CHANNEL ASSIGNMENT
IN
MULTI-HOP TDD W-CDMA CELLULAR NETWORKS

BY

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In the name of Almighty God,
The Merciful, The Compassionate.

Abstract

Relaying is a fundamental concept in multi-hop wireless ad hoc networks whereby communications between mobile terminals are carried out in a distributed manner through intermediate nodes. The small distance and the potential high transmission rate between the relaying entities draws our attention to the significance of multi-hop relaying in *hot* and/or *dead spots*. Consequently, when relaying is employed in cellular networks, poor communications to and from the base station due to severe multi-path fading and/or noise can be avoided. We propose to utilize multi-hop relaying as an overlay architecture for single-hop Time Division Duplex (TDD) Wideband-Code Division Multiple Access (W-CDMA) cellular networks. A major challenge pertaining to the introduction of this technology into cellular networks is the design of an efficient slot assignment algorithm for relaying nodes.

In this thesis, we propose a heuristic slot assignment scheme, namely Delay-Sensitive Slot Assignment (DSSA). The DSSA scheme is composed of two phases, namely, the *elimination phase* and the *selection phase*. In the elimination phase, a slot is eliminated if and only if assigning that slot will cause tangible interference with other ongoing transmissions. This is done based on neighborhood information of the node requesting a channel or a slot. At the end of this phase, a set of candidate slots are obtained and are used in the selection phase. During the selection phase, the slot with the minimum cost will be selected. The cost function is based on computing the *slot waiting time* for each slot. The slot waiting time is defined as the time a mobile terminal has to wait for its designated slot before it starts transmitting.

A simulation model is developed to investigate the performance of the DSSA scheme. Our results reveal that DSSA outperforms both conventional single-hop cellular networks and multi-hop cellular networks with a random slot assignment algorithm in terms of average delay, throughput and spatial reuse.

Keywords: Cellular Networks, Wireless Ad hoc Networks, Multi-hop Relaying, TDD WCDMA, Slot Assignment.

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Contents

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List of Acronyms

2G	2nd Generation Wireless Communication Systems
3G	3rd Generation Wireless Communication Systems
3GPP	3rd-Generation Partnership Project
4G	4th Generation Wireless Communication Systems
4G+	Beyond 4G
A-Cell	Ad hoc-Cellular network
ACK	ACKnowledgement
A-GSM	Ad hoc GSM
ALLC	ALLoCation
AMPS	Advanced Mobile Phone Service
AODV	Ah-Hoc On-Demand Distance Vector
ARS	Ad hoc Relaying Stations
BCR	Base-Centric Routing
BS	Base Station
CDMA	Code Division Multiple Access
CN	Core Network
DCA	Dynamic Channel Allocation

DCH	Dedicated CHannel
DSDV	Destination-Sequence Distance Vector
DSR	Dynamic Source Routing
DSSA	Delay-Sensitive Slot Assignment
ETSI	European Telecommunication Standards Institute
FCA	Fixed Channel Allocation
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FIFO	First In First Out
FM	Frequency Modulation
GPS	Global Positioning System
GSM	Global System for Mobile communications
GSR	Global State Routing
HCA	Hybrid Channel Allocation
HWN	Hybrid Wireless Network
iCAR	integrated Cellular and Ad hoc Relay
IMT2000	International Mobile Telecommunications 2000
IS-136	Interim Standard 136
IS-54	Interim Standard 54
IS-95	Interim Standard 95
LAR	Location-Aided Routing
LSP	Link State Packets
MAC	Medium Access Control

MCN	Multi-hop Cellular Network
MH	Mobile Hosts
MS	Mobile Station
MT	Mobile Terminal
NMT	Nordic Mobile Telephone
NTT	Nippon Telegraph and Telephone
ODMA	Opportunity-Driven Multiple Access
ORACH	ODMA Random Access Channel
PDA	Personal Digital Assistant
PDC	Pacific Digital Cellular
PDU	Packet Data Unit
PRNET	Packet Radio NETwork
QoS	Quality of Service
REQ	REQuest
RERR	Route ERRor
RESP	RESPonse
RNC	Radio Network Controller
RREP	Route REPly
RREQ	Route REQuest
RSA	Random Slot Assignment
SCN	Single-hop Cellular Network
SIR	Signal to Interference Ratio
SMS	Short Mobile Services

SR	Session Request
SURAN	Survivable Adaptive Radio Networks
TACS	Total Access Communication System
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
UCAN	Unified Cellular and Ad-Hoc Network
UMTS	Universal Mobile Telecommunication System
USDC	United States Digital Cellular
UTRA	UMTS Terrestrial Radio Access
W-CDMA	Wideband Code Division Multiple Access

Chapter 1

Introduction

By the end of the next decade, more than half the world population will be using cell phones, according to the world's largest handset manufacturer [1]. At the moment, the most popular mobile communication device is the cellular phone. Mobile communications has improved considerably due to the advancement in electronics and communication technologies. There are three different generations as far as mobile communications is concerned. The first generation of wireless mobile communications systems was deployed in the 1980s. First-generation systems include the advanced mobile phone service (AMPS) in North America, the Total Access Communication System (TACS) in Europe, and Nippon Telegraph and Telephone (NTT) in Japan. They used Frequency Modulation (FM) for voice transmission and digital signaling for control information. The specifications of each of these systems were agreed on between the domestic industries only but not across countries. Therefore, due to the incompatibilities in first-generation networks and the increase in the need for a global mobile communication standard, the second-generation (2G) systems were introduced to the market around 1991. Examples of 2G systems include North American Digital Cellular (USDC) standards IS-54 and IS-136, the Global System for Mobile communications (GSM), Pacific Digital Cellular (PDC) and cdmaOne. These systems offer better voice quality and some data service such as Short Message Service (SMS) messages at low rates of 9.6-14.4 Kbps. Moreover, they take the advantage of compression and coding techniques and employ digital modulation schemes. Both first-generation and 2G systems are circuit-switched, which does not offer high data rate for handling packet-oriented services. Also, due to the regional nature of standardization, the concept of globalization did not succeed completely. As a result, the third generation (3G) systems emerged with the objective of universality, high data rates, flexibility, service quality and service richness. The data transmission rates vary between 144 Kbps and 2 Mbps depending on the service, the topology, and the environment. 3G systems allow both circuit and packet switching. Circuit switching is used for delay-sensitive applications such as voice and video, while packet switching is used for applications capable of tolerating relatively long delays. Examples of 3G systems include code division multiple access 2000 (cdma2000) and the Universal Mobile Telecommunication System (UMTS).

Mobile phones are becoming a necessity in one's life like other media (i.e., radio, TV, printer, and Internet). As a result, the demand for novel communication techniques and network architectures for high data rate multimedia applications with varying requirements for 3G and beyond wireless systems, starts to increase. Moreover, due to dynamic and uneven distribution of cell phone users, some users are in highly congested areas while others are in rural and urban areas. In urban areas, the radio signal decays very rapidly as the distance between the transmitter and the receiver increases. Moreover, obstructions, such as building, trees, mountains, etc., can further weaken the signal to the point where it cannot be correctly detected.

Research on fourth generation (4G) and beyond 4G (4G+) mobile communication systems is already under way to achieve both high data rates and extended coverage of the geographical area [2-9]. Traditionally, in cellular networks this can be achieved by different techniques. A possible solution is to install more base stations in the network. This will resolve the coverage problem to a great extent but still cannot guarantee connectivity for nodes under heavy shadowing. Moreover, this solution is costly and can be considered a waste of resources for low density areas. Another solution is to install repeaters in poorly covered regions, such as subways, tunnels, basements, etc. Although repeaters are inexpensive, they are still not practical. This is because all they do is simply boost all the received signal without any pre-planning or intelligence. However, this will lead to high interference. Furthermore, with current cellular systems (3G and beyond 3G) that support data and multimedia, repeaters need not only boost the signal but also adapt to varying quality of service requirements. Accordingly, the above will not provide a viable solution for these types of systems.

Conversely, relaying [2-5] using mobile terminals can be an alternative or a complementary method to repeaters and base stations. In this case, individual terminals in areas where base station coverage cannot be attained, relay their messages via one or more mobile terminals that have a direct or intermediated link to the base station (see

Figure 1.1). Relaying will not only solve the coverage and high data rate problems but also will provide faster deployment, fewer infrastructures requirement, higher transmission rate due to the short transmission range, and peak power consumption reduction. Therefore, it is more economically desirable. In fact, due to these potential benefits, there has recently been an interest in deploying this technique in cellular systems, particularly for the 3G systems as we will see in the next chapter.

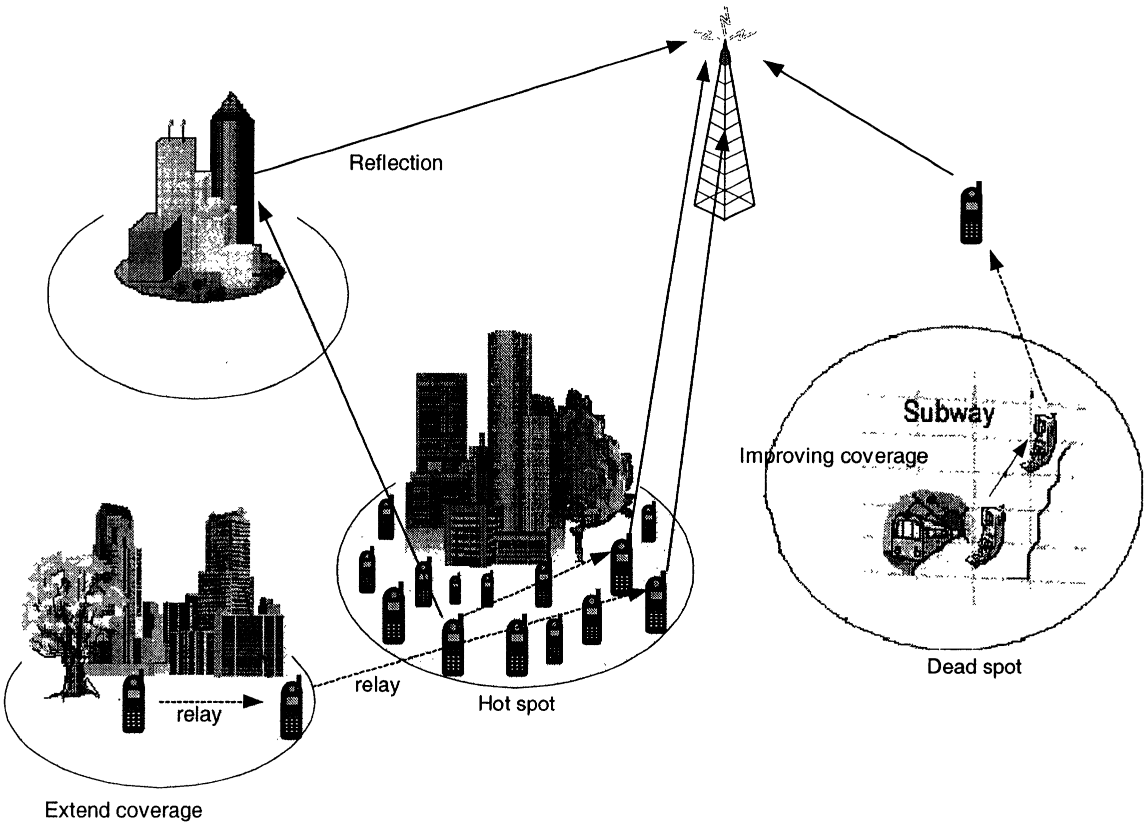

Figure 1.1: Relaying in Cellular Networks

1.1 Thesis Objectives

The main objectives of this thesis are:

- To improve and extend the traditional single-hop (i.e., base station) coverage.
- To investigate the performance gains achieved by enabling relaying in poorly covered environments with high frequency reuse and no separate relaying channel.
- To devise a centralized channel assignment scheme and investigate its effects on the system performance and show its importance in a multi-hop cellular network.

Without loss of generality, we only consider the uplink connection to the base station. However, most of the findings are equally applicable to the downlink connection. In fact, downlink communication via relaying nodes will be more coordinated and well managed since base stations can control network access more easily.

1.2 Thesis Organization

This thesis is organized as follows. Chapter 2 provides a background to the relaying concept that began in an infrastructure-less ad hoc networks and emerged to the cellular networks. A brief background on cellular networks will also be provided in addition to presenting the state of art in multi-hop cellular networks. Chapter 3 describes the proposed Delay-Sensitive Slot Assignment scheme and its system requirements. The simulation parameters, model assumptions, and simulation details are presented in Chapter 4. Chapter 4 also provides the simulation results and discussions pertaining to the objectives outlined in Section 1.1. Finally, Chapter 5 presents the conclusion and possible extensions and implementation issues that could be made as future work.

Chapter 2

Related Work

In this Chapter, we provide a brief background to the multi-hop relaying technology, which originates from ad hoc networks. The interest lies in the fact that a fast, easy to deploy communication network can be established in a distributed fashion, without having to depend on an existing central controller or an infrastructure. However, this concept is still in the developmental stage. Many schemes for routing, multicast, Quality of Service (QoS), and security in large networks, need to be further investigated and tested. In its current state, multi-hop relaying technology is most attractive to those belonging to a small organization or group whose members need to communicate with each other or share information on a demand basis.

Conversely, in cellular networks, even though there exists an underlying infrastructure, by means of using Base Stations (BSs), there are still some areas where coverage cannot be provided via the BS. These areas are often referred to in the literature as *dead spots*. Dead spots include, for example, subway train platforms, indoor environments, and undergrounds. Moreover, in dense areas known as *hot spots*, such as downtown areas and amusement parks, subscribers tend to experience a higher blocking probability. In such circumstances, multi-hop relaying provides a convenient solution to all these problems.

Research in the area of multi-hop cellular networks has been active over the past few years. A few schemes have been proposed and evaluated. The objective of these schemes is to enhance the coverage capacity of the BS and decrease the blocking probability. Most of these schemes are based on integrating cellular networks and ad hoc networks, with each using its own communication medium, rather than enhancing existing cellular networks.

In this Chapter, we discuss multi-hopping in the context of ad hoc networks. We will then briefly describe cellular networks and their radio access technology. Finally, we will discuss the ways relaying is impeded in cellular networks and reveals the benefits and the shortcomings of adopting multi-hopping in cellular systems.

2.1 Relaying in Ad hoc Networks

A wireless mobile ad hoc network is a collection of wireless mobile stations[1] forming a temporary network without the aid of any centralized infrastructure (e.g., base stations or access points). Ad hoc networks can be traced back to 1972 and the Department of Defense (DoD)-sponsored packet radio network (PRNET) [10]. Later on, the idea was adopted by the Survivable Adaptive Radio Networks (SURAN) program [10]. In the

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[1] The terms mobile stations, mobile terminals, and nodes are used interchangeably throughout this document.

early 1990s, notebook computers became popular, as did the equipment based on RF and infrared. Eventually, the term "ad hoc networks" was used by the IEEE 802.11 standardization committee after the idea of infrastructure-less communication was proposed in [11] and [12]. From there on, the interest in ad hoc networking by researchers and commercial vendors started to surge.

Ad hoc networks are quicker to deploy than cellular networks. Consequently, ad hoc networks can be used in situations where there is either no wireless communication infrastructure present, or where such an infrastructure cannot be used because of military tactics, unforeseen emergencies, and/or for cost reasons [13]. Therefore, ad hoc networks can be used in battlefields, major disaster areas and outdoor assemblies.

In an ad hoc network, each mobile station has a limited wireless transmission range. Hence, a node can communicate directly only to nodes within its wireless transmission range. However, if a mobile terminal wants to communicate with a node outside its transmission range, then it has to *relay* its information to those nodes that are within its transmission range. Therefore, some form of routing protocol is necessary between relaying entities for the sake of enabling communication amongst the wireless nodes in the ad hoc network. An example of an ad hoc network topology is depicted in Figure 2.1.

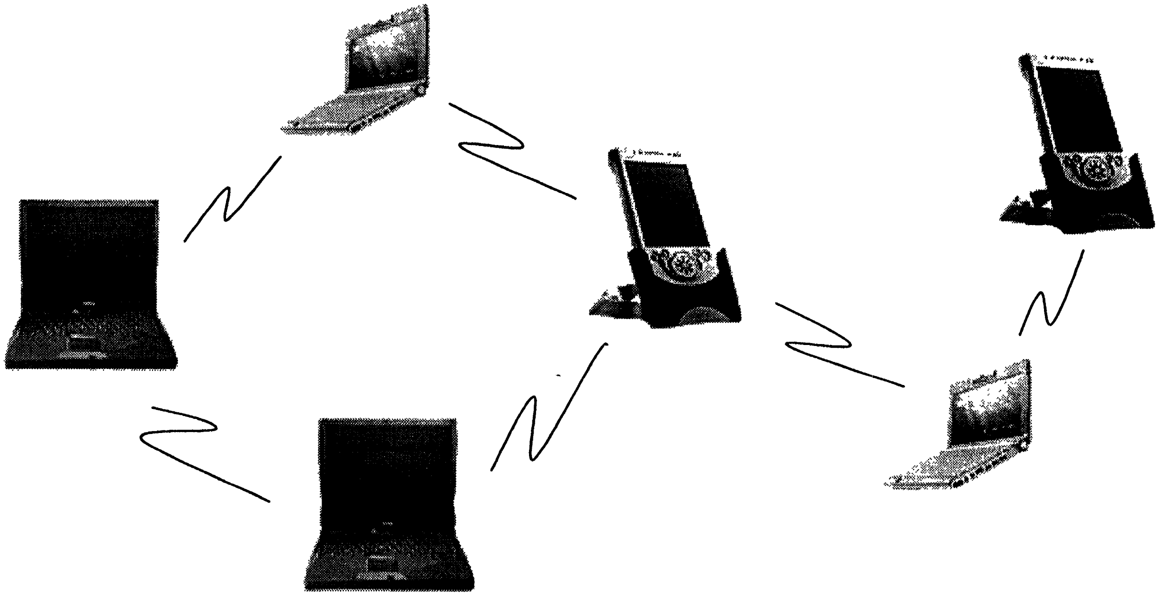

Figure 2.1: Multi-hop Ad hoc Networks

The routing problem in ad hoc network is of a complicated nature due to the inherent non-uniform propagation characteristics of wireless transmissions. For example, an ad hoc routing protocol must be able to decide on a single best path between any two nodes when more than one path exists. Routing protocols also need to be able to minimize the bandwidth overhead while simultaneously enabling proper routing to take place. Moreover, such protocols must deal with frequent changes in the topology of the ad hoc network, since any of the stations involved may move or be shut down at any time.

Ad hoc routing protocols are usually divided into two categories: proactive and reactive protocols. Proactive routing protocols, also known as table-driven routing protocols, require all the mobile stations to have complete knowledge of the network topology at all times. Examples of such routing protocols include Global State Routing (GSR) [14] and Destination-Sequence Distance Vector (DSDV) [11]. In reactive routing protocols, which are also known as on-demand routing protocols, routes are built between nodes only as desired by the source node. Examples of reactive protocols include Dynamic Source Routing (DSR) [15], Location-Aided Routing (LAR) [16] and Ad hoc On-Demand Distance Vector (AODV) [17].

Dynamic Source Routing is the most eminent multihop ad hoc routing protocol. It is designed to allow nodes to dynamically discover a source route across multiple network hops to any destination in the ad hoc network. Due to its importance in literature, as well as this thesis, we will further explore its functionality in more detail next.

Dynamic Source Routing (DSR) [15] is an on-demand routing protocol. It allows nodes to dynamically discover a route in a multi-hop network to any destination. A key advantage of DSR is that intermediate hops do not need to maintain routing information in order to route packets they receive, since route information is stored in the packet itself. Moreover, DSR does not require the periodic broadcast of link status packets, reducing the overhead of Dynamic Source Routing.

In DSR, mobile nodes are required to maintain route caches that contain the source routes that the mobile is aware of. When new routes are learned, entries in the route cache are continually updated. Therefore, when a mobile station wishes to relay its information to another mobile station, it dynamically determines one based on cached information and on the result of a route discovery protocol.

