobile stations (MS(s)) uniformly distributed in a square of unit coverage area ($A = 1 \text{ km}^2$). These mobile terminals act as either
source nodes, destination nodes, or as mobile relays. At any time instant, each MS function either as a transmitter or as a receiver. In this paper, the end-to-end communication between the source node and destination node is termed as ‘link’, and any transmitter and receiver that communicates with each other is termed as ‘pair’. Hence, in a multihop system, a communication link would consist of several communication pairs. A typical multihop scenario is shown in Fig. 1 wherein there are 8 ad hoc nodes (n1, ..., n8) that are randomly distributed. In case of a communication over link n1 – n4, the data is sent in 3 hops across the pairs n1 – n2, n2 – n3 and n3 – n4. The same packet could also be sent over n1 – n3 and n3 – n4, which would then consist of only 2 communicating pairs, or directly across n1 – n4 in a single hop fashion. However, use of multiple hops results in lower transmission power requirement and is shown to have several benefits over the single hop direct communication [9, 10]. In a precursor result, [11], the critical range, and the average system throughput is derived in the following subsection.

In the multihop wireless network, the MS(s) are uniformly distributed in the given coverage area. For any TS, the instantaneous number of simultaneously communicating pairs is defined around the receiver (or an exclusion region) is defined around every communicating receiver such that no other transmitter apart from the desired one transmits in that region. As shown in Fig. 1, an exclusion region circle over the transmission distance, n2 – n3, is given by the ratio, Δ. The area of one exclusion region circle is given by

\[ B = \pi \left( \left(1 + \Delta d_i \right)^2 \right) \]

where \( d_i \) is the transmission distance of the ad hoc nodes. In a precursor result, [11], the critical range, and the average system throughput is derived in the following subsection.

### B. C/I and Average System Throughput for a General Multihop System

In the multihop wireless network, the MS(s) are uniformly distributed in the given coverage area. For any TS, the instantaneous number of simultaneously communicating pairs

\[ \sum_{j \neq i,j \neq l} \left| \log_{10} \frac{P_t}{10} \right| \]

which simplifies to

\[ \gamma_{it} = \frac{d_{int,ij}^{-\alpha}}{\sum_{j=1,j \neq i}^{N} d_{int,ij}^{-\alpha}} \]

where \( d_{int,ij} \) is the distance between the receiver of the \( i \)th communicating pair and the transmitter of the \( j \)th communicating pair. The distance between a desired receiver and an unintentional transmitting entity is given by \( d_{int,ij} \). The expression for \( \gamma_{it} \) can be further simplified by assuming that all the interfering nodes are at the circumference of the exclusion region itself. This models the worst-case interference scenario. Under this assumption, the distance of all the transmitting interferers from the receiver of the \( i \)th communicating pair is \( d_{int,ij} = (1 + \Delta) d_i \). The carrier-to-interference ratio, \( \gamma_{it} \), written in eqn. (3) can therefore be lower bounded as follows:

\[ \gamma_{it} \geq \frac{(1 + \Delta)^{\alpha}}{n_t - 1} \quad \forall \ i \in \{1, 2, ..., n_t\} \]

The average system throughput for the wireless network is calculated from the expected values of \( \gamma_{it} \) and \( n_t \) using the

- **Fig. 2**: TDMA frame with different TS(s) for a multihop communication system in the system, \( n_t \), is a random variable that depends on the location of the communicating pairs. The upper bound on the number of simultaneously communicating pairs for any TS, that can only be reached asymptotically can be calculated as

\[ L_M = \lfloor A/B \rfloor \]

In a practical scenario, the condition for the number of simultaneously communicating pairs for any TS is

\[ 1 \leq n_t \leq L_M \]

