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Performance Evaluation of Mobile Relays in CDMA System

Thesis submitted in partial fulfillment of the
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Supervisor: Prof. Sven-Gustav Häggman

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Abstract:

In this thesis we consider the uplink direction of DS-CDMA (Direct Sequence, Code Division Multiple Access) network with multihop transmission. For the purpose, we discussed simple conditions by which we can understand whether single hop or multihop is better. One promising direction that the current wireless network moves toward is multihopping that allows mobiles to relay packets of other mobiles to their destinations. A major reason for adopting such multihopping is in capacity and range enhancement, which may pay off its increased complexity. Here, we focus on the non-real-time (NRT) services in the uplink of a DS-CDMA cell. Mobiles are moving around the cell, trying to send NRT packets to the base station, possibly by multihopping. Our goal is to derive a per-hop based multihop scheduling algorithm that is easily applicable in a cellular network with high mobility. For the purpose, we utilize the similarity between the basketball game and our multihop uplink packet scheduling problem. By regarding players, the basket and the ball as mobiles, the base station and data packet, respectively, we can mimic passing (multihopping) patterns of the basketball players. A major difference between the two is that in the multihopping problem, there are many packets (balls) while in the basket ball game, there is only one ball to shoot into the basket.

Keywords: DS-CDMA, Scheduling, NRT, multihop transmission.

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Md. Faisal Murad Hossain
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List of Abbreviations

AAA	Authentication, Authorization and Accounting
AC	Alternating Current
ACK	Acknowledgement
AL	Air Link
ANSI	American National Standards Institute
AP	Access Point
ATM	Asynchronous Transfer Mode
BS	Base Station
BSC	Base Station Controller
BSAM	Boundless Simulation Area Mobility
BTS	Base Station Transceiver Subsystem
BW	Broadband Wireless
CDMA	Code Division Multiple Access
CDF	Cumulative Distribution Function
CI	Confidence Interval
CSD	Circuit-Switched Data
DEST	Destination Node
DHCP	Dynamic Host Configuration Protocol
DS-CDMA	Direct Sequence, Code Division Multiple Access
DSSS	Direct Sequencing Spread Spectrum
EM	Electromagnetic
FA	Foreign Agent
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
FHSS	Frequency Hopping Spread Spectrum
FIFO	First-In-First-Out
GHz	Gigahertz
HA	Home Agent
HDLC	High-level Data Link Control
HLR	Home Location Register
ID	Identification
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
IR	Infrared
IS	Information System
ISM	Industrial, Scientific and Medical
IS-95	Interim Standard 95
LAN	Local Area Network
LMDS	Local Multi-point Distribution Service

MCN	Multihop Cellular Network
MMDS	Multi-point Distribution Service
MR	Multihopping Region
MS	Mobile Station
MSC	Mobile Switching Centre
MW	Microwave
NB	Narrowband
NRT	Non-Real Time
OFDM	Orthogonal Frequency-Division Multiplexing
OSI	Open Systems Interconnection
PCF	Packet Control Function
PDA	Personal Digital Assistants
PDSN	Packet Data Serving Node
PPP	Point-to-Point Protocol
PSD	Packet-Switched Data
QoS	Quality of Service
RAN	Radio Access Network
RF	Radio Frequency
RTS	Request to- Send
RWM	Random Walk Mobility
SCN	Single hop Cellular Networks
SD	Standard Deviation
SINR	Signal-to-Interference and Noise Ratio
SMSC	Serving Mobile Switching Centre
SR	Single-hop Region
SRC	Source Node
SS	Spread Spectrum
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telecommunications System
UWB	Ultra-Wideband
VHF	Very High Frequency
WAN	Wide Area Network
WCDMA	Wideband Code Division Multiple Access
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Networks
WWAN	Wireless Wide Area Network
2G	Second Generation
3G	Third Generation
4G	Fourth Generation

Chapter 1

Introduction

Wireless telecommunication networks fall into two main categories: Ad hoc networks and cellular networks. The evolving second and third generation cellular wireless data networks provide the user with high-speed broadband data connection. Bandwidth is a measure of spectrum (frequency) use or capacity of a communication channel. It is a precious resource in the wireless data networks, and it cannot be arbitrarily increased. Thermal noise and interference originate from other users and reduce the possible data rates even further. A new technique, relaying in wireless networks, has been developed to better utilize the potential of existing technology by “pushing” the interference limit.

1.1 Background

Relaying allows multiple wireless hops for data to reach its destination in cellular networks. It has been conceived to improve data throughput and coverage area. Instead of restricting all wireless communication to the link between mobile nodes and base stations, relaying uses other mobile nodes as intermediary nodes on the communication link to or from the base station. This technique has been already used in non-cellular, Ad hoc networks, but for the cellular networks relaying is a modern approach. Fixed relays / MESH networking have drawn a lot of interest for WiFi and WiMAX networks. It is also currently being considered as a technique for range extension for 4G networks. Mobile relays have been considered for some professional radio networks.

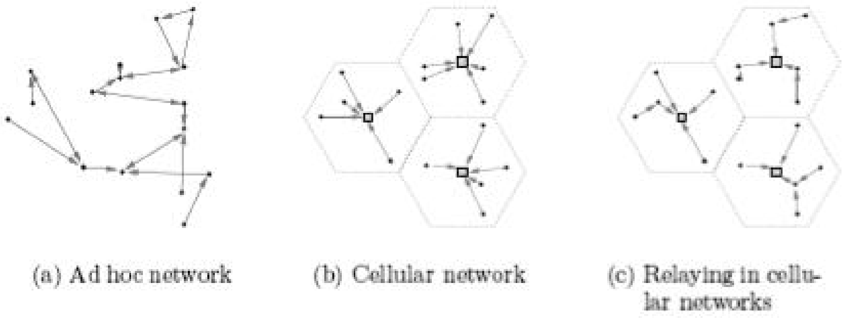
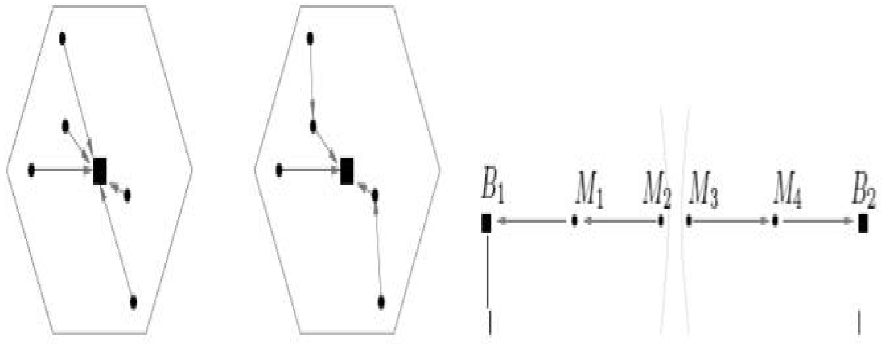

(a) Ad hoc network (b) Cellular network (c) Relaying in cellular networks

Figure 1.1: Mixing communication paradigms [14]

Figure 1.1 contrasts the effects of relaying in cellular networks. In the figure, the arrows, hexagons, squares and dots represent wireless data, cells, base stations and mobile nodes respectively. In case (b) the mobile nodes transmit data straight to the base station, whereas in case (c) some base stations are using intermediary mobile nodes. In contrast to Ad hoc networks, this implies that mobile nodes may never exchange data directly; they are only allowed to transmit data to and receive data from their respective base station. By using relaying in cellular networks, transmission of data can be performed over shorter distances. While this is quite common in most Ad hoc networks, it is normally not used in cellular ones. Relaying can be beneficial due to the reason that transmission speed can adapt several fast, short hops which might be better on the overall than one slow, long hop. An example case is illustrated in Figure 1.2 (c). Here, the two inner mobile nodes M1 and M4 are close enough to the respective base stations B1 and B2 and they are in an ideal position to be utilized as intermediaries by the outer mobile nodes M2 and M3 which are far away from the base stations. Another potential benefit of using relaying is the reduction of transmission power and, thus, interference, improving the transmission situation.



(a) Direct transmission.

(b) Relaying transmission.

(c) Network with high benefit in relaying.

Figure 1.2: Relaying in cellular networks.

In Code Division Multiple Access (CDMA) system, all mobile nodes interfere with each others, thus making the system as interference limited. In this system some mobile nodes might undergo strong shadow effect and some mobile nodes might be far away from the Base Station (BS). In these conditions the mobile nodes need more power than normally needed to reach the latter. So they may transmit the data at their maximum allowed power without satisfying their Quality of Service (QoS) requirements. As a result, some mobile nodes would be out of the system and produce too much interference to the adjacent cells as well. To solve this problem and improve the capacity of the system, numbers of Base Stations (BS) can be increased. However this is not an efficient way to counter the problem as it significantly increases the cost of the network infrastructure. Another solution to improve the capacity of the system is to apply a system with relaying. This means using other accessible mobile nodes located between the source mobile node and the base station in order to retransmit the original packets to their destination. Relays are network elements that store and forward data received from the base station (BS) to the mobile nodes and vice versa. With this relaying process, the mobile nodes located at the boundaries of the cells will require less power to reach the relay node than to reach the base station. As a result these mobile nodes will produce less interference to the adjacent cells, thus improving the capacity of the system. [15]

1.2 Structure of the Thesis

This thesis is organized as follows: Next chapter contains the overview of different wireless networks. Multihop Cellular Networks and design objectives of relaying in Cellular Networks are described in chapter 3. Chapter 4 and chapter 5 explain our proposed system model and packet scheduling algorithm. The effects of different parameters on packet delay and throughput of Cellular Networks with relaying are illustrated in chapter 6 through simulation results and analysis. Finally the thesis concludes with chapter 7.

Chapter 2

Overview of Wireless Networks

Wireless networks have two main categories, infrastructure networks and Ad hoc networks (Figure 2.1). Infrastructure networks include cellular networks, Wireless Local Area Network (LAN's), Wireless Wide Area Network (WAN's) etc. and infostation networks. The network infrastructure is known as base stations in cellular networks; access points in wireless LAN's and infostation in infostation networks, and is connected together to a backbone network by wire.

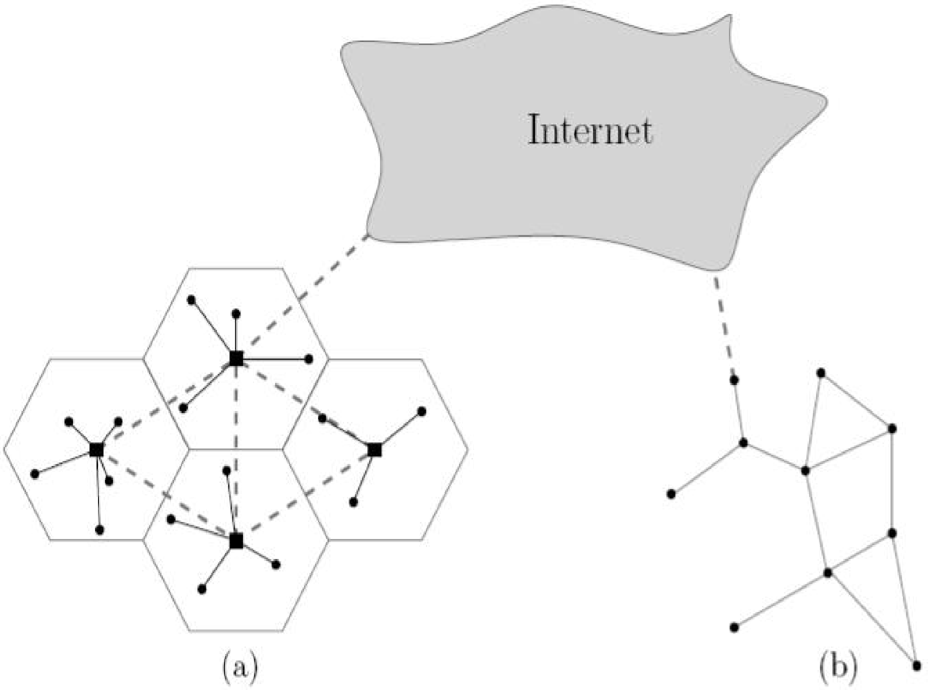


Figure 2.1: Types of wireless networks: (a) a cellular network and (b) an Ad hoc network both connected to the internet. [5]

The communication on wireless medium occurs in a single hop between the mobile nodes and the local base station/access point/infostation. On the other hand, Ad hoc networks, using a wired communications, are applicable to locations where it is not possible to set up an infrastructure network. Ad hoc networks are popular for military applications and rescue operations for long range outdoor networks. Here mobile nodes are connected together to form a network on the fly. These networks have routing capability and may act as the source, sink or a forwarding node to relay packet data for other nodes. [19]

2.1 Introduction to wireless Networks

Broadband Wireless (BW): In BW technology, it is possible to transmit voice data and video simultaneously. It is normally used in metropolitan areas and needs a direct sight between the transmitter and the receiver. BW has two categories which operate in licensed frequency bands:

- LMDS (Local multi-point distribution service) is a high bandwidth wireless networking service which operates in 28-31 GHz range. Its coverage area is around one mile from the LMDS transmitters. [20]
- MMDS (Multi-point distribution service) uses 2 GHz licensed frequency bands and it has wider coverage than LMDS (up to 35 miles) though its throughput rates are lower. [20]

Wireless Wide Area Network (WWAN): WWAN is a network of computer data which has a possibility to extend over a large geographical area (Figure 2.2). They were designed for voice rather than data transmission. Now a day some second generation and new third generation digital cellular networks are capable of transmitting both data and voice. In 3G networks, enhanced transfer speed is a great advantage. [20]

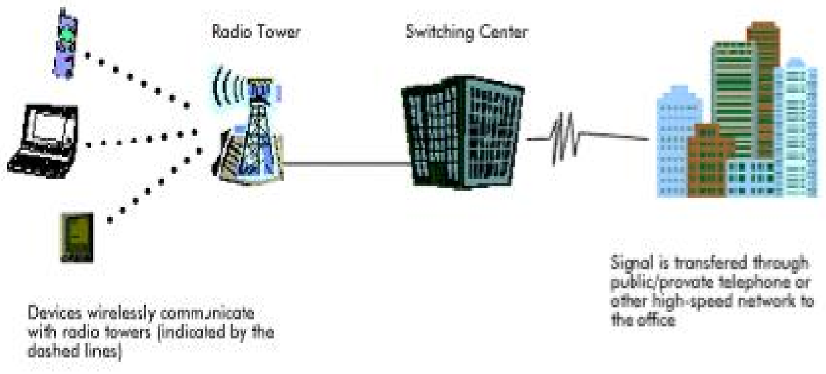


Figure 2.2: An example of Wireless WAN [20]

Wireless LANs (WLAN) [2] is an extension to wired LANs and they can transmit data at high-speed in small areas such as a building, an office or a campus. They provide users with mobility around a limited area within the coverage of the network without any interruption in connectivity. Thus, compared to wired LANs, Wireless Local Area Networks provide flexibility in installation and configuration (Figure 2.3).

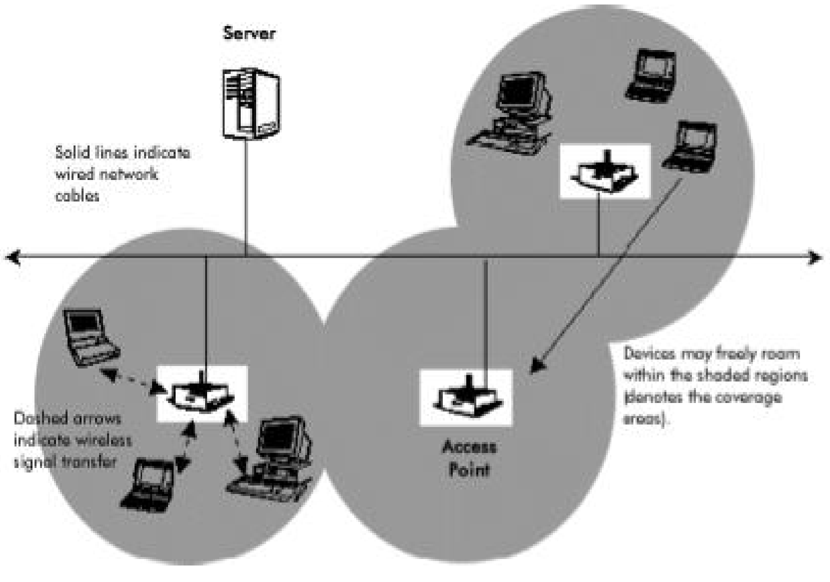


Figure 2.3: An example of Wireless LAN [20]

When the WLAN users roam in space they are occasionally connected to a local access point. This corresponds to the scenario in Figure 2.4 when the access points are far apart and the pockets of coverage areas are disjoint. [19, 20]

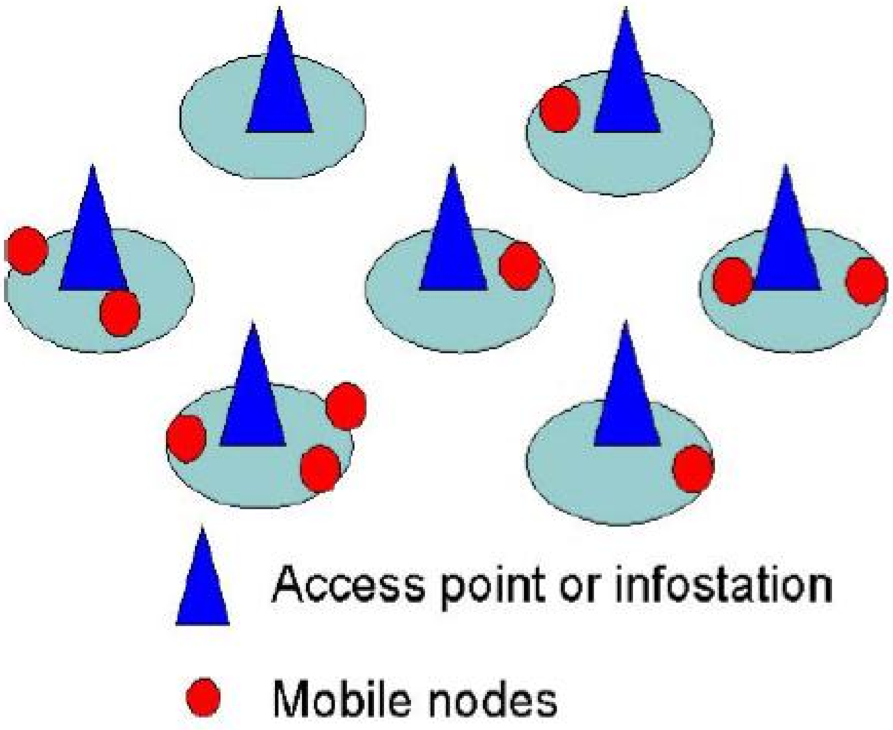


Figure 2.4: Illustration of the infrastructure network model. [19]

In a wireless LAN the data is the traffic type and the applications consume much bandwidth compared to the traditional low bit rate voice service. The existing 802.11a/b/g standards for wireless LAN provides multimegabit throughput for wireless data. In 802.11b the nominal data rate is 2 Mbps and the peak rate is 11 Mbps and uses an unlicensed radio spectrum at 2.4GHz. On the other hand, 802.11a uses Orthogonal Frequency-Division Multiplexing (OFDM) transmission technology and operates at the 5GHz band. The nominal data rate here is up to 54 Mbps. 802.11g is similar to 802.11a, uses OFDM and operates at the 2.4GHz band. [19]

Wireless Personal Area Networks (WPAN): WPAN is necessary when personal devices like mobile phones, computers and Personal Digital Assistants (PDAs) need to share data, have access to the internet, share peripherals and network in other ways. Another technology, namely Bluetooth [3] has been added to construct networks with all kind of computing and communication devices in order to form Ad hoc Wireless Personal Area Networks. [20]

2.2 Multihop Ad hoc Networks

A wireless Ad hoc network is a collection of mobile/semi-mobile nodes without any pre-established infrastructure. A self-configuring network is formed on the fly as two or more nodes “meet”. Every node communicates with each other through a wireless interface as long as both are in radio communication range over either radio or infrared. Some examples of nodes in an Ad hoc network are laptop computers and PDAs (personal digital assistants) which communicate directly with each other. Usually nodes in the Ad hoc network are mobile, but can be of stationary nature too, such as access points to the internet. [21] Wireless mesh networking (described by 802.11s) is implemented over a Wireless LAN. Mesh networks are decentralized, relatively inexpensive, and very reliable. Nodes act as repeaters to transmit data from nearby nodes to peers that are too far away to reach, resulting in a network that can span large distances, especially over rough or difficult terrain.

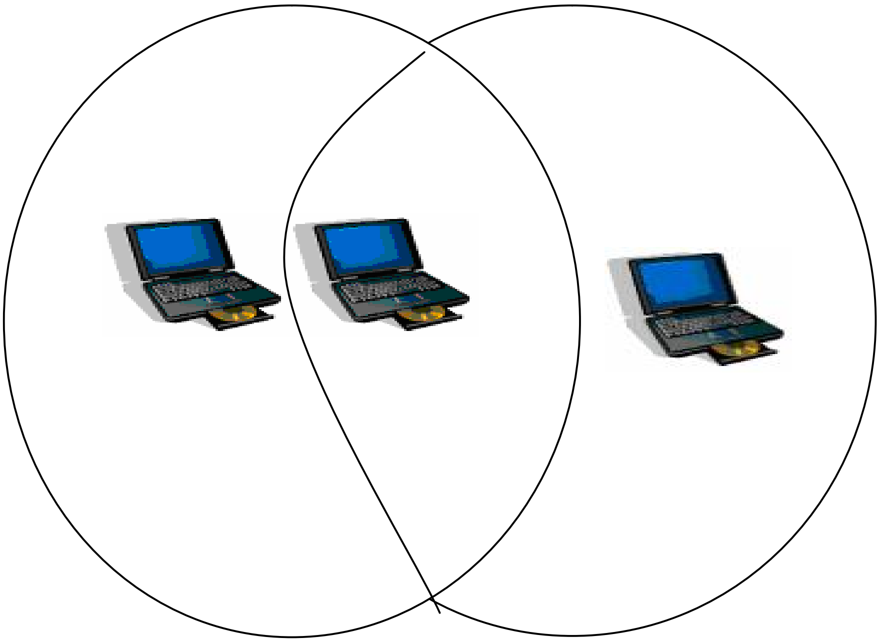


Fig 2.5: Example of a simple Ad hoc network with three participating nodes [21]

In Figure 2.5, we can see a simple Ad hoc network with only three nodes. Here the outermost nodes are out of the transmitter range of each other. So the middle node forwards the packets to and from the outermost nodes. The middle node is acting as a router for other nodes and all the three nodes have formed the Ad hoc network. [21]

An Ad hoc network does not use any centralized administration. This helps the network to sustain the operation even one of the mobile nodes move out of transmitter range of the others. Here nodes are able to enter/leave the network as and when required. Due to the limitation of transmitter range of the nodes, multiple hops are sometimes needed to reach other nodes. Every node which wishes to participate in an Ad hoc network, must forward packets for other nodes. Thus every node in the network acts both as a host and as a router. In the network, every single node can be viewed as an abstract entity consisting of a router and a set of associated mobile hosts (Figure 2.6). A router is a unit, which runs a routing protocol among other things. In the traditional sense a mobile host is simply an Internet Protocol (IP) -addressable host/entity. [21]

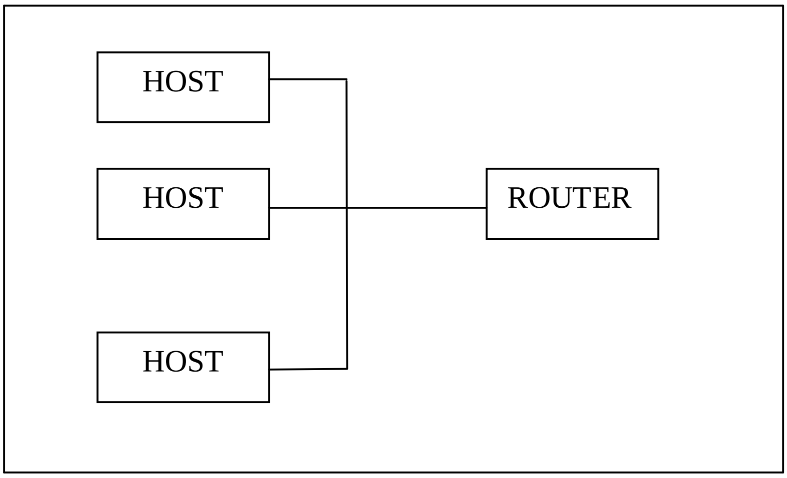


Fig 2.6: Block diagram of a mobile node acing both as hosts and as router [21]

In the Figure 2.7, a multihop Ad hoc network with multi-hop routes is described. It consists of mobile nodes which communicate with each other through those multi-hop routes. As the topology changes vigorously, network routing is an important issue in this context.