A Mobile Terminal (MT) initiating route discovery broadcasts a Route Request (RREQ) packet to its one-hop neighbors. The RREQ contains the address of the destination or the target and the address of the original initiator. The RREQ also contains the request ID and a route record which is a sequence of hops taken by the route request packet as it is propagated through the ad hoc network during the route discovery. The source address and the request id are used to limit the number of RREQs propagated on the outgoing links of a mobile node. Therefore, when a mobile node receives a RREQ packet it checks the source address and the request id and compares them with the recently seen requests. If it has already seen it before, then the mobile node will discard the RREQ packet and will not process it further. Otherwise, it appends its own address to the list of addresses in the route record on the RREQ and forwards the packet to its neighbors. For example, in Figure 2.2, MT 2 appends its own address to the RREQ that it receives form mobile terminal 1. MT 5, on the other hand, receives two copies of the RREQ. It appends its address to the first copy (i.e., the copy it receives from MT 2) and discards the RREQ it receives from MT 4, since it previously received a RREQ with the same source address and request id.

If the receiver of the RREQ is the destination itself, it sends a route reply (RREP) packet to the source after including a copy of the reversed route record of the received RREQ, in the RREP packet. Figure 2.3 demonstrates a scenario where a destination, i.e., MT 8, replies with a RREP packet upon the receipt of a RREQ from MT 1. MT 8 receives MT 5's copy of the RREQ before the copy broadcasted by MT 7. As a result, it appends its own address to the route record of the RREQ received from MT 5, and includes a copy of the reversed route record in the RREP packet. Afterwards, MT 8 forwards the RREP packet to MT 5.

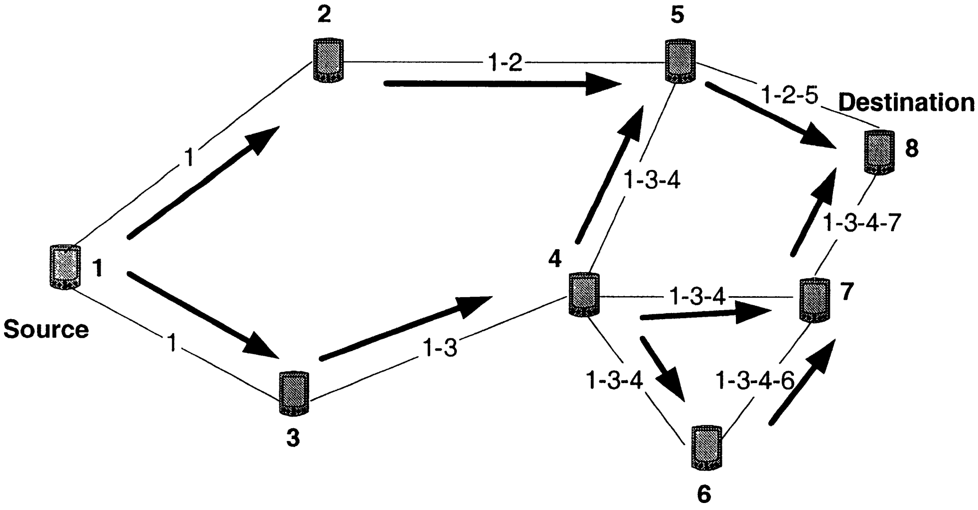

Figure 2.2: Route discovery in DSR [15]

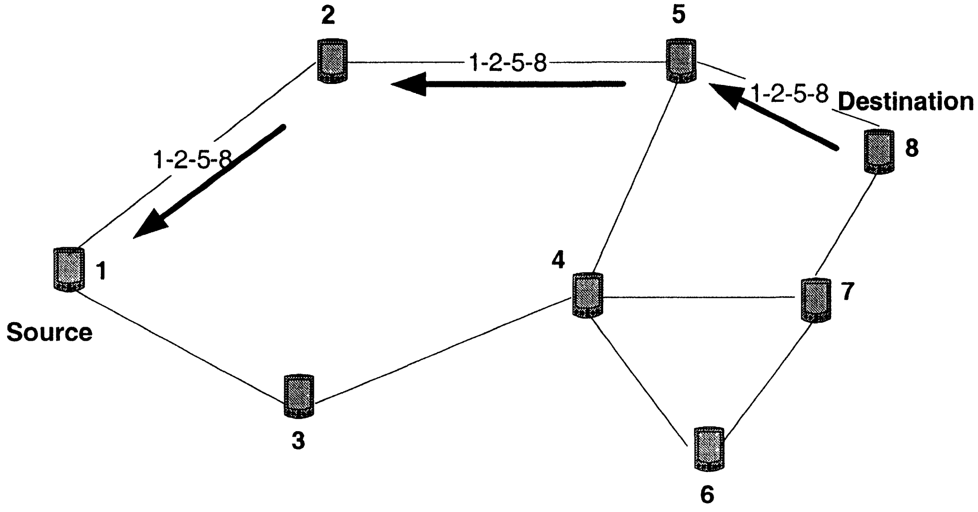

Figure 2.3: RREP propagation in DSR [15]

DSR provides a method for route maintenance. This is important since the dynamic nature of MTs can affect existing routes and hence, disrupt ongoing communications. For example, if a mobile station listed in a source route moves out of wireless transmission range, or is turned off, the corresponding route becomes unusable. The route maintenance procedure monitors the operation of routes and notifies the sources of any route errors. Route maintenance in DSR can be carried out in two different ways depending on whether the data link layer supports acknowledgements or not.

The first method utilizes the hop-by-hop acknowledgements at the data link level to detect lost or corrupted packets and hence, perform retransmissions. The MT transmitting the packet will be able to determine whether the hop to which it transmitted the packet is still functioning or not. A route error (RERR) packet is sent to the original sender whenever the data link layer reports a problem from which it cannot recover. The method of passive acknowledgement is utilized in networks that do not support such lower-level acknowledgements. This method relies on the fact that the sender of a packet may be able to hear the receiver's transmission of the packet to the next hop along the path to the destination. The source, upon the receipt of the RERR packet restarts the route discovery process.

2.2 Cellular Communication Networks

Ten years ago cellular communication was only restricted to a few people; however, recently it is not only regarded as a useful communication tool but it has also become a fashion accessory of one's life. The usage of cellular networks is not only restricted to voice but also high-speed data services and multimedia application. This is evident from the evolution of cellular systems from first-generation cellular system with analog frequency modulation techniques (e.g., AMPS) to third-generation cellular systems with wideband services like high speed Internet access, video and high quality image transmission with the same quality as the fixed networks (e.g., International Mobile Telecommunications 2000 (IMT2000) and UMTS). The way mobile terminals communicate with each other and gain access to the radio spectrum in cellular networks is different from that of the ad hoc networks explained in the above Section. Therefore, in this Section we will look at how MTs communicate with each other, how they can gain access to the radio spectrum, and how channels are allocated to MTs.

2.2.1 Connectivity in Cellular Networks

The cellular concept was first introduced by MacDonald [18] where the radio coverage area of a base station is represented by a hexagonal cell. BSs are placed in a cellular structure covering a geographical area and are connected to a Radio Network Controller (RNC) as shown in Figure 2.4. Neighbouring RNCs are possibly connected to one another and each can support a number of BSs. The RNC is connected to the Core Network (CN). The CN includes all the network elements needed for switching, routing and mobility management. Mobile terminals in each cell will then establish a connection (i.e., register) with the closest BS the moment they power up. Therefore, communications among MTs and communications between MTs and the outside world have to go through the BS. For instance, in Figure 2.4, if MT 1 wants to communicate with MT 2, MT 1 has to forward its data to BS 1 which will then forward it to the destination MT 2. Note that MT 1 cannot directly connect to MT 2 even though both nodes belong to the same cell. And, if MT 1 wants to communicate with MT 3, then it has to connect first with BS 1 which will send the data packets to the RNC which will then send them to BS 3 which will finally forward the data packets to MT 3.

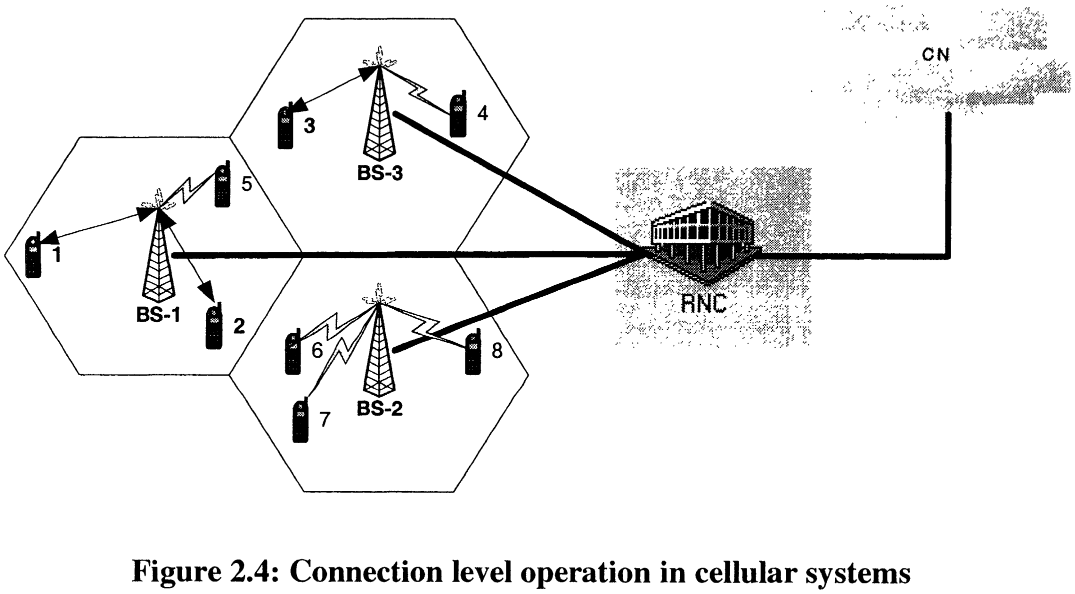

Figure 2.4: Connection level operation in cellular systems

2.2.2 Radio Access

Radio resources in Cellular networks are scarce. Therefore, to achieve high capacity, sharing of the spectrum is required. This will allow mobile users to simultaneously access the radio spectrum. The three major techniques used to share the available bandwidth in a wireless communication system are *Frequency division multiple access* (FDMA), *time division multiple access* (TDMA), and *code division multiple access* (CDMA). These techniques can be classified as *narrowband* or *wideband* systems, depending upon how the available bandwidth is allocated to the users. In narrowband the transmission bandwidth of a single channel is the same as the information bandwidth of the channel, while in wideband the transmission bandwidth of a single channel is much greater than the information bandwidth of the channel [19]. The details of the three techniques are as follows:

- *Frequency Division Multiple Access*

  In FDMA, the total frequency spectrum is divided into frequency bands or channels and assigned to individual users as can be seen in Figure 2.5(a). Once a channel is being assigned to a user, no other user can use that channel even if the channel is idle and not being used. Therefore, there is always a potential waist of system resources. Examples of FDMA based systems include AMPS, TACS, and Nordic Mobile Telephone (NMT).

- *Time Division Multiple Access*

In TDMA, the total frequency may be divided into frequency bands which are further divided into several *time slots* as depicted in Figure 2.5(b). Then each slot is assigned to a user on an on-demand basis. However, this implies that users will not have continuous transmission since they have to wait for their slots in a frame by frame basis. Examples of TDMA based systems include USDC standards IS-54 and IS-136, GSM, and PDC.

- *Code Division Multiple Access*

  In CDMA, the total bandwidth is shared by all users. Therefore, all communicating units transmit at the same time and over the same frequency as can be seen in Figure 2.5(c). This can be reached by spreading the spectrum and assigning a unique code (chip code) to each user. The user will then use that code, which is orthogonal to all other codes, to spread (encode) its narrowband signal to a much wider spectrum prior to its transmission. At the receiving end of the spectrum, the same code will be used to despread (decode) the received composite signal and obtain the original message. It is important to note that due to the act of spreading in CDMA, CDMA is classified as a wideband system. Examples of CDMA based systems include cdmaOne, IS-95, cdma2000, and UMTS.

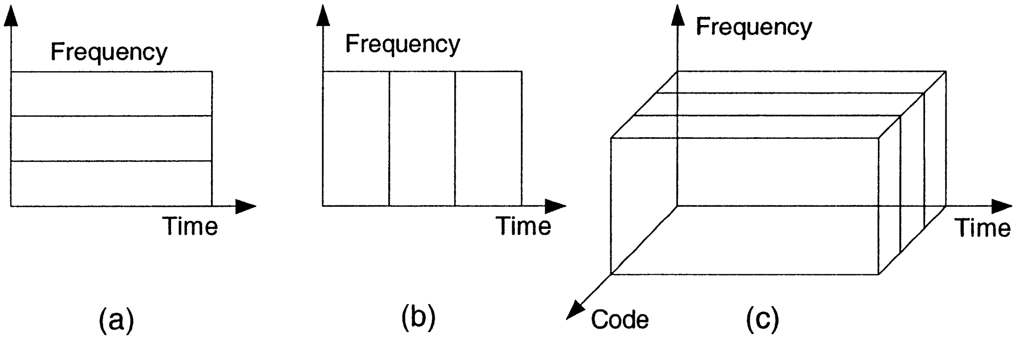

Figure 2.5: Multiple access schemes: (a) FDMA (b) TDMA (c) CDMA

2.2.3 Channel Allocation

Channel allocation in cellular systems is used for two reasons. The first reason is to allocate channels in such a way so that interference can be reduced. This leads to increasing the system capacity and throughput. In general, interference in cellular networks is caused by having two nodes (a transmitter and a receiver), each belonging to a different cell, using the same channel to communicate with other terminals. Therefore, the objective of the channel allocation algorithm is to ensure that such situation will not happen. The second reason is to allocate channels to adapt to traffic changes in the network. In this case, the channel allocation algorithm has to be adaptive to give cells with high traffic more channels to avoid call blocking. Channel allocation algorithms can be classified into three categories: Fixed Channel Allocation (FCA), Dynamic Channel Allocation (DCA) and Hybrid Channel Allocation (HCA). These schemes can be implemented either in a centralized or a distributed fashion. In centralized schemes, channels are allocated by a central controller. In cellular systems, this is usually the RNC. Based on the periodic exchange of information between the BSs and the RNC, the RNC makes the allocation decisions. On the other hand, mobile terminals in distributed schemes decide which channel to use based on local interference measurements. Obviously, this scheme has lower complexity and overhead than that of a centralized scheme but it is less efficient compared to centralized schemes [20].

In fixed channel allocation, channels are permanently allocated to a base station for its exclusive use. Channels that are assigned to one BS can be reassigned to another base station according to a reusability pattern which depends on the signal quality and the distance between the two BSs. FCA schemes are simple to implement; however, they do not adapt to changes in traffic patterns.

In dynamic channel allocation, base stations have no control over any particular channel. This is because all channels are placed in a pool and are assigned as they are needed (dynamically). Once a call terminates, the channel is released and put back in the pool. Therefore, DCA can easily adapt to interference and traffic conditions.

However, simulation results have shown that DCA [20] performs better than FCA under light traffic, but it performs worse than FCA under heavy traffic. As a result, hybrid channel allocation was introduced [20]. HCA is a combination of FCA and DCA whereby the set of channels is divided into two sets. One set is statically assigned to a base station as in FCA while the other set is shared by all BSs and is used as in a DCA. In this way, HCA uses the best of the two schemes by combining them into one.

2.3 Multi-hop Relaying

Several architectures addressing the issue of relaying in cellular networks have been proposed. In [21], the authors propose a new architecture named Unified Cellular and Ad hoc Network (UCAN). The work is based mainly on two assumptions. The first being that a mobile terminal is equipped with two independent interfaces: one for the ad hoc and one for the cellular network. The second assumption is that the BS has prior knowledge of the network topology. Based on the downlink quality between the BS and the destination, the BS instructs the client which interface to use. If the channel quality is poor, the BS will then divert the traffic to a proxy client with a better channel quality using the ad hoc interface. A node is considered to be a proxy if it has a high data rate available to it. The proxy client will then forward the data packets in a multi-hop fashion to the destination. With this architecture being the backbone of the system, the authors propose a novel greedy and on-demand protocol for proxy discovery and ad hoc route selection. The greedy approach is based on having each node proactively maintain a table of its neighbors' average downlink channel rates and then select the one with the highest rate for delivery. In the on-demand approach, the destination client reactively floods the network with a request message within a certain range. The request message carries the destination client's average downlink channel rate. Whenever a mobile client receives the request, it checks the downlink rate in the request with its own downlink rate. If its own downlink rate is higher, it will update the rate in the request and forward it to the BS to request for becoming a proxy client. Moreover, in order to motivate users to relay packets, a crediting mechanism is introduced. Simulation results show that the UCAN architecture can improve the individual user's throughput by up to 310 % and the aggregate throughput by up to 60%. Nevertheless, no means of increasing channel reuse through reassigning resources has been developed.

In [22] another multihop cellular architecture, namely Multi-hop Cellular Network (MCN), is proposed. MCN is similar to UCAN in the sense that users are assumed to be equipped with two interfaces: the ad hoc interface and the cellular interface. However, the objective of MCN is to decrease the infrastructure-related cost through deploying fewer BSs than the single-hop case, or to reduce the transmission power. Therefore, two variant architectures, MCN-b and MCN-p, were considered. As shown in Figures 2.6 and 2.7, in MCN-b the number of BSs is less than the number of BSs used in Single-hop Cellular Network (SCN), and the transmission range is the same as in SCN. Although the transmission range is the same as in SCN, the distance between two neighboring BS is k times the distance used in SCN. However, in MCN-p the number of BS is equal to the number of BS in SCN but with reduced transmission range for both the BS and the MS. The merits and limitations of MCN are examined, and the throughput is obtained and is shown to be higher than in the single-hop case.

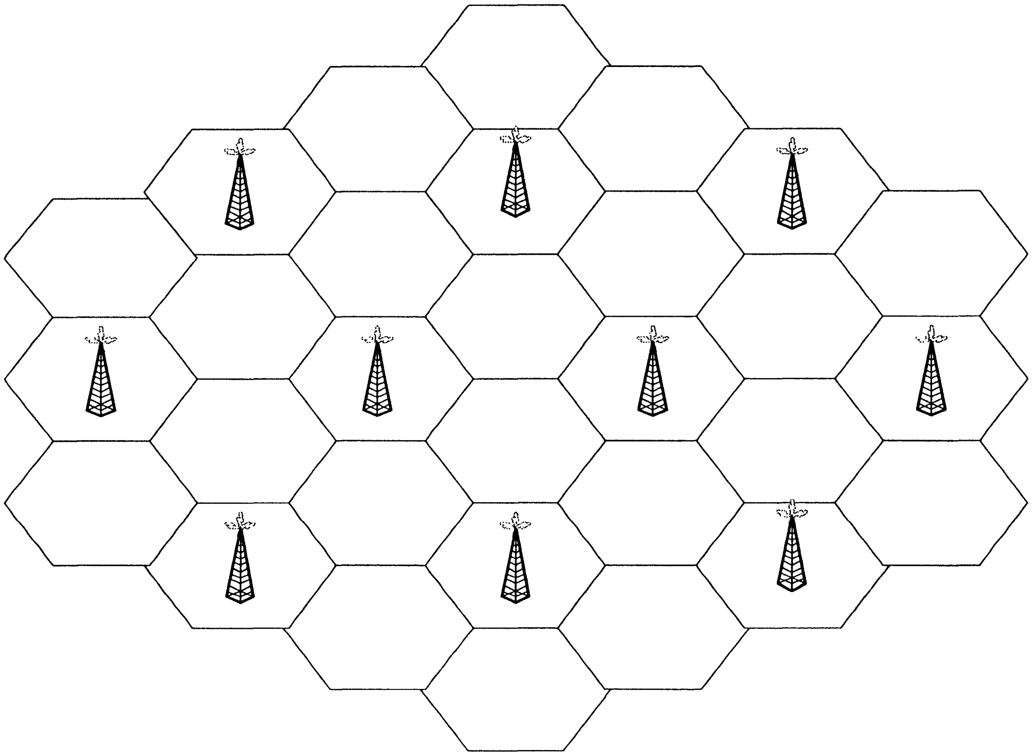

Figure 2.6: The MCN-b architecture [22]: fewer base stations are deployed

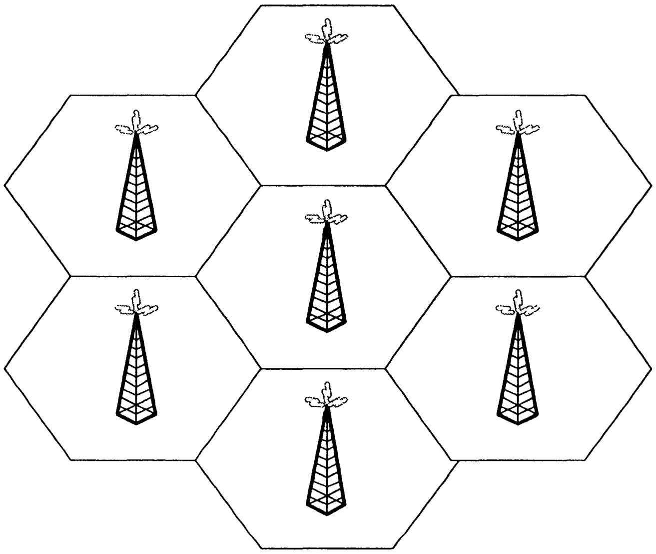

Figure 2.7: The MCN-p architecture [22]: the same set of base stations is used while the transmission power is reduced

A quantitative performance study is conducted in [23]. A Hybrid Wireless Network (HWN) model is proposed in which a node can be in one of three modes: BS-oriented mode, one-hop direct transmission mode and two-hop direct transmission mode. In the one-hop direct transmission mode, the sender can communicate directly with the receiver. In the two-hop direct transmission mode, the receiver can hear the signal through a neighbour of the sender. The BS-oriented mode where the communication is carried out through the BS will only be used if both modes fail to transmit the signal. Thus, multi-hopping will only take place if all the wireless stations lie within the cellular boundaries. As a result, HWN is quite limited since both the source and destination must reside within the same cell. Moreover, this protocol introduces extra overhead to the system due to the usage of nine control messages that have to be exchanged, from ACK, ACCEPT, REJECT messages to WHOSE-BS-ALIVE. This extra overhead makes HWN less attractive than MCN.