The power received at the receiver of any communication pair is found from a generic pathloss model as:

\[ P_r = P_t - (k_1 + 10 \alpha \log_{10}(d)) \quad \text{dB} \]

where \( P_t \) is the transmit power, \( \alpha \) is the pathloss exponent and \( k_1 \) is a constant. A constant transmit power is assumed for all the nodes in the system. For each of the \( n_t \) simultaneously communicating pairs at any time slot, \( t \), the remaining \( n_t - 1 \) simultaneous communicating pairs act as interferers. Therefore the carrier-to-interference ratio, \( \gamma_{it} \), of the \( i \)th communicating pair at \( t \)th TS is given by

\[ \gamma_{it} = \frac{10 \log_{10}(P_t/10) - k_1 - 10 \alpha \log_{10}(d_{int,ij})}{10 \log_{10}(P_t/10) - k_1 - 10 \alpha \log_{10}(d_{int,ij})} \]

\[ \sum_{j=1,j \neq i}^{N} \frac{d_{int,ij}^{-\alpha}}{d_{int,ij}^{-\alpha}} \]

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\[ \sum_{j=1,j \neq i}^{N} \frac{d_{int,ij}^{-\alpha}}{d_{int,ij}^{-\alpha}} \]

The average system throughput for the wireless network is calculated from the expected values of \( \gamma_{it} \) and \( n_t \) using the
It should be noted that the optimum system throughput of the multihop wireless network is an open problem [12] and that the expression for the system throughput given in eqn. (5) is suboptimal. However, the main aim of this analysis has been to derive an expression that would reflect the dependence of the number of communicating pairs and the average system throughput with the number of TS(s) per frame.

The cdf of the total number of communicating pairs given in eqn. (6) is plotted in Fig. 3. As seen in Fig. 3, the number of communicating pairs increases proportionally with the number of TS(s) in the time frame. This is because, with increasing number of TS(s) the duration of each TS is reduced. Hence, as shown in Fig. 2, in order to transmit the same amount of data between any communicating pair, the given pair has to transmit over increased number of TS(s). Therefore, from a system design point of view, the communication has to take place across more number of pairs in order to transmit the same amount of data in the given time frame. As explained in the next section, an increased number of communicating pairs provides a basis for introducing a random component while selecting the simultaneously communicating pairs in the time slot partitioned system.

### III. Random Data Hopping Technique

**A. Underlying Concept**

In order to explain the concept of random data hopping, consider a simple multihop ad hoc system with 2 communication links as shown in Fig. 1. For the ease of understanding, a TDMA frame with 2 slots is considered. Suppose at the $1^{st}$ TS the transmission pair $n_1 - n_2$ is selected for communication. In accordance with the interference avoidance model, the

- **Parameters**
  - **Coverage Area**
  - **4 km$^2$**
  - **No. of MS(s)**
  - **500**
  - **Duration of time frame**
  - **100 ms**
  - **Minimum no. of TS(s) per frame**
  - **5**
  - **Maximum no. of partitions per TS**
  - **20**

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**TABLE I**

**SUMMARY OF SYSTEM PARAMETERS**
In a multihop wireless network with no centralized server, there is no scheduling mechanism under the interference avoidance protocol that would optimize the number of simultaneously communicating pairs. The number of pairs that can communicate in a given coverage area at any time instant is a function of the position of the selected nodes. It is shown in [14], that for any coverage area, there exists optimum patterns for placing the circles (exclusion region circle around the receiver, in our case of interference avoidance model) that would result in maximal number of circles being packed in a given boundary. In order to further explain the effect of placement of nodes on the number of communicating pairs in the coverage area, the system model as described in the analytical section and summarized in Table I is considered here again.

Fig. 5 (a-d) shows 4 cases where an exclusion region circle is defined around every communicating receiver. The radius of the exclusion region circle is twice the transmission distance, \( d \). For the sake of simplicity, it is assumed in Fig. 5 (a-d) that all the circles have the same radii and, hence, the transmission distances of all the simultaneously communicating pairs are the same. Case (a) represents a scenario where more number of pairs could communicate in the given coverage area but there are no more transmission pairs to make any communication. In case (b), the placement of the communicating pair of nodes are such that no more MS(s) could transmit data in the particular TS. Similarly, case (c) depicts a situation where 16 pairs could communicate simultaneously. However, it is to be noted that this is still not an optimal scenario for the placement of nodes. An optimal packing of the communicating nodes in the coverage area is shown in Fig. 5-d wherein there are 18 communicating pairs for any given TS. It can be seen that an efficient placement of nodes results in an increased number of simultaneously communicating pairs for any time instant and hence an increased throughput. As a result, the aggregate throughput over all the TS(s) in the frame increases. Note that the random data hopping technique follows the same principle that is used in the frequency domain by the concept of frequency hopping. The basic idea behind frequency hopping is the periodic change of transmission frequencies carried out in a pseudo-random fashion over a set of carrier frequencies [15]. In a similar manner, the random data hopping scheme randomly changes the time slot over which the data is transmitted.

