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Performance Evaluation of the IS-136 DCCH Reverse Access Channel Mechanism

by

Ghassan Naim

A thesis submitted to the
School of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

MASTER OF APPLIED SCIENCE

Ottawa-Carleton Institute of Electrical Engineering

Department of Electrical Engineering
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to my family .....

Abstract

With the ever evolving mobile cellular technology, more standards are being deployed and upgraded with the goal to provide better service and quality as well as higher capacity to support the higher demand of voice communication. This thesis focuses on the performance of the Mobile/Wireless network interface for IS-136, a North-American standard for digital cellular system. It is no doubt that voice service can be affordable but how does the interface react to the addition of more features and data transfer from the end user onto the system is still under investigation. With the ever increasing need for the wireless data communication features (short messages, fax, digital images and digital video), it is important to answer questions regarding performance and how the cellular system can be improved.

A study of the reverse access control protocol of IS-136 digital control channel is provided and performance results are presented and studied taking in consideration different setups for the access control parameters, input traffic and air link conditions. Finally, guidelines are provided on how to set-up the system when operating under different conditions resulting from different traffic and channel quality characteristics.

Acknowledgment

I would first like to express my deepest appreciation to my thesis supervisor Dr. Luis Orozco Barbosa for his support and guidance every step of the way helping me reshape this work to what it looks like today.

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Finally, I would like express my special thanks to all my family members in Ottawa for their full support and encouragement from the very beginning.

Acronyms

ACA	Adaptive Channel Allocation
ACK	Acknowledgment
ADC	American Digital Cellular
AMPS	Advanced Mobile Phone Service
ARCH	Access Response Channel
ARM	ARQ Response Mode
ARQ	Automatic Retransmission Request
BC	Begin/Continue
BCCH	Broadcast Control Channel
BCN	BCCH Change Notification
BER	Burst Error Rate
BI	Begin Indicator
BMI	Base Station, MSC and Interworking Function
BRI	Busy/Reserved/Idle
BS	Base Station
BT	Burst Type
BU	Burst Usage
CDMA	Code Division Multiple Access
CI	Change Indicator
CLI	Continuation Length Indicator
CPE	Coded Partial Echo
CRC	Cyclic Redundancy Code (Cyclic Redundancy Check)
CSFP	Coded Super Frame Phase
D-AMPS	Dual-Mode AMPS (or Digital AMPS)
DCCH	Digital Control Channel
DECT	Digitally Enhanced Cordless Telecommunication
E-BCCH	Extended Broadcast Control Channel
EC	E-BCCH Change
ECL	E-BCCH Cycle Length
EHI	Extension Header Indicator
E-TACS	Extended TACS
F-BCCH	Fast Broadcast Control Channel

FC	F-BCCH Change
FCC	Federal Communication Commission
FDCCH	Forward Digital Control Channel
FDMA	Frequency Division Multiple Access
FHSS	Frequency Hopping Spread Spectrum
FIFO	First In First Out
FILLER	Burst Filler
FRNO	Frame Number
FRNOMAP	Frame Number Map
GA	Go Away
GSM	Global System for Mobile Communications
HP	Hyperframe
IDT	Identity Type
ID	Identification
IMSI	International Mobile Station Identification
IMTS	Improved Mobile Telephone Service
IS	Interim Standard
JDC	Japanese Digital Cellular
JTACS	Japanese Total Access Communications System
L1	Layer 1
L2	Layer 2
L3	Layer 3
L3DATA	Layer 3 Data
L3LI	Layer 3 Length Indicator
LAN	Local Area Network
MAC	Multiple Access Control
MACA	Mobile Assisted Channel Allocation
MAHO	Mobile Assisted Hand Off
MEA	Message Encryption Algorithm
MEK	Message Encryption Key
MIN	Mobile Station Identification Number
MM	Message Mapping
MS	Mobile Station
MSC	Mobile Switching Center
MSID	Mobile Station Identification
MTSO	Mobile Telephone Switching Office

NADS	North American Digital Standard
NL2M	Number of Layer 3 Messages
NMT	Nordic Mobile Telephone
PAID	PCH Allocation Identification
PAM	Pulse Amplitude Modulation
PCH	Paging Channel
PCM	Pulse Code Modulation
PCON	PCH Continuation
PCS	Personal Communication Service
PDC	Personal Digital Cellular
PE	Partial Echo
PEA	Partial Echo Assigned
PFC	Paging Frame Class
PFM	Paging Frame Modifier
PHS	Personal Handy-phone System
PI	Polling Indicator
R/N	Received/Not-Received
RACH	Random Access Control Channel
RDCCH	Reverse Digital Control Channel
RF	Radio Frequency
RSVD	Reserved
S-BCCH	Short Message Service Broadcast Control Channel
SCF	Shared Channel Feedback
SDMA	Space Division Multiple Access
SF	Superframe
SFP	Superframe Phase
SMS	Short Message Service
SMSCH	Short Message Service Point-to-Point Channel
SOC	System Operator Code
SPACH	SMS, Point-to-Point, Paging and Access Response Channel
SRM	SPACH Response Mode
SYNC	Synchronization
TACS	Total Access Communication Systems
TDMA	Time Division Multiple Access
TMSI	Temporary Mobile Station Identification
UGID	User Group Identity