In [9], MCN and HWN are further analyzed using single data and single control channel. The authors then extend the HWN architecture from a single cell to multiple cells. In the new HWN, mobile terminals are equipped with Global Positioning System (GPS) and have two modes of operation: the cellular mode and the Ad hoc mode. In the ad hoc mode, nodes use DSR to acquire and maintain routes using RREQ, RREP and REER packets. Dijkstra's shortest path algorithm is used to find the favourable path to the destination. The simulation results of the extended HWN show that ad hoc mode works well for dense topologies and the cellular mode is better suited for sparse topologies. As a result, the authors further extend HWN and propose an algorithm which decides when to switch from one mode to another based on the topology of the network in order to maximize the system throughput. However, the extension of this algorithm requires HWN to be capable to operate in multiple cells. This, however, will raise the problem of how to make two cells operating in different modes communicate with each other. In this case, if the source node cell is operating in cellular mode, it will forward the packets to its BS using the cellular mode. The BS will then forward the packets to the destination's BS using the wired connection which will then use the ad hoc mode to reach the destination. However, if the source node is operating in ad hoc mode, then the BS of the destination node will function as a proxy for the destination node. Once a route to the proxy is found, the proxy, i.e. the destination BS, will then forward the packets to the destination using the cellular mode.

Throughput, coverage extension, and power consumption have been the target evaluation metrics for most multi-hop cellular network protocols. In [24], the throughput performance of Ad hoc GSM (A-GSM) system with respect to the number of dead spots locations, average dead spot size, and mobile node population has been investigated and compared to that of a pure GSM system. The results indicate that there is an 8–17 % improvement in the system throughput compared to that of a pure GSM. Area coverage and capacity enhancement have also been investigated in [25] and there the simulation results indicate that multi-hop relaying can increase the area coverage by 40 % compared to single-hop case.

In addition to increasing the system capacity and reducing power consumption, one of the objectives of introducing relaying in cellular networks is load balancing [27]. Load balancing is mainly required in dense and highly populated areas when the incoming traffic to the BS is more than what it can sustain while other BSs are underutilized. As a result, the BS will start dropping calls or connections. However, with multi-hopping, load balancing can be easily achieved by diverting traffic from congested BSs to less congested ones. In [27], a load balancing algorithm for multi-hop cellular networks is proposed. The algorithm can be described as being either a proactive or reactive load balancing algorithm. Proactive means that the algorithm tries to avoid congestion before it happens while reactive tries to divert traffic from congested BSs after it happens. Thus, nodes have to be periodically informed of the state of the cell. The cell can be in either one of two states: moderate congestion or severe congestion. When the BS starts to announce congestion, nodes start to search for relaying nodes to divert traffic from the congested BS. The discovery of relaying nodes is done in a broadcast manner. After finding several relaying routes, the searching mobile will then select the best relay route by computing relay desirability values which are a weighted function of the number of hops, power status of the node in the route and the mobile hosts' motion.

Another load balancing algorithm is introduced in [28]. The proposed scheme is called integrated Cellular and Ad hoc Relay (iCAR). This is similar to the work in [27] in the sense that relaying is used to shift traffic from congested BSs to less congested ones. In iCAR, the relaying is done by placing ad hoc relaying stations (ARS) at specific location to efficiently balance traffic. Normal mobile terminals are not allowed to relay traffic.

ARS functions as a mini-BS but with much less transmission range. ARS and mobile terminals are equipped with two interfaces: C interface, which is used for communicating with BS and operates around 1900 MHz, and R interface, which is used for communicating with ARS or mobile terminals and operates using an unlicensed band at 2.4 GHz. iCAR uses three types of relaying strategies: Primary relaying, Secondary relaying, and Cascaded relaying. In primary relaying, the MT will first send the request to the BS. If the BS does not send back an acknowledgement, this indicates the BS is in a congested state and can not support any more users. As a result, the MT will switch to the R interface and find the closest ARS which will relay the request to another less congested BS. If primary relaying is not possible, because the ARS is not close enough to the MT, then it restores to secondary relaying so as to free up a Dedicated Channel (DCH) from the congested BS for use by MT. This is done by finding a source and a destination in the same cell that can communicate with each other using ARS. If the second relaying fails, the MT will then use cascaded relaying at which point the request will be cascaded through ARS to further less congested BSs. Simulation results indicate that with iCAR power consumption can be reduced and load balancing can be achieved. However, iCAR introduces excess overhead to the system and may degrade the Quality of Service (QoS) due to switching from one interface to another by interrupting ongoing communications.

Load balancing can be also viewed as a routing problem since a route to a less congested BS needs to be found. Route selection criteria can differ from one routing scheme to another. For example, in [29] a hybrid of table-driven and on-demand routing protocol, called Base-Centric Routing (BCR) protocol, is proposed. The BS in this routing protocol uses the table-driven method to track topological changes and computes paths for MSs. On-demand routing is used to query the BS for paths and if the BS doesn't have a path to the destination, the path will be obtained by flooding as in AODV [17]. The BS obtains topology information by collecting Link State Packets (LSPs), each of which carries the list of neighbours of a specific MS. MSs obtain the neighbour list through the periodic BEACON messages from their neighbours. Hence, each MS must periodically send BEACON and LSP messages. MSs learn the paths to the BS via the flooded HELLO messages which are periodically sent out by the BS. The path with the smallest hop count will then be selected. The data will then be forwarded on this route until the packets reach the BS. The work in [30] is similar to BCR in the sense that the path will be selected based on the shortest overall path or based on the path with the least longest hop count. However, in [30], relaying nodes that form the route are selected either based on distance path-loss or randomly. The simulation results show that selection schemes based on path-loss offer a superior performance to those based on the distance and randomness. Path-loss selection strategy is further investigated in [31] and [8]. Minimum transmit power is another selection scheme and has been investigated in [32] where the routing protocol will select the path with the minimum interference-sensitive link cost rather than with minimum path loss. The cost function will then take into consideration the aggregate power, and the interference caused at both the relaying node and the destination. The path with the smallest cost will then be selected. However, the control overhead associated with routing is known to degrade the throughput of a multi-hop wireless network, which can make multi-hopping inefficient.

Most of the multi-hopping schemes that we have considered so far use two independent interfaces: a cellular interface and an ad hoc interface. As a result, interference is not a major concern when it comes to the system throughput and coverage extension. However, using two interfaces not only increases the system complexity but also adds extra costs to the user equipment [33]. A. Zaheh and B. Jabbari propose the use of a single interface in [34] and derive a closed form expression for the probability density function of interference at the receiving node. In this work, both uplink and downlink are considered and CDMA is used as the radio access technique. Packet relaying is done in the same frequency band using the Time Division Duplex (TDD) scheme. The channel interference model applied is based on summing the interference powers and treating the total interference as Gaussian noise. The noise at the receiver is due to constant background thermal noise[2] and interference from all transmitting terminals and router. Similarly, in [35] users' equipment have only one interface. CDMA-TDD is also used as the radio access technique; however, only the uplink connection is considered. In [35], each mobile is informed of the path loss of its link to the BS via the control signal received from the BS. So a node far from the BS will send a packet to the BS via neighbouring mobile that has a better link to the BS. The relaying will continue to the BS unless the path loss between the relaying mobile and the BS is less than a predetermined threshold or the number of hops is more than a predetermined value. In this scheme, a source node with a weak link to the BS broadcasts a request to its neighbouring mobile terminals. The neighbouring nodes will then use the pilot channel to send information back to the source. The information includes the strength of the link between the relaying node and the BS.

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[2] Thermal noise is a measure for the amount of external interference generated by various sources in and around the cell.

The nodes with the strongest connection to the BS will be selected and notified by the source. The relaying node will then allocate the uplink slot for the data packet, and the source mobile finally transmits its data packets via the allocated uplink slot. The frame structure consists of a number of uplink and downlink slots. The uplink slots can only be used for relaying packets and signaling. Each signaling slot is further divided into a number of minislots and the uplink data traffic is transmitted in the whole uplink slot. The signaling message is transmitted in only one of the minislots. During an uplink slot, interference between the data traffic of one relaying node and signaling traffic of another node can happen. However, the data traffic and signaling messages are encoded with different CDMA codes. Therefore, any mobile that sends a request should encode that message with one of the request (REQ) codes from a predetermined set of CDMA codes allocated for REQ communications (C_Q). When a mobile station powers up, a temporary unique user identification (ID) is allocated to the mobile. In finding a mobile to relay a packet, another number referred to as a "group ID" is used. When a source receives the response (RESP) message from its neighbours and selects the one with the smallest group ID, it will send an allocation (ALLC) packet to the relaying node. The allocation message includes user ID or the source mobile, the packet type, the number of hops, bit rate, required SIR, and data packet length. Upon receiving the ALLC packet from the source mobile, the relaying node transmits the data packet as well the user ID of the relaying mobile and the data transmission code. In the next frame, the source starts transmitting its data packets with the code and the time slot received from the permission (PMT) message.

Opportunity-Driven Multiple Access (ODMA) has been proposed by the 3rd-Generation Partnership Project (3GPP) [36] to increase the efficiency of UMTS using the TDD mode. ODMA was first introduced by the European Telecommunication Standards Institute (ETSI) in 1996, after which a number of contributions have been presented. One of the objectives of ODMA is to increase the capacity and efficiency of radio transmissions towards the boundaries of the cell. This can be achieved by relaying weak transmissions over a number of hops with a high data rate. Each relaying node must be in the planned coverage area of the BS and hence any node outside the coverage area of the BS will not be able to use relaying. One possible implementation of ODMA functions is to integrate them with the TDD functions (see Figure 2.8). However, such kind of integration will require changing information such as synchronization and paging messages. Another possible implementation is to use FDD rather than TDD. However, incorporating relaying into FDD system requires deploying last-hop gateway relay nodes.

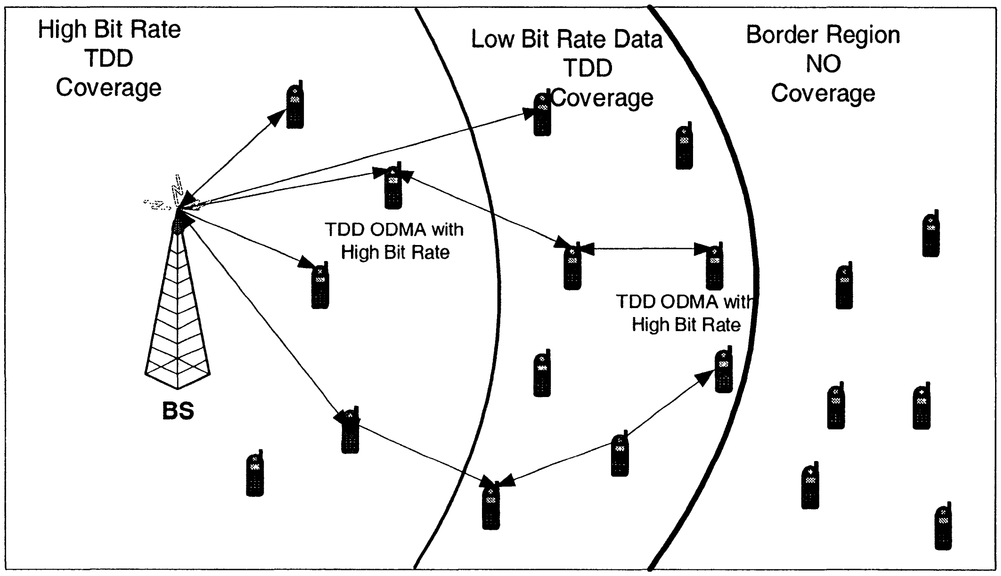


Figure 2.8: ODMA Border Coverage

Neighbour list are a key element in ODMA. Each terminal maintains a neighbour list that contains information about the neighbours that are necessary to access the links. Neighbours' information are acquired by a mechanism called probing. Probes, props responses and route request responses are broadcasted on ODMA Random Access Channel (ORACH). Other mobile terminals that are listening on that channel will receive the broadcast packet and each will register the sender mobile as a neighbour and send an addressed probe as a response.

Even though ODMA has been dropped from the UMTS standard due to concerns over complexity and signaling overhead issues, it still attracts researchers [37], [38], and [39]. In [37], a new result of the potential gain for ODMA has been investigated through link layer and system simulation. Propagation of lognormal slow fading environments and open and closed loop power control mechanisms have been deployed. Two simulation models have been implemented: static model and dynamic model. In the static model nodes are assumed to be fixed while in the dynamic model nodes are moving. The simulation results show that there is large reduction in power consumption due to the introduction of ODMA in UMTS system. In [39], a new admission control and routing algorithm based on path and/or the location of the recipient are studied. Methods for single-hop, two-hop and interference-based ODMA are proposed. Interference-based ODMA allows the network to adapt to interference by computing the total path loss from an immediate neighbour and the target node. Simulation results show that the latter scheme enhances capacity (defined as the number of supported calls/users), and reduces power consumption, which confirms the result reported in [37].

2.4 Summary

Multi-hop relaying has found its way to cellular networks and has become the center of research not only in ad hoc networks but also in cellular networks. A few schemes and architectures have been proposed to address the problem of adopting multi-hopping in cellular networks. The objective of these schemes is to enhance the coverage and capacity of the network and decrease the blocking ratio. Most of the proposed architectures assume that the user equipment is equipped with two independent interfaces. Such assumption oversimplifies the problem since interference in such cases is not of a major concern due to the operation in two separate frequency bands. However, such techniques will not only increase the device cost but also add extra overhead to the system. As a result, schemes that use one interface for both the cellular system and relaying are emerging. The major obstacle that these schemes have to face is interference. This is because if interference is not being handled carefully, relaying will not enhance the system performance but rather degrade the performance. Nevertheless, these schemes only look at the surface level of the relaying concept and fail to look at the in-depth picture of adopting such technology; therefore, leaving many details unexplored. Such details can have a large impact on the system performance which might lead to incorrect results. Slot assignment is one of these details, which impacts performance results. Moreover, it is worth mentioning that most of the work done in multi-hop cellular networks avoids computing the end-to-end delay due to the general misconception that the delay with multi-hopping is higher than that of a single-hop. Therefore, in Chapter 3 we propose a simple yet affective Delay-Sensitive Slot Assignment (DSSA) scheme for Time Division Duplex (TDD) WCDMA cellular networks.

Chapter 3

Delay-Sensitive Slot Assignment (DSSA)

This Chapter gives a detailed overview of the proposed channel assignment scheme for Time Division Duplex (TDD) WCDMA multi-hop cellular networks. The proposed scheme utilizes the architecture developed in [2], [3], [4], namely the A-Cell architecture, and devises a heuristic slot assignment scheme. First, we present the network architecture including the advantages of adopting the TDD technology over the Frequency Division Duplex (FDD) technology. Then, we describe the TDD frame structure and the traffic model. After that, two slot assignment schemes, namely Random Slot Assignment (RSA) and Delay-Sensitive Slot Assignment (DSSA), are presented and illustrated.

3.1 Network Architecture

The network architecture is shown in Figure 3.1. A cellular infrastructure consisting of a single node B, referred to as BS in the rest of this thesis, and the corresponding radio network controller is used as the system's forwarding backbone. The network topology is stored, and periodically updated, in the RNC. The mobile terminals are uniformly distributed throughout the cell.

All the MTs are equipped with GPS chips and are thus capable of computing their distances to the BS. They are also equipped with a single transceiver. Even though only one transceiver exists, normal user terminals still act as a relay for other nodes (i.e., there are no separate relay entities in the network); hence, no additional infrastructure is needed. This interface uses the TDD W-CDMA radio access technology. TDD W-CDMA is described in more detail in Section 3.1.2. The terminologies for the network entities that will be used hereafter are defined as follows:

- ***Source Node:*** The user node at which the data transmission is initiated.
- ***Relay Node:*** The user node that assists a source node or an intermediate node, which can be inside the transmission rage of the BS or in a dead spot, to forward their traffic to the BS or another relaying node apart from its own data traffic.
- ***Base Station:*** The base station is primarily responsible for connecting nodes to the backbone and acquaints the RNC of the network topology. It is also assumed to be the ultimate destination for all source nodes and relaying nodes in its domain. This is mainly because only uplink or reverse link connections are considered.
- ***RNC:*** The RNC is mainly responsible for managing the system resources in its domain (i.e., channel assignment and scheduling).

- ***Uplink Channel:*** Is a channel that carries data or control information towards node B.

Aggressive channel reuse is considered in the cell. To our best knowledge we are the first to consider channel reuse in the same cell. This means no cell planning is required and same-entity interference is considered. Same-entity interference is a mobile to mobile interference while other-entity interference is BS to MT or MT to BS interference and is not considered because only one cell scenario is being studied. Using the same channel frequency for relaying as well as for regular single–hop communication, a fair spectral comparison of multi-hop cellular network with traditional single-hop cellular network, is ensured.