A comprehensive system level simulation has been conducted under different traffic demands in order to assess the performance of the random data hopping scheme for a time slot partitioned multihop wireless system. A UMTS indoor path loss model values [16], with \( b_1 = 37 \) and \( \alpha = 3 \), have been considered in the simulations.

B. Simulation Results

The simulation parameters are the same as described in the system model. The number of MS(s) that have data to transmit determine the traffic demand. A 100% traffic load indicates that half the total number of MS(s) in the system act as source nodes, and the other half act as destination nodes. Hence for a system with 500 nodes, a 100% traffic would indicate that there are 250 communication links. The source node communicates to its intended receiver in multiple hops, wherein the MS(s) located between the source and destination act as relays. These relay MS(s) may have their own data to transmit depending on their traffic pattern. It is to be noted that at any node, the data is transmitted to the immediate receiver after employing the random data hopping technique.
The simulation model gives the expected values of the number of simultaneously communicating pairs and the carrier-to-interference ratio at the receiver of each of these communicating pairs. The average system throughput is calculated from these parameters using eqn. (5). The simulation result plotted in Fig. 6 illustrates that due to TS partitioning, with an increase in the number of TS(s) per frame from 5 to 100, the average system throughput shows a significant improvement. This is because of the following two reasons. Firstly, at 5 TS(s) per frame, the communicating pairs assigned to each of the TS remains static over the entire duration of the TS. Secondly, at higher number of TS(s), the random data hopping technique produces an inherent randomness in the placement of nodes that results in an increased number of occasions when a high number of hops could be served in any TS. The simulation result also shows that for low traffic load, the obtainable system throughput is higher than the case for high traffic load. This is because, when the traffic is low, the number of purely relaying nodes, \( m \), are quite high in comparison to the number of source nodes, \( s \). Therefore, as mentioned in [2], the throughput scales as \( \Theta(\sqrt{(s+m)\log(s+m)}) \).

It can also be observed from Fig. 6 that for an increasing number of TS(s) per frame, the absolute value of the number of occasions, when the communicating pairs are placed in locations that result in optimum or near optimum packing saturates. Thus the average system throughput saturates after a certain number of TS partitioning. For high traffic load (80% and 100% traffic in Fig. 6), the system throughput saturates at around 100 TS(s) per frame as compared to low traffic load (30% and 40% traffic) where the throughput does not saturate even at 100 TS(s) per frame. A further work in this direction would be to theoretically analyze the precise value of TS partitioning where the system throughput would saturate for different traffic loads.

![Variation of Average System Throughput with TS(s) (n=3)](image)

**IV. Conclusions**

In this paper, a random data hopping technique is developed for a TDD based multihop ad hoc wireless network. The key idea of the random data hopping technique is that for a multihop system with an interference avoidance model, there exists a region around every communicating receiver wherein no other MS can communicate. Hence, the number of MS(s) that can communicate simultaneously in a finite coverage area is a function of the position of selected nodes. An efficient selection of communicating nodes results in high number of transmission pairs and hence an increase in the average system throughput. In order to improve the performance of the multihop ad hoc system, a random selection of simultaneously communicating pairs that varies over different time instants is proposed. This is realized by partitioning each TS of the TDMA frame equally into several TS(s) and then applying the random data hopping scheme. It has been shown in the simulation results that this technique provides a higher system throughput as compared to the static scenario with no TS partitioning.