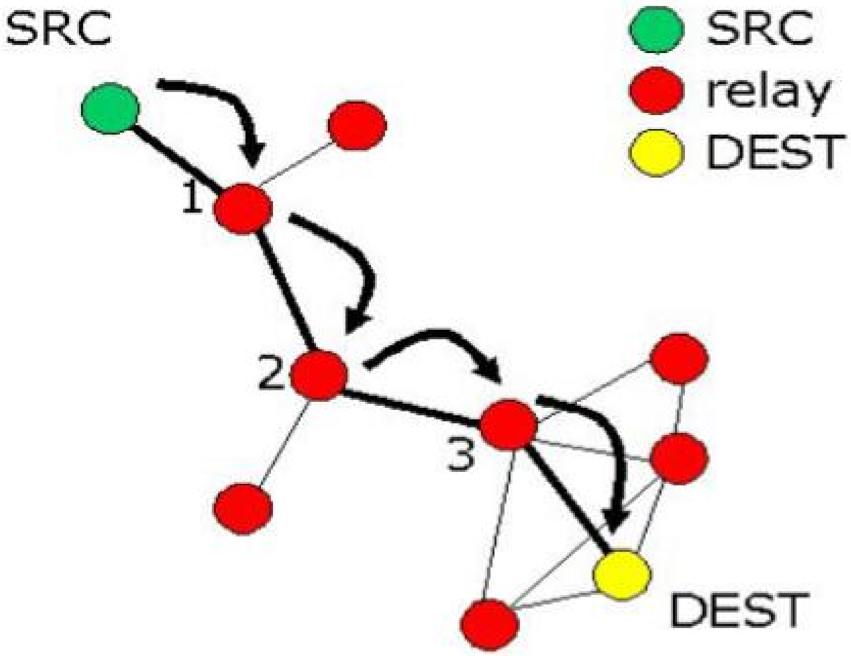


Figure 2.7: Illustration of the multihop Ad hoc network model. [19]

Ad hoc networks can also handle the changes in topology and can provide remedy if there is any malfunction in the participating nodes. These are made through network reconfiguration. For example, when a node leaves the network and the link is broken, the affected nodes can make requests for new routes and thus the link-breakage problem will be solved. This will increase the delay a little bit, but the network will still be operational.

Wireless Ad hoc networks have an advantage due to the nature of the wireless communication medium. Simply speaking, in a wired network the physical cabling restrict the topology of connections of the nodes. This restriction is not present in the wireless domain and, an instantaneous link between two nodes may form, provided that the nodes are within the transmission range of each other.

2.3 Cellular CDMA networks

A cellular network is a radio network which consists of a number of hexagonal cells. Each of the cells is served by a fixed transmitter, known as a cell site or

base station. These cells are used to cover different areas in order to provide radio coverage over a wider area than the area of one cell. Cellular networks are naturally asymmetric in nature. It has a set of fixed transceivers each serving a cell and a set of mobile transceivers which provide services to the users.
Cellular networks have the following advantages over the other solutions:

- Capacity enhancement
- Coverage improvement
- Power usage reduction. [7]

CDMA, Code Division Multiple Access is a multiplexing scheme. It is a multiple access method which does not divide up the channel by time (as in Time Division Multiple Access, TDMA), or frequency (as in Frequency Division Multiple Access, FDMA). Rather CDMA encodes the original information signal with a special code associated with each channel and then it uses the constructive interference properties of the special code to perform the multiplexing operation. [7]

The primary service of cellular networks is to provide voice service and it has witnessed the most successful story in infrastructure networking for the last two decades. Usually, the base stations provide universal coverage to all mobile nodes at all locations in the network. This is illustrated in Figure 2.8 when the base stations are so close to offer seamless coverage to all areas served by the network operator. 2G (second generation) cellular networks provide primarily voice service whereas 3G (third generation) cellular networks offer diverse voice and data services. [19]

In this network model, there is an infrastructure of fixed entities, called base stations (Figure 2.8) and the mobile stations physically communicate only with base stations. Again, the base stations communicate among themselves over a wired network. The area that a base station covers around it, in which communication from and to the base station is achievable, is called its cell, thus the term comes “cellular network”. Cells are rather a logical concept than physical areas. When a new base station is set-up, consequently a new cell is created. We will however assume a cell as disc-shaped areas in the plane with a base station in the middle which corresponds to the use of isotropic antennas. Another term for cellular networks is infrastructured networks. If a mobile station wishes to connect to the system, initially it has to find a base station that is close enough to it. This is usually done with preprogrammed so-called beacon signals which are emitted by the base stations from time to time. If the mobile station receives that beacon signal, it can subscribe to the base station by sending a subscription request. If the base station accepts this request, consequently the mobile node is added to the corresponding cell. As a result the mobile node can enter any other nodes in the network through the base station. Thus another term for base station is access point (AP). A potential reason that the base station would refuse the subscription request from the mobile station is that it has already reached the maximum limit of the mobile nodes it can accommodate and its capacity is exhausted. When the mobile nodes roam in space and move out of the transmission range of their corresponding base station, they must look for a new cell and base station to subscribe to and they completely unsubscribe from their previous base station. This procedure is called hand-over. Especially for CDMA, there is another handover called soft-handover. It occurs when the mobile node

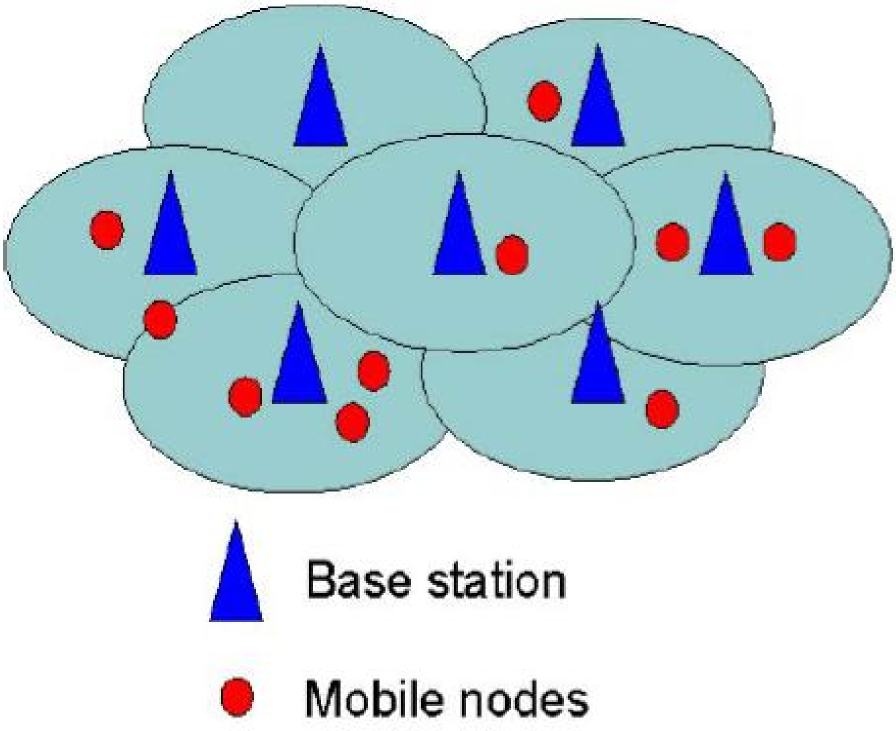


Figure 2.8: Illustration of the infrastructure network model. [19]

belongs to more than one base station. If a mobile node needs to exchange any information with any other mobile node in the network it transmits the information signal to the base station. The base station then determines the present location of the other mobile node and sends the information signal to that node’s base station. This transmission of data is done over a wired network which connects all the base stations, for instance UMTS (Universal Mobile Telecommunications System) R99 uses ATM (Asynchronous Transfer Mode)over digital synchronous/plesinchronous hierarchy (E or T trunk lines) In R5 IP networks (such as high speed Ethernet) are specified. The base station of the destination node then transmits the data to the destination mobile node over the wireless link. The same process is performed if a mobile node needs to transmit data to another mobile node within its own cell. In that case, the base station receives the original information signal from the source node and sends it to the destination node. Thus the task of the base station is to keep track of the mobile nodes which are located within its cell, to identify any new node that comes into its cell or are switched on. After tracking the new node the base station can allocate resources for wireless communication to the mobile nodes. Hence the base station helps the mobile nodes to communicate by forwarding data traffic, etc. [5]

Now we will describe the UMTS architecture.

‘UMTS Architecture

The public land mobile network (PLMN) described in UMTS Rel. '99 incorporates three major categories of network elements:

- GSM phase 1/2 core network elements—Mobile services switching center (MSC), visitor location register (VLR), home location register (HLR), authentication center (AuC), and equipment identity register (EIR)
- GPRS network elements—Serving GPRS support node (SGSN) and gateway GPRS support node (GGSN)
- UMTS-specific network elements—User equipment (UE) and UMTS terrestrial radio access network (UTRAN) elements

The UMTS core network is based on the GSM/GPRS network topology. It provides the switching, routing, transport, and database functions for user traffic. The core network contains circuit-switched elements such as the MSC, VLR, and gateway MSC (GMSC). It also contains the packet-switched elements SGSN and

GGSN. The EIR, HLR, and AuC support both circuit- and packet-switched data. The Asynchronous Transfer Mode (ATM) is the data transmission method used within the UMTS core network. ATM Adaptation Layer type 2 (AAL2) handles circuit-switched connections. Packet connection protocol AAL5 is used for data delivery. The UMTS architecture is shown in Figure 2.9.

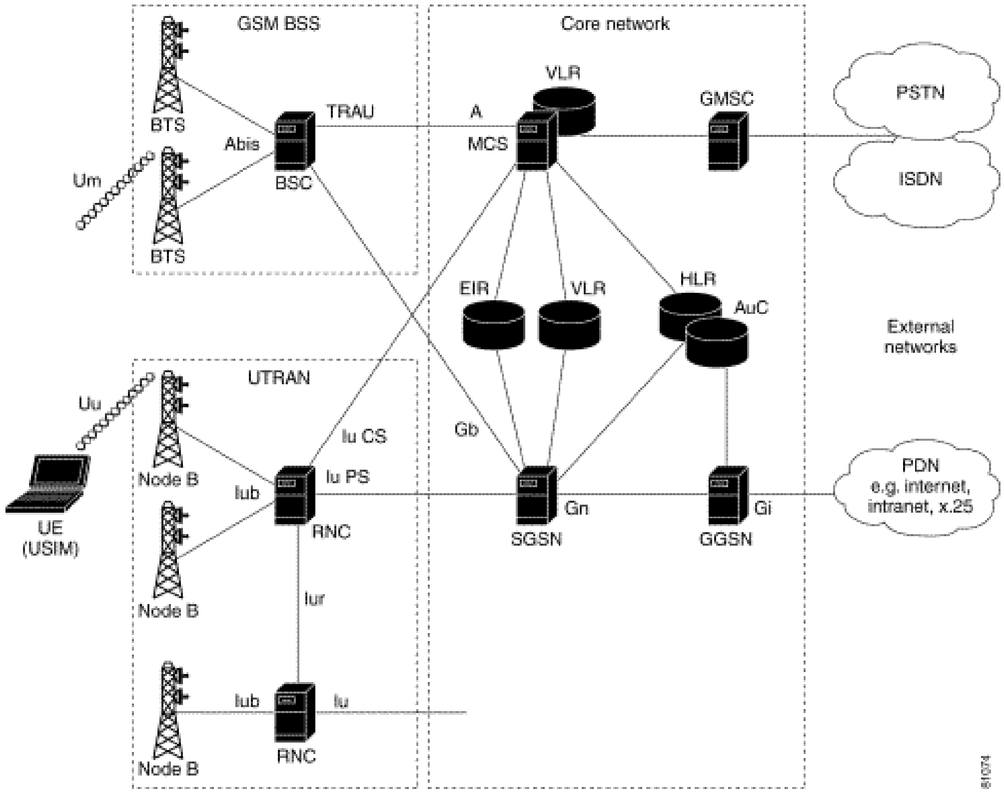


Figure 2.9: UMTS Architecture

General Packet Radio System

The General Packet Radio System (GPRS) facilitates the transition from phase1/2 GSM networks to 3G UMTS networks. The GPRS supplements GSM networks by enabling packet switching and allowing direct access to external packet data networks (PDNs). Data transmission rates above the 64 kbps limit of integrated services digital network (ISDN) are a requirement for the enhanced services supported by UMTS networks. The GPRS optimizes the core network for the transition to higher data rates. Therefore, the GPRS is a prerequisite for the introduction of the UMTS.

UMTS Interfaces

The UMTS defines four new open interfaces (see Figure 2.9):

- *Uu* interface—User equipment to Node B (the UMTS WCDMA air interface)
- *Iu* interface—RNC to GSM/GPRS (MSC/VLR or SGSN)
    - *Iu-CS*—Interface for circuit-switched data
    - *Iu-PS*—Interface for packet-switched data
- *Iub* interface—RNC to Node B interface
- *Iur* interface—RNC to RNC interface (no equivalent in GSM)

The *Iu*, *Iub*, and *Iur* interfaces are based on the transmission principles of aynchronous transfer mode (ATM).

UMTS Terrestrial Radio Access Network

The major difference between GSM/GPRS networks and UMTS networks is in the air interface transmission. Time division multiple access (TDMA) and freqency division multiple access (FDMA) are used in GSM/GPRS networks. The air interface access method for UMTS networks is wide-band code division multiple access (WCDMA), which has two basic modes of operation: frequency division duplex (FDD) and time division duplex (TDD). This new air interface access method requires a new radio access network (RAN) called the UTMS terrestrial RAN (UTRAN). The core network requires minor modifications to accommodate the UTRAN.

Two new network elements are introduced in the UTRAN: the radio network controller (RNC) and Node B. The UTRAN contains multiple radio network systems (RNSs), and each RNS is controlled by an RNC. The RNC connects to one or more Node B elements. Each Node B can provide service to multiple cells. The RNC in UMTS networks provides functions equivalent to the base station controller (BSC) functions in GSM/GPRS networks. Node B in UMTS networks is equivalent to the base transceiver station (BTS) in GSM/GPRS networks. In this way, the UMTS extends existing GSM and GPRS networks, protecting the investment of mobile wireless operators. It enables new services over existing interfaces such as *A*, *Gb*, and *Abis*, and new interfaces that include the UTRAN interface between Node B and the RNC (*Iub*) and the UTRAN interface between two RNCs (*Iur*). The network elements of the UTRAN are shown in Figure 2.10.

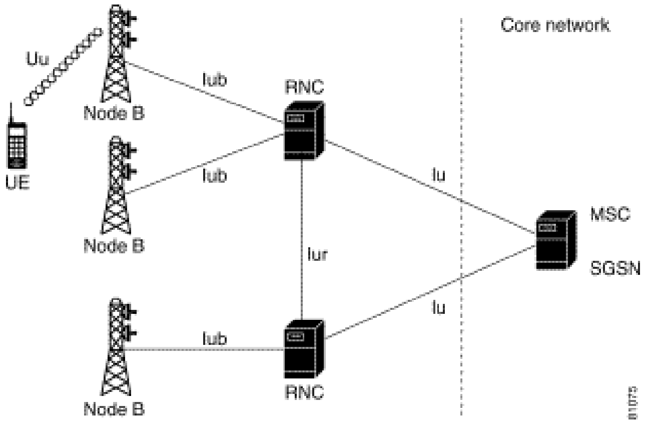


Figure 2.10: UTRAN Architecture

Radio Network Controller

The radio network controller (RNC) performs functions that are equivalent to the base station controller (BSC) functions in GSM/GPRS networks. The RNC provides centralized control of the Node B elements in its covering area. It handles protocol exchanges between UTRAN interfaces (*Iu*, *Iur*, and *Iub*). Because the interfaces are ATM-based, the RNC performs switching of ATM cells between the interfaces. Circuit-switched and packet-switched data from the *Iu-CS* and *Iu-PS* interfaces are multiplexed together for transmission over the Iur, Iub, and Uu interfaces to and from the user equipment (UE). The RNC provides centralized operation and maintenance of the radio network system (RNS) including access to an operations support system (OSS).

The RNC uses the *Iur* interface. There is no equivalent to manage radio resources in GSM/GPRS networks. In GSM/GPRS networks, radio resource management is performed in the core network. In UMTS networks, this function is distributed to the RNC, freeing the core network for other functions. A single serving RNC manages serving control functions such as connection to the UE, congestion control, and handover procedures. The functions of the RNC include:

- Radio resource control
- Admission control
- Channel allocation
- Power control settings
- Handover control

- Macro diversity
- Ciphering
- Segmentation and reassembly
- Broadcast signalling
- Open loop power control

Node B

Node B is the radio transmission/reception unit for communication between radio cells. Each Node B unit can provide service for one or more cells. A Node B unit can be physically located with an existing GSM base transceiver station (BTS) to reduce costs of UMTS implementation. Node B connects to the user equipment (UE) over the *Uu* radio interface using wide-band code division multiple access (WCDMA). A single Node B unit can support both frequency division duplex (FDD) and time division duplex (TDD) modes. The *Iub* interface provides the connection between Node B and the RNC using asynchronous transfer mode (ATM). Node B is the ATM termination point.

The main function of Node B is conversion of data on the *Uu* radio interface. This function includes error correction and rate adaptation on the air interface. Node B monitors the quality and strength of the connection and calculates the frame error rate, transmitting this information to the RNC for processing. The functions of Node B include:

- Air interface transmission and reception
- Modulation and demodulation
- CDMA physical channel coding
- Micro diversity
- Error handling
- Closed loop power control

Node B also enables the UE to adjust its power using a technique called downlink transmission power control. Predefined values for power control are derived from RNC power control parameters.

UMTS User Equipment

The UMTS user equipment (UE) is the combination of the subscriber's mobile equipment and the UMTS subscriber identity module (USIM). Similar to the SIM in GSM/GPRS networks, the USIM is a card that inserts into the mobile equipment and identifies the subscriber to the core network. The USIM card has the same physical characteristics as the GSM/GPRS SIM card and provides the following functions:

- Supports multiple user profiles on the USIM
- Updates USIM information over the air
- Provides security functions
- Provides user authentication
- Supports inclusion of payment methods
- Supports secure downloading of new applications

The UMTS standard places no restrictions on the functions that the UE can provide. Many of the identity types for UE devices are taken directly from GSM specifications. These identity types include:

- International Mobile Subscriber Identity (IMSI)
- Temporary Mobile Subscriber Identity (TMSI)
- Packet Temporary Mobile Subscriber Identity (P-TMSI)
- Temporary Logical Link Identity (TLLI)
- Mobile station ISDN (MSISDN)
- International Mobile Station Equipment Identity (IMEI)
- International Mobile Station Equipment Identity and Software Number (IMEISV)

The UMTS UE can operate in one of three modes of operation:

- PS/CS mode—The UE is attached to both the packet-switched (PS) and circuit-switched (CS) domain, and the UE can simultaneously use PS and CS services.
- PS mode—The MS is attached to the PS domain and uses only PS services (but allows CS-like services such as voice over IP [VoIP]).
- CS mode—The MS is attached to the CS domain and uses only CS services.’

2.4 Mobile Infostation Network

In a mobile infostation network, any pair of nodes communicates only when they are close enough to each other and they have a high-quality radio channel between them. According to this transmission criterion, any pair of nodes is linked as mobility shuffles the location of the nodes. [19]

Let us assume that each mobile node within the network chooses an arbitrary target location. We take a source node (SRC), which has some packets in its buffer to deliver to a destination node (DEST), as illustrated in Figure 2.11. The mobile node SRC roams along an arbitrary path as time passes and ultimately reaches the mobile nodes 1 and 2. Here none of the nodes 1 and 2 are the destination of SRC; still SRC relays the packets to the nodes 1 and 2. Here SRC expects that when each of the relay nodes 1 and 2 arrive DEST, the destination node for SRC, they will complete the second hop of relaying on behalf of the node SRC. When the steady state is reached, each of the other n −2 nodes has packets which were generated by the node SRC and had a destination to the node DEST. If we take any network snapshot, obviously it will be found that the adjacent neighbor of the node DEST contains

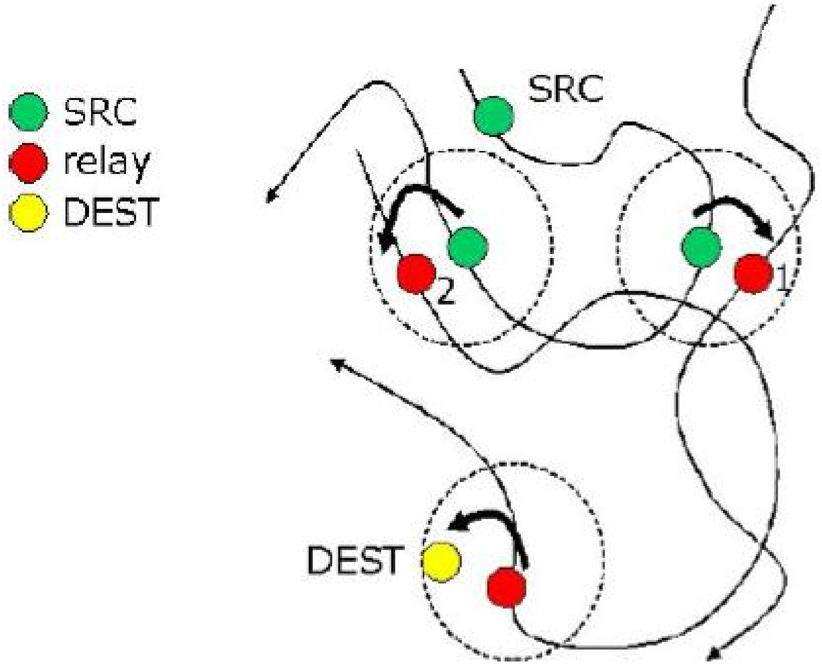


Figure 2.11: Illustration of the mobile infostation network model. [19]

packets which are generated from the node SRC and completes the second hop of relaying on the behalf of SRC. Thus, the ultimate throughput for each node is constant and does not depend on the size of the network. Hence the capacity of the network is improved which is the result of the utilization of node mobility to physically take the packets around the network, and this does not depend on the underlying mobility model either. [19]

On the other hand, the network capacity cannot be improved to a high value as it incurs an arbitrary delay for the end-to-end transmissions and the delay is at the same time scale of the mobility process. Hence, a mobile infostation network is suitable for the applications which can tolerate delays and require a high bandwidth, e.g.; in a content distribution application where all mobile nodes are subscribers to a movie or news content provider. The advantage in this type of applications is that the user is not worried about the download schedules of the content. While the user roams around different places in his daily life, the specific application normally runs in the background for a few hours or even a few days and finally the user gets the content downloaded. [19]

Chapter 3

Multihop Cellular Networks

We have seen the Ad hoc networks and cellular networks before. Using the infrastructure of Ad hoc network and the concept of cellular network, the new combined concept is the multihop cellular network (MCN) as shown in the Figure 3.1. MCN preserves the benefit of conventional single hop cellular networks (SCN) where the service infrastructure is constructed by fixed bases, and it also incorporates the flexibility of Ad hoc networks where wireless transmission through mobile stations in multiple hops is allowed. This multihop cellular network offers the advantages of potential multihop relaying which in turn can lead to enhanced coverage, improved capacity and flexibility. MCN can reduce the required number of bases or improve the throughput performance, while limiting path vulnerability encountered in Ad hoc networks. Hence, multihop cellular networks have been attracting significant consideration. Opportunistic driven multiple access (ODMA) was considered for 3G networks in the initial phase of the standardization, but has since been rejected by the 3GPP. Hence, relaying is not currently considered for 3G networks. Fixed relays and MESH networking is currently being considered for WiMAX and WLAN networks. There are also some 4G proposals that are based on fixed relays. Mobile relays are not (yet) of practical interest except in some specific applications such as professional radios for emergency response, police and security organizations. Nevertheless, there exist academic proposals for using mobile relays for range and capacity enhancement for cellular radio and the topic is currently under research. [23]

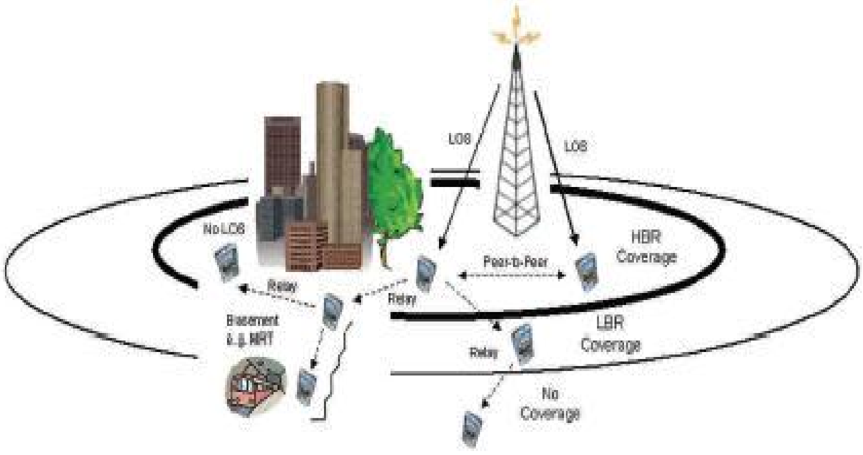


Figure 3.1: Multihop Cellular Network architecture. [8]

At present, the cellular networks use centralized infrastructure where every communication link between two mobile nodes is made through the central base station. But the emerging multihop cellular network architecture provides future cellular systems with the opportunity of peer-to-peer (mobile to mobile) communication as well as communication relayed through other fixed and/or mobile terminals. [8]

Since the difference of power level difference between the transmit and the receive signals is high, transmission and reception simultaneously in the same frequency band is not realistic. Hence, the transmission using the WCDMA-TDD (Wideband Code Division Multiple Access-Time Division Duplex) mode is the appropriate duplexing mode for the multihop cellular networks. On the other hand, transmission through multihop will consume more radio resources for only one transmission. Again, different selection algorithm of the relay station might give different performance level to the overall system. Thus in order to have reasonable performance in multihop cellular networks, these points must be considered carefully. [8]

3.1 MCN System Architecture

In Single-hop Cellular Networks (SCNs) base stations can be reached by mobile stations in a single hop, whereas in Mutlihop Cellular Networks (MCNs), base stations can not always be reached by mobile stations in a single hop. We can define the area reachable by a base station in SCN as a cell, which is covered by a radius of fixed distance, R. And we can define the area of a cell in MCN in a same way. The radius of a cell in MCN is half the distance between two neighboring base stations. Again, we can define a sub-cell in MCN as the area reachable in a single wireless hop by a base station or a mobile station whereas in SCN, the area of a sub-cell is the same as the area of a cell. [10]