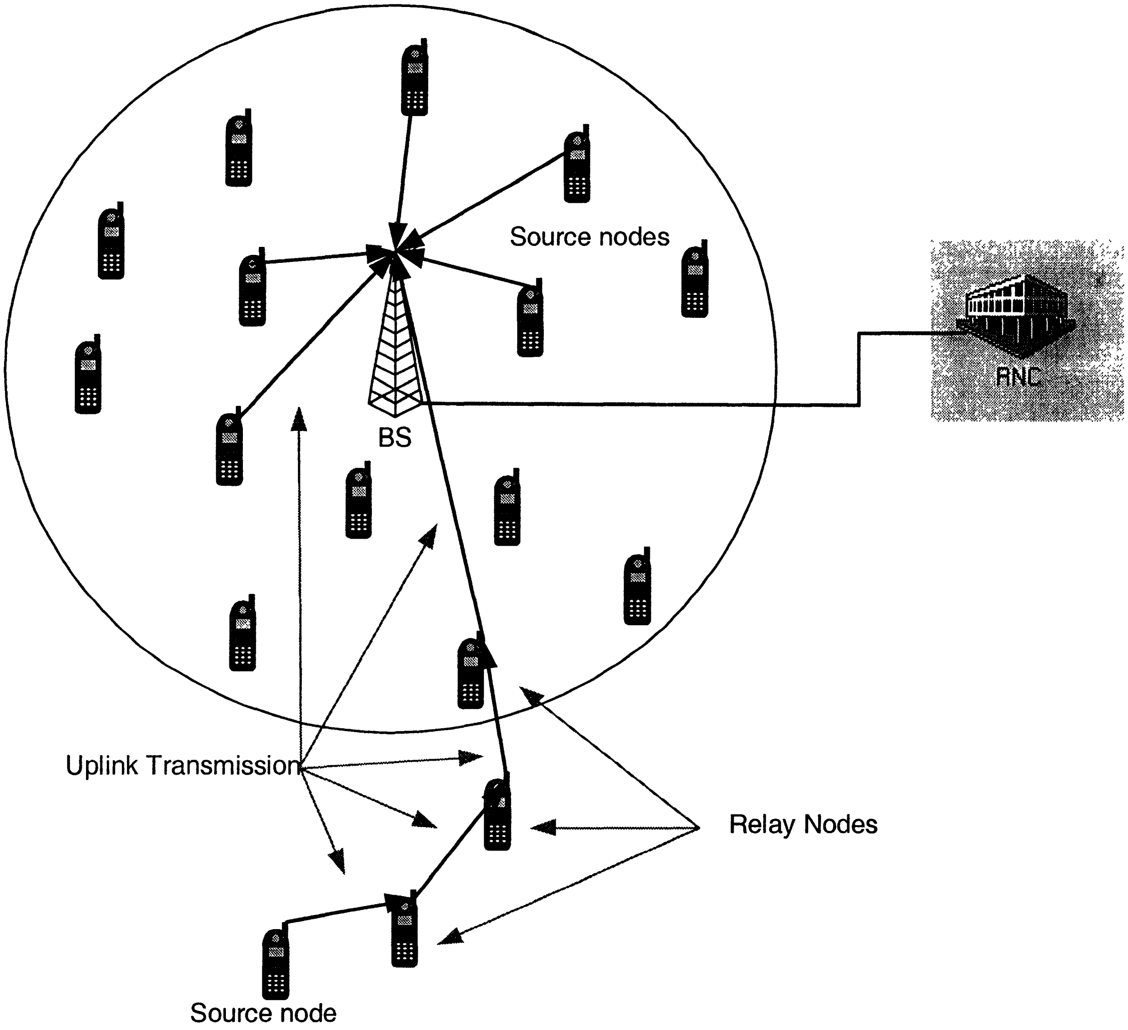


Figure 3.1: Multi-hop cellular network

3.1.1 The Ad hoc-Cellular Architecture (A-Cell)

In A-Cell [2], [3], [4] nodes are also assumed to have directive antennas to increase the spatial reuse. The use of directive antennas in a multi-hop TDD W-CDMA wireless network reduces interference and power consumption and enhances spatial reuse.

Nodes at the edge of the cell or in heavy populated areas experience poor single-hop coverage. Therefore, to reduce the call blocking and increase system capacity (defined as the number of supported calls/users), the call initiator or the source node broadcasts the RREQ omni-directionally to its neighbours in the same manner as in DSR (see Section 2.1 for more details). The RREQ contains the location information of the source node. Upon receipt of the RREQ, a neighbour rebroadcasts the RREQ if, and only if, it has not seen the RREQ before. The neighbour node also stores the location of the source and appends its own location information in the RREQ. The RREQ propagates in this fashion until it reaches a node which can communicate directly with the BS (see Figure 3.1). Once the BS receives the request and the locations of all nodes from the source to the BS, it updates its stored route record with the new information and passes on the location information to the RNC to update the topology information and neighbourhood information. The RNC then computes the slot assignment algorithm and if all nodes in the route can be accommodated, it will grant the RREQ.

The RNC then returns an accept message to the BS with the channel assigned to each node in the route. The BS then replies back with a RREP packet which includes the route record, location information and slots assigned to each relaying node. The RREP will be sent in a unicast fashion as in DSR. However, nodes now will use the location information stored in the RREP to direct their antenna to the next node toward the source node. Upon receipt of the RREP packet the source node will use the channel assigned to it and direct its antenna to the next hop and start transmitting traffic.

If there are not enough channels to support the multi-hop route from the source node to the BS, the RNC will not reply back causing the RREQ sent by the source to time out. The source node will then back off for some time and try again.

3.1.2 Wideband-CDMA

CDMA is the access scheme for UMTS Terrestrial Radio Access (UTRA). The information is spread over a band of approximately 5 MHz. This wide bandwidth has given rise to the name Wideband CDMA or W-CDMA. The key features of W-CDMA radio interface are [40]:

- Support of high data rate transmission: 384 kbps with wide area coverage and 2 Mbps with local area coverage.
- Coexistence of both Frequency Division Duplex (FDD) and Time Division Duplex (TDD).
- Support of variable user rate services on each connection.
- Support of future capacity and coverage enhancing technologies like adaptive antennas, advanced receiver structures and transmitter diversity.

3.1.2.1 FDD vs. TDD

UMTS, defines two different duplexing schemes for the radio access:

- Frequency Division Duplex (FDD)

FDD, also known as full duplex, uses two separate frequency bands, one for the downstream transmission and another for the upstream transmissions. Each of the two frequency bands is 5 MHz. The two frequencies are separated by a frequency guard-band. A frequency guard-band is used to ensure that no self-interference is present between the uplink and the downlink transmission. See Figure 3.2 for details.

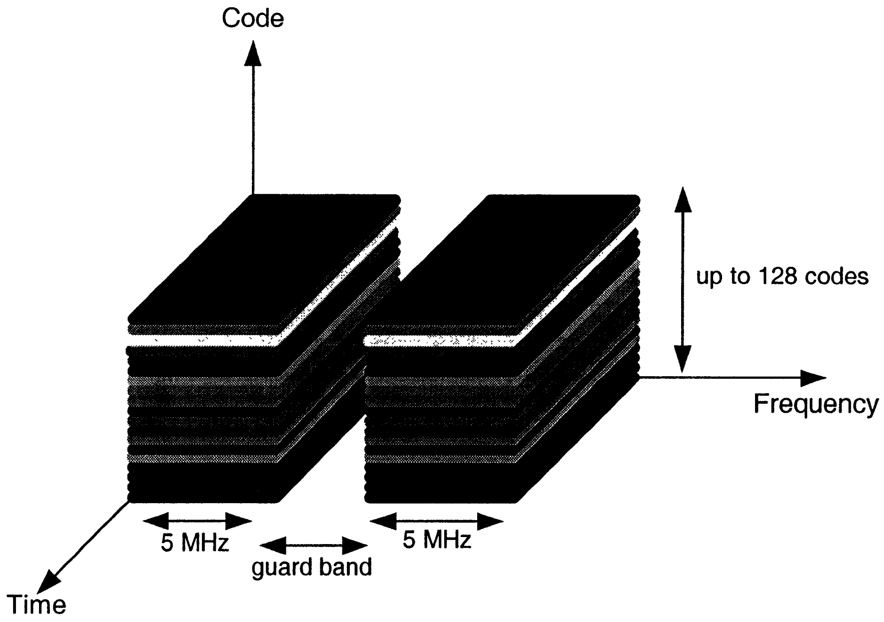


Figure 3.2: FDD duplex scheme

- Time Division Duplex (TDD)

TDD, also known as half duplex, uses the same frequency band of size 5 MHz for both the downstream and upstream transmission. Uplink and downlink transmissions take place at different times, hence self-interference between the two is completely avoided. Nevertheless, the guard period between the uplink and downlink still exists. However, here it is not used to avoid interference but rather to avoid the overlapping of transmission (collision) due to propagation delay and switching time between uplink and downlink. See Figure 3.3 for details.

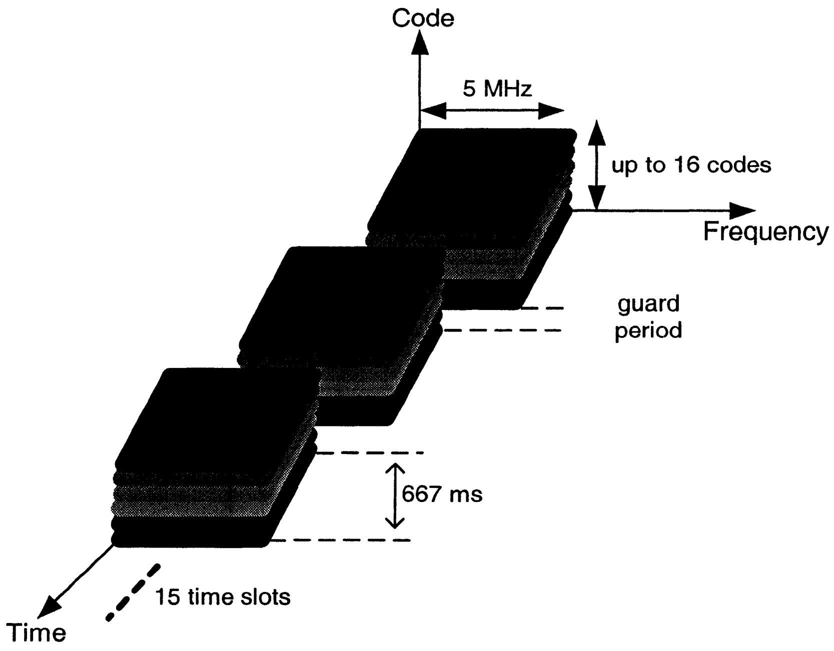


Figure 3.3: TDD duplex scheme

In the context of multi-hop relaying in cellular networks, TDD would offer more advantages over FDD for the following reasons:

- TDD is more flexible in terms of adapting to asymmetric data traffic. This is because the number of time slots allocated for the uplink and downlink can vary as a function of the service demand. However, in this study we assume that a fixed number of slots are allocated for the uplink in order to reduce system complexity, thereby concentrating only on the slot assignment mechanism.

- TDD radio allows communications over a single physical radio channel and is thus simpler than using FDD operation which requires two physical radio channels. However, since the cost is generally related to complexity, TDD radio can be expected to be less expensive than that of FDD.
- Currently adapting FDD for multihop relaying is physically impossible. This is because a node cannot transmit and receive at the same time. For instance, in Figure 3.4, both MT 1 and MT 2 need to be receiving in frequency 1 and transmitting in frequency 2 in order to enable communication with the BS. However if we want to make the two MTs communicate with each other, for the purpose of relaying, then one has to transmit in frequency 1 and the second has to receive in frequency 1 but this is physically impossible. In TDD the situation is different because one frequency is used for both transmissions and receptions.

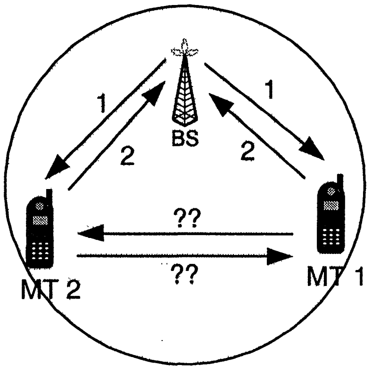


Figure 3.4: FDD uplink, downlink transmission

3.1.2.2 TDD Frame Structure

As depicted in Figure 3.5, the TDD frame has a duration of 10 ms and is subdivided into 15 time slots each with a duration of 667 μs according to the 3GPP specifications [41]. The time slots are used in the same manner as in TDMA to separate user signal in the time and code domain. Each time slot is allocated either to uplink or downlink transmission. However, in any allocation, at least one slot is allocated for the uplink transmission and at least two slots are allocated for the downlink transmission. Each time slot has up to 16 orthogonal codes. Two codes are said to be orthogonal if, and only if, the dot product of codes equals to zero. A combination of code and slot forms a channel. Therefore, one frame can contain a total of $16 \cdot 15 = 240$ channels.

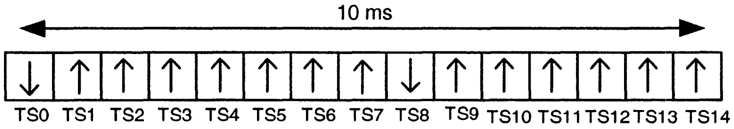


Figure 3.5: Frame structure of TDD

3.2 Antennas

In the context of a multi-hop cellular network, antennas are deployed by the mobile terminals to reduce the affect of same-entity interference (MT to MT interference). They can operate in two modes: *Omni* and *Directional.* We assume that a node can operate in any one mode at a given time. In the *Omni* mode, the beamwidth of the antenna is set to be 360°; hence, covering the entire plane. This mode is mainly used by the source node and the relaying nodes to broadcast the RREQ. However, in the transmission of RREP and data packets, each node knows the location of the next hop and hence it uses the *Directional* mode and sets its beamwidth to 45° toward the next hop. For more details please refer to Figure 3.6.

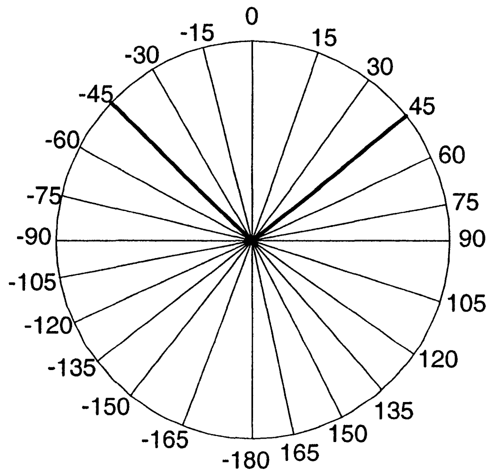


Figure 3.6: Omni/Directional antenna's beamwidth

3.3 Slot Assignment Schemes

Channel assignment schemes can be carried out in either a centralized fashion or a distributed fashion. The latter requires each node to make a channel (slot and code) selection on the fly based solely on locality information. Distributed channel assignment schemes tend to be more appealing for ad hoc networks due to the absence of a centralized entity. However, in a multi-hop cellular network one needs to take advantage of the existence of the centralized entities (i.e., nodes Bs and RNCs). Since the RNC has a wider knowledge of the system topology than that of a node B, we decided to devise a centralized RNC-driven channel assignment algorithm. Moreover, connection billing and monitoring may thus be handled easily by the service provider.

3.3.1 Random Slot Assignment (RSA)

Most of the work done in slot allocation using TDD [42], address only the *switching point* problem. The switching point problem in TDD is the problem of deciding how many slots should be allocated to the uplink transmission and how many slots should be allocated to the downlink transmission. A Random Slot Assignment scheme can be used. However, we show that the deployment of such naïve channel assignment scheme, which is assumed by most of the work done in multi-hop cellular networks, can have adverse effects on the system performance.

In RSA, channels are placed in a pool. RSA then randomly selects a channel from the pool. Once a channel is selected, this channel is not allowed to be reassigned to another mobile. This will ensure that same-entity interference is completely avoided. Once a connection is terminated, the corresponding channels are released and returned to the channel pool.

3.3.2 Delay-Sensitive Slot Assignment (DSSA)

DSSA is a heuristic fixed slot assignment scheme. It is composed of two phases, namely the *elimination phase* and the *selection phase*. In the elimination phase, a slot is eliminated if, and only if, assigning that slot will cause a large interference with other ongoing transmissions. This is done based on the neighborhood information of the node requesting a channel or a slot. At the end of this phase a set of slots will remain as possible candidates at which point the selection phase will be activated. During the selection phase, the slot with the minimum cost will be selected. The cost function is based on computing the *slot waiting time* for each slot. The slot waiting time is the time a mobile terminal has to wait for its designated slot before it starts transmitting. Once a channel is assigned to a node, all incoming traffic to that node will be aggregated and transmitted on that channel.

The DSSA algorithm is executed by the RNC. The execution of the algorithm is triggered by the arrival of the RREQ (session request) at the RNC. The variable definitions and the algorithm are formally stated in Figure 3.7. Line 1 determines the number of slots that should be allocated to the uplink and downlink transmissions. However, as mentioned above, the purpose of DSSA is not to estimate the switching point but rather to assign the slots in an effective manner after the number of available uplink slots has been determined. The reason this part is added, is to ensure that the algorithm is compatible with any *switching point* algorithm. We allocated the maximum number of slots, which is 13 according to the 3GPP specifications [41], to the uplink transmissions. The algorithm then reverses the route in the RREQ. This will ensure that the closest node to the BS (i.e. zero hops away from the BS) is handled first (see Lines 3-5). Since the BS is the destination of all nodes, we need to make sure that all incoming connections to the BS arrive in different channels. This is necessary to ensure interference free situation at the BS (see Lines 6-8). If one channel is available then assign that channel; however, if more than one exists then select the one with the maximum slot number. The reason for this will be clear when we discuss the slot selection procedure (Figure 3.8).

Line 13 handles the channel assignment for nodes that are more than zero hops away from the BS. It starts by invoking the elimination phase (see Lines 14-18). The elimination phase here is different from that of a single or zero hops away from the BS. Here, the RNC uses the neighbourhood information to eliminate candidates. It initially, selects a channel from the pool of channels and then performs two tests (Lines 16 and 17). First, it makes sure that none of the neighbours of the previous node in the route is transmitting on channel $C_{<i,j>}$. This will avoid interference at the previous node caused by using $C_{<i,j>}$. Second, it checks whether any neighbour of the node in consideration is receiving on channel $C_{<i,j>}$. This will prevent interference from happening at the neighbours of the node in consideration. If the channel passes these two tests, the channel is added to the set of possible candidates

```
Let $i$ be the time slot number where $i$ = 1, 2, 3, ..., NumOfSlots.
Let $j$ be the orthogonal code number in a slot where $j$ = 1, 2, 3, ..., NumOfCodes.
Let the superscript $u$, $d$ refers to the uplink or downlink connection respectively.
Let $C_{<i,j>}$ represents uplink channel using slot $i$ and code $j$.
Let $R^r$ represents a request for channels for all nodes in route $r$ sent by source node to the
    BS. $r$ is an order list of nodes.
Let $F_C$ is a set representing the channel profile stored at the BS.
Let $N_v$ set of neighbours of node $v$ stored in the BS.
Let $S_{BS}$ be the set of incoming channel connections to the BS.
Let $S^v$ be the set of channels that can be a possible candidate for node $v$.

Begin
 {
1.      Based on the current system load, estimate uplink to downlink slot ratio

2.      for each $R^r$ received by the BS
```

```
    {
    reverse the route $r$ and store the reversed route in $r'$

    for each node $v_t \in r'$
    {
       if $v_t$ is 0 hops away from node B
       {
          for $i = 1 \rightarrow NumOfSlots$
          // elimination phase
          {
             for $j = 1 \rightarrow NumOfCodes$
             {

                if $C_{<i,j>} \notin S_{BS}$ then add $C_{<i,j>}$ to $S^{v_t}$

             }
          }


    // selection phase
            if $S^{v_t}$ has a single member then assign that channel
            else $(\forall C_{<i,j>} \in S^{v_t})$ select the channel with max $i$


            // update the channel table and the set of incoming connection to BS
            Add $C_{<i,j>}$ to $F_C$
            Add $C_{<i,j>}$ to $S_{BS}$


          }
          else if $v_t$ is $h$ hops away from the BS
          {
             // elimination phase
             for $i = 1 \rightarrow NumOfSlots$
             {
                for $j = 1 \rightarrow NumOfCodes$
                {
                    if any neighbour of $v_{h-1}$ is transmitting on $C^u_{<i,j>}$ then
                       break;
                    else if any neighbour of $v_h$ is receiving on $C^u_{<i,j>}$ then
                       break;
```

```
18.                 else add $C^{u}_{<i,j>}$ to $S^{v_h}_{C}$
                }
            }

            // selection phase
19.         // call the selection procedure and pass $S^{v_h}_{C}$ as a parameter
20.         // add the selected channel to $F_C$
        }
    }
  }
} // end
```