**References**


VARIATION OF SPATIAL PROTECTION MARGINS ON MULTIHOP WIRELESS NETWORKS

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ABSTRACT

In this paper, the effect of variation in the spatial protection margin, is investigated for multihop wireless networks under the interference avoidance Protocol Model [1] and compared to single-hop communication network. Under the Protocol Model, the interference is avoided by the application of the exclusion range concept. This means that a spatial protection region (or a circular exclusion region) is specified around all receiving nodes so that any node other than the intended transmitter is not allowed to reuse the same frequency resource within this region. It is demonstrated that for an asymptotically infinite coverage area, the spatial reuse efficiency for a multihop design increases proportionally with the number of multiple hops per link, and with the spatial protection margin. However, under a finite coverage area, the monotonic increase of spatial reuse efficiency does not remain completely valid. In order to analyze the performance of such a system, a relation for the system throughput is derived from the Shannon capacity equation. It is found that the system throughput attains a peak when the value of spatial protection margin is nearly unity. The exact value of spatial protection margin when the throughput reaches its maximum is found to be a monotonically increasing function of the number of multiple hops and the pathloss exponent.

Index Terms - Multihop wireless network, interference avoidance model, spatial reuse efficiency, spatial protection margin.

I. INTRODUCTION

A multihop wireless network exploits the properties of multihop relaying between a transmitter and receiver for efficient resource reuse. Multihop system is a key enabler for very high data rates of power limited wireless communication, and is a very effective means to combat ‘dead zones’. It has been found that the integration of multihop communication into cellular networks significantly increases the connectivity of the combined network [2]. In their landmark paper [1], Gupta and Kumar derived the equation for achieving global transmission rate of an ad hoc network (in bit-meters per second) under the assumption of point-to-point coding, for both interference-avoidance Protocol Model and the alternate Physical Model. In a Protocol Model, an exclusion region (or a protection region) is defined around each receiving node of a communicating link such that any other potential transmitter is prevented from transmitting at the same time within the exclusion region using the same radio resource.

The exclusion region range is always greater than the transmission distance by some proportionality factor, which is termed as the spatial protection margin, \( \Delta \). The significant result reported by [1] is that, in a unit disk with a uniform distribution of \( n \) source nodes and \( m \) relays, the capacity obtainable for each of the source nodes under the Protocol Model is \( O \left( \frac{n}{\sqrt{(n+m) \log((n+m))}} \right) \) bit-meters per second.

A multihop hybrid cellular wireless network with an interference avoidance model has been studied in [3], and the scaling behavior of the throughput capacity with the number of base stations (BS(s)) is studied. Also, a specific scenario of a 2-hop hybrid cellular network has been extensively analyzed and the variation of throughput capacity has been studied in [4]. At the same time, the authors in [4] proposed a scheme that takes advantage of the mobility of the nodes. By allowing only one-hop relaying (2 hops with a single relay), the aggregate throughput scales as \( O(n) \), but at the cost of unbounded buffer and delay requirement.

The recent research works on multihop wireless networks have mostly concentrated on the increase in the throughput capacity, the scaling behavior and the call blocking as well as outage probability of the system. However, the dependence of the system throughput, \( C \), on the number of multiple hops, \( M \), and in particular, the dependence on \( \Delta \), in case of the interference avoidance model has not yet been dealt with. Similarly, though spatial reuse in TDMA based mobile multihop systems have been considered and analyzed in detail, [5], [6], to the best of the knowledge of the authors, there has been no work carried out till now on establishing a relationship between the spatial protection margin, \( \Delta \), and the spatial reuse efficiency, \( \eta \), of the multihop wireless network over a single-hop architecture. An analysis for calculating the reuse efficiency based on a statistical model was done by the authors in [7]. In this paper, a deterministic approach is chosen and the dependence of spatial reuse efficiency on the number of hops per link and on the spatial protection margin is computed. Further, the expressions for the carrier-to-interference-ratio, \( \gamma \), and the system throughput is calculated for this system deployment, but under a finite coverage area. The system throughput is found to reach a maximum for a certain value of the spatial protection margin. The value of \( \Delta \) for which the system throughput attains a peak depends in turn on the number of hops per link, \( M \), and the pathloss exponent, \( \alpha \).