Single-hop Cellular Network (SCN)

For SCN, base station and mobile stations both being in the same cell area, are always reciprocally accessible in a single hop. If a mobile station has some packets to send, wherever the location of destination mobile node is, the source mobile node always sends the packets to the base station in the same cell. If the source mobile node and the destination mobile node are located in the same cell, as mobile nodes 1 and 4 in Fig. 3.2, the base station directly forwards the packets to the destination mobile node. On the other hand, if the destination is located in a different cell other than the location of the source mobile node, the base station forwards the packets received from the source mobile node to the base station of the cell where the destination mobile node is located. The base station of the latter cell then finally forwards the packets to the destination mobile node in a single hop. Thus, the routing path of SCN is showed by the dashed lines in Figure 3.2 and 3.3. [10]

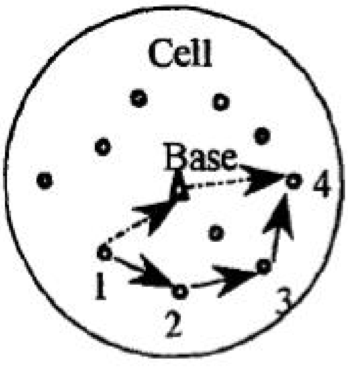


Figure 3.2: Multihop routing vs. single-hop routing. [10]

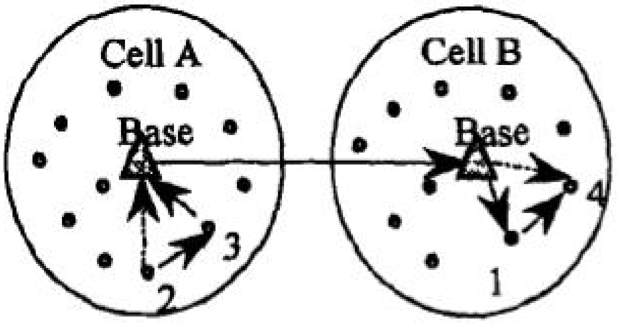


Figure 3.3: Different routing paths of MCN and SCN. [10]

Multihop Cellular Network (MCN)

The architecture of MCN is almost similar to that of SCN but the basic difference is that in MCN the base station and mobile stations are not always reciprocally accessible in a single hop. In MCN, the transmission range of base station and mobile stations is reduced than that in SCN. Accordingly, the accessible area by a base station or a mobile station is basically the area of a sub-cell. In contrast to SCN, the key advantage in MCN is that the mobile stations can directly communicate with each other provided that they are mutually reachable. With this characteristic MCN can perform multihop routing. When both the source mobile node and the destination mobile node are located in the same cell, the packets from the source mobile node can be relayed through other mobile stations to the destination mobile node. On the other hand, when the destination mobile node is located in a different cell apart from the source mobile node, the source mobile node sends the packets to the base station first, could be in multiple hops or single, and then the base station forwards the packets to the base station of the cell where the destination mobile node is located. And finally the latter base station forwards those packets to the destination mobile node. This forwarding within the latter cell might happen in multiple hops again or single. [10]

The above two cases are illustrated by the solid lines in Figure 3.2 and 3.3. These figures show the different routing paths of MCN and SCN by solid and dashed lines, respectively. The increase in system throughput is the major advantage of MCN. For example, from Figure 3.4, we can see that the mobile stations 1, 3, and 5, located in the same cell, can transmit packets at the same time without interfering each other. On the other hand, for the same system snapshot, in SCN only one packet can be transmitted. [10]

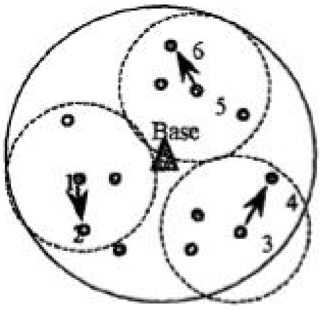


Figure 3.4: Three stations in a cell transmit at the same time in MCN. [10]

3.2 Relaying design objectives in Multihop Cellular Networks

Using relays in multihop cellular networks has some potential benefits. These are described below:

- **Communication range**
  We know from the propagation properties of a radio signal that the signal strength decays quickly with growing distance; hence every radio device has its own radio transmission range. Relaying can be very effective when the overall area of the network exceeds the respective radio transmission range of a radio device. If a mobile node wants to communicate with any other mobile node that is not in its transmission range, the intermediate relay nodes can forward the data from the source mobile node to the destination mobile node. The first benefit of relaying is thus to extend the "communication range" of a mobile node in the wireless network beyond the transmission range of its radio device and hence to eliminate the black spots throughout the coverage region. [5]

- **Energy Efficiency**
  The transmission power required to achieve constant received signal strength is not proportional to the transmission distance. When a mobile

node wants to communicate with another mobile node which is located far away, the source node has to “disproportionately” increase the transmission power. For network types where power is a strictly limited resource, use of several hops is thus reasonable. Let us consider for example the network in Figure 3.5 with N +1 mobile nodes on a straight line with distance d between two neighbors. Let us assume, node 1 wants to transmit data to node N + 1. If a target received power of $\overline{P}_{rcv}$ is desired, the required transmission power is,

$$P_{snd}(1hop) = \frac{\overline{P}_{rcv}}{a_1}(N.d)^{\alpha} \tag{3.1}$$

where a_1 is real antenna efficiency and α is the pathloss coefficient. On the other hand, if node 1 transmits the same data to node N+1 by relaying via all intermediate nodes, the overall transmission power is only

$$P_{snd}(Nhops) = N.\left(\frac{\overline{P}_{rcv}}{a_1}d^{\alpha}\right) \tag{3.2}$$

If we neglect the power consumed for receiving the messages, this is a power saving factor of $N^{\alpha-1}$. If energy consumption at the receiver is taken into account, relaying becomes beneficial only if d is large. [5]

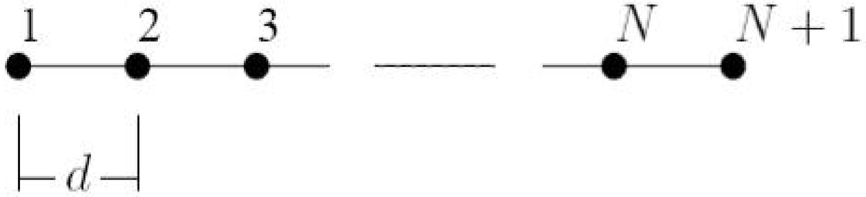


Figure 3.5: Line network with (N + 1) nodes [5]

- **Higher data rates**

  Some wireless transmissions are performed over a short distance, but more transmissions are scheduled. As the received signal is stronger for shorter transmission, it produces a higher SINR (signal-to-interference and noise ratio) for the transmission with relaying. This interprets directly to higher data rate by the goodput vs. SINR graph as illustrated in Figure 3.6.

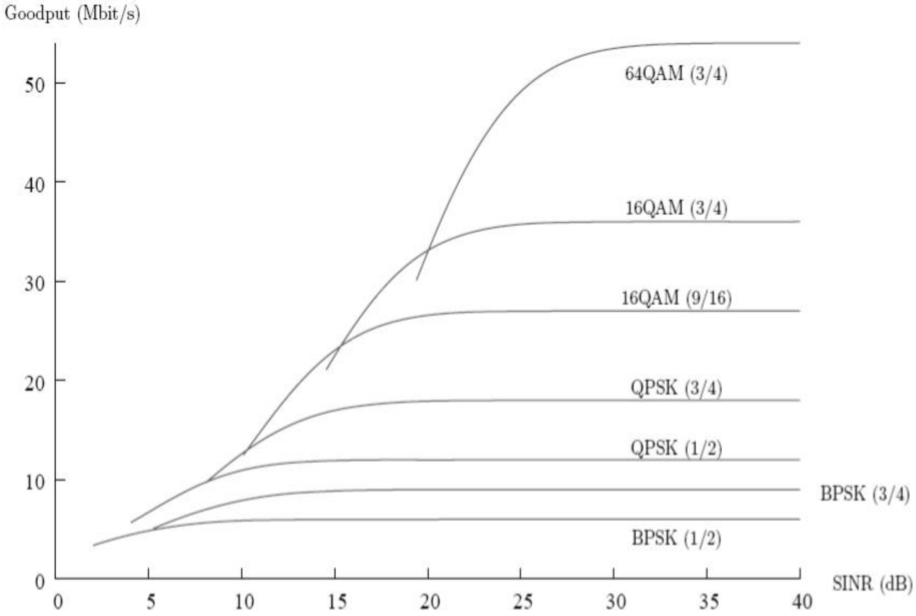


Figure 3.6: Goodput vs. signal-to-noise ratio for HiperLAN/2. [5]

Relaying is beneficial if it takes shorter time to transmit the same amount of data through several hops of transmission (Figure 3.7) than by using a single hop in direct communication. Thus another potential benefit of relaying is higher data rates for the mobile nodes located at the edge of a cell if they use relaying. [5]

As relaying can extend the high data rate coverage range of a single base station; therefore through the increase of the relaying capability in conventional cellular networks, it is possible to have cost-effective high data rate coverage in the whole network.

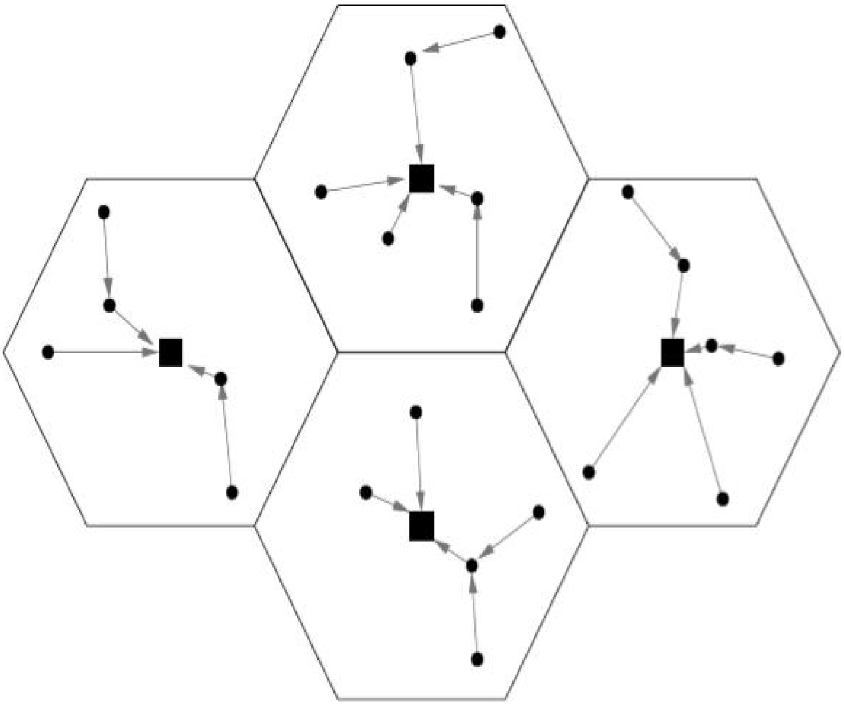


Figure 3.7: Relaying in cellular networks. [5]

- **Better Quality**

  Relaying allows substituting a poor quality (due to high pathloss) single-hop wireless link with a composite, two- or more hop, better-quality link. It would be possible to coherently combine both the original message and the message transmitted by the relay at the destination. Cooperative relaying is a better idea in this situation. In cooperative relaying original signal is received by several relays and forwarded to the destination through different paths, it takes the advantage of diversity so that the original signal does not get stuck with a bad path and can be switched to a good path. Cooperative relaying shares the same radio resource; therefore multiple synchronized and orthogonal transmissions are possible. Cooperative relaying provides

  –Better BER performance due to spatial diversity

  –Higher efficiency due to spatial multiplexing

  –Enhanced bandwidth efficiency (capacity) while providing energy savings

–Higher throughput and link robustness
–Relay resources such as time-slots and sub-carriers can be saved
–Better performance is expected because of the higher SINR
–Requires less hardware complexity (MS specification is not changed, little update in Base Station) [9]

- **Capacity Gain**
  Through deploying relays it is possible to have simultaneous transmissions by both the base station and the relays. Hence capacity gains may also be achieved. ‘The mechanism that allows capacity increase is threefold:
  1. The breakdown of each path into multiple paths will reduce the interference generated into neighbor cells, thus improving the network capacity.
  2. The power requirements for the in-cell far users are break down in multiple hops, and cell breathing effect is reduced. This allows a better efficiency in DL channels at the BS.
  3. As the DL users are near the BS, the near-far effect is alleviated. This is particularly important for terminals not using multiuser detection at the DL

In this way, better efficiency is observed in DL. Points 2 and 3 are specially important when considering that the very nature of a multihop system will require a high number of channels for BS-relay links. Any action oriented to improve the efficiency of the DL (as developing affordable MUD in BS-relay link) is of foremost relevance’. [26]

Chapter 4

System Model

This chapter describes the system models which include the Signaling Model, Traffic Model, Packet Transmission Model and Mobility Model.

4.1 Signaling Model

Basketball scheduling is a multihop scheme used in DS-CDMA (Direct Sequence, Code Division Multiple Access) uplink channel to improve throughput performance. The basic idea of basketball scheduling is to deploy multihop transmission from mobile terminals back to the base station. For each CDMA time slot, a number of mobile terminals are selected as relays to let other terminals nearby to send the packets to them. A transmitting terminal may select a relaying terminal that is close to it and meanwhile the relaying terminal is located closer to the base station than that transmitting one.

Let us consider a cellular radio network in which the base stations are distributed on a hexagonal grid. We assume that the cells cover a disc shaped service area. ‘We consider the uplink of a DS-CDMA cell with M mobiles, in which each mobile wishes to send its NRT (Non-Real Time) data to the base station (BS), possibly by multihop routing. We assume that a mobile cannot receive and send data simultaneously; when a mobile relays packets, it first receives packets and then forwards them to the other mobile. Each mobile i has a buffer B_i of a finite size. The cell is partitioned into two regions, where the closer region to BS is called single-hop region (SR) and the other one is called multihopping region

(MR). A mobile can decide whether it is in SR or MR, by the signal strength of the pilot symbols from BS. If the signal strength is above a certain threshold, then it is decided to be in SR. Mobile *i* which is currently in MR cannot transmit the data directly to BS. Instead, it sends out a kind of Request to- Send (RTS) to its neighboring mobiles. In an RTS frame header, there should be the identification (ID) of mobile *i*, the owner of the RTS. Each neighboring mobile *j*, after receiving RTS, checks its buffer B_j. If the buffer contains less packets than the threshold ($B_j < B_{tj}$), it sends out Acknowledgement (ACK). Otherwise it will not send the ACK signal and the node cannot be selected as a relay if it does not transmit an ACK. In an ACK packet header, there are the pilot signal strength measured at mobile *j* and the ID of mobile *j*, contained.' [17]

4.2 Traffic Model

'Traffic modeling plays a fundamental role in the performance assessment of packet scheduling strategies for NRT data services. Although different services are characterized by different data traffic profiles, it is possible to underline some features common to nearly all NRT services:

1. At the start of a connection, some small messages are typically exchanged to setup the service
2. During the packet data session, packets are generated by the application level and transmitted over the air interface
3. At the end of the service often some small packages are exchanged between the peer entities.' [24]

'At the beginning of each simulation mobile nodes are placed in the network, and for the entire simulation time nodes neither enter nor leave the system. Though the total number of mobile nodes in the system is a fixed parameter, the number of users having data packet to transmit can fluctuate during the simulation time.' [24] In Figure 4.1, each packet arrival is represented by an arrow. The time between two consecutive packet arrivals is the inter-arrival time. The counter, $N(t)$ tells the number of arrivals that have occurred in the interval (0, *t*). [24]

$$\text{Expected data rate is} = \text{Packet size} / E\{\text{Inter-arrival time}\} \qquad (4.1)$$

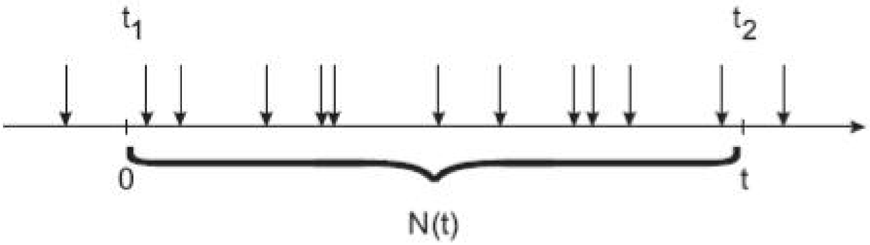


Figure 4.1: Packet Arrival Process

In our simulation, only the second feature is modeled (mentioned above). All the mobile nodes are independently initialized and all nodes are assumed to have active sessions where interarrival time of the packets follows log-normal distribution (Figure 4.2). That is, the logarithm of the time between consecutive packets follows normal distribution. The packets are assumed to have fixed size [25].The sources generate packets at a fixed average rate. The incoming packets are stored in a packet buffer of infinite length. The FIFO (First-in-first-out) algorithm keeps the arriving order when selecting the next packet to send. The aim of all active mobile nodes is to transmit the maximum possible number of packets from the sources to the receivers.

Log-normal distribution is a continuous distribution in which the logarithm of a variable has a normal distribution. It is a general case of Gibrat's distribution, to which the log normal distribution reduces with $S=1$ and $M=0$. A log normal distribution results if the variable is the product of a large number of independent, identically-distributed variables in the same way that a normal distribution results if the variable is the sum of a large number of independent, identically-distributed variables.

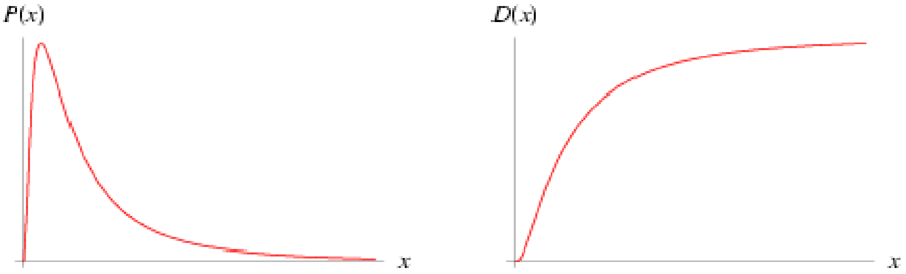


Figure 4.2: The probability density and cumulative distribution functions for the log normal distribution [22]

The probability density and cumulative distribution functions for the log normal distribution are

$$P(x) = \frac{1}{S\sqrt{2\Pi}x} e^{-(\ln x - M)^2/(2S^2)} \tag{4.2}$$

$$D(x) = \frac{1}{2}\left[1 + erf\left(\frac{\ln x - M}{S\sqrt{2}}\right)\right] \tag{4.3}$$

Where $erf(x)$ is the "error function", [22]

$$M = \log\left(\frac{\mu^2}{\sqrt{(\mu^2 + \sigma^2)}}\right) \tag{4.4}$$

$$\text{And } S = \sqrt{\log\left(\left(\frac{\sigma}{\mu}\right)^2 + 1\right)} \tag{4.5}$$

Where μ is the mean of inter-arrival time and σ is the standard of inter-arrival time.

4.3 Packet Transmission model

Let us assume that the capacity of the network follows the Shannon bound when multi-user interference is treated as noise. That is, we assume that multi-user detection and interference cancellation is not utilized and coding and modulation scheme is perfectly matched to the current SINR level.

For simplicity, we ignore the effects of fast fading and focus only on the effect of distance based attenuation. Our model could e.g. correspond to the case where the number of multipath components resolved by RAKE receiver is large. In that case, the fading gets to be averaged over multiple RAKE fingers.

For each mobile, SINR determines the transmission rate that the mobile can achieve. The packet size is assumed to be equal to $r_{\min} * T_s$ where T_s is the scheduling interval and $r_{\min}$ is the minimum data rate. Furthermore, we assume that the packets cannot be cut into fractions. Hence if the capacity of the link is less than $r_{\min}$ then no packet is transmitted. For each time slot, the number of packets n_{ij} that can be delivered from the mobile node i to j is dependent on the instantaneous SINR and is denoted as

$$n_{ij} = \min\left\{ \left\lfloor \frac{W \log_2\left(1 + SINR_{ij}\right)}{r_{\min}} \right\rfloor, q_i \right\} \tag{4.6}$$

Where $\lfloor . \rfloor$ denotes floor operation, $r_{\min}$ is the minimum data rate, i.e., one packet transmitted in one time slot, q_i is the queue size of the transmitter i, $SINR_{ij}$ is Signal-to-Interference-and-Noise ratio.

Signal-to-Interference-and-Noise ratio (SINR) is the ratio between the power received at a base station from the mobile and the sum of the powers corresponding to interferences from other mobiles and of noise. $SINR_{ij}$ is defined as,

$$SINR_{ij} = \frac{g_{ij} P}{\sum_{k \neq i} g_{kj} P + N_0} \tag{4.7}$$

Where $g_{ij} = d_{ij}^{-\alpha}$, d_{ij} is the distance between transmitter j and receiver i, g_{ii} is the link gain between the mobile and the base station, P is the transmit power of the mobile node, g_{kj} is the link gain between other mobile (than the current mobile) and the base station and N_0 is the noise power.

4.4 Mobility Model

We have used a combination of two mobility models here: Random Walk Mobility (RWM) model and Boundless Simulation Area Mobility (BSAM) model. The simulation environment consists of a set of mobile nodes randomly distributed in a hexagon cell. The mobile nodes are moving on the simulation area according to a combination of two different mobility models, Random Walk Mobility (RWM) model and Boundless Simulation Area Mobility (BSAM) model. Each mobile node moves with a constant speed. In the beginning of the simulation, each mobile node picks a random destination in the area according to RWM model and traverses to that destination in a straight line at a uniform speed. When the destination is reached, each mobile node chooses a new destination according to BSAM model, and then they travel towards the newly chosen destination and so on. Each mobile node has a higher probability in moving in the same direction as the previous move. And we assigned different probabilities for all other directions as shown in the figure below. In Figure 4.3, $p_o = 0.7, p_1 = 0.1, p_2 = 0.05$

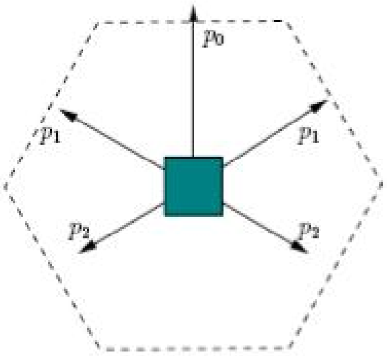


Figure 4.3: Directional Random Walk mobility scheme

A mobile node at each moment has 5 different possible directions to move with each direction a different probability so that

$$p_o + 2 * p_1 + 2 * p_2 = 1, \tag{4.8}$$

where $p_0 > p_i$; i=1, 2; denotes the moving direction that is randomly selected when the selection starts and other possibilities give fluctuation of movement. The new location of the mobile node depends on the previous location/direction and speed of the mobile node. When a mobile node reaches the boundary of the cell, it should flip-over to the reverse direction of the cell.

We saved the initial locations, directions and the speeds of the mobile nodes after a simulation has executed and used this position file as the initial starting point of the mobile nodes in all future simulations.

Chapter 5

Basketball Packet Scheduling Algorithm

This chapter contains the algorithm for packet scheduling we propose, namely Basketball Packet Scheduling Algorithm. In the algorithm we utilize the similarity between the basketball game and our multihop uplink packet scheduling problem. By regarding players, the basket and the ball as mobiles, the base station and data packet, respectively, we can mimic passing (multihopping) patterns of the basketball players. A major difference between the two is that in the multihopping problem, there are many packets (balls) while in the basketball game, there is only one ball to shoot into the basket.

5.1 The Algorithm

In this scheduler, there are two control parameters: Transmission range r, and Relay probability p. According to the scheduling rule a mobile will act as a relay with probability p. If it switches to relay mode, it only receives packet during the time slot. On the other hand, a mobile who does not act as relay will try to transmit. If the base station is in its transmission range r, it will transmit to it directly (Figure 5.1). Otherwise if base station is not in its range, the mobile will select the relay node which is closest to the base station and transmit the packet to it. (Figure 5.1).In the worst case, if there are no relay nodes closer to the base station than the mobile itself, the mobile will remain idle during the slot. See the flowchart for Transmit Mode in Figure 5.2.