Figure 3.7: DSSA algorithm

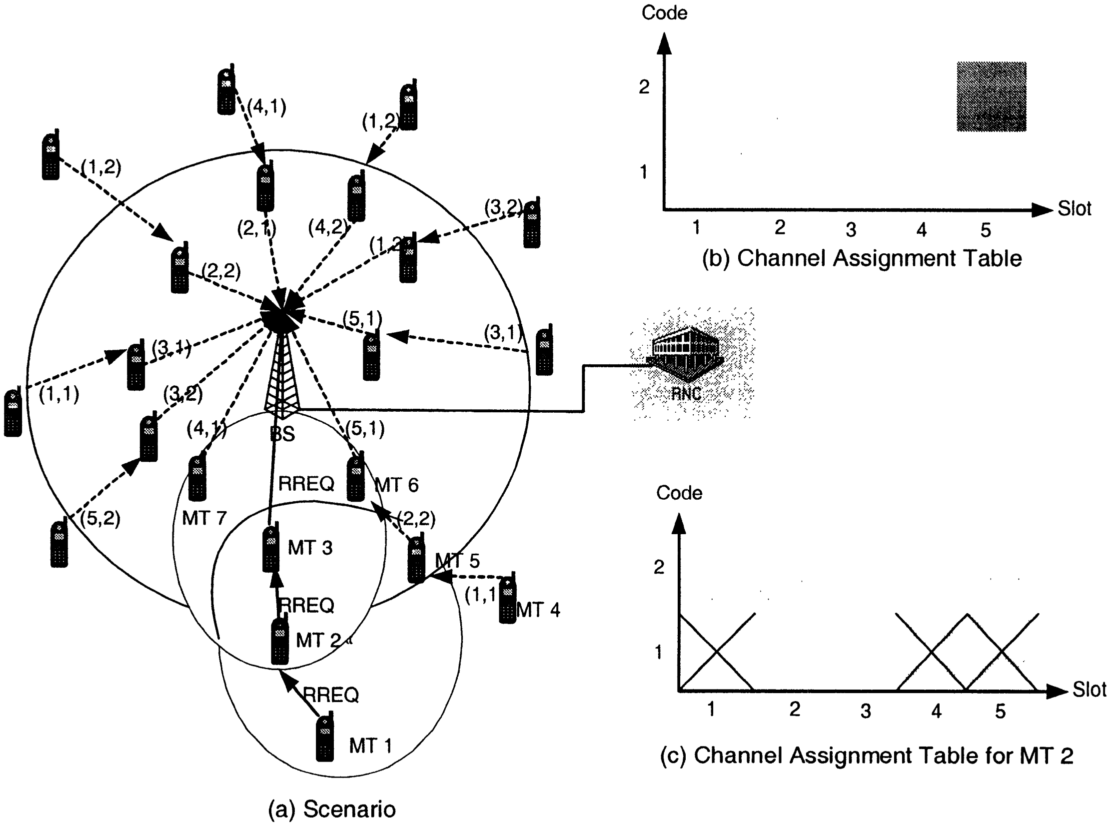
The set of possible candidates for a node in a route is then passed to the slot selection routine, which is depicted in Figure 3.8. The slot waiting time is calculated for each slot and the slot with the minimum waiting time is selected (see Lines 1 and 2). The objective of this calculation is to ensure that when a packet is sent from node v to node $v+1$, and by the time the packet reaches node $v+1$, the time slot assigned to that node is up. Therefore, the slot waiting time of the packet at node $v+1$ is as small as possible. Hence, nodes that are zero hops away from the BS need to have the highest slot number assigned to them. This will guarantee fast delivery of data from the source node to the BS. In other words, a route with slots (1, 2, 3, 4, 5) assigned from the source to the BS is better than a route with slots (1, 2, 3, 4, 2). This is because the last node with slot 2, in the latter route, has to wait for the next frame since slot 2 has already passed in the current frame. However, in the first route the last node with slot 5 does not need to wait for the next frame but rather transmits in the current frame.

```
Let $SW_{v,k}$ be the slot waiting time for node $v$ in route $k$.
Let $FL$ be the frame length in seconds.
Let $SS$ be the slot size in seconds (i.e., $SS = FL/NumOfSlots$).
Let $SN_{v,k}$ be the slot number assigned to node $v$ in route $k$.
Let $i$ be the slot number where $i = 1, 2, 3, \ldots, NumOfSlots$.
Let $C_{<i,j>}$ represents uplink channel using slot $i$ and code $j$.

Begin
{
    // for each channel $C_{<i,j>}$ from the set of possible channels compute the slot waiting
    // time of using slot $i$.

    1. $SW_{v,k}(i) = \begin{cases} (SN_{v-1,k} - (i+1)) * SS & \text{if } i < SN_{v-1,k} \\ (NumOfSlots - 1) * SS & \text{if } i == SN_{v-1,k} \\ ((NumOfSlots - i) + (SN_{v-1,k} - 1)) * SS & \text{if } i > SN_{v-1,k} \end{cases}$

    // from the set of possible slots select the one with the minimum slot waiting time

2.  $C_{<i,j>} = \min_{1 \le i \le NumOfSlots} (SW_{v,k}(i))$
} // end
```

Figure 3.8: Slot selection procedure

3.4 DSSA Illustrated

To further demonstrate how DSSA works, consider the multi-hop cellular network in Figure 3.9 (a). In this example, we only consider five slots and two orthogonal codes for simplicity. A dashed line represents an ongoing uplink transmission and the channel is represented by the pair (x, y), where x is the time slot number and y is the code number. The current state of the channel assignment table is also shown in Figure 3.9 (b). A darkly shaded slot indicates that the channel does not belong to the set of incoming connections to the BS while a lightly shaded slot indicates the opposite. Currently, channel (5, 2) is the only channel that does not belong to the set of incoming connections to the BS and MT 1 is the source node requesting a channel.



(b) Channel Assignment Table

(c) Channel Assignment Table for MT 2

(a) Scenario

Figure 3.9: Elimination phase in DSSA

Initially, MT 1 broadcasts a RREQ. MT 2 receives the RREQ and rebroadcasts it. This process will be repeated until the RREQ reaches the BS. As mentioned in Section 3.1.1, the RREQ arriving at the BS will have the route record [MT 1, MT 2, MT 3] (see Figure 3.9 (a)). The BS will forward the RREQ to the RNC, which will then invoke the DSSA scheme and attempt to assign channels to these nodes based on the stored topology information. The process will first start by assigning a channel to MT 3. However, since in this case only one channel is available (i.e., channel (5, 2)), it will only be temporarily assigned. Note that assigning any other channel to MT 3 will cause interference at the BS. The RNC will then process MT 2 and execute the elimination phase of the DSSA scheme. In this phase, all channels will be tested for validity. For instance, DSSA checks if any neighbour of MT 3 is transmitting on channel (1, 1). In this example, none of the neighbours of MT 3 is transmitting on that channel. DSSA then checks if any neighbour of MT 2 is receiving on channel (1, 1). It can be seen that one neighbour of MT2, namely MT 5, is in fact receiving on channel (1, 1). As a result, this channel assignment option will be eliminated as it leads to interference at MT 5. This process will be repeated for the remaining channels. Eventually, channels (1, 1), (4, 1), and (5, 1) are eliminated (see Figure 3.9 (c)). The rest of the channels are then passed to the slot selection procedure, described in Figure 3.8. The resulting assignment is shown in Figure 3.10. Finally, the slot with the minimum slot waiting time (i.e., channel (4, 2)) will be assigned to MT 2. In a similar manner, channel (3, 1) will be assigned to MT1. Once all the nodes in the route are accommodated, a RREP will be sent back with the channel assigned to each node, as depicted in Figure 3.10.

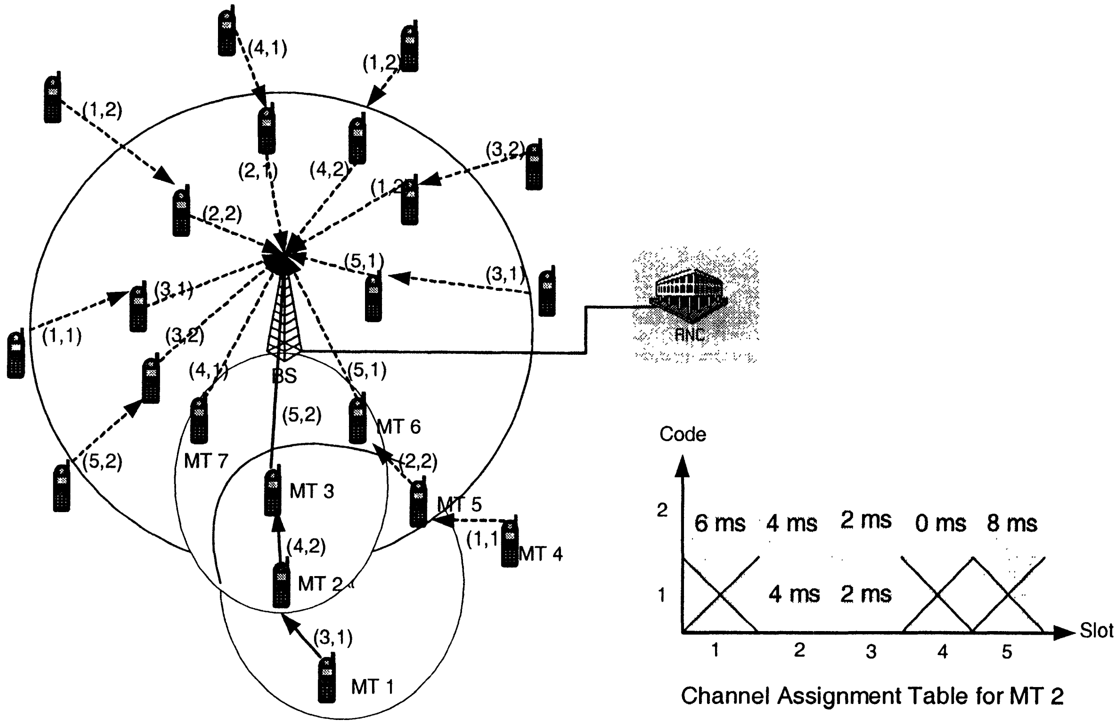


Figure 3.10: Selection phase in DSSA

3.5 Summary

In this Chapter, the network architecture as well as the radio access technology used are explained. In this architecture, only one radio interface is used in order to reduce the system cost. We also provided an in-depth description of DSSA. The proposed scheme uses neighbourhood information and directional antennas to avoid interference. It also tries to guarantee fast delivery of traffic from the source to the BS by estimating the slot waiting time. The selection of the slot with the minimum waiting time will eventually lead to the reduction in the overall system delay, as we will see in the next Chapter.

Chapter 4

Performance Evaluation

In this Chapter, we describe the simulation model, simulation assumptions and simulation parameters. We also present a comparative performance evaluation study of TDD W-CDMA single-hopping, Random Slot Assignment (RSA), and Delay-Sensitive Slot Assignment (DSSA). The schemes are further tested and investigated under specific scenarios and using a variety of traffic conditions and measurement parameters.

The performance metrics that are considered in this Chapter include:

- *Average end-to-end delay*: this includes all the delays caused by queuing, slot waiting time, transmission time and signal propagation. The smaller the delay the faster the packets are delivered to the BS.
- *System throughput*: is defined as the number of successfully received bits per unit time.

- *Blocking ratio*: *is* the ratio of the session requests denied by the RNC to those generated by the source nodes. The less the blocking ratio the less congested the system is.

4.1 Simulation Description

This Section describes the system simulation developed to analyze the performance of the multi-hop cellular network with the DSSA scheme. Section 4.1.1 includes a list of all system parameters, their types and chosen values used in the simulation. The traffic model used in the simulator is described in Section 4.1.2. The major assumptions made in this simulation along with the reasoning and limitations of each are discussed in Section 4.1.3. Finally, Section 4.1.4 briefly describes the simulation process and algorithms.

4.1.1 Simulation Parameters

System Parameter	Type	Simulation Value
Network Architecture	Cellular	- circular shaped cell with 1000 m transmission radius in the case of single-hop. - circular shaped cell with 200 m transmission radius in the case of multi-hop.
Network Elements	Node, Base Station, & RNC	
Multiple Access	TDD W-CDMA	
Link Analysis	Uplink/Reverse Link	
Frame Specs	Fixed time slot duration	- Frame duration = 10 ms - No. of uplink slots per frame = 13 - No. of codes per slot = 16
Channels		No. of channels = 13 * 16 = 208 with 5 MHz each
Antenna Type	Directional switched beam at nodes	45° beamwidth

Relaying Channel	No separate relaying channels.	Zero
Maximum Permissible hops		6 hops
Node Buffer Size		Unlimited
Node Queue	First In First Out (FIFO)	
Traffic Model	Quasi-continuous	- Sessions arrival rate: Poisson distributed with a mean $\mu = 0.01$ SR/sec - Packet arrival rate: Poisson distributed with mean $\lambda = 0.5$ packet/sec
Transmission Rate		- Single-hop = 144 Kbps - Multi-hop = 2 Mbps
Simulation Time		1800 sec

4.1.2 Traffic Model

The source nodes generate quasi-continuous traffic sessions, typical of http, ftp and some audio and video download applications. Session arrivals follow a Poisson distribution with a mean value of μ Sessions Requests (SR) per second. Once the session request is accepted, the source node generates traffic. Packets arrive according to a Poisson distribution with a mean arrival rate of λ packets per second. In the simulation, when the session ends, the event queue is searched for packet arrival events related to that session, so that they can be removed. The process of packet generation will start again upon the arrival of a new session.

4.1.3 Simulation Assumptions

- Perfect power control: In the uplink, means equal received power at the BS from all MT belonging to that cell. Also it means that the mobile transmits with enough power for the receiving node to detect the signal. This is a valid assumption due to the existence of a power control mechanism in the UMTS system.

- Unlimited buffer capacity of each node: This is assumed for modeling and simulation simplicity. In addition, memory chips are quite cheap to support this assumption.

- All nodes are active: This means that each node is generating the average node traffic under consideration. Moreover, nodes have to be in an alert condition regardless of whether they are sending data or not. This assumption guarantees that a node is always ready to serve as a relay whenever needed.

- Snap shot processing at frame level: This means that node distribution, and route constructions are carried out at the start of the simulation. Nothing is changing in between the frames.

- Slot can only fit one packet: This means that message and packet fragmentation is done before hand. This is a valid assumption, due to the fact that in reality messages tend to be larger than a slot. The message will then passed to the Medium Access Control (MAC) layer at which point it will be fragmented into packets. These packets are further fragmented into Packet Data Unit (PDU) to fit in a slot. Also, to avoid overlapping of data at the receiving entity, we add the propagation delay to the packet size.

- Transmission takes place only at the beginning of a slot: This means that a node can not transmit at the middle of a slot. This is related to the assumption above, since a slot can fit one packet plus the propagation time. Hence, if a packet arrives at the middle of a slot it has to wait until the beginning of its slot before it starts transmitting.

- Fully orthogonal codes: This means that two channels with different orthogonal codes can not interfere with each other even though they are using the same slot.

4.1.4 Simulation Algorithm and Flowchart

A packet-level discrete-event simulator was developed to monitor, observe and measure the performance of both single-hop cellular networks and multi-hop A-Cell networks. The simulator was written using the Java programming language. The simulation was conducted for a multi-hop cellular network with 20, 90, 160, 230, and 300 mobile nodes. Mobile terminals are uniformly distributed by assigning a unique node ID and a random position in the x-y plane. A 90 % confidence level with 10 % confidence intervals was used in the simulation, see Appendix A.

A node can either be a source, a relay, or both. Static routes are built from each source node to the BS at the start of the simulation, and are called as needed. Due to the deployment of directional antennas, the interference experienced by nodes and BS depend on the directivity of each transmitter. The antenna is directed based on the location of the next hop node, making the next hop node to be in the center of the beamwidth of the antenna.

The simulation is conducted based on two arrivals: session arrival and packet arrival. First, session request is established due to the arrival of a new session. The session request (RREQ) will propagate to the BS. Once the session is accepted, the generation process of packets is activated. At the end of the session, the resources allocated to that session are freed. If there is not enough resources to accommodate the request, the session is blocked and the source will time out and send a new request again.

The flowchart of the simulation procedure is depicted in Figure 4.1.

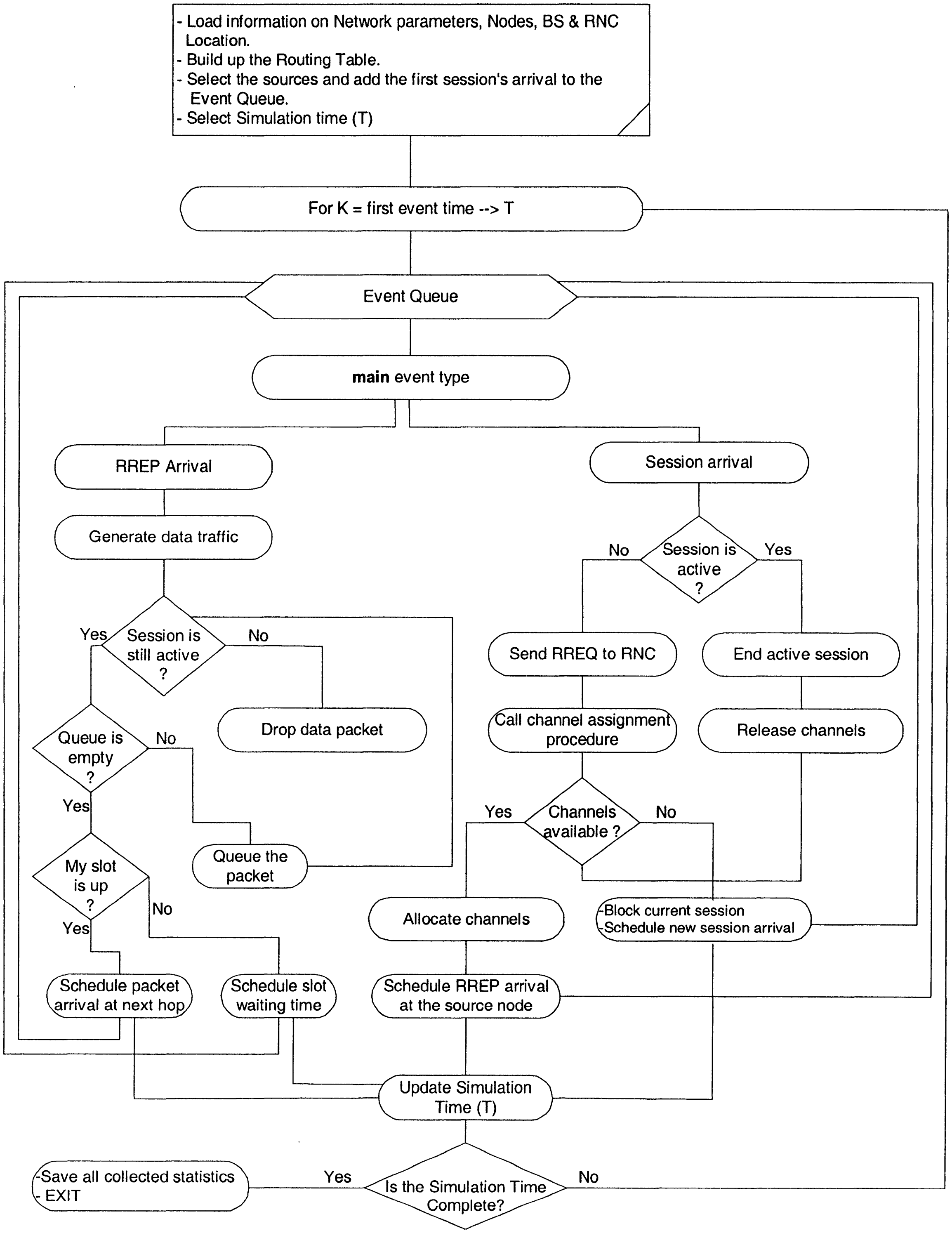


Figure 4.1: Flowchart of the main events in the simulation

4.2 Single-hop Cellular Network vs. Multi-hop Cellular Network with RSA

In this scenario, we compare the conventional cellular network with the multi-hop cellular network using random slot assignment in terms of the average end-to-end delay, throughput and blocking ratio. In order to ensure an accurate and fair comparison between the two systems, the transmission speed deployed by each system has to vary. This is because the actual distance between nodes and the BS in case of single hop is much higher than the distance between two entities (BS to MT or MT to MT) with multi-hop relaying. Accordingly, we set the transmission speed for the single hop case to be 144 Kbps and to 2 Mbps in the case of multi-hop relaying. We then vary the packet arrival rate and see how the two systems behave under low arrival rate and high arrival rate. As the packet arrival rate increases, queuing may start to affect the system delay. Therefore, we need to see how the two systems (RSA and DSSA) behave with different arrival rates.