The rest of the paper is organized as follows. Section II, describes the network model and provides a mathematical re-
The relationship between the spatial reuse efficiency and the spatial protection margin, for an unbounded system. Section III provides an analytical derivation that relates the system throughput performance with the spatial protection margin. The simulation model and results are given in Section IV, and the concluding remarks are provided in Section V.

II. NETWORK MODEL

Case 1: MultiHop Scenario

![Case 1: MultiHop Scenario](image)

Figure 1: Single hop and multiple hop transmission between the source, $P$, and destination, $Q$.

A. System Analysis

In the multihop scenario (case 1 in Figure 1), the transmission from source $P$ to destination $Q$ takes place using $M$ hops whereas in case of single-hop scenario (case 2 in Figure 1), the transmitter directly communicates to the receiver. In the latter case, $P$ and $Q$ are the centers of the transmission and the exclusion region circles - because of space constraint, they are represented as ellipse. A TDMA (time division multiple access) based air-interface is assumed where a timeslot, $t_{sl}$, is subdivided into $M$ mini-slots, $t_{sub}$; i.e., $t_{sub} = t_{sl}/M$. A transmission density parameter, $\delta$, is defined as the ratio of the time duration used for data transmission per hop, $t_{sub}$, to the area of the exclusion region, $B$, per hop. The radius, $r$, of the exclusion region circle is $r = d(1 + \Delta)$, where $\Delta$ is a factor that determines the spatial protection margin added to the transmission distance. It follows, $B = \pi r^2 = \pi d^2(1 + \Delta)^2$. For the multi-hop (mh) scenario, this results in $A_{mh} = \pi B = \pi d^2(1 + \Delta)^2$, and for the single-hop (sh) scenario, this results in $A_{sh} = \pi d^2$. The units for the transmission density being defined as channel utilization in seconds/square meter. The channel transmission rate, $\zeta$, for the multihop case is therefore defined as:

$$\zeta_{mh} = \frac{1}{t_{sub}} \frac{MB}{A_{mh}}$$

where $A_{mh}$ is the total exclusion area required to be able to serve the entire link, and it can be determined as $A_{mh} = MB - (M - 1)B_s$, where $B_s$ indicates the overlapping area between two exclusion range circles. For a multi-hop scenario, there is a certain amount of overlapping between two adjacent exclusion region circles of the same link which results in a reduction in the occupied area; hence the term $(M - 1)B_s$ has been subtracted from $MB$ while calculating $A_{mh}$. Note that Figure 1 shows a specific scenario where all the multihop mobile stations (MSs) are in a straight line [7]. However, there is no difference in the result even if the multihop MS(s) form a skewed line as long as the overlapping area remains the same. Given that all the exclusion region circles have the same radius and the distance between the centers of adjacent circles are separated by the transmission distance, $d$, the distance between the points of intersection of the overlapping circles is $c = 2\sqrt{((1 + \Delta)d)^2 - (d/2)^2}$. The angle $\theta$ (formed by the lines joining the center of a circle to the point of intersections of the two overlapping circles; as shown in Figure 1 at the point $Q$) is calculated as $\theta = 2\arcsin\left(\frac{c}{2d}\right) = 2\arcsin\left(\sqrt{T - \left(0.5/(1 + \Delta)\right)^2}\right)$ and is given in radians. The overlapping area is then given by $B_s = ((1 + \Delta)d)^2(\theta - \sin \theta) = B_s \left(\frac{\Delta - \sin \theta}{\pi}\right)$. For mathematical simplicity, an intermediate variable, $p$, is defined such that $p = \frac{\Delta - \sin \theta}{\pi}$ and is used in all further part of analysis. Hence, $B_s$ can be written in a simplified form as, $B_s = \left(\frac{p}{\pi}\right)$. For the corresponding single-hop scenario, the total exclusion area for the entire link is equivalent to the exclusion region for a single hop. Hence the channel transmission rate is given by:

$$\zeta_{sh} = \frac{1}{t_{sub}}$$

A direct comparison of the channel transmission rate of the single-hop and the multihop scenario yields the spatial reuse efficiency.