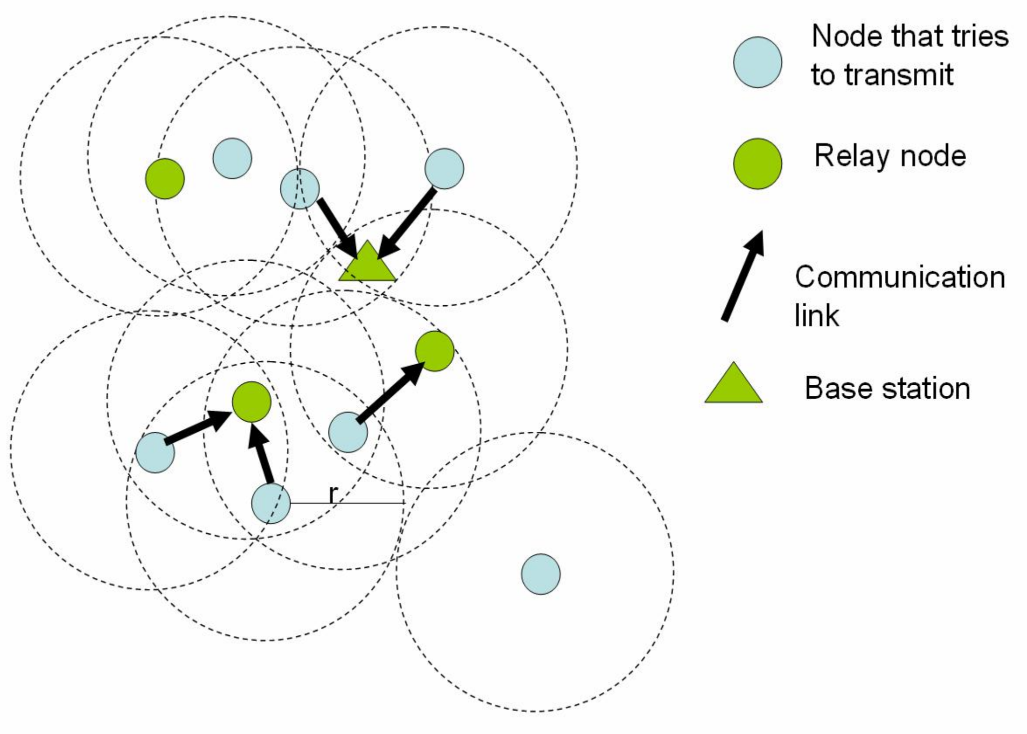


Figure 5.1: Basketball Scheduler Example

5.2 Structure of the Simulation

The structure of the simulation is described in this segment. At each time slot there is a check if the terminal generates a new packet. Given that a packet was generated, the size and arrival time slot are stored in a buffer for each user. Then it is checked that which terminals are acting as relays and which are acting as transmitters. The active links for all the transmit mode users are determined. For each active link, SINR at the receiver is calculated and the packet transmissions for those links are determined. Then the transmitted packets from the transmission buffer of the source terminal are removed and added to the end of the queue at the destination terminal. Finally if any packet was transmitted to the base station, the packet delay for the specific mobile node that generated that packet is recorded. The packet delay is the time between when the packet was generated and when the base station finally receives the packet. For the pseudocode of the simulation please refer to Appendix C.

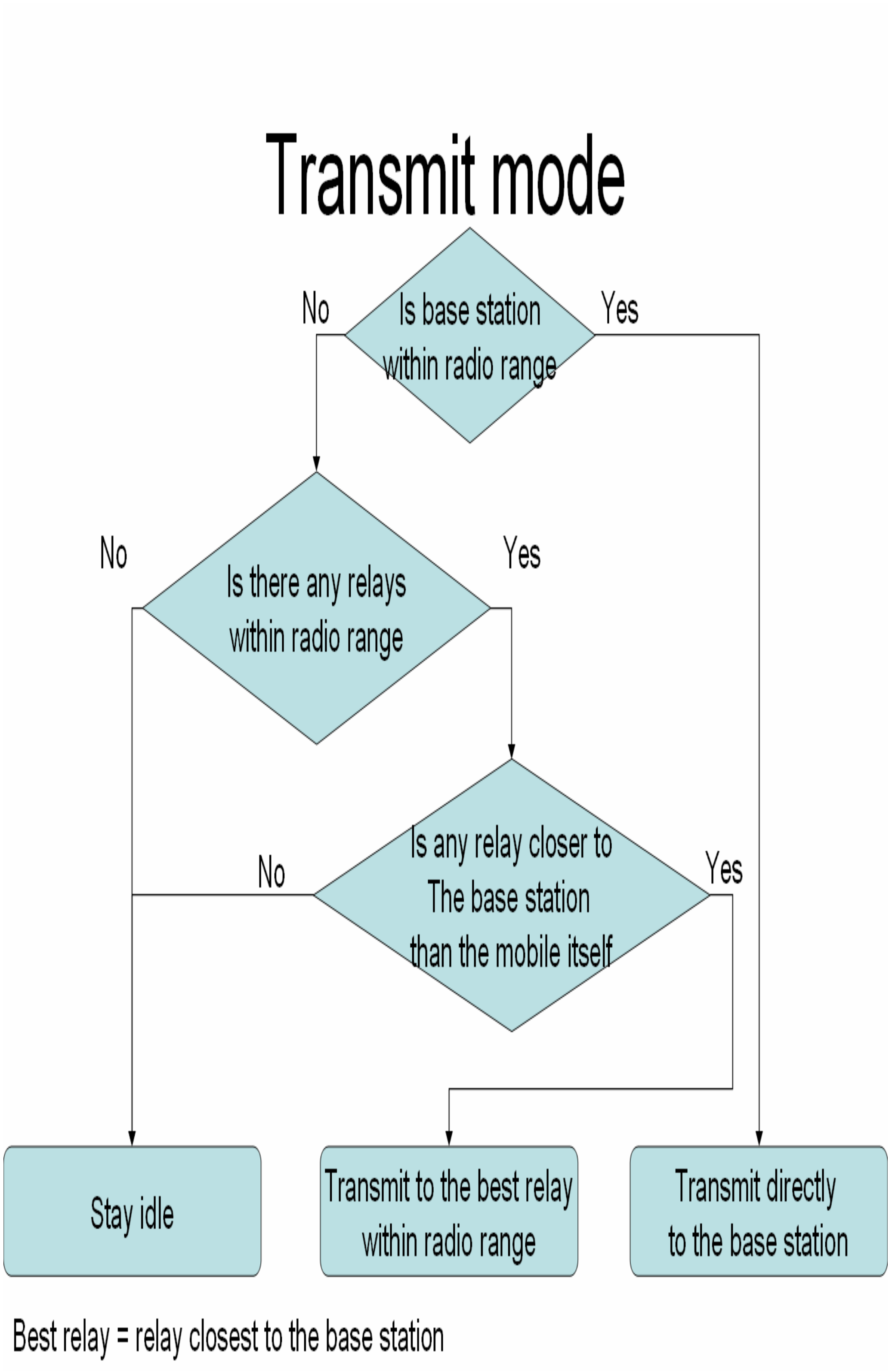


Figure 5.2: Flowchart of Transmit mode

5.3 Relay Selection

In this section we describe the procedure how we chose the relay node. Let $d_{ij}(t)$ denote the distance between mobile *i* and mobile *j* at time *t*. Let index *0* denote the base station. The distance parameters $d_{i0}(t)$ and $d_{j0}(t)$ are the distances between mobile *i* and base station, and mobile *j* and base station respectively at time instant *t*. Again, $d_{ij}(t)$ is the distance between mobile *i* and mobile *j*, and *r* is the transmission range for any mobile. Clearly, $d_{00}(t) = 0$ for all *t*. Let $M=\{1,2,\ldots,N\}$ denote the set of mobiles and let $N=\{0,1,2,\ldots,N\}$ denotes the set of nodes including the base station $(i=0)$. Let $R(t) \in N$ denotes the set of relay nodes at time slot *t*. We assume that a node *i* becomes a relay at time *t* with certain probability. That is the base station is always willing to act as a relay for all the mobile nodes. All other nodes are wireless relays except the base station which relays the packet to the core network.

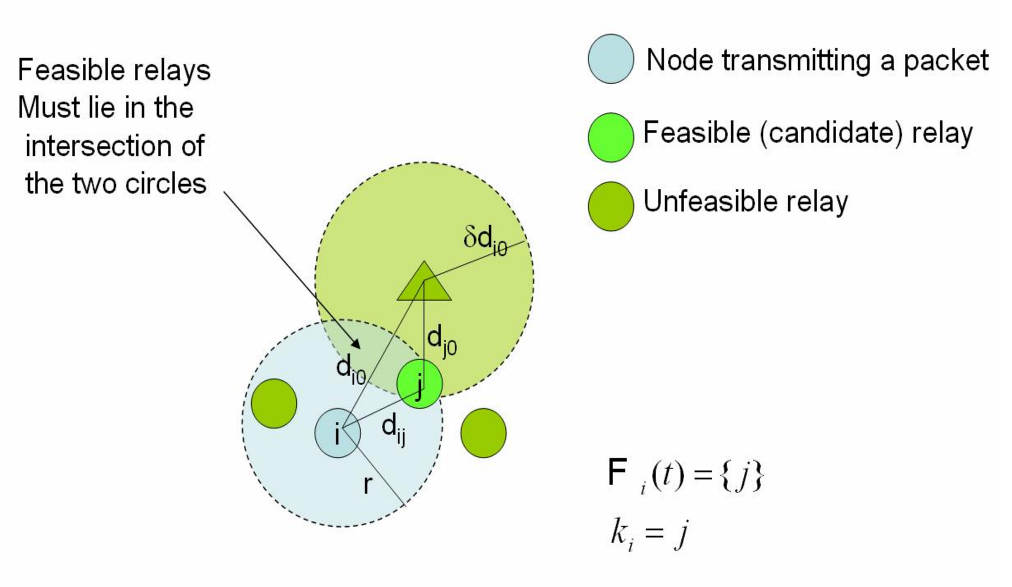


Figure 5.3: Relay Selection

Let $A(t) \in M$ denotes the set of active nodes. i.e. the nodes that are not acting as relays. A node $i \in A(t)$ selects relay k_i using the following rule (Figure 5.3),

$$k_i = \arg\min_{j \in F_i(t)} \{\lambda d_{ij} + (1-\lambda) d_{j0}\}, \forall i \in A(t) \tag{5.1}$$

Where $0 \leq \lambda \leq 1$ is a weighting parameter and $F_i(t)$ denotes the set of feasible relays for mobile *i*.

$$F_i(t) = \left\{ j \middle| j \in R(t), d_{ij} < r, d_{j0} < \partial d_{i0} \right\} \tag{5.2}$$

The feasible set includes all the nodes that are within the radio range r from the mobile *i* and are closer to the base station than the node *i* (Figure 5.3). The parameter $0<\delta<1$ denotes a margin. A relay node is only accepted if its distance to the base station is less than for node *i*.

Chapter 6

Performance Analysis

This chapter contains the simulation results used for three different networks namely Basketball multihop network, CDMA network and one hop infostation network. We ran the simulation for each of the networks using different parameters. We analyzed the simulation results based on two important performance metrics: *Packet Delay* and *Throughput*. The analysis shows that the Basketball multihop system that we propose has considerable advantages over the existing CDMA and infostation networks.

Packet delay is the total time it takes for a packet to reach the Base Station either directly or through relaying in several hops after it leaves the buffer of the originator mobile node. Average packet delay can be calculated from the average number of packets in the system using Little's formula $N = \lambda T$, where λ denotes the arrival rate of the packets, T is the total waiting time in the system and N is the number of packets in the system. In simulation, we counted the packet delays by recording during which slot a packet was generated and during which slot it was received by the base station. The difference is the packet delay for that individual packet. Then averaging over the packets sent by one user, we got his packet delay and averaging over all the packets we got the mean packet delay in the system.

Throughput is the amount of data that can be transmitted by a device or the amount of output that be produced by a system in a given period of time. In our simulation we recorded each packet for each user when it finally reached the Base Station. Then we counted all the packets for each user at the end of simulation and calculated Throughput in packets per second for the specific user. Averaging over all the packets we got the mean throughput in the system.

Simulation results are analyzed with the help of CDF (cumulative distribution function) plots. The CDF plots are analyzed according to the following QoS formula:

From the CDF plots for Packet Delays,

$$\textit{Delay Outage} = \Pr\{Delay >= Y\} = 1 - \Pr\{Delay <= Y\} \quad \textit{[Inverse CDF]} \tag{6.1}$$

From the CDF plot for Throughput,

$$\textit{Throughput Outage} = \Pr\{Throughput <= X\} \quad \textit{[CDF]} \tag{6.2}$$

We ran several simulations for each of the systems and defined the Confidence Interval (CI) for the mean of packet delays and throughput measurements as CI:[$(\mu-\sigma),(\mu+\sigma)$] so that the mean value will be in the range $(\mu-\sigma)$ <mean< $(\mu+\sigma)$, with confidence more than 0.6, where μ is the mean value and σ is the standard deviation. (Please refer to Appendix B).

6.1 Simulation setup

The simulation parameters are summarized in Table 6.1 below:

Table 6.1: Simulation Parameters

Parameter	Value
No. of Nodes	100
Relay Probability	0.2
Simulation Time	120 sec.
Radius of Cell	5000 m
Attenuation Factor	4
MS Transmit Power	0.1 Watt
Noise Power	1 pW
Slot Length	10 ms .
Mean Inter-Arrival Time	(80e-3)/3 sec.
Std. of Inter-Arrival Time	5e-3
Transmission Range	250 m.
Min. Mobile Speed	70*1000/3600 m/s.
Max. Mobile Speed	100*1000/3600 m/s.
Packet Size	10 bytes
Bandwidth	1.25e6 Hz.

6.2 Effect of User Density

User density is really important factor for any network. If the network incurs increased packet delay or decreased throughput with higher user density, it obviously degrades the quality of the network. Hence it is interesting to see the behavior of the network at different load conditions.

From the table (Table 6.2), it can be said that with 100 users in the cell, the Basketball multihop system incurs less mean packet delay than CDMA and Infostation systems. System Packet Delay for Basketball multihop system is almost similar as Infostation system but significantly less than CDMA system. Again from the table throughput for Basketball multihop is similar as infostation system but worse than CDMA system. On the other hand, from the table (Table

6.3) it can be seen that with 750 users in the cell, the Basketball multihop system incurs less packet delay than CDMA and Infostation systems. Again from the table throughput for Basketball multihop is greatly increased than the other two systems.

Table 6.2: System Comparison (N=100)

Cases	**Mean Packet Delay**	**Mean Normalized Throughput**	**System Packet Delay**	**System Throughput**
Basketball multihop	0.6e+3 **CI: 0.64**	2.7 **CI: 0.64**	1.0	271.5
Pure CDMA	1.3e+3 **CI: 0.68**	6.9 **CI: 0.72**	6.1	697.8
One hop Infostation	2.2e+3 **CI: 0.72**	1.0 **CI: 0.72**	0.9	103.6

Table 6.3: System Comparison (N=750)

Cases	**Mean Packet Delay**	**Mean Normalized Throughput**	**System Packet Delay**	**System Throughput**
Basketball multihop	2.0e+3 **CI: 0.72**	8.1 **CI: 0.60**	29.0	6e+3
Pure CDMA	2.3e+3 **CI: 0.72**	2.0 **CI: 0.72**	2.8	1.5e+3
One hop Infostation	2.1e+3 **CI: 0.72**	0.8 **CI: 0.72**	0.7	654.2

For 100 Users

It can be seen from the Figure 6.1 that for Basketball multihop case, within 2000 time-slots, 80% of the packets will be delivered with 0.2 outage probability whereas for CDMA case, 70% of the packets will be delivered with 0.3 outage probability and for infostation case, 60% of the packets will be delivered with 0.4 outage probability respectively for the same duration. Hence Basketball multihop system is clearly better than the other two systems with respect to delay outage as the Service probability is better in this system with less delay maintaining good Quality of Service (QoS).

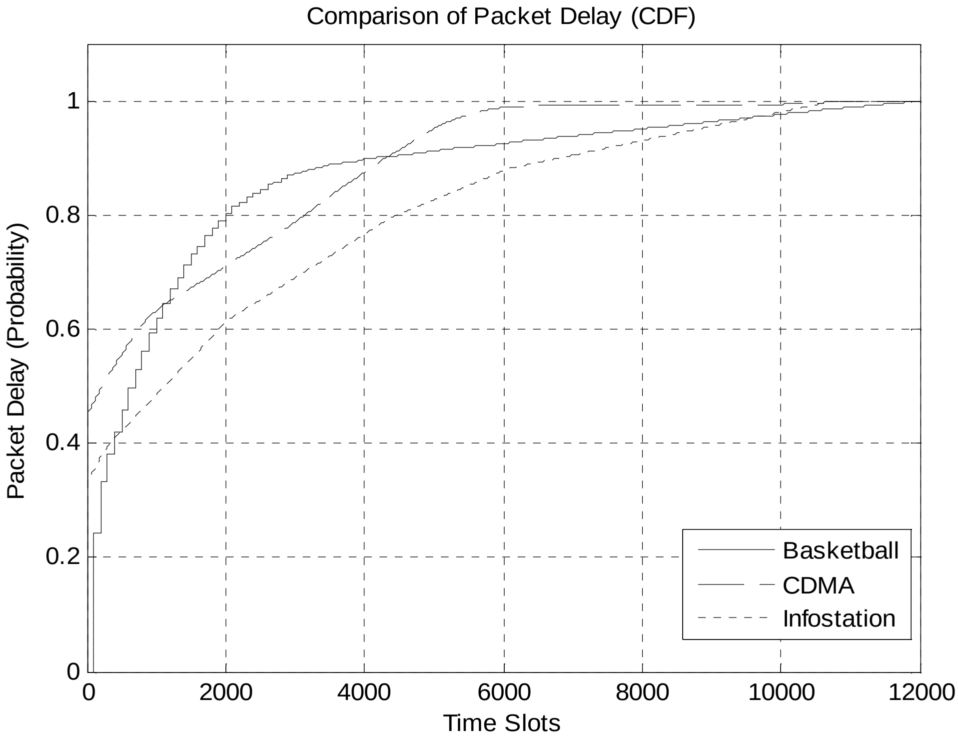


Figure 6.1: Comparison of Packet Delays for different systems, N=100

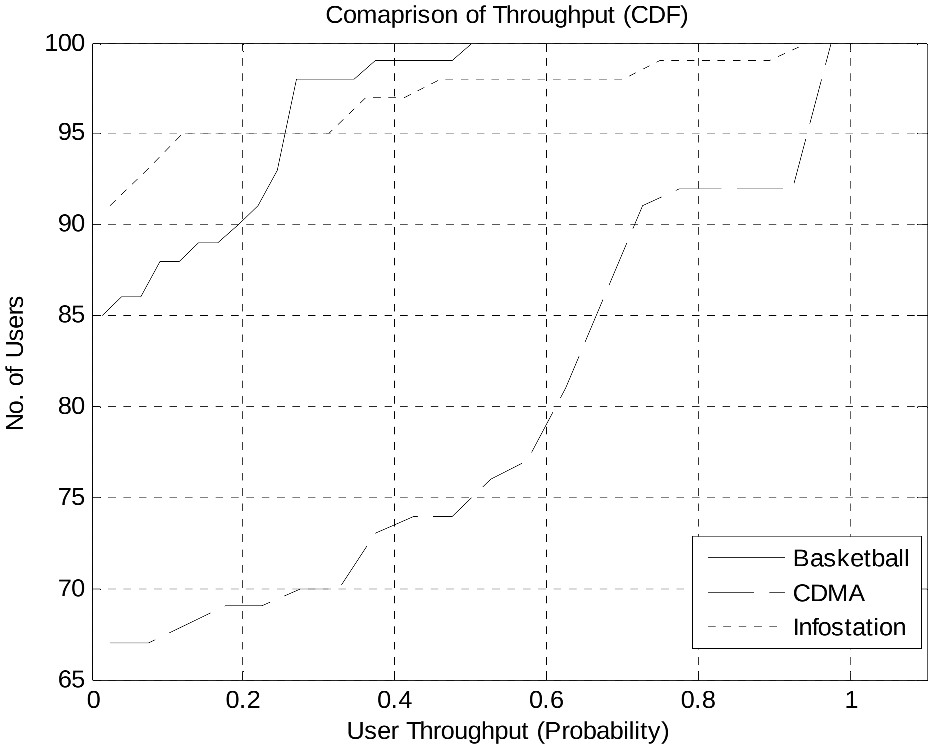


Figure 6.2: Comparison of Throughputs for different systems, N=100

Again from Figure 6.1, for initial short duration (less than 1000 time slots) and for high duration (greater than 5000 time slots), CDMA works better than Basketball multihop.

From the CDF plot for throughput in Figure 6.2, our results indicate that for Basketball multihop case 90 users can be supported with 0.2 outage probability whereas for CDMA case 90 users can be supported with 0.68 outage probability and for Infostation case 90 users can be supported with 0.02 outage probability. Hence Basketball multihop system is better than CDMA but a bit worse than infostation with respect to throughput outage.

For 750 Users

In Figure 6.3, from the CDF plots for Packet Delays, the results indicate that for Basketball multihop case, within 6000 time-slots 78% of the packets will be delivered with 0.22 outage probability whereas for CDMA case, 92% of the packets will be delivered with 0.08 outage probability and for infostation case, 90% of the packets will be delivered with 0.1 outage probability respectively for the same duration. Hence Basketball multihop system is worse than other two systems with respect to delay outage.

From the CDF plot for throughput in Figure 6.4, the results suggest that for basketball multihop case 650 users can be supported with 0.65 outage probability whereas for CDMA case 650 users can be supported with 0.02 outage probability and for Infostation case 650 users can be supported with 0.01 outage probability. Thus, it can be said that if the number of user is increased, the throughput for Basketball multihop system is increased significantly and incurs less packet delay. In the same cell area, If the number of mobiles is low a node situated far away from the base station has high chances of staying idle due to the lack of suitable relays within range. When the number of users is increased, it becomes likely that the source finds a good relay node. Thus reducing the packet delay while increasing the capacity of the network as a whole and vice versa. But for CDMA, many mobile nodes can be located far away from the base station with less SINR, thus the bit rate is less for them. Again for infostation case, many mobile nodes can travel so far from the base station that the BS is out of their transmit range and eventually cannot transmit packet at all to the BS.

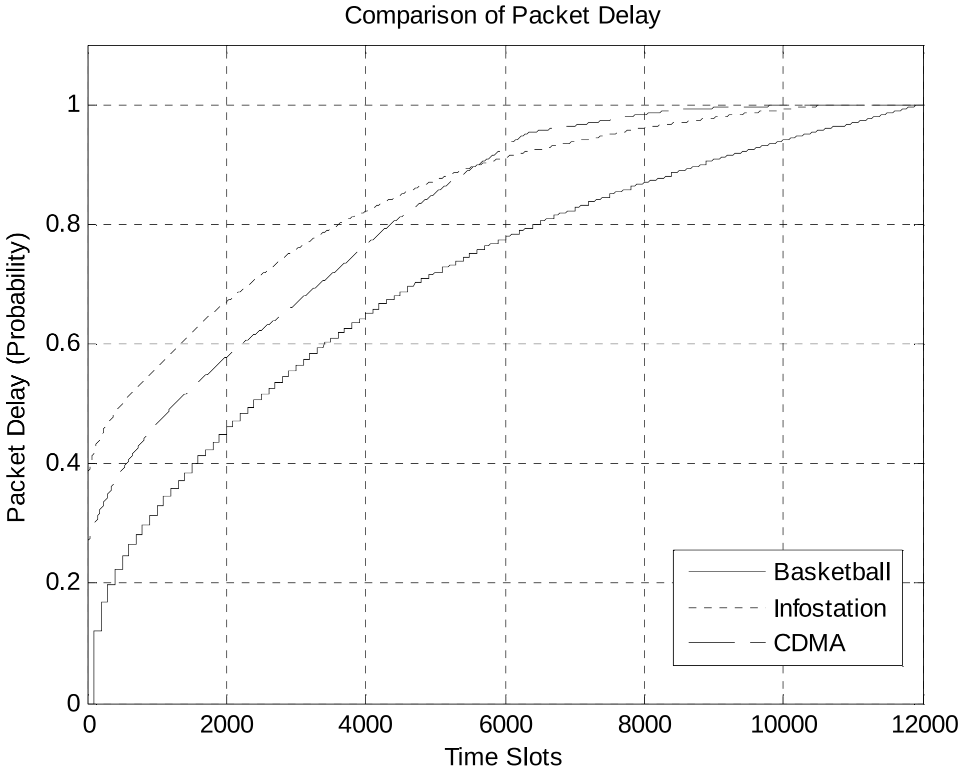


Figure 6.3: Comparison of Packet Delays for different systems, N=750

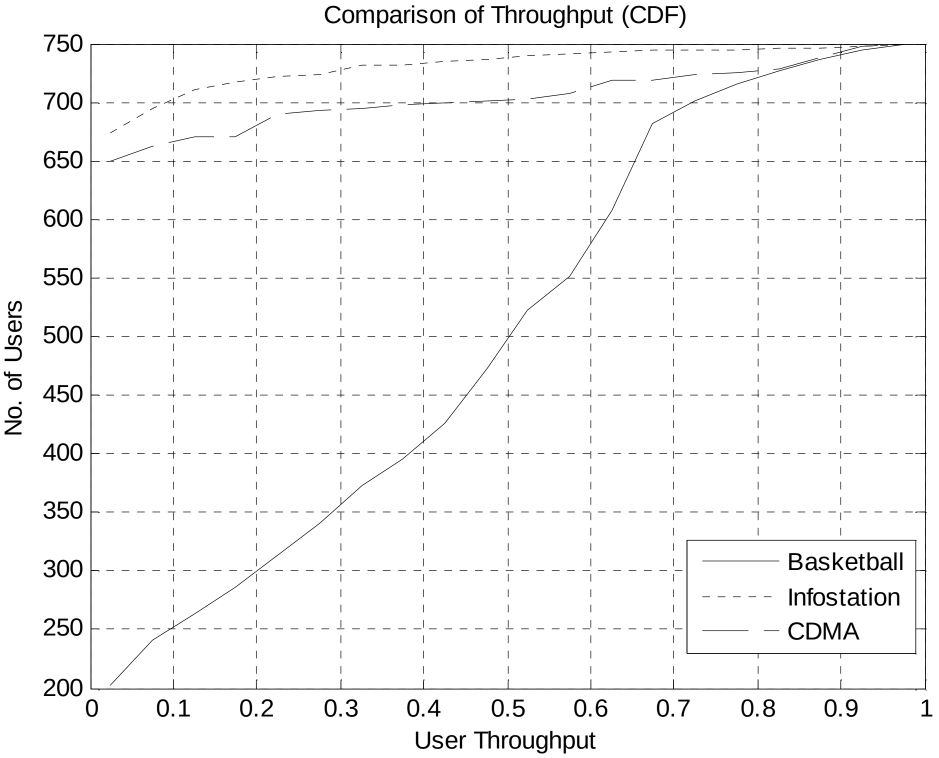


Figure 6.4: Comparison of Throughputs for different systems, N=750

6.3 Effect of Cell-Radius

We are interested to observe the effect of cell radius. Because due to fading and the difference in distance between mobile nodes and base station, mobile nodes suffer from non-uniform data rate across a cell. The above problems aim at providing range extension, improved coverage of the cell and enhance Quality of Service (QoS) through relaying.