4.2.1 Low Packet Arrival Rate

Figure 4.2 shows that multi-hop cellular network with RSA has a better delay than that of a single-hop case. This is because of the high transmission rate which overcomes the queuing delay introduced by multi-hopping. This corrects the miss-conception that most people have that multi-hop has higher delay than that of a single-hop. The high transmission rate not only reduces the delay but also increases the system throughput as shown in Figure 4.3. The throughput increases by more than two-fold the case with single-hop cellular network.

Figure 4.4 shows that the ratio of the sessions blocked in multi-hop with RSA is much higher than that of a single-hop. This can be explained by the fact that the maximum number of available channels is 208. Initially with 20 users no sessions are blocked for both systems but as the number of users reaches 90, around 10 % of the sessions are blocked with multi-hopping. This is because channels are assigned randomly with no planning for reusability. As a result, a route with four hops in multi-hopping requires four different channels to avoid same-entity interference. However, this is equivalent to four distinct users in single hop. The single hop case would start to experience blocking as the number of users reach 209 and this is evident from the graph.

4.2.2 High Packet Arrival Rate

Under high packet arrival rate, multi-hop cellular network with RSA starts to behave differently than under low arrival rate. We increase the packet arrival rate from 0.5 packets/sec to 10 packets/sec. The result in Figure 4.5 shows that the average end-to-end delay of RSA is worse than that of single-hop case. This can be related to the fact that queuing delay will start to have a large impact on the system, especially on relaying nodes. Moreover, the effect of slot waiting time will be more apparent due to the high incoming traffic and the randomness in assigning slots. Nevertheless, the throughput of multi-hopping with RSA still outperforms that of single-hop cellular networks as shown in Figure 4.6. As for the blocking ratio, the result in Figure 4.7 shows that the blocking ratio is not affected with the increase in the packets arrival rate and this is mainly because the session's arrival rate is still the same.

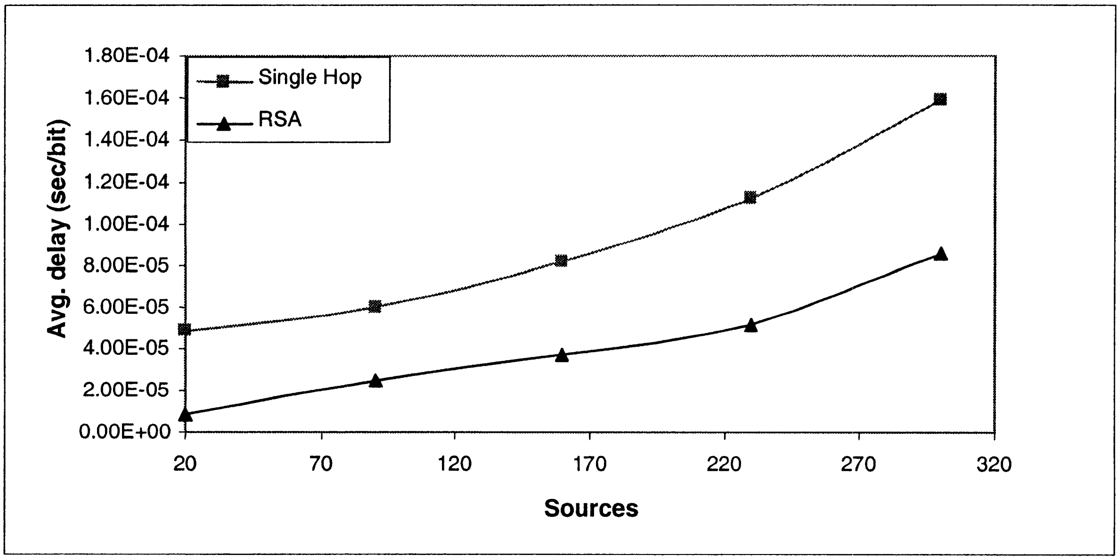


Figure 4.2: Average end-to-end delay for single and multi-hop cellular network with low packet arrival rate

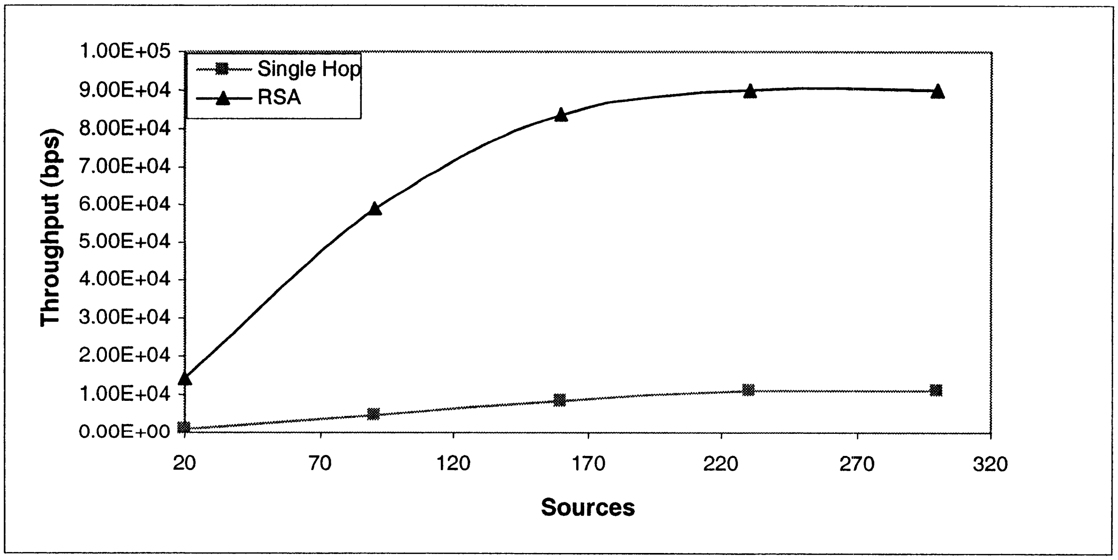


Figure 4.3: System throughput for single and multi-hop cellular network with low packet arrival rate

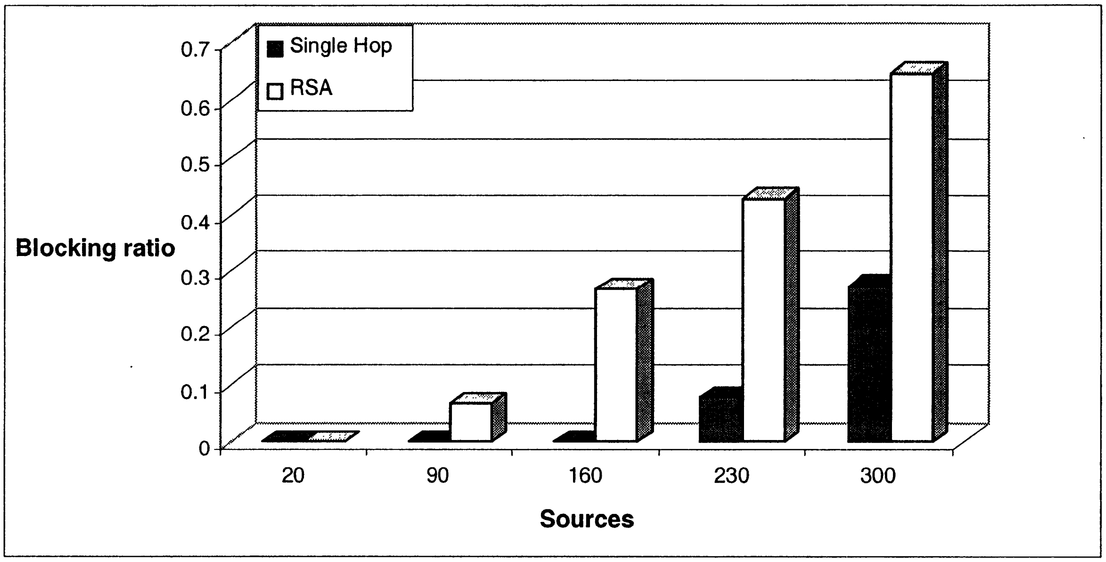


Figure 4.4: Session blocking ratio for single and multi-hop cellular network with low packet arrival rate

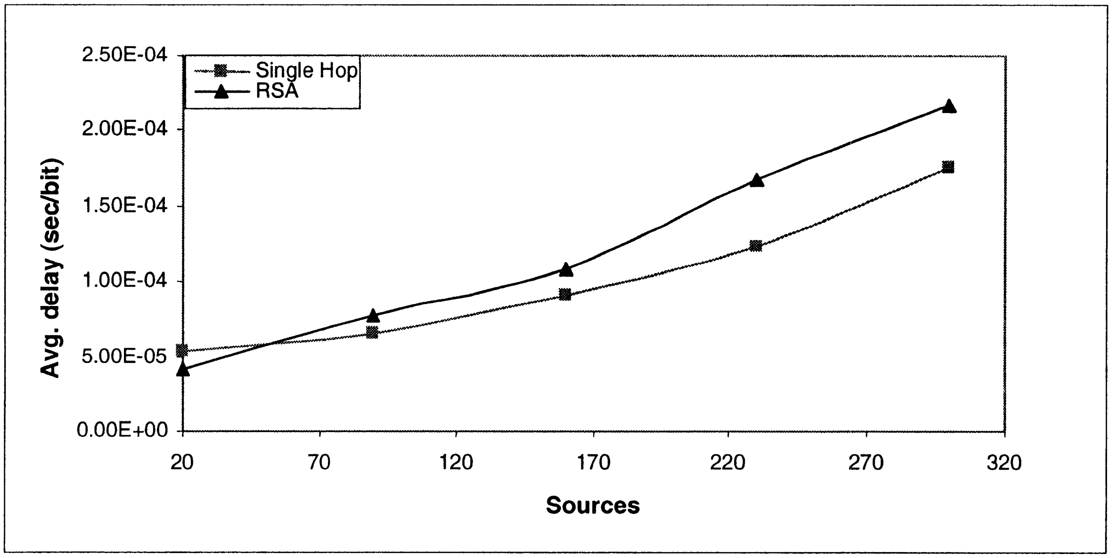


Figure 4.5: Average end-to-end delay for single and multi-hop cellular network with high packet arrival rate

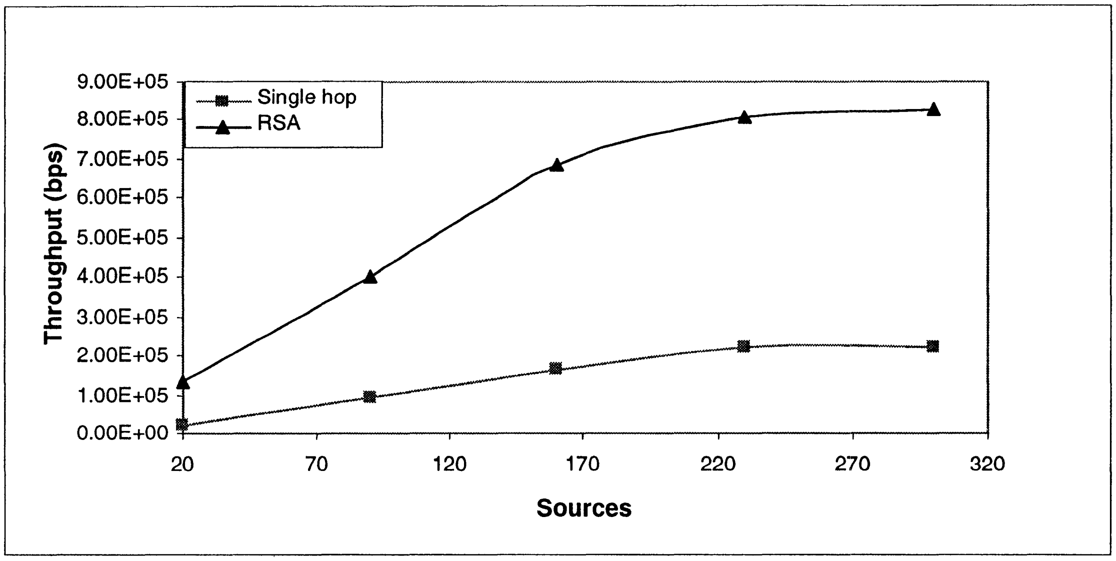


Figure 4.6: System throughput for single and multi-hop cellular network with high packet arrival rate

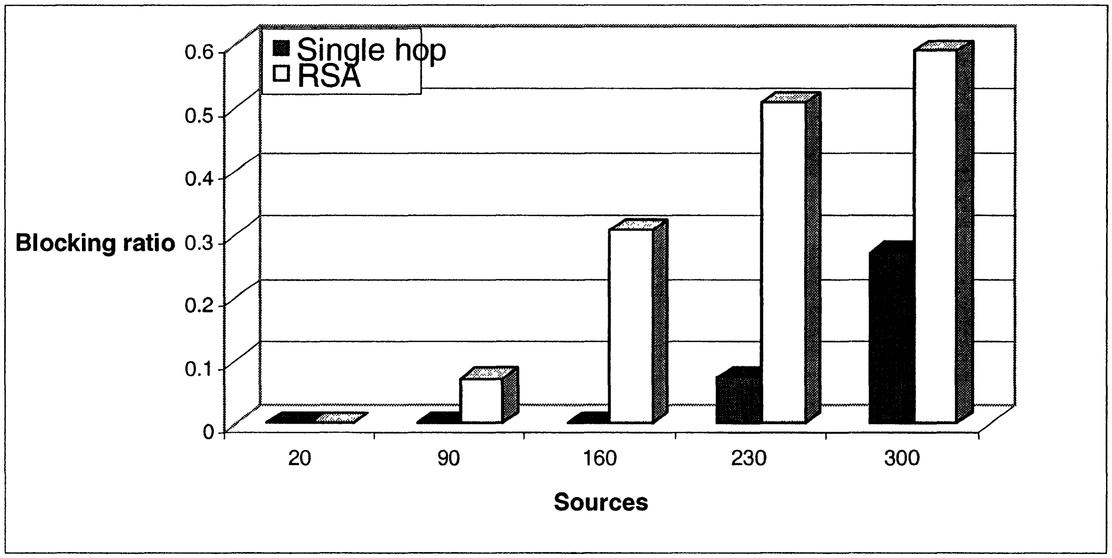


Figure 4.7: Session blocking ratio for single and multi-hop cellular network with high packet arrival rate

4.3 RSA vs. DSSA

In the previous section, we saw that a multi-hop cellular network with RSA functionality outperforms a conventional single-hop cellular network in terms of throughput. However, the number of session blocking ratio is much higher than single-hop. Moreover, with high packet arrival rate the average end-to-end delay is higher than that of a single-hop case. Therefore, the number of sessions blocked and the average delay will be adversely affected if RSA is adopted. In this section, we study the performance of DSSA and compare it to that of RSA under low and high packet arrival rates.

4.3.1 Low Packet Arrival Rate

As shown in Figure 4.8, DSSA outperforms RSA with respect to the average end-to-end delay. This is due to the fact that the assignment of channels (slots/codes) in DSSA is done in such a way that reduces the effects of slot waiting time and the overall delay. Note that the confidence intervals have been explicitly depicted in Figures 4.8 and 4.9. For presentation clarity of the remainder of the results we omit the confidence interval from the rest of the graphs.

In Figure 4.9, the results indicate that enhances the throughput of a multi-hop cellular network. Initially, the throughput is identical for both schemes. However, as the number of users increases the throughput starts to vary. As the number of users starts to reach the total system capacity 208 users, RSA starts approaching the saturation point while DSSA keeps increasing. This can be attributed to the blocking ratio results shown in Figure 4.10. With DSSA, the blocking ratio remains at zero even with 300 users. This is because of the aggressive channel reusability deployed by DSSA as well as the aggregation of traffic. Therefore, with DSSA the system capacity can be increased by more than 50 %.

4.3.2 High Packet Arrival Rate

We now look at how a system deploying the DSSA scheme behaves under high packet arrival rate compares to that with the RSA scheme and the single-hop case. The results in Figure 4.11 show that the average end-to-end delay of multi-hop cellular network deploying DSSA is less than both schemes. This is mainly due to both high reduction in slot waiting time and high transmission rate. This proves the importance of slot waiting time and how it can affect the overall end-to-end delay. As for the throughput and blocking ratio, DSSA still maintains its precedence over RSA and single-hop, even under high traffic conditions (see Figures 4.12 and 4.13).

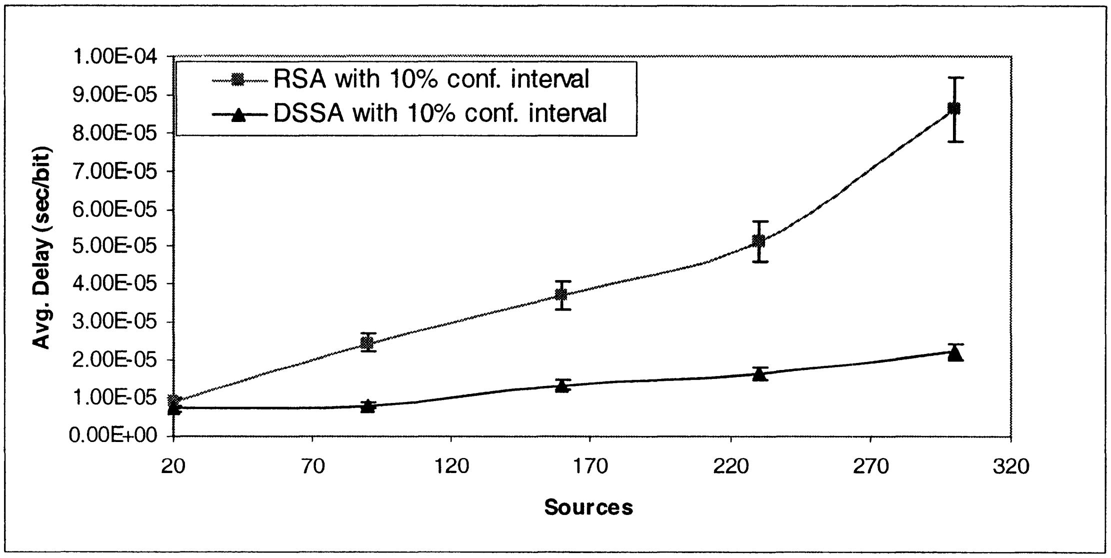


Figure 4.8: Average end-to-end delay for multi-hop cellular network using RSA and DSSA under low packet arrival rate

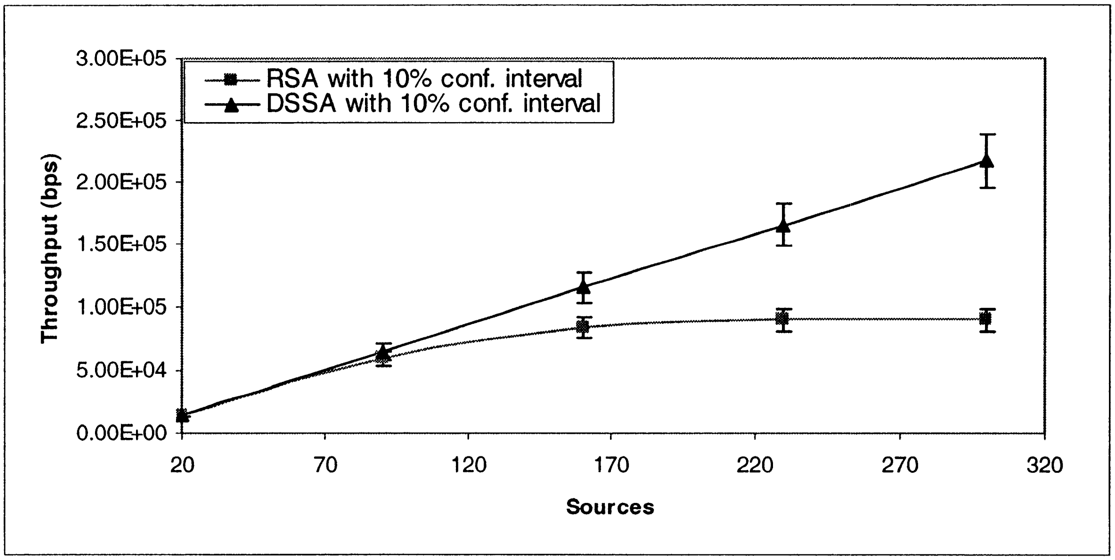


Figure 4.9: System throughput for multi-hop cellular network using RSA and DSSA under low packet arrival rate