$$\eta = \frac{\zeta_{mh}}{\zeta_{sh}} = \frac{MB}{M(p - 1) + 1} \quad M \geq 1; p \geq 1$$

Eqn. (3) exhibits the relation between the spatial reuse efficiency and the number of hops and is plotted in Figure 2 for different values of $\Delta$. It can be seen that for any value of $\Delta$, the presence of multihop component increases the spatial reuse efficiency as compared to a single-hop network design. Again, with increasing values of $\Delta$, $\eta$ always increases. For an asymptotic case of $\Delta \to \infty$, $p \to 1$ for each of the multiple hops and hence $\eta \to M$ for these multiple hops; i.e., the increase in $\eta$ for the multihop system is equal to the maximum number of multiple hops between any communicating link which is a first, non-intuitive, but important result. The spatial reuse efficiency can therefore be optimized as follows:

1. Maximizing the spatial protection margin, $\Delta$. 

The 18th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC’07)
Protocol Model of the to the desired receiver (Rx). In this work, a restrictive version located beyond the exclusion region act as potential interferers power. On account of the interference avoidance protocol de-
The MS(s) are assumed to be uniformly distributed and all considered and the variation of throughput with aggregate system throughput is calculated from the Shannon
The 18th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC’07)
2. Maximizing the number of multiple hops, M, for a communicating link.
The calculation of η for an asymptotically infinite area therefore provides a quantitative insight into the gain obtained from a multihop wireless architecture. This result is particularly significan
tic while evaluating the performance of a wide area ad hoc network like the ADHOC city described in [8] where an in
finitely large coverage area is considered. However, for an indoor or a campus environment where the wireless network is designed for a confined area, a higher value for ∆ would result in an increase in the radius of the exclusion region circle and as a result, the number of hops and hence the number of MS(s) that can communicate simultaneously for a given area would decrease. At the same time, this reduction in the number of simultaneously communicating pairs decreases the amount of interference experienced by any receiver. Therefore, the coverage area serves as a bottleneck, on account of which the analysis of the dependence of η with ∆ does not remain completely valid. In order to evaluate the performance of such a system, and determine the impact of the spatial protection margin on the network performance of a bounded system, the aggregate system throughput is calculated from the Shannon capacity equation. In the next section, a finite coverage area is considered and the variation of throughput with ∆ is studied for different limiting values of M.

III. CAPACITY ANALYSIS
The MS(s) are assumed to be uniformly distributed and all the transmitting MS(s) are assumed to transmit with the same power. On account of the interference avoidance protocol design, all the transmitting MS(s) in the coverage area that are located beyond the exclusion region act as potential interferers to the desired receiver (Rx). In this work, a restrictive version of the Protocol Model is considered in the capacity analysis wherein not only the undesired concurrently communicating transmitter but also the corresponding receiver of the undesired transmitter does not lie in the exclusion region. Hence, the exclusion region of all the simultaneously communicating pairs does not overlap with each other. The coverage area considered for the wireless network is a square as depicted in Figure 3 and is given by A = s², where s is the side length. For any value of the maximum number of multiple hops per link, a MS located at the edge of the coverage area would employ a maximum of M hops per link to communicate to its destination. As a result, the maximum transmission distance for any communicating pair is given by the diagonal of the square that is normalized by the number of multiple hops per link, i.e.,
d_c = 1.414s/M. The received power, P_Ri, for any commu
nicate pair in an omni-directional system and using a generic propagation model is given as follows:

\[ P_R = P_T - (k_1 + 10\alpha \log_{10}(d)) \text{ dB} \]

(4)

Here, \( P_T \) is the transmit power, \( k_1 \) is a propagation constant, \( d \) is any distance between transmitter and receiver, and \( \alpha \) is the pathloss exponent. Therefore the carrier-to-interference ratio, \( \gamma \), for any MS is given by

\[ \gamma = \frac{10^{P_T/10} - 10^{(k_1 + 10\alpha \log_{10}(d_{int}))/10}}{\sum_{i=1}^{N_{th}} 10^{P_T/10} - 10^{(k_1 + 10\alpha \log_{10}(d_{int}))/10}} \]