From the table (Table 6.4) it can be seen that Basketball multihop system can provide less packet delay and more throughput than CDMA and Infostation systems in a small cell with 1 km radius.

Table 6.4: System Comparison (R=1 Km)

Cases	Mean Packet Delay	Mean Normalized Throughput	System Packet Delay	System Throughput
Basketball multihop	211.5 **CI: 0.72**	31.5 **CI: 0.72**	2.1	3.1e+3
Pure CDMA	2.4 e+3 **CI: 0.72**	23.0 **CI: 0.72**	33.9	2.3e+3
One hop Infostation	2.6e+3 **CI: 0.72**	12.5 **CI: 0.72**	14.9	1.2e+3

Table 6.5: System Comparison (R=5 Km)

Cases	Mean Packet Delay	Mean Normalized Throughput	System Packet Delay	System Throughput
Basketball multihop	0.7e+3 **CI: 0.68**	7.1 **CI: 0.68**	0.8	711.5
Pure CDMA	1.1e+3 **CI: 0.68**	4.9 **CI: 0.72**	4.1	497.8
One hop Infostation	2.2e+3 **CI: 0.72**	1.0 **CI: 0.72**	0.9	103.6

On the other hand, from the table (Table 6.5), it can be said that with large cell radius (5 Km) Basketball multihop system provides less delay than the other two systems CDMA and Infostation systems. Again from the table, Throughput for Basketball multihop is better than Infostation and CDMA systems when the cell radius is increased to 5Km.

For 1 km Radius

From the CDF plots for Packet Delays in Figure 6.5 it can be seen that for Basketball multihop case, within 4000 time slots, 80% of the packets will be delivered with 0.2 outage probability whereas for CDMA case, 78% of the packets will be delivered with 0.22 outage probability and for infostation case, 68% of the packets will be delivered with 0.32 outage probability respectively for the same duration. Hence Basketball multihop system is clearly better than the other two systems with respect to delay outage. Again from Figure 6.5, for initial short duration (less than 1000 time slots) and for high duration (greater than 5500 time slots), CDMA works better than Basketball multihop.

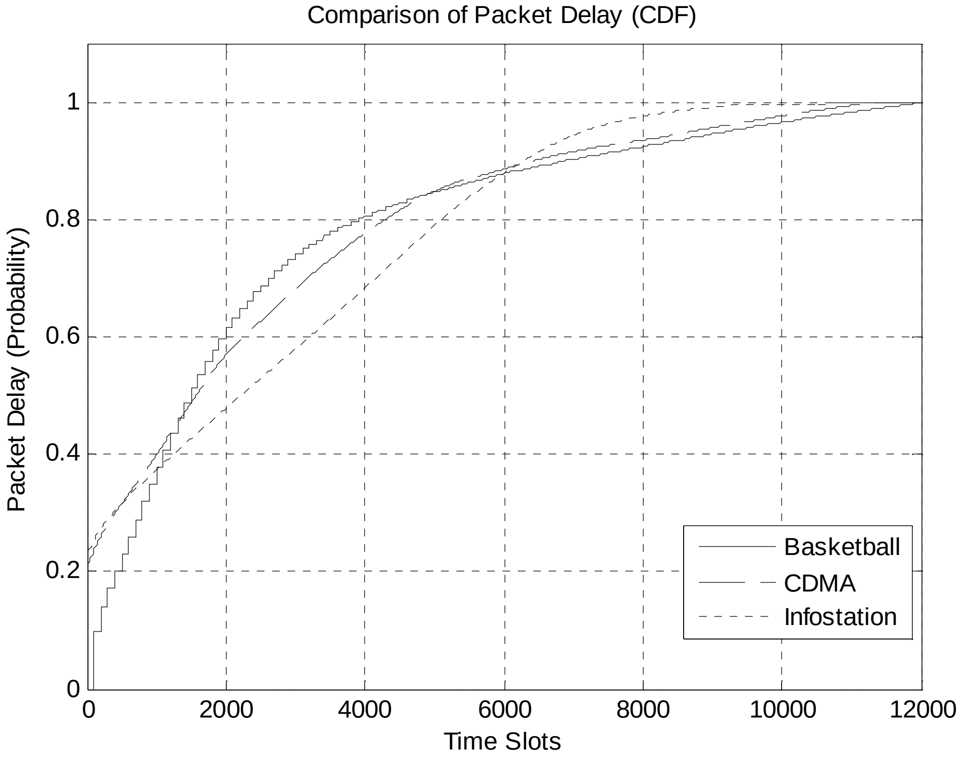


Figure 6.5: Comparison of Packet Delays for different systems, R=1 Km

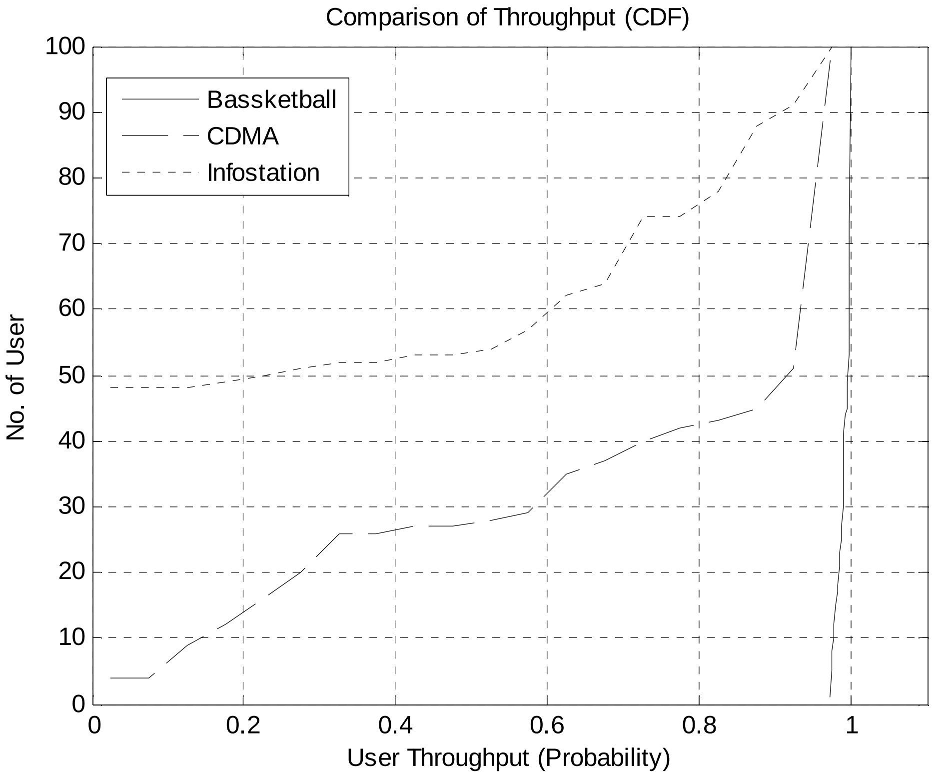


Figure 6.6: Comparison of Throughputs for different systems, R= 1 Km

In Figure 6.6, from the CDF plot for throughput, the results indicate that for basketball multihop case 90 users can be supported with 1.0 outage probability whereas for CDMA case 90 users can be supported with 0.97 outage probability and for Infostation case 90 users can be supported with 0.9 outage probability. Thus Basketball multihop system is worse than the other two systems with respect to Throughput outage.

For 5 km Radius

From the CDF plots for Packet Delay in Figure 6.7, the results suggest that for Basketball multihop case, within 2000 time slots 91% of the packets will be delivered with 0.09 outage probability, whereas for CDMA case, 74% of the packets will be delivered with 0.26 outage probability and for infostation case, 75% of the packets will be delivered with 0.25 outage probability respectively for the same duration. Hence Basketball multihop system is clearly better than the other two systems with respect to delay outage.

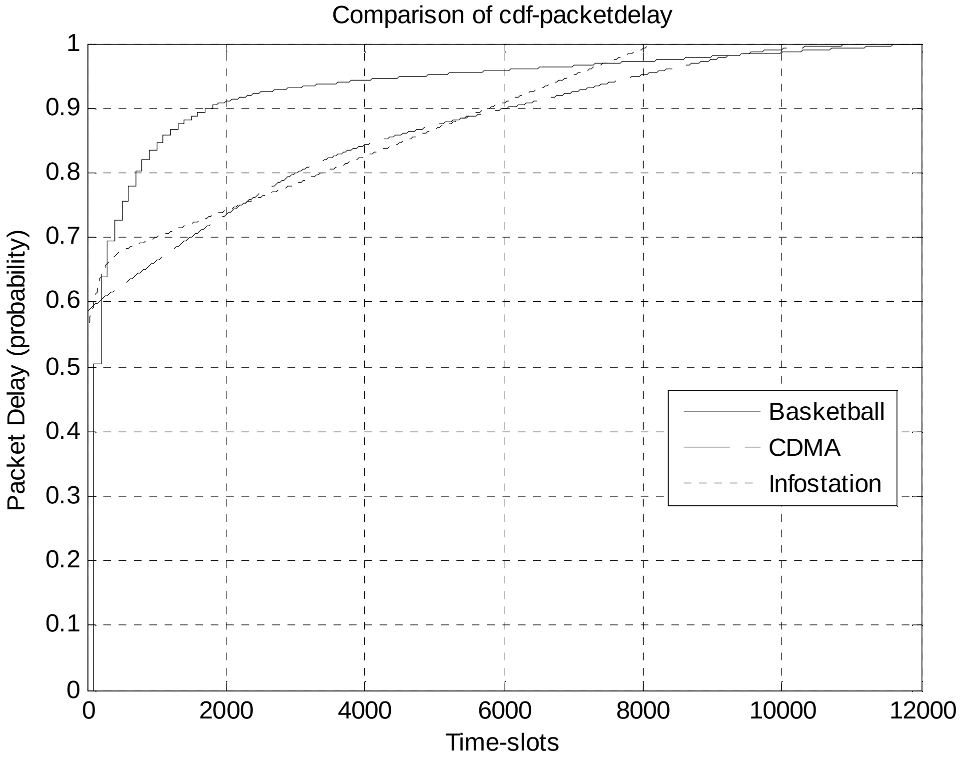


Figure 6.7: Comparison of Packet Delays for different systems, R=5 Km

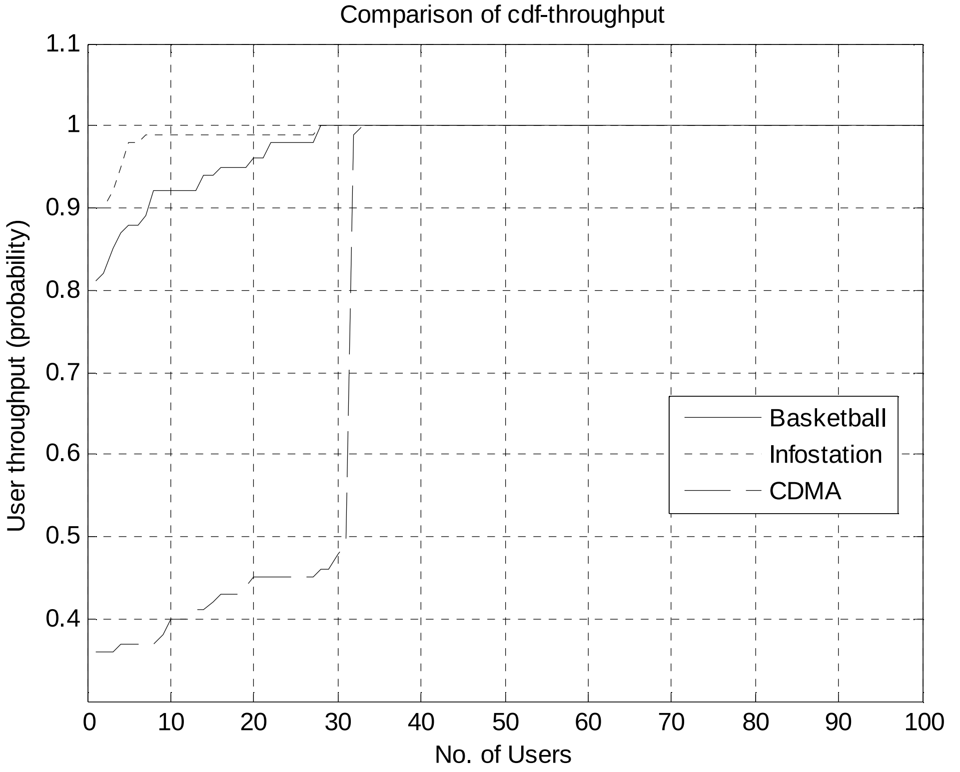


Figure 6.8: Comparison of Throughputs for different systems, R=5 Km

In Figure 6.8, from the CDF plot for throughput, it can be seen that for Basketball multihop case, from 90 users can be supported with 100% probability whereas for CDMA case from 90 users can be supported with 100% probability and for Infostation case from 90 users can be supported with 100% probability. Yet Basketball multihop system is more stable than CDMA because it can provide any user with more than 80% probability which CDMA cannot provide.

Thus we can see that the Basketball multihop system works better in a larger cell with respect to both packet delay and throughput. It is expected because for a larger cell in CDMA, there could be a lot of mobile nodes at the edge of the cell and cannot have higher SINR to transmit packets at higher bit rate and for the Infostation case the similar mobile nodes cannot transmit packets at all. But in case of Basketball multihop system, the mobile nodes, which are located at the edge of the cell far away from the base station, still can transmit through relaying their packets to the base station and thus can increase their throughput and improve delays.

6.4 Effect of Simulation Time

We are interested in the steady state behavior. So we have increased the simulation time long enough to average over the different mobile positions efficiently.

Table 6.6: System Comparison (time= 900 sec)

Cases	Mean Packet Delay	Mean Normalized Throughput	System Packet Delay	System Throughput
Basketball multihop	0.8e+4 **CI: 0.72**	18.4 **CI: 0.72**	55.6	1.8e+3
Pure CDMA	1.0e+4 **CI: 0.72**	16.8 **CI: 0.72**	94.1	1.6e+3
One hop Infostation	1.9e+4 **CI: 0.72**	6.3 **CI: 0.72**	71.9	637.2

From the table (Table 6.6), it can be said that when we ran the simulation for longer time (900 sec) Basketball multihop system provides less delay than the other two systems CDMA and Infostation systems. Again from the table (Table 6.6), Throughput for Basketball multihop is better than Infostation and CDMA systems.

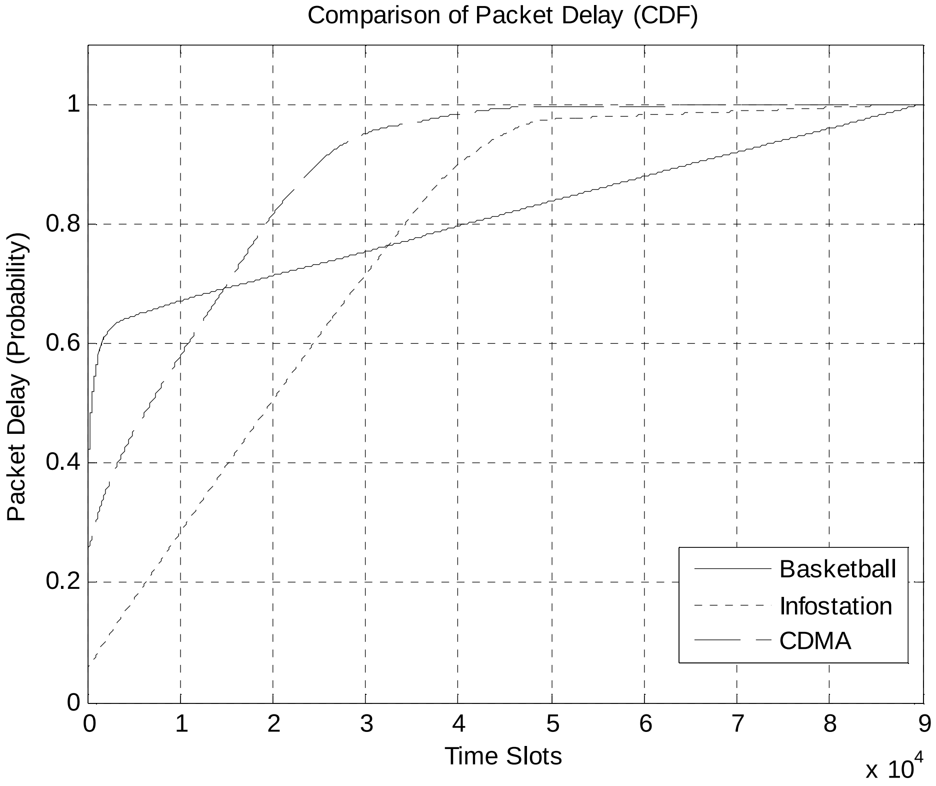


Figure 6.9: Comparison of Packet Delays for different systems, time= 900 sec

In Figure 6.9, from the CDF plots for Packet Delays, it is clear that for Basketball multihop case, within 40000 time slots, 80% of the packets will be delivered with 0.2 outage probability, whereas for CDMA case, 98% of the packets will be delivered with 0.02 outage probability and for infostation case, 90% of the packets will be delivered with 0.1 outage probability. Hence Basketball multihop system is worse than the other two systems with respect to delay outage.

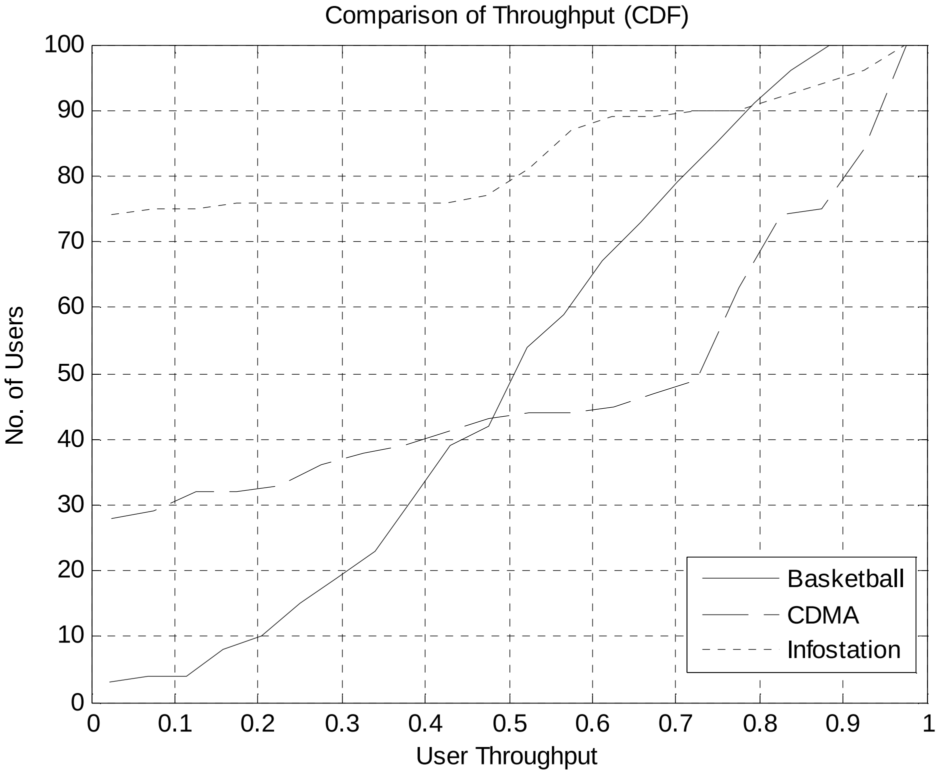


Figure 6.10: Comparison of Throughputs for different systems, time= 900 sec

From the CDF plot for throughput in Figure 6.10, the results suggest that for basketball multihop case 80 users can be supported with 0.7 outage probability whereas for CDMA case 80 users can be supported with 0.9 outage probability and for Infostation case 80 users can be supported with 0.51 outage probability. Thus Basketball multihop system works better than CDMA system but worse than infostation system with respect to throughput outage.

6.5 Effect of Node Mobility

Node mobility is another important factor. We have divided the users into three groups: highway vehicle users, city vehicle users and pedestrian users. Now we will investigate how node mobility can affect throughput and delays in different systems for each category of users.

From the table (Table 6.7), it can be said that for highway vehicle users, Basketball multihop system provides less delay than the other two systems CDMA and Infostation systems. Again, Throughput for Basketball multihop is also better than Infostation and CDMA systems in case of highway vehicle users. On the other hand, from the table (Table 6.8), it can be said that for Pedestrian users, Basketball multihop system provides less delay than CDMA but more than Infostation systems. Again, Throughput for Basketball multihop is also better than Infostation but less than CDMA. Furthermore, from the table (Table 6.9), it can be said that for City Vehicle users, Basketball multihop system provides less delay than CDMA but more than Infostation systems. Again, Throughput for Basketball multihop is also better than Infostation but less than CDMA.

Table 6.7: System Comparison (Highway Vehicle)

Cases	Mean Packet Delay	Mean Normalized Throughput	System Packet Delay	System Throughput
Basketball multihop	0.7e+3 **CI: 0.68**	7.1 **CI: 0.64**	0.8	711.5
Pure CDMA	1.1e+3 **CI: 0.68**	4.9 **CI: 0.72**	4.1	497.8
One hop Infostation	2.2e+3 **CI: 0.72**	1.0 **CI: 0.72**	0.9	103.6

Table 6.8: System Comparison (Pedestrian User)

Cases	Mean Packet Delay	Mean Normalized Throughput	System Packet Delay	System Throughput
Basketball multihop	0.7e+3 **CI: 0.68**	1.3 **CI: 0.68**	0.4	139.2
Pure CDMA	0.6e+3 **CI: 0.60**	4.8 **CI: 0.68**	1.8	481.9
One hop Infostation	0.3e+3 **CI: 0.68**	1.1 **CI: 0.68**	0.1	115.1

Table 6.9: System Comparison (City Vehicle)

Cases	Mean Packet Delay	Mean Normalized Throughput	System Packet Delay	System Throughput
Basketball multihop	1.7e+3 **CI: 0.68**	1.8 **CI: 0.68**	1.7	186.8
Pure CDMA	1.8e+3 **CI: 0.68**	6.5 **CI: 0.68**	8.2	653.3
One hop Infostation	0.3e+3 **CI: 0.68**	0.8 **CI: 0.72**	0.1	88.8

For Highway Vehicle user

From the CDF plots for Packet Delay in Figure 6.11, the results suggest that for Basketball multihop case, within 2000 time slots 90% of the time the packets will be delivered with 0.1 outage probability, whereas for CDMA case, 75% of the time the packets will be delivered with 0.25 outage probability and for Infostation case, 75% of the time the packets will be delivered with 0.25 outage probability respectively for the same duration. Hence Basketball multihop system is clearly better than the other two systems with respect to delay outage.

In Figure 6.12, from the CDF plot for throughput, it can be seen that for Basketball multihop case, from 28 to 100 users can be supported with 100% probability whereas for CDMA case from 32 to 100 users can be supported with 100% probability and for Infostation case from 28 to 100 users can be supported with 100% probability. Yet Basketball multihop system is more stable than CDMA because it can provide any user with more than 80% probability which CDMA cannot provide.

Thus we can see that the Basketball multihop system works better for Highway vehicle users with respect to both packet delay and throughput.