VLSI	Very Large-Scale Integrated
VMLA	Virtual Mobile Location Area

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CHAPTER 1

Introduction

1.0 Background

Looking around the world today, one can easily see the interest and expansion of mobile communication services for personnel and business use. In today's busy life, an individual needs to have the freedom to get in contact with others at anytime of the day, anywhere in the world. This degree of freedom can only be provided through mobile cellular communications.

It is no doubt that wireless communication is one of the hottest topics today. Replacing all wiring systems and complexity by the wireless technology introduces simpler and more flexible systems that are easier to maintain and upgrade. Nowadays, wireless popularity can be seen by simply taking a look at the lifestyle and environment we live in. With so many devices that are too much to list, we can only mention a few common systems such as cordless phones used around the house, cellular phones used across the nation, pagers, walkie-talkies, laptops, live broadcasting of major events via satellite, missile guidance in military applications, wireless robotics control over long distance such as the guidance of a space shuttle coming into the Earth orbit. An additional technology that is currently under development known by wireless *Local Area Network* (LAN) looks promising as well.

1.1 Motivation

Wireless communication is in no doubt the future vision. Today the market is in need for voice and higher system capacity to support more subscribers. Tomorrow, people will be asking for data transmission over the air. This may include short text message, digital images, fax and even video sequences. The vision for the future is to be able to do everything via a single handset that includes placing a telephone call, booking a flight, exchanging stocks, or even doing banking transactions. The vision extends even further making all these facilities available worldwide. This will truly mean total freedom, better security and most definitely more efficiency in the way we communicate and acquire information.

1.2 Objectives

In this study, we take the opportunity to examine the performance of one of the most important component in a cellular system: the mobile/wireless network interface. The North-American standard IS-136 was selected. The standard was deployed for the digital cellular technology, and is currently under improvement.

We focus our study on providing a performance evaluation of the IS-136, digital control channel access mechanism. Given a set of access parameters defined by the IS-136 standard, our objectives are to provide guidelines for setting these parameters to improve the system performance. We also have an objective to study the system under various conditions and provide feedback on its performance when short message service is supported. This information can be used by a designer to understand some of the limitations provided by the IS-136 air interface and its effect on the wireless system with and without the short message service support. The study also suggest to the designer optimum settings for the IS-136 air interface access parameters under various system conditions .

1.3 Thesis Organization

Five chapters compose this thesis. Following this introduction, chapter 2 provides a brief description of the basics in mobile cellular communications along with some history regarding this technology. Several standards on mobile communication that are used today around the globe are also introduced.

In chapter 3, given that IS-136 is the main focus of this research, we will take a closer look at the standard, at the rules and characteristics of the features that are chosen to be investigated throughout the thesis. The main interest will be focused on the digital control channel (DCCH) access mechanism of the standard in the uplink between a cellular user and the base station.

In chapter 4, we provide simulation results performed using a software model of the IS-136 DCCH features. The main objective of the study has been to perform a performance evaluation of the interface between a population of cellular users and their serving base station in a given geographical region. We also monitor the base station capacity during the various changes applied on the system. We also present the system behavior when supporting the short message service and point the weaknesses and limitations coming with the new service. We end the chapter with a summary of the results and some guidance on the settings of the IS-136 air interface access parameters.

All the performance results presented in chapter 4 can be used as a presentation of the system behavior and BS requirements when the RACH characteristics vary from one end to the other. This will give the designer a clear understanding of the system behavior when pushed to its limits whether in message load capacity, integrity with respect to air channel quality or best performance that can be obtained with variation of the RACH access parameters.

In chapter 5 we present a conclusion and summary of the study present herein and open new doors to future research possibilities that can take the current study to the next level.

CHAPTER 2

Mobile Cellular Telecommunications Systems

2.0 Introduction

In this chapter, we take the opportunity to introduce some of the popular mobile cellular systems used around the world. The chapter starts with a brief description of the cellular concept followed by some history and background on mobile communications and its principals. In the third part of the chapter we present a more detailed explanation on the operation and characteristics of a mobile cellular system nationwide then move on to introduce the second generation of mobile cellular in today's digital wireless systems operating around the world.