(5)

Here, \( d_{int} \) is the distance between the transmitter (Tx) and the desired receiver (Rx), and \( d_{int,i} \) is distance between the \( i^{th} \) interfering transmitter and the ‘victim’ receiver. For a UMTS based indoor propagation model, \( k_1 = 37 \). The number of communicating pairs, \( N \), at any time instant, depends on two parameters: the exclusion region circle, \( B \), which is a function of the parameter \( \Delta \), and the total coverage area, \( A \). The system throughput per unit area is computed using Shannon’s channel capacity equation:

\[ C = \frac{1}{N B} \sum_{i=0}^{N} \log_2((\gamma)_i + 1) \text{ bps/Hz/area} \]

(6)

It should be noted at this stage that the determination of the Shannon capacity region of ad hoc networks remains an open problem [9] and that the equation for system throughput given in eqn. (6) is suboptimal. However, the main aim of this analysis has been to derive an expression that would reflect the dependence of \( \gamma \) and \( C \) with \( \Delta \). In the numerical analysis for calculating the number of concurrently communicating pairs in the given coverage area, a constant transmission distance, \( d_c \), is assumed for all the communicating pairs. Since the spatial protection margin, \( \Delta \), remains the same for all the concurrent pairs, this implies that the radius of the exclusion region circle for all the concurrently communicating pairs are the same. The placement of the exclusion region circles in the square-shaped coverage area is explained in detail in [10]. Figure 3 shows two cases where the exclusion region circles are distributed within the bounded coverage area. Case (a) represents a scenario where the concurrently communicating pairs the not optimally located. The placement of the communicating pairs are such that no more MS(s) could transmit data in the particular time instant. An optimal packing of the communica
ing nodes in the coverage area is shown in Figure 3-b under

Figure 2: Variation of spatial reuse efficiency with different values of spatial protection margin, ∆, and number of multiple hops per link, M, for an unbounded system

2. Maximizing the number of multiple hops, M, for a communicating link.

The calculation of η for an asymptotically infinite area therefore provides a quantitative insight into the gain obtained from a multihop wireless architecture. This result is particularly significant while evaluating the performance of a wide area ad hoc network like the ADHOC city described in [8] where an infinitely large coverage area is considered. However, for an indoor or a campus environment where the wireless network is designed for a confined area, a higher value for ∆ would result in an increase in the radius of the exclusion region circle and as a result, the number of hops and hence the number of MS(s) that can communicate simultaneously for a given area would decrease. At the same time, this reduction in the number of simultaneously communicating pairs decreases the amount of interference experienced by any receiver. Therefore, the coverage area serves as a bottleneck, on account of which the analysis of the dependence of η with ∆ does not remain completely valid. In order to evaluate the performance of such a system, and determine the impact of the spatial protection margin on the network performance of a bounded system, the aggregate system throughput is calculated from the Shannon capacity equation. In the next section, a finite coverage area is considered and the variation of throughput with ∆ is studied for different limiting values of M.

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the condition that the exclusion region is completely within the coverage area. In all further part of the analysis, while calculating the system throughput, it is assumed that there is always an optimal packing of the number of circles. It should be noted that even though this optimal packing condition simplifies the analysis by considering a regular and optimal alignment of the communicating nodes, there exists no general solution in literature for the optimal packing problem [11].

Given that an optimal packing of circles is considered, the number of circles that can be placed in the coverage area depends on the radius of the circle, , which in turn depends on the factor . When , , and correspondingly, the number of circles . An increase in the ratio, , would result in a reduction in the maximum number of possible circles. Therefore the optimum number of circles in the coverage area, , depends on and . For any fixed value of (given a coverage area), depends entirely on : i.e., where the aggregate throughput reaches its peak depends on and . In the absence of a general equation for calculating the precise value of , the different values of , the number of circles that can be placed in the coverage area, is obtained numerically using the “billiards” simulation algorithm as done in [12]. Table I shows the value of for certain selected values of . As seen in Table I, the maximum value of for which the multiple number of pairs can be supported in the system increases with increasing . In the next section, the numerically obtained analytical results are compared with the simulation results.