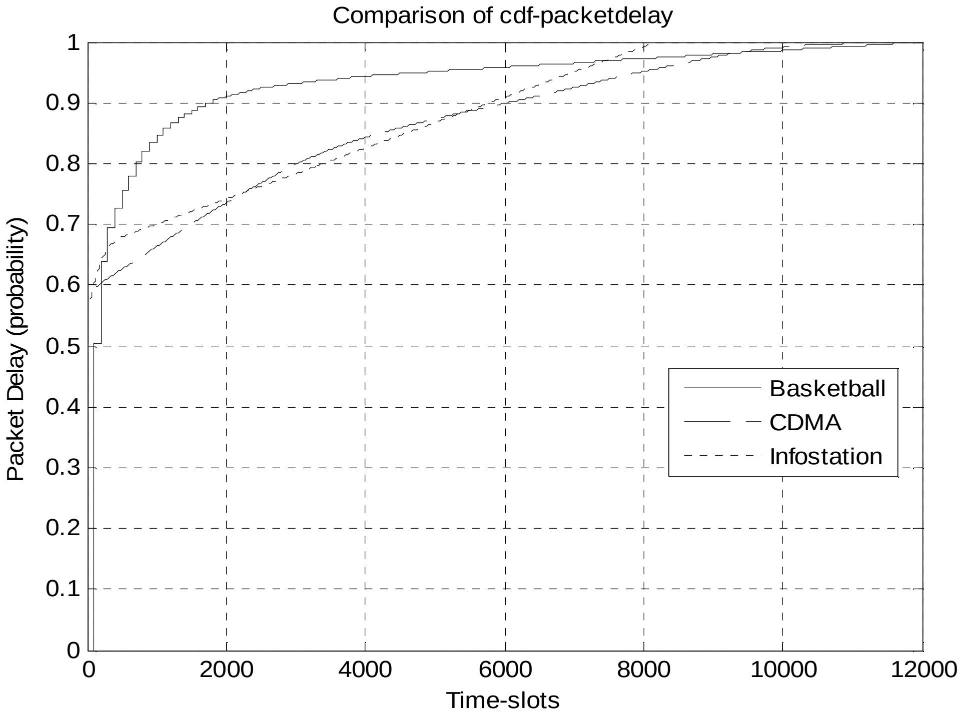


Figure 6.11: Comparison of Delays for different systems, Highway Vehicle

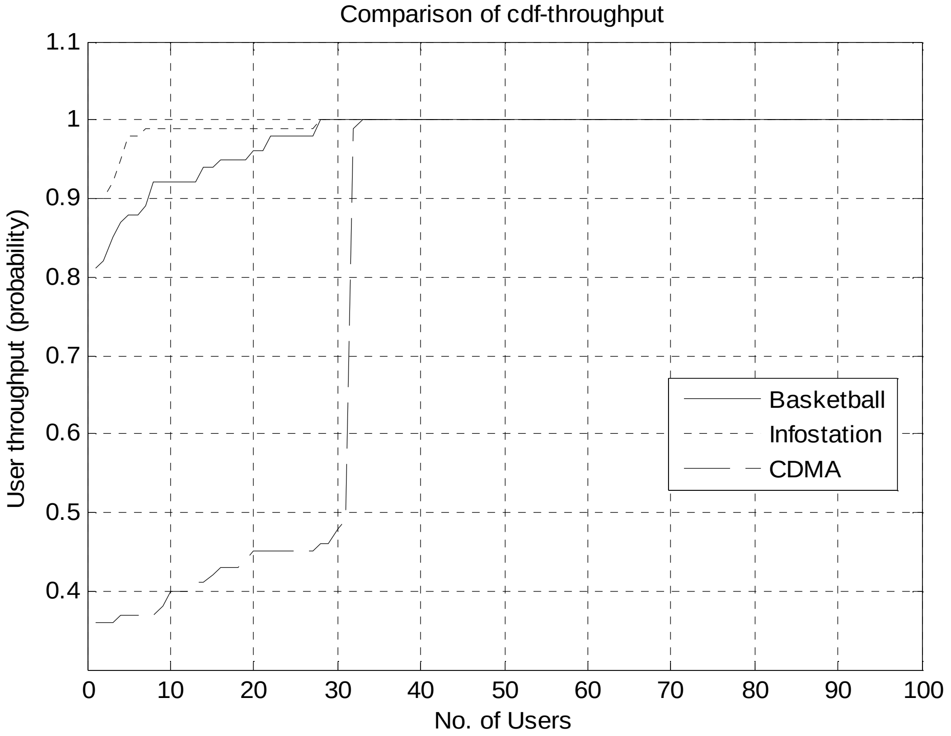


Figure 6.12: Comparison of Throughputs for different systems, Highway Vehicle

For Pedestrian User

In Figure 6.13 from the CDF plots for Packet Delays, the results indicate that for Basketball multihop case, within 2000 time slots, 98% of the packets will be delivered with 0.02 outage probability, whereas for CDMA case, 88% of the packets will be delivered with 0.12 outage probability and for infostation case, 92% of the packets will be delivered with 0.08 outage probability respectively for the same duration. Thus Basketball multihop system works better than the other two systems with respect to delay outage.

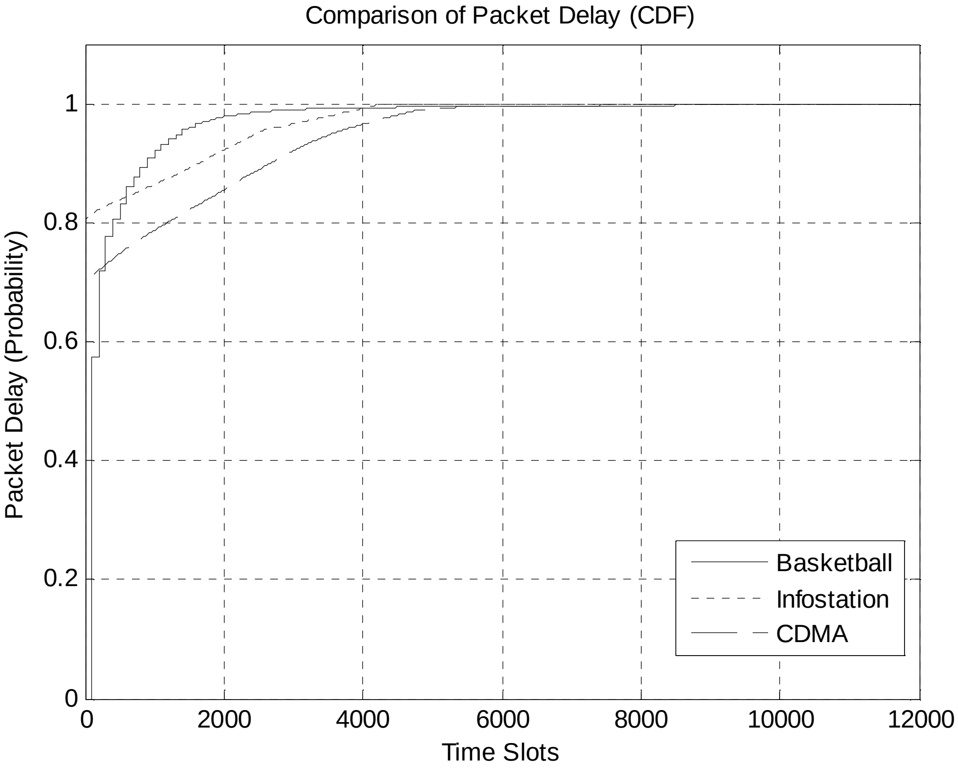


Figure 6.13: Comparison of Delays for different systems, pedestrian user

From the CDF plot for throughputs in Figure 6.14, the results suggest that for Basketball multihop case 95 users can be supported with 0.55 outage probability whereas for CDMA case 95 users can be supported with 0.95 outage probability and for Infostation case 95 users can be supported with 0.0 outage probability. Thus Basketball multihop system works better than CDMA but worse than infostation system in terms of throughput outage.

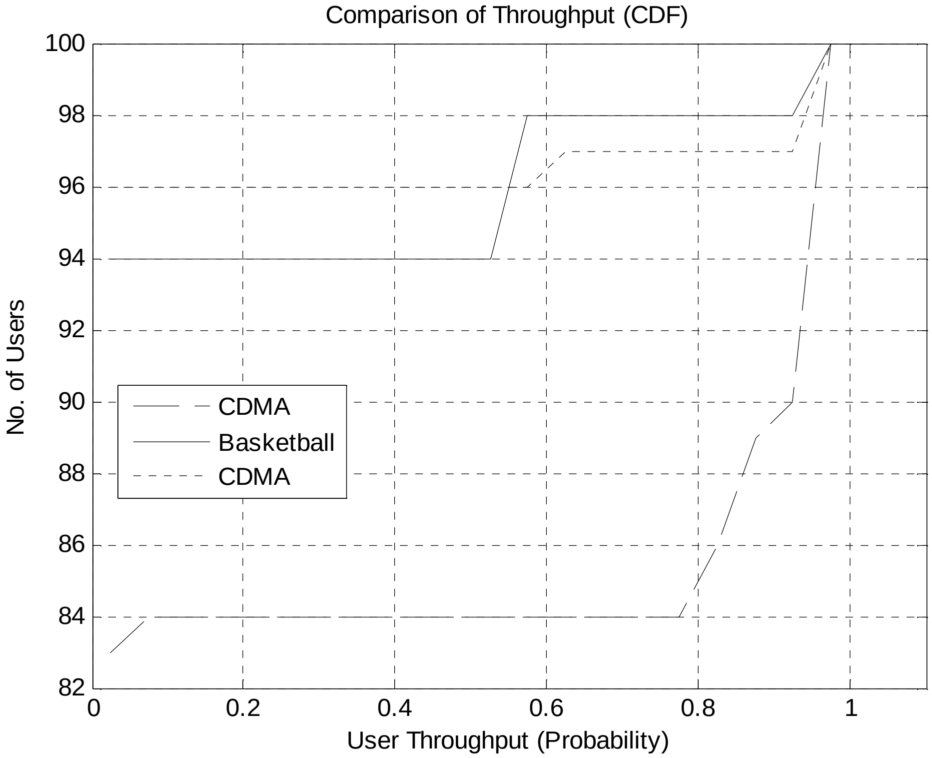


Figure 6.14: Comparison of Throughputs for different systems, pedestrian user

For City-Vehicle User

In Figure 6.15, from the CDF plots for Packet Delays, the results indicate that for Basketball multihop case, within 2000 time slots 92% of the packets will be delivered with 0.08 outage probability, whereas for CDMA case, 70% of the packets will be delivered with 0.3 outage probability and for infostation case, 96% of the packets will be delivered with 0.04 outage probability respectively for the same duration. Thus Basketball multihop system works better than CDMA but worse than infostation system with respect to delay outage.

From the CDF plot for throughput in Figure 6.16, our results indicate that for Basketball multihop case 95 users can be supported with 0.38 outage probability whereas for CDMA case 95 users can be supported with 0.95outage probability and for Infostation case 95 users can be supported with 0.2 outage probability. Thus Basketball multihop system works better than CDMA but worse than infostation system with respect to throughput outage.

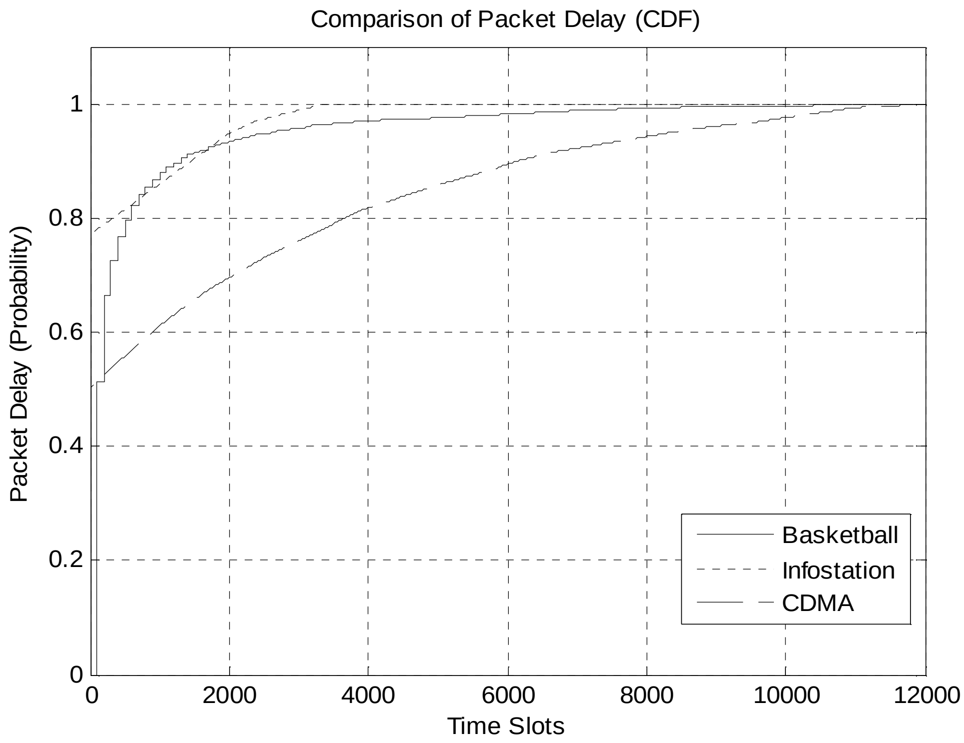


Figure 6.15: Comparison of Packet Delays for different systems, city vehicle

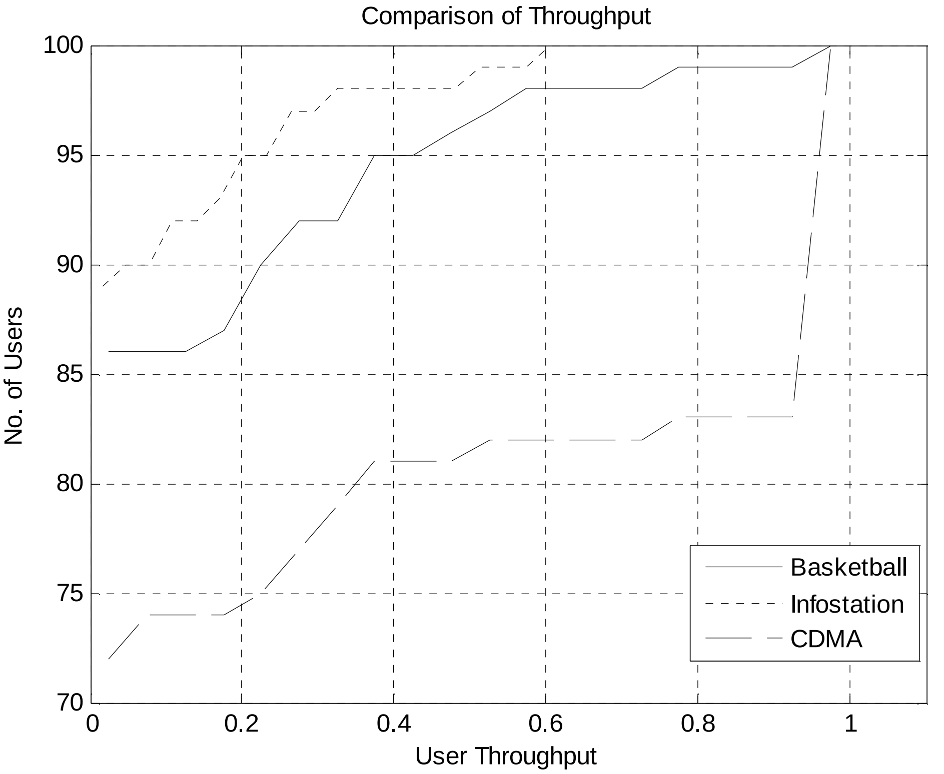


Figure 6.16: Comparison of Throughputs for different systems (city vehicle)

Thus, Basketball multihop system is best suited for Highway Vehicle users than pedestrian users and city-vehicle users with respect to both packet delay and throughput. The result is expected because when the node mobility is higher the nodes in Basketball multihop system have more probability to get closer to other mobile nodes in order to relay their packets and vice versa.

6.6 Effect of Traffic Volume

It is important to know how the different systems behave with varying amount of traffic volume. We will investigate the effect of different traffic volume now.

From the table (Table 6.10), it can be said that for high traffic volume, Basketball multihop system incurs less packet delay than both CDMA and Infostation systems. However, Throughput for Basketball multihop is more than Infostation systems but less than CDMA. On the other hand, from the table (Table 6.11), it can be said that for low traffic volume, Basketball multihop system provides less delay than CDMA and Infostation systems. Again, Throughput for Basketball multihop is less than the other two systems.

Table 6.10: System Comparison (High Traffic)

Cases	Mean Packet Delay	Mean Normalized Throughput	System Packet Delay	System Throughput
Basketball multihop	0.6e+3 **CI: 0.68**	1.1 **CI: 0.64**	1.0	111.5
Pure CDMA	1.3e+3 **CI: 0.68**	6.9 **CI: 0.72**	6.1	697.8
One hop Infostation	2.2e+3 **CI: 0.72**	1.0 **CI: 0.72**	0.9	103.6

Table 6.11: System Comparison (Low Traffic)

Cases	**Mean Packet Delay**	**Mean Normalized Throughput**	**System Packet Delay**	**System Throughput**
Basketball multihop	0.1e+3 **CI: 0.68**	0.3 **CI: 0.68**	0.1	39.3
Pure CDMA	1.1e+3 **CI: 0.68**	5.8 **CI: 0.68**	8.8	589.7
One hop Infostation	3.7e+3 **CI: 0.68**	0.4 **CI: 0.72**	0.9	42.4

For High traffic volume (Mean_inter=(40 e-3)/3)

In Figure 6.17, from the CDF plots for Packet Delays, the results suggest that for Basketball multihop case, within 2000 time slots 80% of the packets will be delivered with 0.2 outage probability, whereas for CDMA case, 70% of the packets will be delivered with 0.3 outage probability and for infostation case, 60% of the packets will be delivered with 0.4 outage probability respectively for the same duration. Hence Basketball multihop system is works better than the other two systems in terms of delay outage.

From the CDF plot for throughput in Figure 6.18, the results indicate that for Basketball multihop case 90 users can be supported with 0.04 outage probability whereas for CDMA case 90 users can be supported with 0.96 outage probability and for Infostation case 90 users can be supported with 0.0 outage probability. Hence Basketball multihop system serves better than CDMA systems but worse than the infostation system with respect to throughput outage.

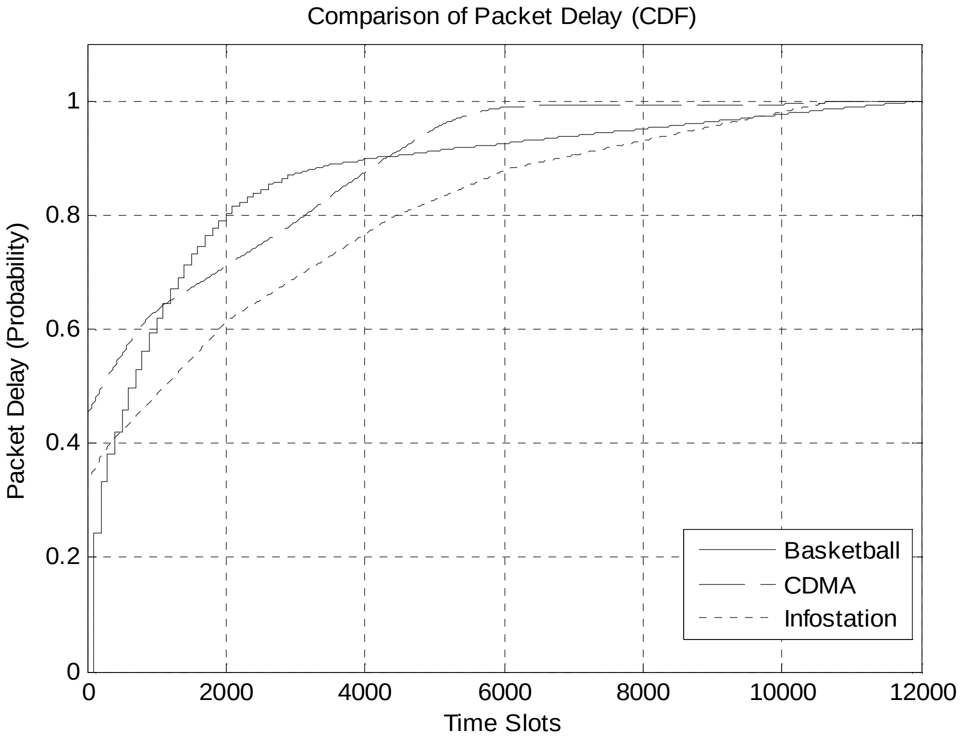


Figure 6.17: Comparison of Packet Delays for different systems, high traffic

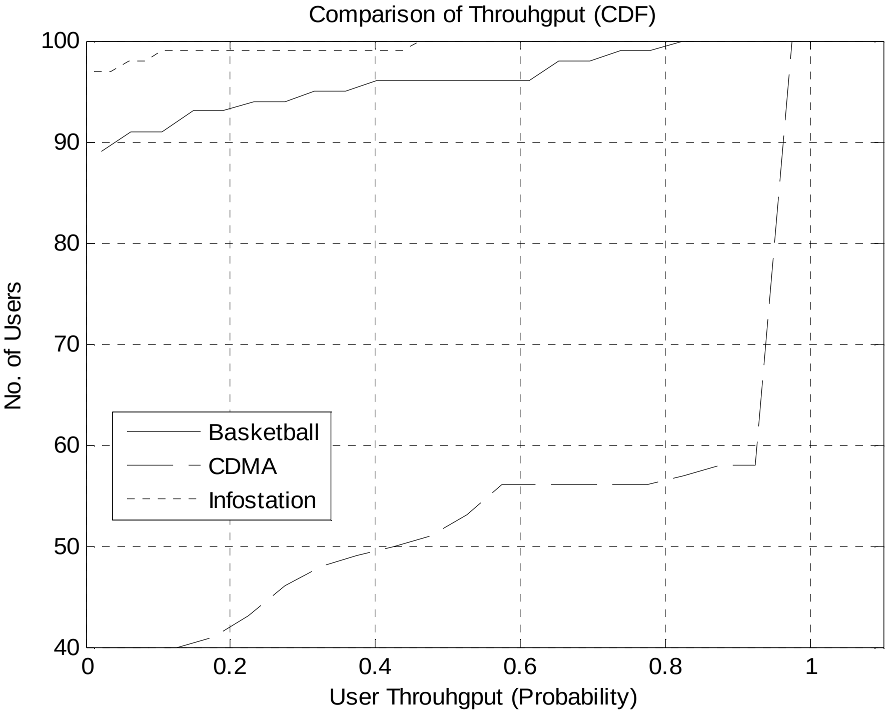


Figure 6.18: Comparison of Throughputs for different systems, high traffic

For Low Traffic volume (Mean_inter (160 e-3)/3)

In Figure 6.19 from the CDF plots for Packet Delays, the results indicate that for Basketball multihop case, within 2000 time slots, 95% of the packets will be delivered with 0.05 outage probability, whereas for CDMA case, 79% of the packets will be delivered with 0.21 outage probability and for infostation case, 43% of the packets will be delivered with 0.57 outage probability respectively for the same duration. Hence Basketball multihop system is clearly better than the other two systems with respect to delay outage.

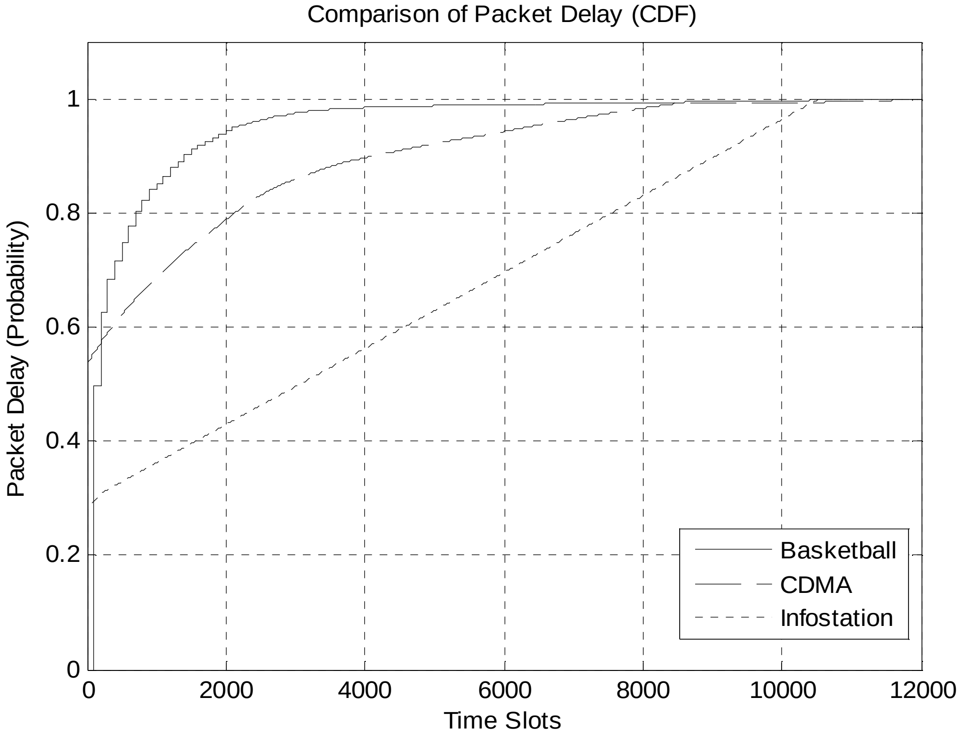


Figure 6.19: Comparison of Packet Delays for different systems, low traffic

From the CDF plot for throughput in Figure 6.20, the results suggest that for Basketball multihop case, 95 users can be supported with 0.23 outage probability whereas for CDMA case 95 users can be supported with 0.95 outage probability and for Infostation case 95 users can be supported with 0.025 outage probability. So Basketball multihop system works better than CDMA but worse than infostation system regarding the throughput outage.

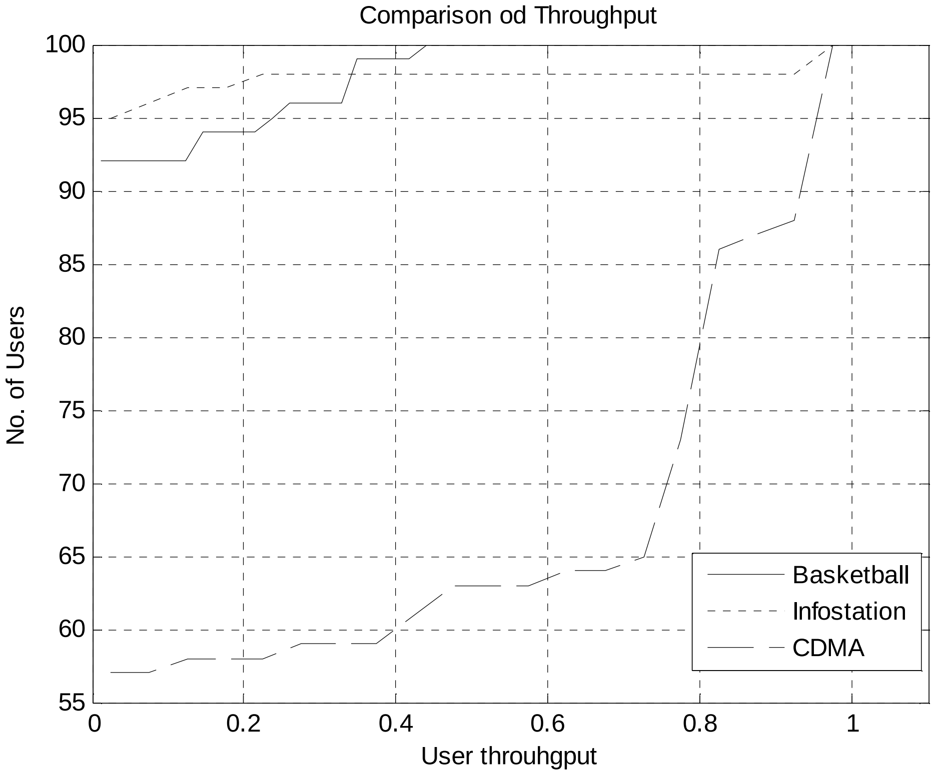


Figure 6.20: Comparison of Throughputs for different systems, low traffic

Thus, the Basketball multihop system incurs much packet delay when the traffic volume is increased. But the Throughput is increased for high traffic volume. One possible reason behind this is due to the fact that when the traffic volume is higher there are more packets that can be transmitted in a single slot. Usually throughput is maximized when the buffers are full, so that all available link capacity is exploited. With all other parameters remaining the same, when the traffic volume is increased, the mobile nodes originates more packets than before and store them in their buffer until it can send the packets to the Base Station or to the relay node. When it sends its packets, it can exploit the active link efficiently and send the packets with a high bit rate. So it is more likely that with high traffic volume the packets will be delayed to reach the base station with increased throughput and vice versa.