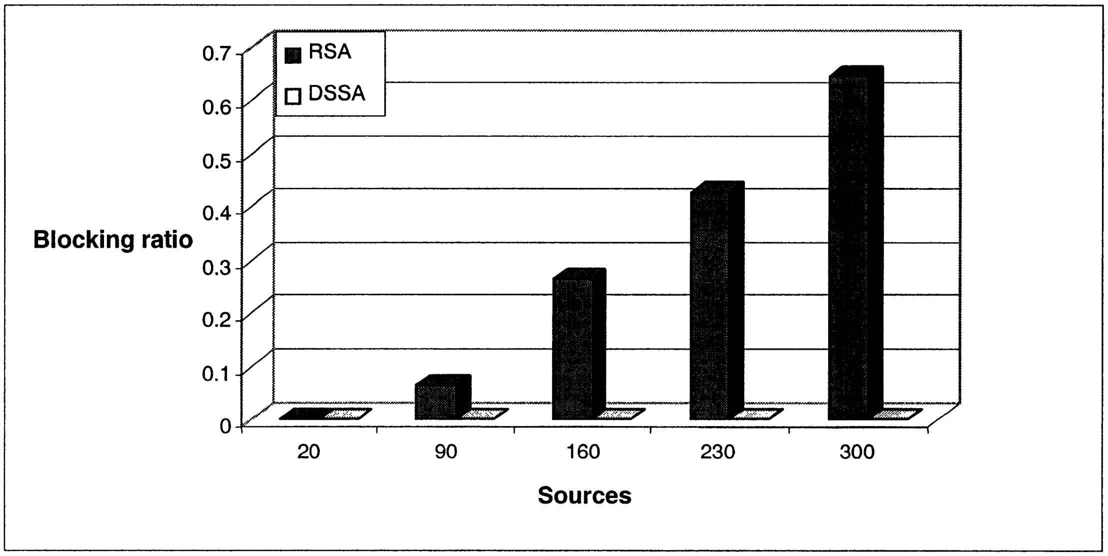


Figure 4.10: Session blocking ratio for multi-hop cellular network using RSA and DSSA under low packet arrival rate

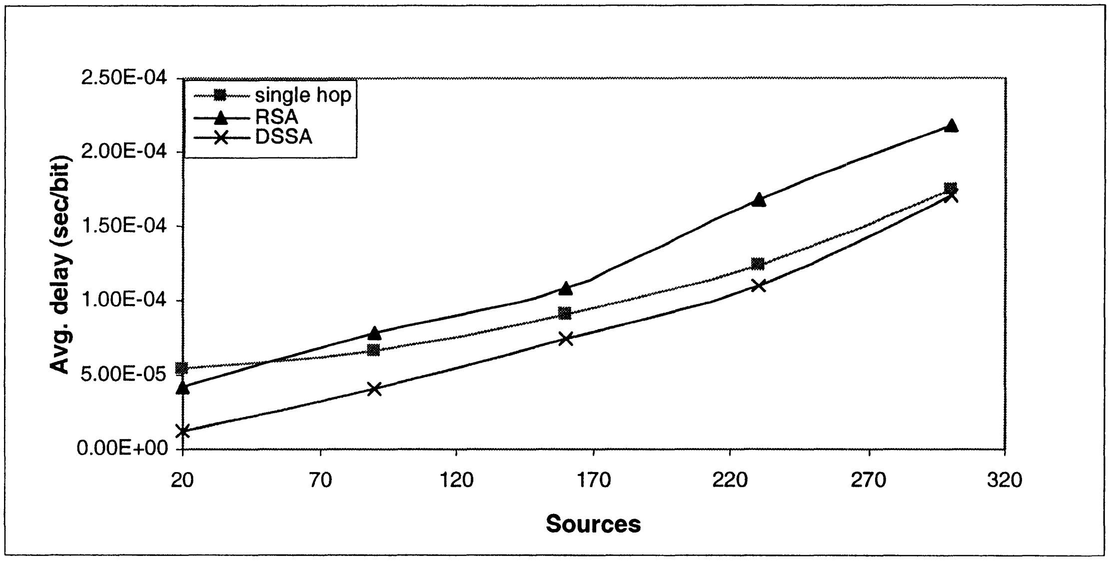


Figure 4.11: Average end-to-end delay for single-hop and multi-hop cellular network using RSA and DSSA under high packet arrival rate

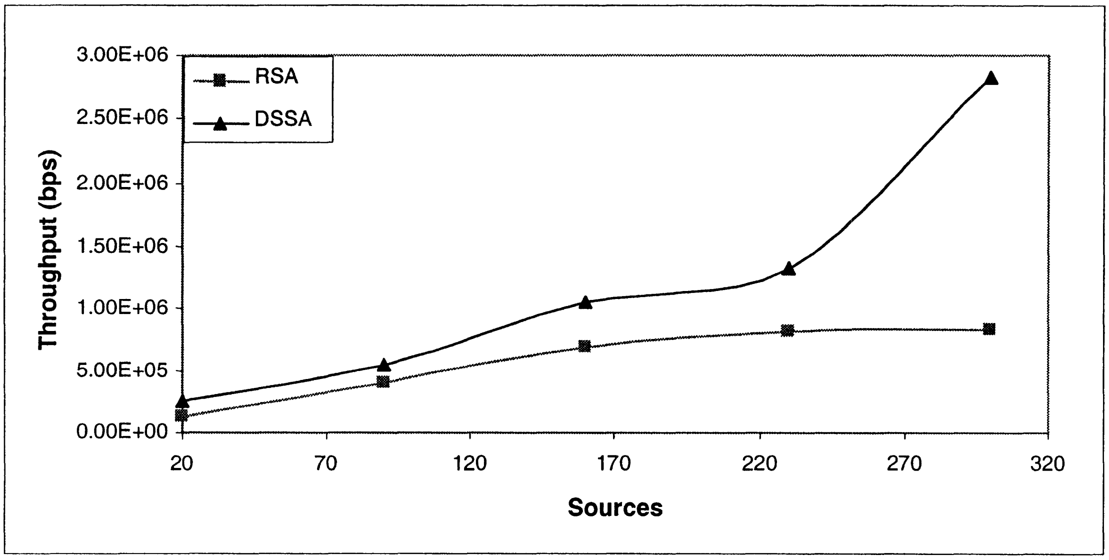


Figure 4.12: System throughput for multi-hop cellular network using RSA and DSSA under high packet arrival rate

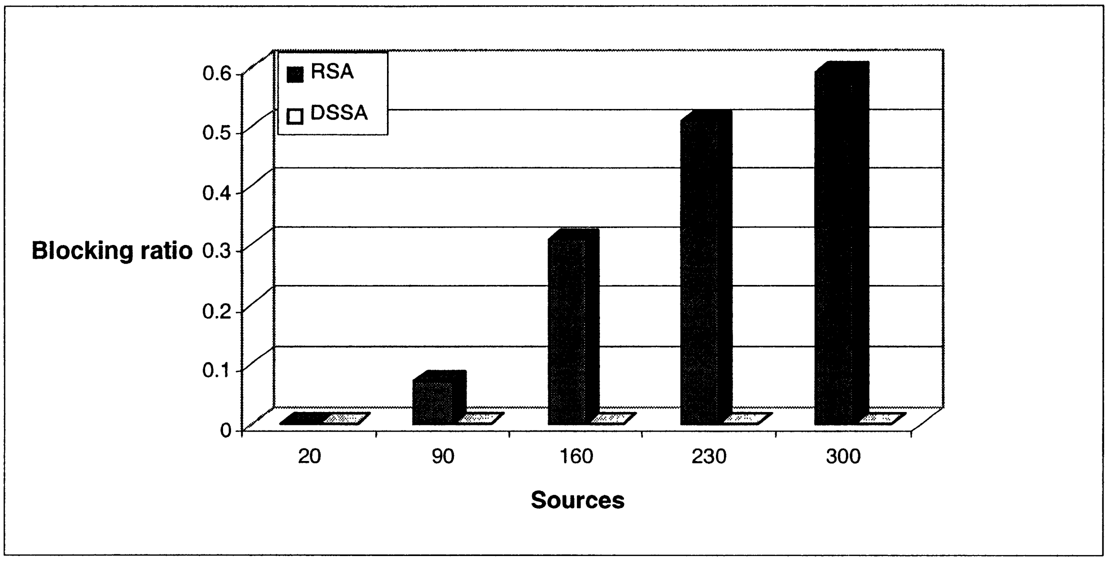


Figure 4.13: Session blocking ratio for multi-hop cellular network using RSA and DSSA under high packet arrival rate

4.4 Delay-Throughput Characteristics

To fairly compare multi-hop cellular networks using RSA, multi-hop cellular networks using DSSA, and single-hop cellular networks, we look at the delay-throughput characteristics. Figure 4.14 and 4.15 show the comparative results of RSA, DSSA, and single-hop under a low packet arrival rate and a high packet arrival rate, respectively. As the throughput increases, the delay increases for both RSA and DSSA. However, the increase in DSSA is very small compared to that of RSA and single-hop. It is clear that DSSA can achieve significantly higher throughput while maintaining a relatively low delay.

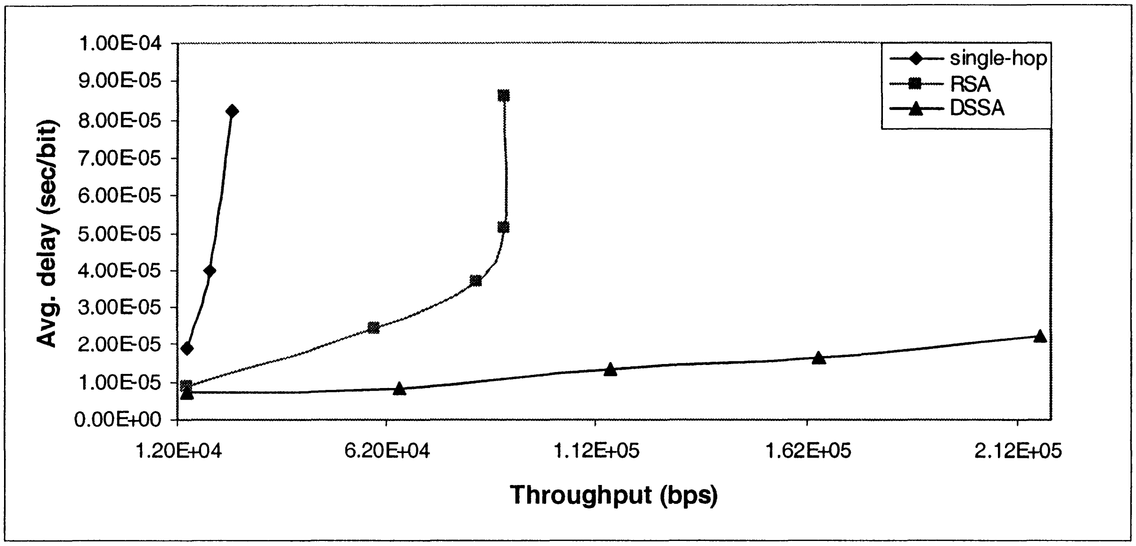


Figure 4.14: Delay, throughput relationship in single hop and multi-hop cellular using RSA and DSSA under low packet arrival rate

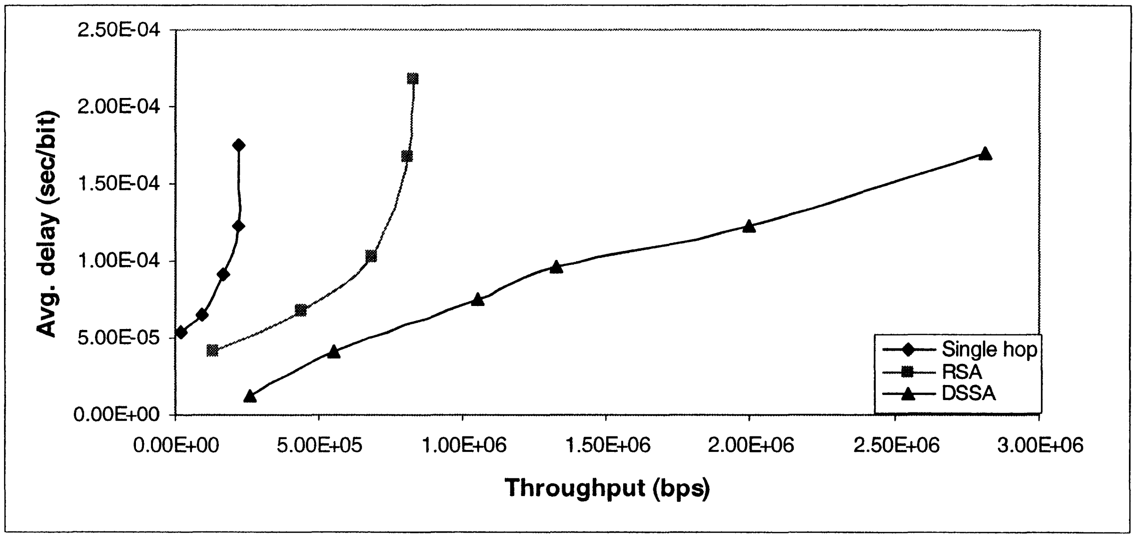


Figure 4.15: Delay, throughput relationship in single-hop and multi-hop cellular using RSA and DSSA under high packet arrival rate

4.5 The Impact of the Number of Hops

In this Section, we study the effect of the number of hops on the multi-hop cellular network. The maximum number of hops is varied from 2 to 6 hops. Figure 4.16 shows that as the number of hops increases, the average end-to-end delay also increases. This is expected since a packet has to wait in each slot for queuing time and slot waiting time of each hop. A closer look at the results show that using DSSA with maximum number of hops equal to 6 is still much better, in the long run, than RSA with maximum number of hops equal to 2. From this we can observe that with DSSA users in dead spots or far away from the BS can obtain connection with the BS and start communicating with the BS within a reasonable delay.

Figure 4.17 shows the impact of different number of hops in the DSSA scheme. As expected, the delay decreases as the number of hops decrease. This implies that if two MTs want to communicate with each other and they are 2 hops a way from each other, then they are better off using multi-hopping since their data traffic will experience low delay and high throughput compares to using the BS for delivering the data traffic.

As for the throughput, the effects of decreasing the number of hops on the system are minimal. This is because the number of sessions blocked remains the same as we decrease the number of hops (see Figures 4.18 and 4.20 for RSA). For DSSA, the throughput results are shown in Figure 4.19. We remark that there is no observed blocking under DSSA regardless of the number of hops used, hence the identical throughput results.

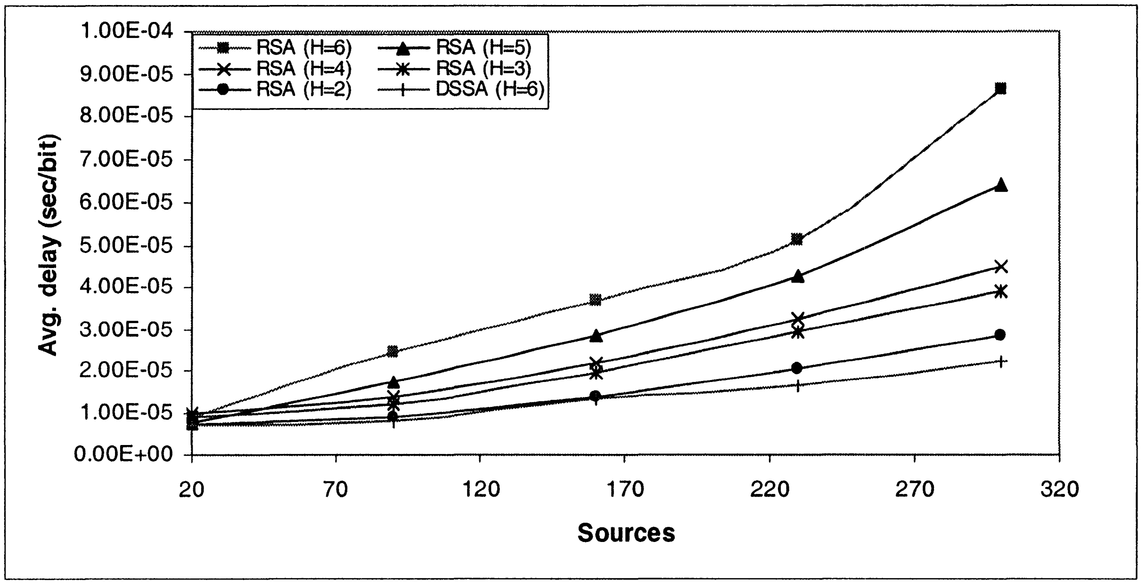


Figure 4.16: The impact of the number of hops on the average end-to-end delay for RSA

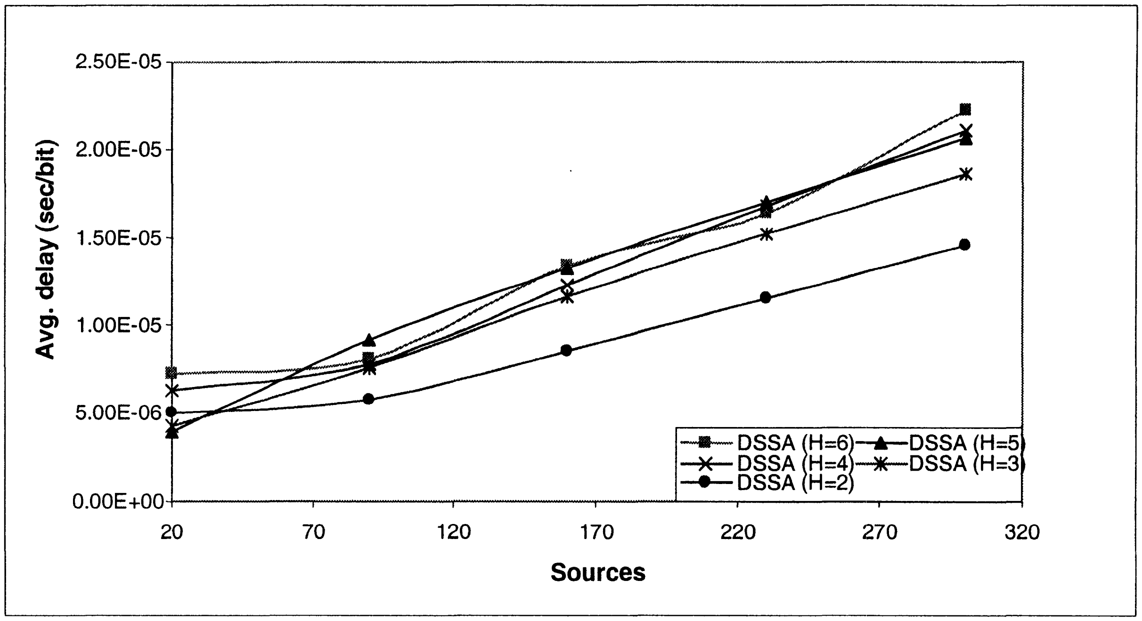


Figure 4.17: The impact of number of hops on the average end-to-end delay for DSSA