IV. SIMULATION MODEL AND RESULTS

A multihop wireless network with 500 uniformly distributed MS(s) is considered in a coverage area of 1 km². The carrier-to-interference ratio, , is estimated for each MS from the carrier strength of the desired Rx and from the interference arising from all the MS(s) that are communicating simultaneously. With an increase in the radius of the exclusion region around the receiver, the interference coming from other MS(s) decreases and hence there is an increase in for every communicating pair. But at the same time, the number of simultaneously communicating pairs decreases for a given coverage area, which in turn reduces the overall system throughput. Hence, the obtainable system throughput is not a monotonically increasing function of ; instead it is a concave function and observes a bell-shaped performance, as is shown in Figure 4.

The numerically obtained analytical results are then compared with the simulation results for two different cases of and . It is observed that for a given , the aggregate throughput does not increase linearly with , but reaches a peak when is about 1.0 and then starts decreasing. The variation of with and that maximizes the system throughput is shown in Table II which shows the numerically obtained analytical results and the simulation results. It could be seen that as the value of or increases, the value of for the maximal throughput also increases marginally. The exact value of where the aggregate throughput reaches its peak depends on and .

A noteworthy observation that could be made from Figure 4 is that for each different value of , there exists a specific value of above which the analytically obtained throughput results are not plotted. This is because an increase in the value of results in a scenario where there is only one exclusion region circle in the given area, i.e., there is only one communicating receiver at any time instant. There is no interfering entity for such a situation. The main aim of the capacity analysis has been to study the behavior of under the interference limited communication under Protocol Model and observe its effect on the system throughput. The effect of noise is not considered as it is outside the scope of this work. Hence, the throughput is not plotted in the absence of any interfering entity. Also, as seen in Figure 4, there is a difference in the absolute value of the system throughput attained in the analytical and simulation results. This arises from the fact that in the analysis, an optimal packing of the equal circles is considered; whereas in the simulations, the circles are placed with the receiving node of the communicating pair as the center of the circle. Hence, in practice, the placement of circles is governed by the distribution of the mobile terminals and the number of MS(s) in the coverage area. However, as can be seen, this does not affect the general findings for the variation in .

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Figure 3: Packing equal shaped circles in the square

![Packing equal shaped circles in the square](image)

Table 2: Values of spatial protection margin, , for achieving maximal system throughput

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Simulation results

Table 2: Values of spatial protection margin, , for achieving maximal system throughput

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Numerically obtained analytical results

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![Variation of System Throughput with M and Δ when n = 3](image)

**Table 1**: Values of spatial protection margin, \( \Delta \), for varying number of maximum pairs, \( N_\Delta \), and different values of \( M \)

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<tr>
<th>( M = 4 )</th>
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<td>( \Delta = 0 )</td>
<td>( \Delta = 0.008 )</td>
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<td>( \Delta = 1.0 )</td>
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**Figure 4**: Variation of system throughput for different values of spatial protection margin, \( \Delta \), for a bounded system

V. CONCLUSION

A multihop wireless network is analyzed under the interference avoidance Protocol Model. For a spatially unbounded system with an asymptotically infinite coverage area, the spatial reuse efficiency is found to increase unidirectionally with an increase in the number of multiple hops and the spatial protection margin, \( \Delta \). However, for a bounded system, the finite coverage area serves as a bottleneck in the calculation of \( \eta \). The subsequent analysis of aggregate system throughput for a confined area indicates that the throughput of this multihop wireless model does not increase monotonically with \( \Delta \); but is a concave function, and hence a maximum can be observed. The precise value of the spatial protection margin for which the throughput attains this maximum depends in turn on the number of multiple hops per link and the path loss exponent of the propagation model. This provides a new paradigm in the design of short-range multihop wireless network where it is suggested to dynamically adjust the value of \( \Delta \) so as to optimize the system performance.

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