On the other hand, for CDMA, the mobile nodes have to send their packets to the base station in a single hop, so there is a possibility for some mobile nodes to be located far away and cannot transmit all packets with high bit rate.

6.7 Effect of Transmission Range

In a large distributed network, a mobile node cannot always send its packets directly to the Base Station because it might be the case that the Base Station is out of the transmitter’s range. So it needs to relay it’s packets through hops. And in that case it is likely that there will be some delays for the packets to reach the Base Station though it would increase the throughput. Hence we are interested to see the effects of different transmission ranges on different systems.

From the table (Table 6.12), it can be said that with shorter transmission range (d_min=125) Basketball multihop system provides less delay than the other two systems CDMA and Infostation systems. Again from the table, Throughput for Basketball multihop is more than Infostation and CDMA systems. On the other hand, from the table (Table 6.13), it can be said that with medium transmission range Basketball multihop system provides less delay than both CDMA and Infostation systems. Again from the table, Throughput for Basketball multihop is better than Infostation and CDMA systems. Furthermore, from the table (Table 6.14), it can be said that with higher transmission range Basketball multihop system provides less delay than the other two systems CDMA and Infostation systems. Again from the table, Throughput for Basketball multihop is better than Infostation but a little bit less than CDMA systems when the transmission range is increased (500 m).

Table 6.12: System Comparison (d_min=125 m)

Cases	Mean Packet Delay	Mean Normalized Throughput	System Packet Delay	System Throughput
Basketball Multihop	2.2e+3 **CI: 0.68**	1.9 **CI: 0.72**	0.3	196.1
Pure CDMA	2.7e+3 **CI: 0.64**	0.9 **CI: 0.72**	23.3	90.8
One hop Infostation	4.4e+3 **CI: 0.72**	0.3 **CI: 0.68**	0.4	30.7

Table 6.13: System Comparison (d_min=250 m)

Cases	**Mean Packet Delay**	**Mean Normalized Throughput**	**System Packet Delay**	**System Throughput**
Basketball multihop	0.7e+3 **CI: 0.68**	7.1 **CI: 0.64**	0.8	711.5
Pure CDMA	1.1e+3 **CI: 0.68**	4.9 **CI: 0.72**	4.1	497.8
One hop Infostation	2.2e+3 **CI: 0.72**	1.0 **CI: 0.72**	0.9	103.6

Table 6.14: System Comparison (d_min=500 m)

Cases	**Mean Packet Delay**	**Mean Normalized Throughput**	**System Packet Delay**	**System Throughput**
Basketball multihop	0.8e+3 **CI: 0.68**	8.8 **CI: 0.64**	9.4	884.9
Pure CDMA	2.4 e+3 **CI: 0.68**	9.7 **CI: 0.72**	5.2	979.6
One hop Infostation	2.0e+3 **CI: 0.72**	0.8 **CI: 0.72**	0.3	85.0

For Low Transmission Range (d_min=125)

From the CDF plots for Packet Delay in Figure 6.21, the results suggest that for Basketball multihop case, within 2000 time slots, 90% of the packets will be delivered with 0.1 outage probability, whereas for CDMA case, 60% of the time the packets will be delivered with 0.4 outage probability and for Infostation case, 30% of the time the packets will be delivered with 0.7 outage probability respectively for the same duration. Hence Basketball multihop system is clearly better than the other two systems with respect to delay outage.

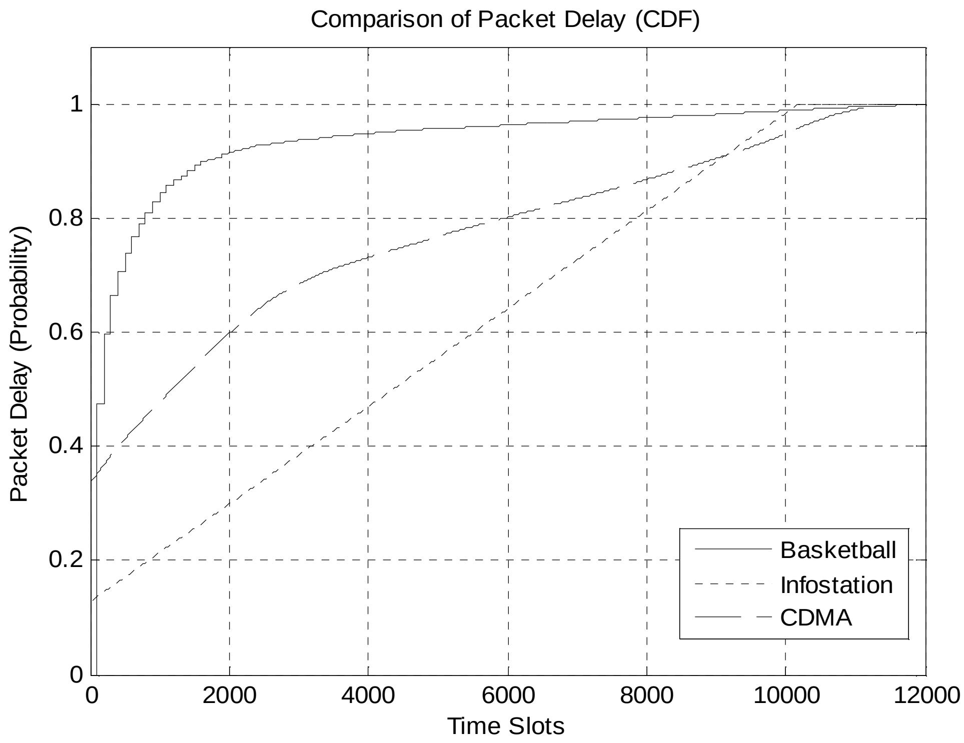


Figure 6.21: Comparison of Packet Delays for different systems, d_min=125

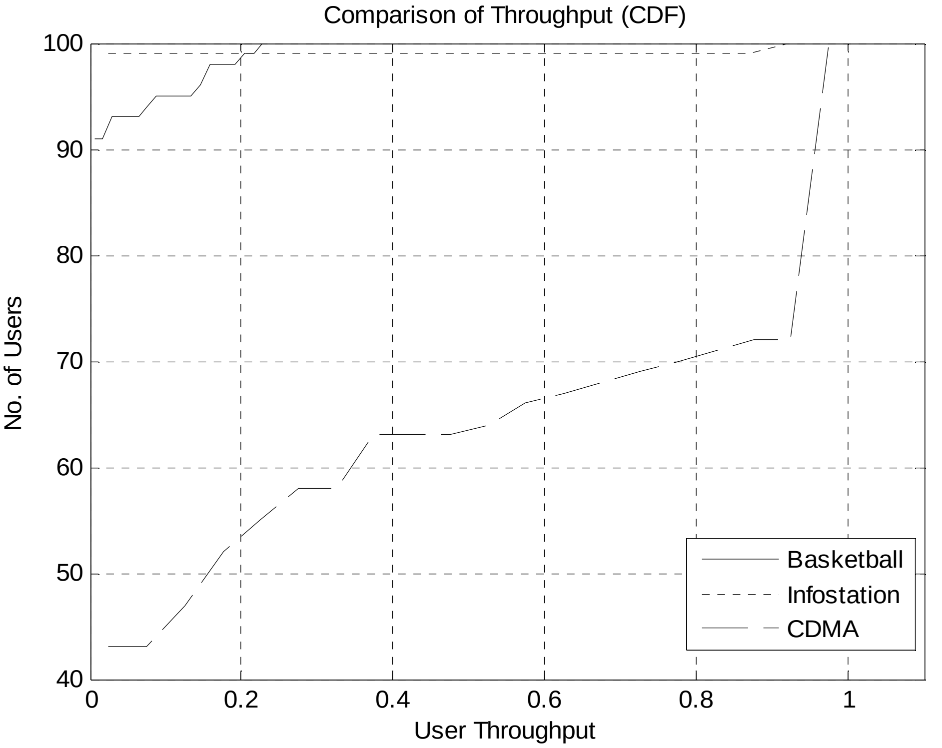


Figure 6.22: Comparison of Throughputs for different systems, d_min=125 m

In Figure 6.22, from the CDF plot for throughput, it can be seen that for Basketball multihop case, 90 users can be supported with 0.0 outage probability whereas for CDMA case 90 users can be supported with 0.96 outage probability and for Infostation case 90 users can be supported with 0.0 outage probability. Thus we can see that the Basketball multihop system works better in shorter transmission range with respect to both packet delay and throughput.

For Medium Transmission Range (d_min=250 m)

From the CDF plots for Packet Delay in Figure 6.23, the results suggest that for Basketball multihop case, within 2000 time slots, 90% of the packets will be delivered with 0.1 outage probability, whereas for CDMA case, 74% of the packets will be delivered with 0.26 outage probability and for infostation case, 74% of the time the packets will be delivered with 0.26 outage probability respectively for the same duration. Hence Basketball multihop system is clearly better than the other two systems with respect to delay outage.

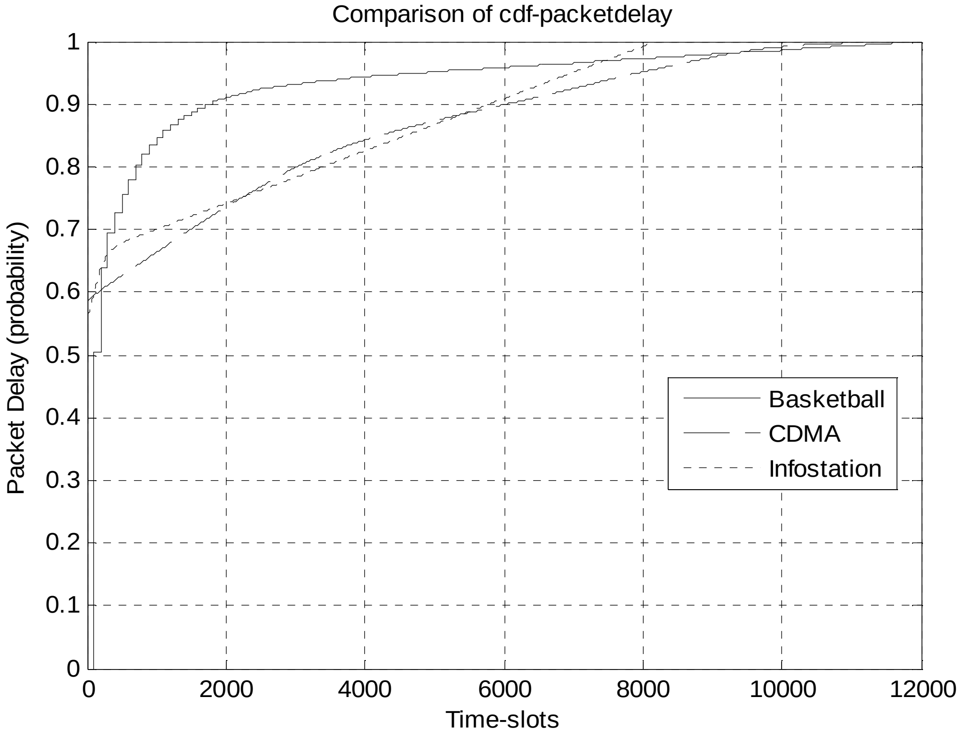


Figure 6.23: Comparison of Packet Delays for different systems, d_min=250m

In Figure 6.24, from the CDF plot for throughput, it can be seen that for Basketball multihop case, from 28 to 100 users can be supported with 100% probability whereas for CDMA case from 32 to 100 users can be supported with 100% probability and for Infostation case from 28 to 100 users can be supported with 100% probability. Yet Basketball multihop system is more stable than CDMA because it can provide any user with more than 80% probability which CDMA cannot provide.

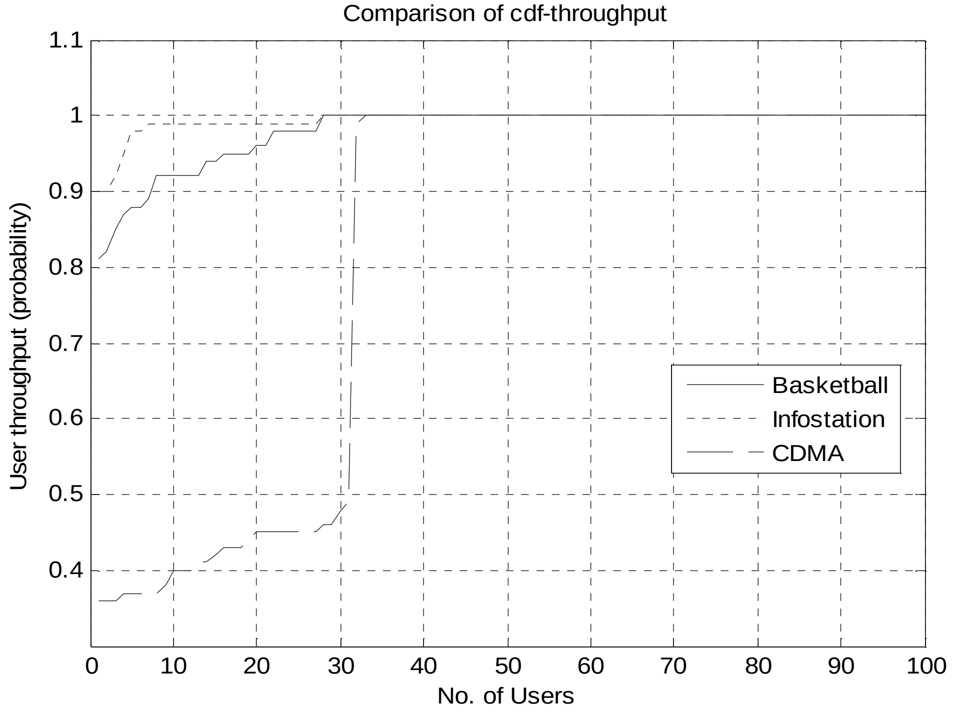


Figure 6.24: Comparison of Throughputs for different systems, d_min=250m

Thus we can see that the Basketball multihop system works better even in medium transmission range with respect to both packet delay and throughput.

For High Transmission Range (d_min=500 m)

From the CDF plots for Packet Delay in Figure 6.25, the results suggest that for Basketball multihop case, within 2000 time slots 75% of the packets will be delivered with 0.25 outage probability, whereas for CDMA case, 82% of the packets will be delivered with 0.18 outage probability and for Infostation case, 91% of the packets will be delivered with 0.09 outage probability respectively for the same duration. Hence Basketball multihop system is worse than the other two systems with respect to delay outage.

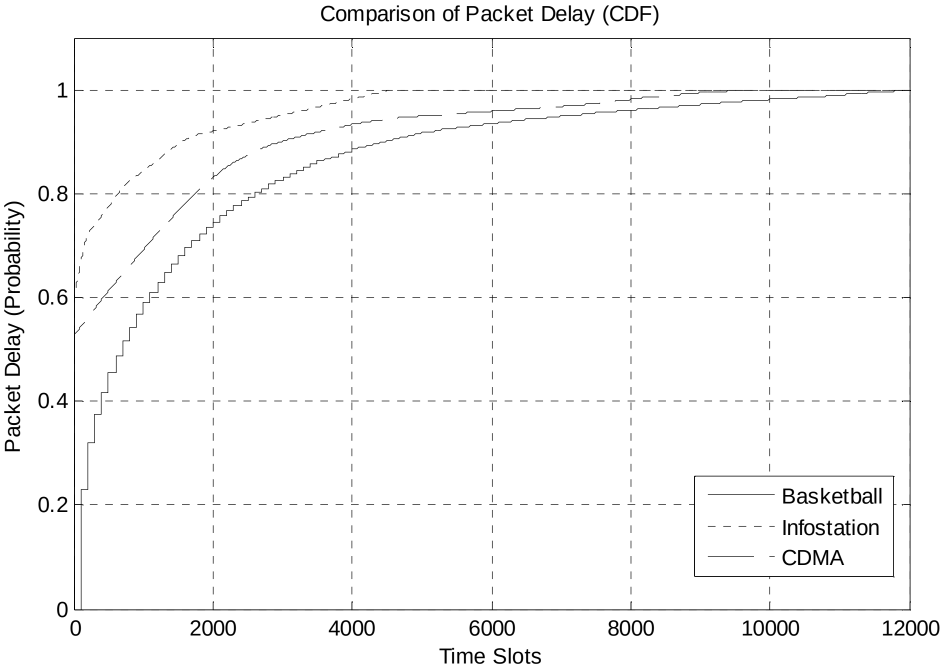


Figure 6.25: Comparison of Packet Delays for different systems, d_min=500 m

In Figure 6.26, from the CDF plot for throughput, it can be seen that for Basketball multihop case, 90 users can be supported with 0.65 outage probability whereas for CDMA case 90 users can be supported with 0.9 outage probability and for Infostation case 90 users can be supported with 0.0 outage probability. Thus we can see that the Basketball multihop system works better than CDMA system but worse than infostation system in terms of throughput outage.

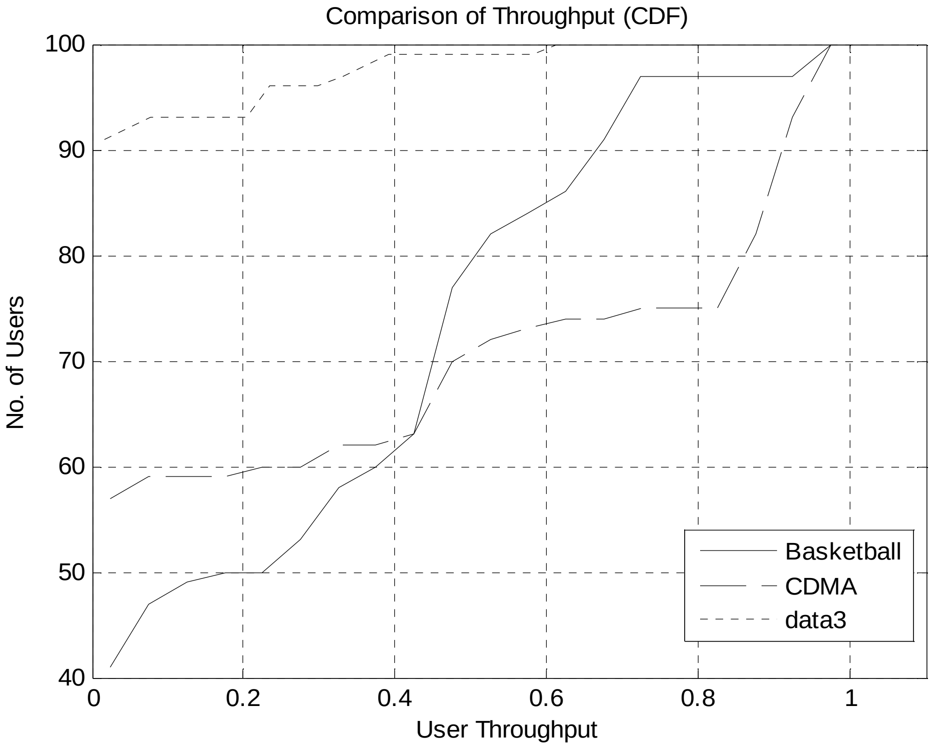


Figure 6.26: Comparison of Throughputs for different systems, d_min=500m

Thus our results suggest that Basketball multihop system works fine with higher transmission range. Thus Basketball multihop system serves the purpose of extending the range with better throughput and shorter delays than the other two systems CDMA and Infostation.

One possible reason behind this is due to the fact that when the transmission range is higher the mobile nodes in Basketball multihop system can transmit packet with high data rate due to strong SINR directly to the base station and even outside the transmit range they will have relays with long transmit range. So it is more likely that Basketball multihop System will have more throughput and good coverage. But mobile nodes in CDMA system in the same scenario cannot transmit with high data rate and for the infostation system, outside the transmit range the mobile nodes cannot

Chapter 7

Conclusion and Further Work

The simulations have shown that there certainly is a need for relaying in cellular networks due to improved capacity and shorter delays. However the Basketball multihop system works better than CDMA system and infostation systems for the following conditions:

- More users for increased throughput and reduced delay
- Larger cell for both shorter delay and improved throughput
- Highway-vehicle users for both increased throughput and improved delay
- High traffic volume for higher throughput
- High Transmission range for both increased throughput and improved coverage.

Relying in cellular network is rather a hot concept in wireless communications. This means that there is considerable research going on and many issues that remain to be solved. We have only focused on some parameters and have seen the effects of those parameters. However there are some issues that could be subject to further studies.

One promising study could be to find a better scheme to choose the most appropriate relay. In the original Basketball multihop scheme, relays are selected in a random fashion. This may result in that a terminal far away from the base station is selected as relay. However, according to its location, no transmitter will select it as relaying terminal. So it is better to select relays according to terminal distance to the base station. A terminal closer to the base station should have higher probability to be acting as relay.

So far in this thesis we have seen the effects of some parameters, still some other effects of parameters could be seen for example SINR-target, buffer threshold etc.

Appendix A

Simulation Tables

In this segment we present the simulation tables which we used in our data analysis for different systems.

System packet delay is determined by averaging over all the packet delays from all the users in the system.

System Throughput is determined by summing up all the packets in the system that has been transmitted to the base station.

Normalized Throughput is the ratio between the number of packets transmitted to the Base Station and the number of generated packets by the user.

The Standard Deviation (SD) is the square root of the variance.