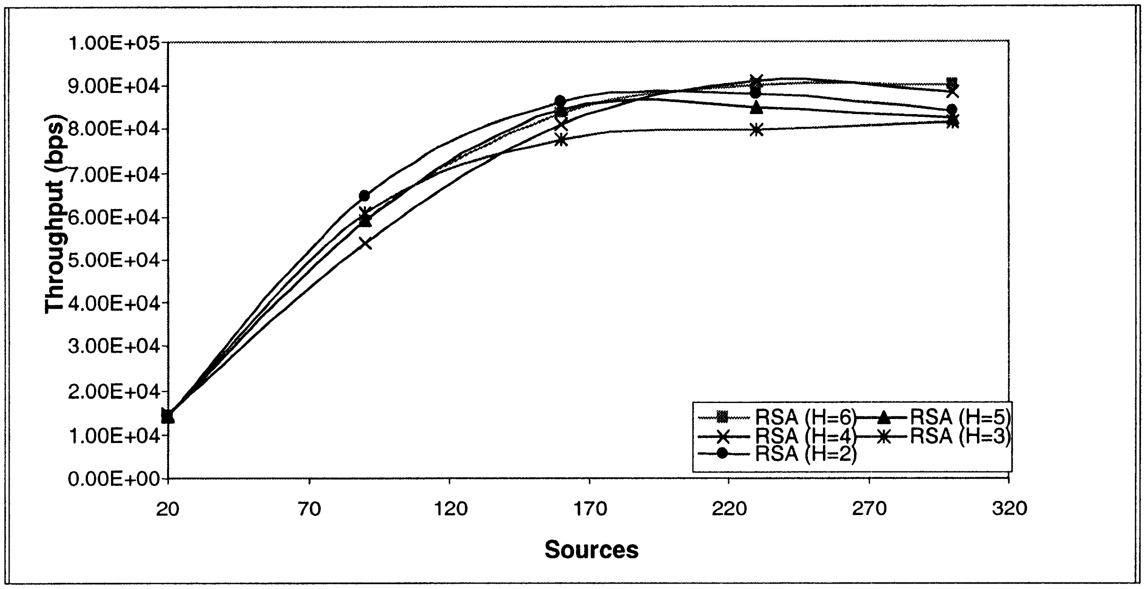


Figure 4.18: System throughput with different number of hops using RSA

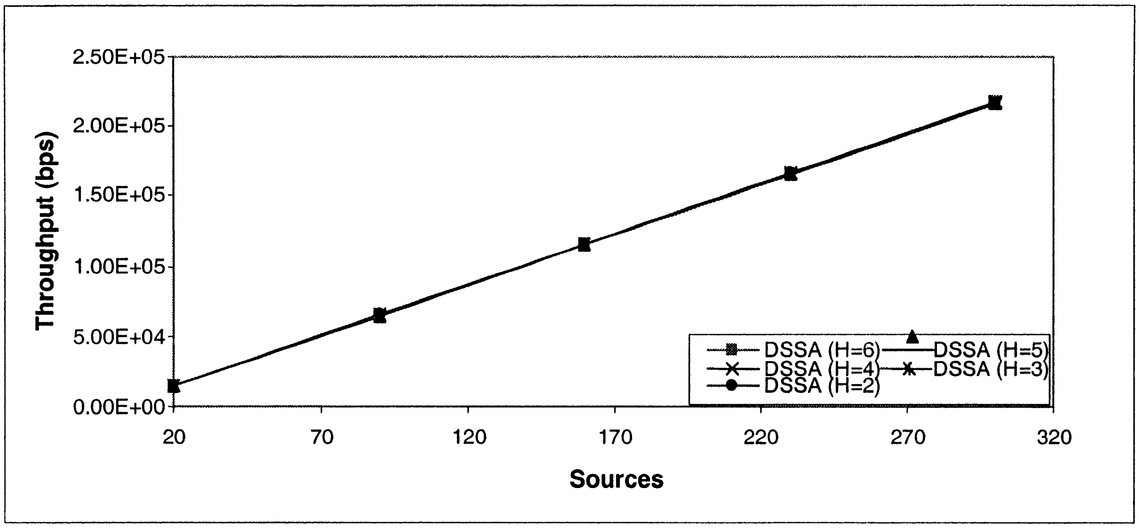


Figure 4.19: System throughput with different number of hops using DSSA

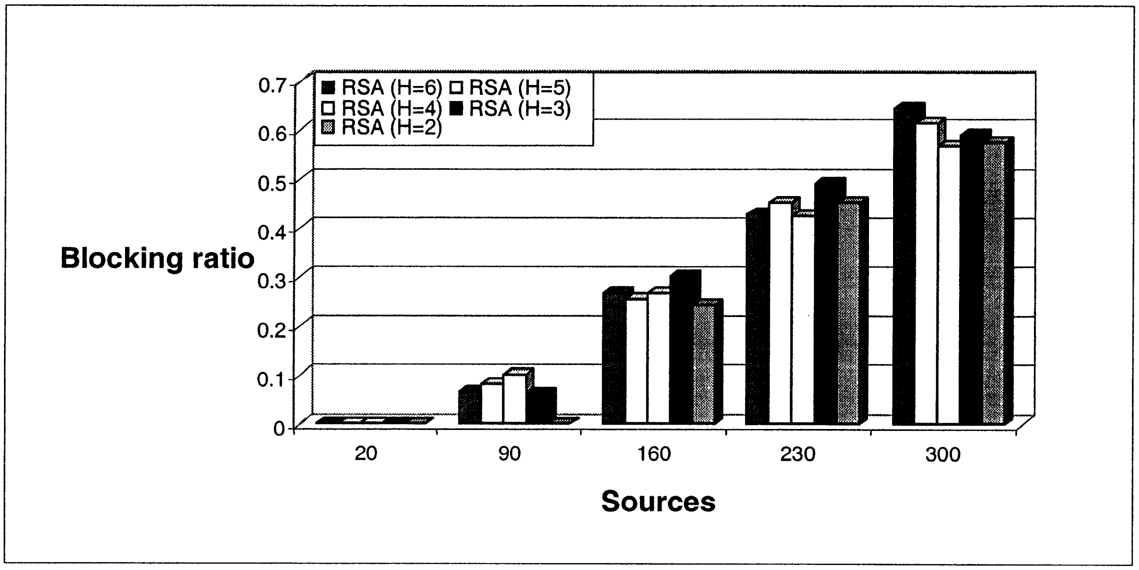


Figure 4.20: Session blocking ratio with different number of hops using RSA

4.6 The Impact of Nodal Distribution and Directional Antenna

In this scenario, we concentrate 75 % of the nodes in an area and vary the beamwidth of the directional antenna. This scenario is similar to the case when a new, say, amusement park is open in an existing cell and users start drifting to that area, causing that area to be a hot spot. Figure 4.21 below shows the results for the case where only 15 channels are used and the beamwith is varied from 360° to 45°. The results indicate that as the beamwidth of the antenna decreases the throughput increases. This result is closely related to the blocking ratio, see Figure 4.23. As the beamwidth decreases the blocking ratio decrease too and hence the throughput increase. The reason behind the reduction in the blocking ratio goes back to the elimination phase of the DSSA scheme described in

Section 3.4.2. In DSSA, the elimination phase is based on the neighbourhood information, and, hence, as the beamwidth gets smaller, fewer channels get eliminated.

Varying the beamwidth of the antenna has negligible effects on the average end-to-end delay, as depicted in Figure 4.22. This is because nodes in a multi-hop cellular network are assigned dedicated channels. Hence, nodes do not compete for resources (contention free) unlike the case in pure ad hoc network which will definitely have an effect on the average end-to-end delay.

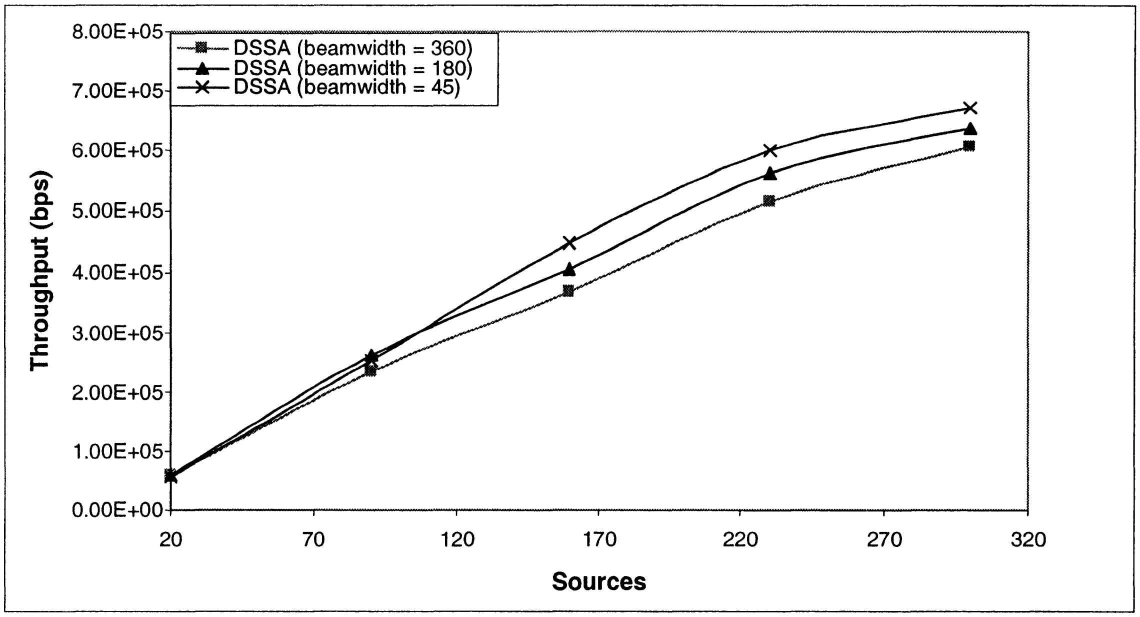


Figure 4.21: The impact of directional antenna on the system throughput

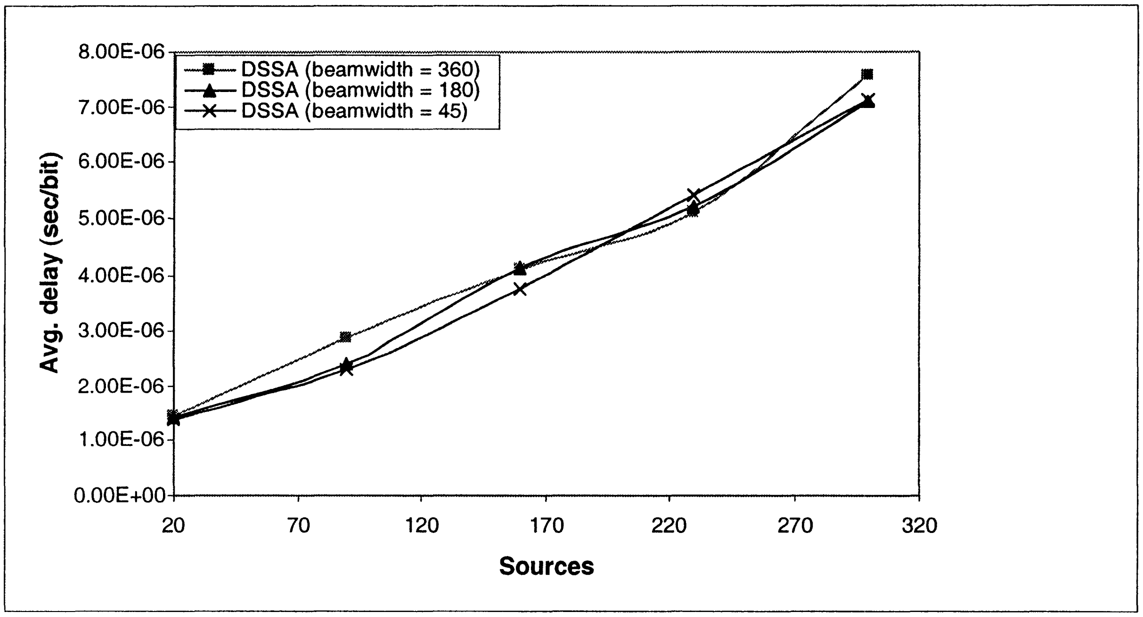


Figure 4.22: The impact of directional antenna on the average end-to-end delay

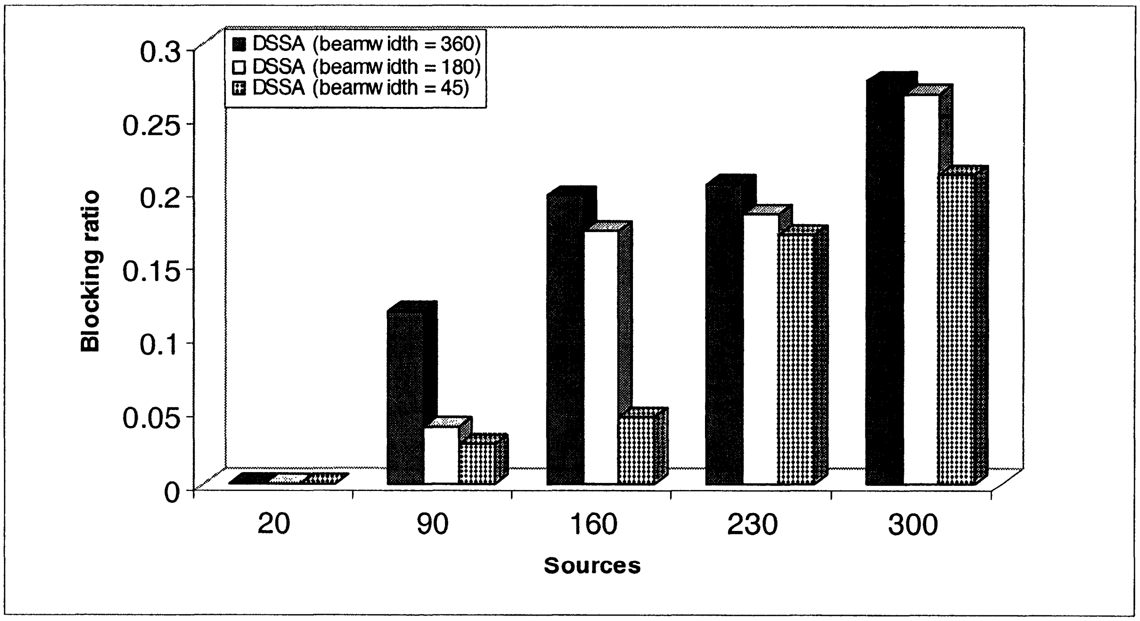


Figure 4.23: The impact of directional antenna on session blocking ratio

4.7 Summary

In this Chapter, the packet-level simulator, simulation parameters and simulation algorithm flow chart are presented. Also the performance evaluations of multi-hop cellular networks deploying Delay-Sensitive Slot Assignment (DSSA) are discussed. The performance of DSSA is compared to that of conventional single-hop cellular network and multi-hop cellular network using Random Slot Assignment (RSA). Various simulation parameters and scenarios were conducted to investigate the effects of network density, number of hops, and directional antenna on the performance of the system compared with the other schemes. Also the diverse effects of multi-hopping on the existing backbone system were investigated.

The conducted simulation experiments showed that multi-hop cellular network with DSSA outperformed multi-hop cellular network with RSA and single hop cellular network in terms of the average end-to-end delay, system throughput, and sessions blocking ratio. DSSA has also demonstrated superior average end-to-end delay under light traffic as well under heavy traffic. Moreover, with DSSA the system capacity can be increased by more than 50 % before calls start be blocked. This is mainly due to the high channel reuse and directional antenna that DSSA fully utilized.

Chapter 5

Conclusions and Future Work

In this thesis, we investigated and analyzed the performance gains as well as the constraints associated with multi-hop relaying in a cellular network. The developed scheme is aimed to work with any cellular system using Time Division Duplex (TDD) Wideband-CDMA as its radio access mechanism. We also looked at the in-depth dynamics of adopting relaying in a cellular network and devised a centralized, delay-sensitive slot assignment scheme and compared it to that of a random slot assignment scheme that is usually assumed in related work. The performance metrics that were used are the average end-to-end delay, system throughput, and sessions blocking ratio. Sensitivity of these performance metrics, as the number of active users increased, was analyzed and discussed.

In Delay-Sensitive Slot Assignment (DSSA), mobile terminals are only equipped with one wireless interface. This interface is used for both direct connectivity to the BS and for multi-hop relaying. Hence, no additional cost is required to enable this relay. However, this bears a potential of leading to high interference if channels are not carefully assigned. The inherent problem of random slot assignment is that it may lead to such interference. DSSA tries to avoid RSA's potential risk by using neighborhood information and directional antennas. Having found the channels that does not lead to interference with the on going transmissions DSSA selects channels with the least slot waiting time. It works in a route by route basis. This means that if at least one mobile terminal *enroute* that can not be accommodated due to lack of non-interfering channels, the request for the whole route will be denied. Packet-level simulation for both single-hop and multi-hop cellular networks was conducted to investigate the cause and effects analysis of all the performance measures mentioned above.

Simulation results show that multi-hopping using DSSA provides not only significant improvement in terms of capacity, throughput, and blocking ratio, but also ensures low average end-to-end delay in addition to high channel utilization. The results also show how the average end-to-end delay of DSSA is relatively low even with a high number of hops. This indicates the significance of DSSA and how it can still outperform RSA even in extreme scenarios

The results in general are very appealing. They show that multi-hopping, with careful planning, presents an attractive alternative for service providers looking to provide an affordable, high-data-rate service to all users, even in dead and hot spots. Moreover, with multi-hop-capable cell phones or Personal Digital Assistants (PDAs), service providers can decrease the infrastructure costs by deploying fewer base stations.

The work in this thesis can be extended in many ways. First, we can consider a scenario with more than one BS and study the effects of multi-hopping on the system. DSSA will not be adversely affected by incorporating more than one cell in the system. This is because DSSA is a centralized scheme and is implemented in the RNC which supports more than one BS. The only additional processing that DSSA might need to take into consideration, however, is computing BS to MT or MT to BS interference.

Another possible extension to the scheme is to make it more dynamic. This involves rearranging the slot assignment every time a request for a channel is required. In other words, if there is one free channel and that channel cannot be assigned to the node currently looking for channel due to the high interference considerations, then we desire the scheme to be able to find another channel from the set of occupied channels and switch that channel with the available channel. This kind of action will definitely cause some interruption to the ongoing connections due to the channel switching. We can extend DSSA to incorporate some load balancing mechanism when assigning slots. The objective of computing slots to be assigned in such a manner is to reduce congestion at the relaying nodes. Also, and as aforementioned, we have seen in the previous chapter that a relaying node tends to suffer extra queuing delay due to the extra traffic that they are required to handle. This can be handled by incorporating priority queuing at the relaying nodes, giving high priority to the node's own data over other data. We can also extend DSSA to handle the downlink as well. Although in this thesis we only considered uplink connections, most of the findings are equally applicable to the downlink. In fact, downlink communication via relaying nodes will be more coordinated and well managed since base stations can control network access more easily.

Moreover, the deployment of directional antennas at the BS may also be considered. However, because the BS needs to serve more than one MT at the same time, an array of M directional antennas is required. The gain of the directive antenna is higher than that of an isotropic antenna, and is inversely proportional to its beam width. The antennas have perfectly non-overlapping beam forming directions. This will play a major role in reducing the interference at the BS and increasing the number of users that each BS can support leading to further system capacity gains.

In conclusion, DSSA is a strong candidate for multi-hop cellular networks. It is not possible to build a multi-hop cellular network and claim its effectiveness without developing and adopting a good slot assignment scheme. Currently, there is a lack of slot assignment schemes developed for multi-hop cellular networks. Having shown the effect of slot assignment scheme on the performance of multi-hop relaying, it is our hope, that through this work we provide an incentive to seek further, more capable schemes for this and other related problems.

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Appendix A

Confidence Intervals

Normally, confidence intervals placed on the mean values of simulation results can be used to describe the accuracy of the simulation results. Consider the results of N statistically independent simulation runs for the same experiment: X_1, X_2, ..., X_N. The sample mean, $\overline{X}$ is given as:

$$\overline{X} = \frac{\sum_{i=1}^{N} X_i}{N}$$

The variance of the distribution of the sample values, S_x^2 is:

$$S_x^2 = \frac{\sum_{i=1}^{N} (X_i - \overline{X})^2}{N-1}$$

The standard derivation of the sample mean is given by: $\frac{S_x}{\sqrt{N}}$.

Under the assumption of independence and normality, the sample mean is distributed in accordance to the T-Distribution, which means the sample mean of the simulation runs fall in the interval $\pm \varepsilon$ within the actual mean with a certain probability drawn from the T-Distribution.

$$\varepsilon = \frac{S_x t_{\alpha/2,N-1}}{\sqrt{N}}$$

where $t_{\alpha/2,N-1}$ is the value of the T-distribution with N-1 degrees of freedom with probability $\alpha/2$.

The upper and lower limits of the confidence interval regarding the simulation results are:

$$\text{Lower Limit} = \overline{X} - \frac{S_x t_{\alpha/2,N-1}}{\sqrt{N}}$$

$$\text{Upper Limit} = \overline{X} + \frac{S_x t_{\alpha/2,N-1}}{\sqrt{N}}$$