Table A.1: Mean and Variance of data (N=100)

	Packet Delay		**Normalized Throughput**			
Cases	**Mean (sec.)**	**Variance (sec.)**	**Mean**	**Variance**	**System Packet Delay (sec.)**	**System throughput (pkts/sec)**
Basketball multihop	0.6e+3 **CI: 0.64**	7.8e+5 **SD: 883.1**	2.7 **CI: 0.64**	9.0 **SD:3**	1.0	271.5
Pure CDMA	1.3e+3 **CI: 0.68**	3.6e+6 **SD: 1.8e+3**	6.9 **CI: 0.72**	119.6 **SD:10.9**	6.1	697.8
One hop Infostation	2.2e+3 **CI: 0.72**	8.0e+6 **SD: 1.8e+3**	1.0 **CI: 0.72**	18.8 **SD:4.3**	0.9	103.6

Table A.2: Mean and Variance of data (N=750)

	Packet Delay		Normalized Throughput			
Cases	**Mean (sec.)**	**Variance (sec.)**	**Mean**	**Variance**	**System Packet Delay (sec.)**	**System throughput (pkts/sec)**
Basketball multihop	2.0e+3 **CI: 0.72**	6.8e+6 **SD:2.6e+3**	8.1 **CI: 0.60**	81.3 **SD: 9.01**	29.0	6e+3
Pure CDMA	2.3e+3 **CI: 0.72**	5.3e+6 **SD: 2.3E+3**	2.0 **CI: 0.72**	39.8 **SD:6.3**	2.8	1.5e+3
One hop Infostation	2.1e+3 **CI: 0.72**	6.3e+6 **SD:2.5e+3**	0.8 **CI: 0.72**	12.9 **SD:3.6**	0.7	654.2

Table A.3: Mean and Variance of data (R=1 Km)

	Packet Delay		Normalized Throughput			
Cases	**Mean (sec.)**	**Variance (sec.)**	**Mean**	**Variance**	**System Packet Delay (sec.)**	**System throughput (pkts/sec)**
Basketball multihop	211.5 **CI: 0.72**	1.0e+5 **SD: 316.2**	31.5 **CI: 0.72**	0.07 **SD:0.26**	2.1	3.1e+3
Pure CDMA	2.4 e+3 **CI: 0.72**	7.3e+6 **SD:2.7e+3**	23.0 **CI: 0.72**	119.2 **SD:10.9**	33.9	2.3e+3
One hop Infostation	2.6e+3 **CI: 0.72**	6.3e+6 **SD:2.5e+3**	12.5 **CI: 0.72**	167.8 **SD:12.9**	14.9	1.2e+3

Table A.4: Mean and Variance of data (R=5 Km)

	Packet Delay		**Normalized Throughput**			
Cases	**Mean (sec.)**	**Variance (sec.)**	**Mean**	**Variance**	**System Packet Delay (sec.)**	**System throughput (pkts/sec)**
Basketball multihop	0.7e+3 **CI: 0.68**	6.9e+5 **SD:830.6**	7.1 **CI: 0.68**	11.0 **SD:3.31**	0.8	711.5
Pure CDMA	1.1e+3 **CI: 0.68**	3.3e+6 **SD:1.81e+3**	4.9 **CI: 0.72**	117.6 **SD:10.8**	4.1	497.8
One hop Infostation	2.2e+3 **CI: 0.72**	8.0e+6 **SD:2.82e+3**	1.0 **CI: 0.72**	18.8 **SD:4.3**	0.9	103.6

Table A.5: Mean and Variance of data (time= 900 sec)

	Packet Delay		**Normalized Throughput**			
Cases	**Mean (sec.)**	**Variance (sec.)**	**Mean**	**Variance**	**System Packet Delay (sec.)**	**System throughput (pkts/sec)**
Basketball multihop	0.8e+4 **CI: 0.72**	4.2e+8 **SD:2e+4**	18.4 **CI: 0.72**	48.0 **SD:6.9**	55.6	1.8e+3
Pure CDMA	1.0e+4 **CI: 0.72**	1.2e+8 **SD:1e+4**	16.8 **CI: 0.72**	160.2 **SD:12.6**	94.1	1.6e+3
One hop Infostation	1.9e+4 **CI: 0.72**	2.1e+8 **SD:1.4e+4**	6.3 **CI: 0.72**	99.8 **SD:9.9**	71.9	637.2

Table A.6: Mean and Variance of data (Highway Vehicle)

	Packet Delay		Normalized Throughput			
Cases	**Mean (sec.)**	**Variance (sec.)**	**Mean**	**Variance**	**System Packet Delay (sec.)**	**System throughput (pkts/sec)**
Basketball multihop	0.7e+3 **CI: 0.68**	6.9e+5	7.1 **CI: 0.64**	11.0	0.8	711.5
Pure CDMA	1.1e+3 **CI: 0.68**	3.3e+6	4.9 **CI: 0.72**	117.6	4.1	497.8
One hop Infostation	2.2e+3 **CI: 0.72**	8.0e+6	1.0 **CI: 0.72**	18.8	0.9	103.6

Table A.7: Mean and Variance of data (Pedestrian User)

	Packet Delay		Normalized Throughput			
Cases	**Mean (sec.)**	**Variance (sec.)**	**Mean**	**Variance**	**System Packet Delay (sec.)**	**System throughput (pkts/sec)**
Basketball multihop	0.7e+3 **CI: 0.68**	1.9e+6	1.3 **CI: 0.68**	32.9	0.4	139.2
Pure CDMA	0.6e+3 **CI: 0.60**	1.6e+6	4.8 **CI: 0.68**	122.8	1.8	481.9
One hop Infostation	0.3e+3 **CI: 0.68**	7.6e+5	1.1 **CI: 0.68**	33.2	0.1	115.1

Table A.8: Mean and Variance of data (City Vehicle)

	Packet Delay		**Normalized Throughput**			
Cases	**Mean (sec.)**	**Variance (sec.)**	**Mean**	**Variance**	**System Packet Delay (sec.)**	**System throughput (pkts/sec)**
Basketball multihop	1.7e+3 **CI: 0.68**	9.1e+6	1.8 **CI: 0.68**	28.9	1.7	186.8
Pure CDMA	1.8e+3 **CI: 0.68**	7.8e+6	6.5 **CI: 0.68**	145.9	8.2	653.3
One hop Infostation	0.3e+3 **CI: 0.68**	5.0e+5	0.8 **CI: 0.72**	9.5	0.1	88.8

Table A.9: Mean and Variance of data (High Traffic)

	Packet Delay		**Normalized Throughput**			
Cases	**Mean (sec.)**	**Variance (sec.)**	**Mean**	**Variance**	**System Packet Delay (sec.)**	**System throughput (pkts/sec)**
Basketball multihop	0.6e+3 **CI: 0.68**	7.8e+5	1.1 **CI: 0.64**	9.0	1.0	111.5
Pure CDMA	1.3e+3 **CI: 0.68**	3.6e+6	6.9 **CI: 0.72**	119.6	6.1	697.8
One hop Infostation	2.2e+3 **CI: 0.72**	8.0e+6	1.0 **CI: 0.72**	18.8	0.9	103.6

Table A.10: Mean and Variance of data (Low Traffic)

	Packet Delay		Normalized Throughput			
Cases	**Mean (sec.)**	**Variance (sec.)**	**Mean**	**Variance**	**System Packet Delay (sec.)**	**System throughput (pkts/sec)**
Basketball multihop	0.1e+3 **CI: 0.68**	1.3e+5	0.3 **CI: 0.68**	2.0	0.1	39.3
Pure CDMA	1.1e+3 **CI: 0.68**	4.4e+6	5.8 **CI: 0.68**	51.2	8.8	589.7
One hop Infostation	3.7e+3 **CI: 0.68**	1.2e+7	0.4 **CI: 0.72**	5.9	0.9	42.4

Table A.11: Mean and Variance of data (d_min=125 m)

	Packet Delay		Normalized Throughput			
Cases	**Mean (sec.)**	**Variance (sec.)**	**Mean**	**Variance**	**System Packet Delay (sec.)**	**System throughput (pkts/sec)**
Basketball multihop	2.2e+3 **CI: 0.68**	3.4e+5	1.9 **CI: 0.72**	1.7	0.3	196.1
Pure CDMA	2.7e+3 **CI: 0.64**	1.1e+7	0.9 **CI: 0.72**	187.5	23.3	90.8
One hop Infostation	4.4e+3 **CI: 0.72**	1.0e+7	0.3 **CI: 0.68**	8.9	0.4	30.7

Table A.12: Mean and Variance of data (d_min=250 m)

	Packet Delay		Normalized Throughput			
Cases	Mean (sec.)	Variance (sec.)	Mean	Variance	System Packet Delay (sec.)	System throughput (pkts/sec)
Basketball multihop	0.7e+3 **CI: 0.68**	6.9e+5	7.1 **CI: 0.64**	11.0	0.8	711.5
Pure CDMA	1.1e+3 **CI: 0.68**	3.3e+6	4.9 **CI: 0.72**	117.6	4.1	497.8
One hop Infostation	2.2e+3 **CI: 0.72**	8.0e+6	1.0 **CI: 0.72**	18.8	0.9	103.6

Table A.13: Mean and Variance of data (d_min=500 m)

	Packet Delay		Normalized Throughput			
Cases	Mean (sec.)	Variance (sec.)	Mean	Variance	System Packet Delay (sec.)	System throughput (pkts/sec)
Basketball multihop	0.8e+3 **CI: 0.68**	3.2e+6	8.8 **CI: 0.64**	82.8	9.4	884.9
Pure CDMA	2.4 e+3 **CI: 0.68**	3.3e+6	9.7 **CI: 0.72**	159.9	5.2	979.6
One hop Infostation	2.0e+3 **CI: 0.72**	9.1e+5	0.8 **CI: 0.72**	9.1	0.3	85.0

Appendix B

Confidence Interval

In this segment we will show how we calculated the confidence interval that we used for our simulation results.

B.1 Calculation of Confidence Interval for Packet Delay (For N=100, Basketball multihop)

The mean for packet delay in each simulation are:

```
DelayMean =
1.0e+003 *
Columns 1 through 11
2.2671    0.1829    3.6180    1.8040    1.4981    0.4840    0.4241    0.8999    0.7810
2.8741    1.2841
Columns 12 through 22
0.7431    3.9001    1.2602    0.2501    2.6790    1.0714    4.3784    1.1545    2.4839
0.9527    1.3047
Columns 23 through 25
3.0200    3.7601    0.6296
```

The mean of these 25 values is:

```
mean(DelayMean)
ans =
1.7482e+003
```

The variance of these 25 values is:

```
var(DelayMean)
ans =
1.5740e+006
```

Now we define the left range for calculating the Confidence Interval as $(\mu - \sigma)$ where μ is the mean value and σ is the standard deviation.

```
(mean(DelayMean)-sqrt(var(DelayMean)))
ans =
 493.6077
```

Now we define the right range for calculating the Confidence Interval as $(\mu + \sigma)$ where μ is the mean value and σ is the standard deviation

```
>> (mean(DelayMean)+sqrt(var(DelayMean)))
ans =
3.0028e+003
```

Now we investigate how many of those 25 values lie in our specified interval:

```
>>(DelayMean>(mean(DelayMean)-sqrt(var(DelayMean))))&
(DelayMean<(mean(DelayMean)+sqrt(var(DelayMean))))
ans =
Columns 1 through 13

   1    0    0    1    1    0    0    1    1    1    1    1    0

 Columns 14 through 25

   1    0    1    1    0    1    1    1    1    0    0    1
```

We got 16 values out of 25 values lie in our specified range for confidence interval.

```
>> 16/25
ans =
0.6400
```

Thus we can say that our mean values for Packet Delay have 64% confidence to lie in the interval.

B.2 Calculation of Confidence Interval for Throughput (For N=100, Basketball multihop)

The mean for Throughput in each simulation are:

```
ThroughputMean =
Columns 1 through 10
1.7084    1.3373    2.3155    2.4612    1.5853    1.1395    0.9095    0.8129    2.1545
1.3903
Columns 11 through 20
```

```
1.4489   1.4281   2.7320   2.1455   1.4401   1.7800   1.1150   1.3355   1.3788
2.7674
Columns 21 through 25
1.4944   1.0419   2.0090   1.8331   1.1160
```

The mean of these 25 values is:

```
>> mean(ThroughputMean)
ans =
1.6352
```

The variance of these 25 values is:

```
>> var(ThroughputMean)
ans =
0.2978
```

Now we define the left range for calculatingthe Confidence Interval as $(\mu - \sigma)$ where μ is the mean value and σ is the standard deviation.

```
>> (mean(ThroughputMean)-sqrt(var(ThroughputMean)))
ans =
1.0895
```

Now we define the right range for calculating the Confidence Interval as $(\mu + \sigma)$ where μ is the mean value and σ is the standard deviation

```
>> (mean(ThroughputMean)+sqrt(var(ThroughputMean)))
ans =
2.1810
```

Now we investigate how many of those 25 values lie in our specified interval:

```
>>(ThroughputMean>(mean(ThroughputMean)-sqrt(var(ThroughputMean))))&
(ThroughputMean<(mean(ThroughputMean)+sqrt(var(ThroughputMean))))

ans =
 Columns 1 through 13
   1   1   0   0   1   1   0   0   1   1   1   1   0
 Columns 14 through 25

   1   1   1   1   1   1   0   1   0   1   1   1
```

We got 18 values out of 25 values lie in our specified range for confidence interval.

```
>> 18/25
ans =
0.7200
```

Thus we can say that our mean values for Throughput have 72% confidence to lie in the interval.

Appendix C

Pseudocode

In this segment we will present the pseudocode of the Basketball multihop system that we used in our simulation.

```
clear all;
simRun =25;
index = 1;
DM = 0;
TM = 0;
save index index;
save DM DM;
save TM TM;
save simRun simRun;
for index = 1:simRun
    save index index;
    parameters;
    Nodes;
    packet_arrivals;
    load parameters
    load arrived_packets;   % Generate the arrival time-slots of packets for each MS
    for j=1:N
        queue{j}=[];
        slot_difference{j}=[];
        recieved_packets_bs{j}=[];
        packet_number_of_the_transmitted_packet{j}=[];
        average_packet_delay_sec{j}=[];
        user_throughput{j}=[];
        normalized_throughput{j}=[];
        L{j}=length(packet_arrival{j});
        next_arrival_index{j}=1;            % index to count packet arrival
    end;
```

```
  %load positions users;                    %Nodes initialization
  load positions;
  for t=0:mobility_slot                 %To make the mobiles moving
    %Nodes Mobility
    users=move(users);
    users(:,2)=users(:,4);            %New y-coordinate of the node is updated
    users(:,1)=users(:,3);            %New x-coordinate of the node is updated
    showpos(users,t,N,R);
    pause(0.01)
    for i=1:N
      d_m(i)=sqrt(users(i,1)^2+users(i,2)^2);   % distance to the base station for
all the mobiles
      G_allbs(i)=(d_m(i))^(-alpha);    %G{i} is the link gain for all the mobiles
and the base station
      for j=(i+1):N
        d(i,j)=sqrt((users(i,1)-users(j,1))^2+(users(i,2)-users(j,2))^2); %
distance between the mobiles itself
        d(j,i)=d(i,j);
      end;
    end;
    for k=1:K
      relays=[];
      transmitters_list=[];
      tx_num=[];
      relays_list=[];
      rel_num=[];
      actv_txs=[];
      G_alltxbs=[];
      G_txbs=[];
      G_othertxbs=[];
      transmitter=[];
      relay=[];
      actv_txs=[];
      actv_txs_num=[];
      packets_transmitted=[];
      tr=[];
      g_br={};
      slot=k+(K*t);                       % Overall slot index
      users(:,7)=zeros(N,1);               % reset the transmitter list
      for n=1:N                           % update the queue
        if(slot==packet_arrival{n}(next_arrival_index{n}))
          queue{n}=[queue{n} [slot;n]];   % keeping time-slot & user
information
          if(L{n}>next_arrival_index{n})
            next_arrival_index{n}=next_arrival_index{n}+1;
          end;
```

```
                end;
            end;
            relays=rand(1,N)<p;                 % Find the mobiles that can act as relay
            transmitters_list=find(relays~=1);   % Find the mobiles that can act as
transmitter
            tx_num=length(transmitters_list);
            relays_list=find(relays==1);
            rel_num=length(relays_list);
            G_alltxbs=G_allbs(transmitters_list);   %Picking link gains for all the
transmitters;
            % Finding active transmitters
            for m=1:tx_num
                transmitter=transmitters_list(m);
                if d_m(transmitter)<=d_min         % Base station is within the transmit
range
                    users(transmitter,7)=1;
                else
                    for n=1:rel_num               % To look for relays
                        relay=relays_list(n);
                        if (d(transmitter,relay)<=d_min) & (d_m(relay)<d_m(transmitter))
                            users(transmitter,7)=1;
                            break;
                        end;
                    end;
                    if n==(rel_num+1)
                        users(transmitter,7)=0;
                    end;
                end;
            end;
            actv_txs=find(users(:,7)==1);
            actv_txs_num=length(actv_txs);
            G_actv_txsbs=G_allbs(actv_txs);
            for n=1:actv_txs_num                          % Go for all active transmitters
                comp=[];
                f=[];
                transmitter=actv_txs(n);

                if length(queue{transmitter})>0              % The base station is within
radio-range and the queue is not empty

                    if d_m(transmitter)<=d_min              % Deciding Data Rate &
Packet transmission
                        G_txbs=G_actv_txsbs(n);                                 % The link
gain for the current transmitter
                        G_othertxbs=sum(G_actv_txsbs)-G_txbs;
% Sum of all other transmitter gains
```

```
SINR_bs{transmitter}=(G_txbs*p_max)/((G_othertxbs*p_max)+nu);              %
SINR for the current mobile to the base station
            C_bs{transmitter}=W*log2(1+SINR_bs{transmitter});

packets_transmitted=min(floor(C_bs{transmitter}/r_min),length(queue{transmitt
er}(1,:)));      %transmit directly to the base station
            if packets_transmitted>=1

pkt_sent_bs{transmitter}=queue{transmitter}(:,1:packets_transmitted); % slot
number of the transmitted packets

queue{transmitter}=queue{transmitter}(:,(packets_transmitted+1):length(queue{t
ransmitter}(1,:)));     % Refresh queue

received_packets_bs{transmitter}=[(slot+1)*ones(1,packets_transmitted);pkt_sen
t_bs{transmitter}(2,:)];  % Recieved packets in the BS
              for h=1:packets_transmitted % go throught all the received
packets
                original_tx = received_packets_bs{transmitter}(2,h);
                time_slot_difference=received_packets_bs{transmitter}(1,h)-
pkt_sent_bs{transmitter}(1,h);
                slot_difference{original_tx}=[slot_difference{original_tx}
time_slot_difference];
              end
            end;
          else      %    The base station is too far away from the current mobile
            r=0;
            for u=1:rel_num   % To look for relays
              relay=relays_list(u);
              if d(transmitter,relay)<=d_min & d_m(relay)<d_m(transmitter)
%There are relays within radio-range and closer to the base station than the
mobile itself
                r=r+1;
                comp(r)=(lambda*d(transmitter,relay))+((1-
lambda)*d_m(relay)); %Select the best relay within radio range through
comparison
                f(r)=relay;
              end;
            end;          % end of u loop
            [v,index]=min(comp);
            best_relay=f(index);
            if isempty(best_relay)
              packets_transmitted=0;
            else
              %The transmitter will send the packet to this best_relay
```

```
                            G_BR{transmitter}=d(transmitter,best_relay)^(-alpha); %G{n}
is the link gain for the current mobile and the best relay
                            for z=1:actv_txs_num
                                tr=actv_txs(z);
                                if tr~=transmitter
                                    g_br{tr}=d(tr,best_relay)^(-alpha); %g{i}  is the link gain
for the other mobiles and the best relay
                                end;
                            end;

SINR_br{transmitter}=(G_BR{transmitter}*p_max)/(p_max*sum([g_br{:}])+nu
);
                            C_br{transmitter}=W*log2(1+SINR_br{transmitter});

packets_transmitted=min(floor(C_br{transmitter}/r_min),length(queue{transmitte
r}(1,:)));  %transmit to the bets_relay
                            if packets_transmitted>=1

packets_to_relay{transmitter}=queue{transmitter}(:,1:packets_transmitted);

queue{transmitter}=queue{transmitter}(:,(packets_transmitted+1):length(queue{t
ransmitter}(1,:)));
                                %The packet will be recieved by the best_relay


%recieved_packets{best_relay}=packets_to_relay{transmitter}
                                queue{best_relay}=[queue{best_relay}
packets_to_relay{transmitter}];
                            end;
                        end;        % end of isempty if loop

                    end;              % end of transmission range if loop
                end;
            end;                  % end of n loop
        end;                    % end of k loop
    end;                    % end of t loop
    for n=1:N
        if length(slot_difference{n})>0

average_packet_delay_sec{n}=(sum(slot_difference{n})/length(slot_difference{n
}))*T_s;     %Packet Delay for each user in sec
        end;
        user_throughput{n}=length(slot_difference{n})/(mobility_slot+1);
%Throughput in packets/sec
        normalized_throughput{n}=length(slot_difference{n})/L{n};       %no.of
packets_transmitted/all generated packets
```

```
   end;
   served_users=length(average_packet_delay_sec);

   average_packet_delay_sec
   normalized_throughput
   system_packet_delay_sec =sum([average_packet_delay_sec{:}])/served_users
%System mean Packet Delay for all users in sec
   system_throughput=sum([user_throughput{:}])                    %System
Throughput
   %Plotting cdf for packet delay
   all_slot_difference=[];
   for n=1:N
      all_slot_difference=[all_slot_difference slot_difference{n}];
   end;
   max_delay=max(all_slot_difference);
   a=histc(all_slot_difference,0:0.01:mobility_slot);
   sum(a);
   figure(2);
   stem(a);
   b=a/sum(a); %probability distribution function
   stem(b);
   for n=1:(mobility_slot)*100
      c(n)=sum(b(1:n));
   end
   figure(3);
   plot(c,'k');% cdf for packet_delay
   %Plotting cdf for throughput
   pp=[normalized_throughput{:}];
   [qq, xx]=hist(pp,20);
   rr=qq;
   for n=1:20
      cdf_throughput(n)=sum(rr(1:n));
   end;
   figure(4);
   plot(xx, cdf_throughput,'k'); %cdf (throughput)
   % %Plotting cdf for normalized_throughput
   % ss=[normalized_throughput{:}];
   % tt=histc(ss,0:N);
   % uu=tt/sum(tt);
   % for n=1:N
   %     cdf_normalized_throughput(n)=sum(uu(1:n));
   % end;
   % figure(5);
   % plot(cdf_normalized_throughput,'k');
   load index index;
   load DM DM;
```

```
   load TM TM;
   load simRun simRun;

   DM(index) = mean(all_slot_difference)% Mean of packet delay
   var(all_slot_difference)% Variance of packet delay
   TM(index) = mean([user_throughput{:}])% Mean of Throughput
   var([user_throughput{:}]) % variance of Throughput
   %sum(((mean(all_slot_difference)-sqrt(var(all_slot_difference))) <
all_slot_difference) & ((mean(all_slot_difference)+sqrt(var(all_slot_difference)))
>all_slot_difference))/length(all_slot_difference)
   save DM DM;
   save TM TM;
end
sum(((mean(DM)-2*sqrt(var(DM))) < DM) & ((mean(DM)+2*sqrt(var(DM)))
>DM))/length(DM)% Confidence interval of Packet Delay
sum(((mean(TM)-2*sqrt(var(TM))) < TM) & ((mean(TM)+2*sqrt(var(TM)))
>TM))/length(TM) % Confidence interval of Throughput
```

References

[1] Cisco Systems, Inc, Overview of GSM, GPRS and UMTS "http://www.cisco.com/univercd/cc/td/doc/product/wireless/moblwrls/cmx/mmg_sg/cmxgsm.htm" (visited on 06.09.06)

[2] The Wireless LAN Association (WLANA), "http://www.wlana.com" (visited on 29.05.06)

[3] S.M. Cherry. "*Wi-fi takes new turn with 'wireless-g'*". *IEEE Spectrum Magazine*, pages 12–13, August 2003.

[4] Web-based networking-specific information, "http://searchnetworking.techtarget.com/sDefinition/0,,sid7_gci214263,00.html" (visited on 29.05.06)

[5] Hans-Florian Geerdes, "*Capacity improvements in TDMA-based cellular networks by relaying and Flexible transmission scheduling*". Master's thesis, TU Berlin, 2002.

[6] Enrico Zanoio and Steve Urvik, "*White Paper: CDMA Network Technologies: A Decade of Advances and Challenges*", Monitoring and protocol test Tektronix Inc, "http://www.tek.com/ir/whitepaper/WP_CDMA.pdf" (visited on 15.05.06)

[7] Web-based free encyclopedia, "http://en.wikipedia.org/wiki/CDMA" (visited on 20.05.06)

[8] Peter H J Chong, Project Abstract ,Mobile Networking Technology Research Project, Nanyang Technology University, Singapore, "http://www.ntu.edu.sg/ntrc/research_4.htm" (visited on 25.05.06)

[9] Xitirnin Deng; Haimovich, A.M.; *"Power allocation for cooperative relaying in wireless networks"* Communications Letters, IEEE Volume 9, Issue 11, Nov. 2005 Page(s):994 – 996

[10] Y. D. Lin and Y. C. Hsu, "*Multihop cellular: A new architecture for wireless communication*," in IEEE INFOCOM'2000, 2000, pp. 1273-1282.

[11] IEEE Computer Society LAN MAN Standards Committee, "*Wireless LAN medium access control (MAC) and physical (PHY) layer specifications"*. IEEE Standard 802.11-1997. The Institute of Electrical and Electronics Engineers, New York, NY, 1997.

[12] ETSI collaborative portal, "http://www.etsi.org/bran" (visited on 15.05.06)

[13] Web-based free encyclopedia, "http://en.wikipedia.org/wiki/HIPERLAN" (visited on 05.05.06)

[14] Hans-Florian Geerdes, *"Assessing Capacity improvements by Relaying in Cellular Networks"*, Proc, OR'2003, Heidelberg, Germany, 2003.

[15] Hamed Nourizadeh, *"Multihop Cellular Networks"*, Research Excellence Awards Competition, UniS, UK, 2004.

[16] J.J. Garcia-Luna-Aceves and Jyoti Raju. "*Distributed Assignment of Codes for Multihop Packet-Radio Networks"*. Proceedings of IEEE MILCOM' 97, Monterey, California. November 2-5, 1997.

[17] Y. Hwang, R. Jäntti, and S.-L. Kim, *"Multihop "Basketball" Packet Scheduling in Uplink DS-CDMA Systems"* to appear in IEEE VTC 2006 fall, Montreal, 2006.

[18] T. Camp, J. Boleng, and V. Davies, "*A Survey of Mobility Models for Ad Hoc Network Research"*, Wireless Communication & Mobile Computing (WCMC): Special issue on Mobile Ad Hoc Networking: Research, Trends and Applications, vol. 2, no. 5, pp. 483-502, 2002

[19] Wing Ho Yuen, "*Fundamental network behavior of mobile adhoc networks*", PhD thesis, Rutgers, The State University of New Jersey, January, 2004.

[20] Juan Francisco, "*Ad Hoc Networks – design and performance issues*", Masters Thesis, Helsinki University of Technology, May, 2002.

[21] Tony Larsson, Nicklas Hedman, "*Routing Protocols in wireless adhoc networks-a simulation study*", Masters Thesis, Stockholm, Luleå University of Technology, 1998.

[22] Web-based Mathematics resource "http://mathworld.wolfram.com/LogNormalDistribution.html" (visited on 29.05.06)

[23] Halim Yanikomeroglu, "*Cellular Multihop Communications: Infrastructure-Based Relay Network Architecture for 4G Systems*" Queen's University 22nd Biennial Symposium on Communications (QBSC'04), Kingston, Ontario, Canada, 1 June 2004

[24] Claudio Rosa, "*Enhanced Uplink Packet Access in WCDMA–combined performance of advanced packet scheduling techniques, Fast L1 HARQ, Interference Cancellation, and 4-Branch Antenna Diversity*", Department of Communication Technology, Institute for Electronic Systems, Aalborg University, December 2004.

[25] Klemm, A.; Lindemann, C.; Lohmann, M; **"***Traffic modeling and characterization for UMTS networks***",** "Global Telecommunications Conference, 2001. GLOBECOM '01. IEEE" Volume 3, 25-29 Nov. 2001 Page(s):1741 - 1746 vol.3

[26] J. Vidal1, M. Madueño1, J. R. Fonollosa1, S. Barbarossa2, O. Gasparini3, S. Ponnekanti4, A. Andritsou5, A. Nix6, "Multihop networks for capacity and coverage enhancement in TDD/UTRAN1" available at http://www.ist-romantik.org/publicationsp/Vidal_MedHocNet2002.pdf (visited on 06.09.06)