2.1 Mobile Communication Concept and Operation

Communication being the aim of wireless technology, voice is probably one of the most important features that is being looked at through mobile cellular telecommunication systems. The main goal is to be able to be in contact at any time anywhere in the world and on the move by simply using a single handset. This system is known today as Personal Communication Service, or just PCS, and was started in late 1995 with the first carrier in Washington/Baltimore area [Gibs2-97].

Before introducing a brief history on wireless communication and cellular technology, we would like to present in this section the concept and basic operation of the cellular system.

In general, a wireless communication system takes place in a portion of the available electromagnetic spectrum. The later consists of the set of electrical and magnetic wavelength that cover all frequencies from the audible frequencies to the radio, then through the visible light to the X-rays and gamma rays. Figure 2.1 shows the distribution of the above frequencies in the limited spectrum available to us today. Other usage of the spectrum is shown for AM/FM radio, television stations, marine radio, police and others too many to list. The limits are fixed and cannot be stretched no matter what we do. This is why, the government limits the use of frequency bands for a given service.

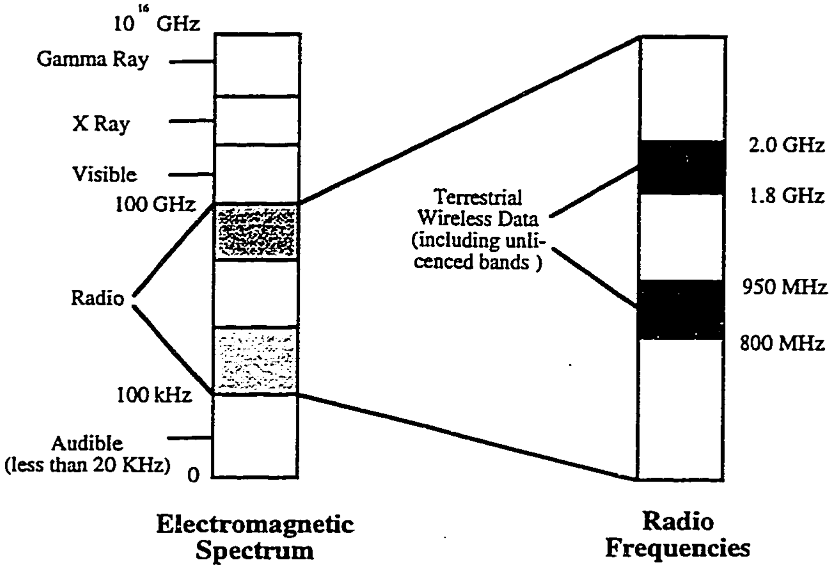


Figure 2.1: Electromagnetic Spectrum [Gibs1-97].

An analog voice signal transmitted from a cellular phone requires 30 kHz of frequency band from the 150 MHz assigned to the cellular service. Each 30 kHz band of frequency is often referred to as a channel. With the limited radio frequency available from the spectrum, a limited number of voice channels is assigned to a given region in which a cellular service is provided. In digital form, the voice signal transmission requires only 10 kHz. This obviously leads to more voice channels availability which means more capacity. This is one of many advantages of the digital communication.

In Figure 2.2 we present the basic operation and setup of a cellular system in a given city. As it can be seen, the city is subdivided into regions that are known as cells. Each cell is managed by a cell site, often referred to a Base Station (BS), that covers a limited area in its geographical surrounding. With the limited number of voice channels available to the system, including all cells, each cell is pre-assigned a set of frequencies that are effectively not to be used in adjacent cells to avoid signal interference. The BS establishes a voice communication channel with the serviced mobiles using these frequencies. A number of these channels are used to transfer information regarding system control/management and call set-up. These channels are known as control or call set-up channels. All the BS's are connected to a Mobile Telephone Switching Office (MTSO) through a high-speed physical link. The MTSO in turn is connected to the Public Telephone Switched Network (PTSN) which is provided by the local telephone company, and via this network, a connection is established between a mobile station and the telephone network.

From operation point of view [Oett-83], [Bell-79], a mobile cellular (or Mobile Station (MS)) initiating a call, must first select a cell. This is done by locking on the strongest control channel in its area, and therefore selecting the nearest cell. During an originated call from the MS, the MS would submit its request to the serving BS which transfers it to the MTSO. Using the identification number of the party to be called (attached with the request message sent from the MS), the MTSO scans the cells and the telephone network (via the PTSN) for a matching number. Once found, the MTSO assigns a voice channel, if one is available, to the calling MS and establishes a communication link with the contacted party. Figure 2.3 illustrates a more detailed procedure for link establishment of calls from and to the MS [Gibs3-97].

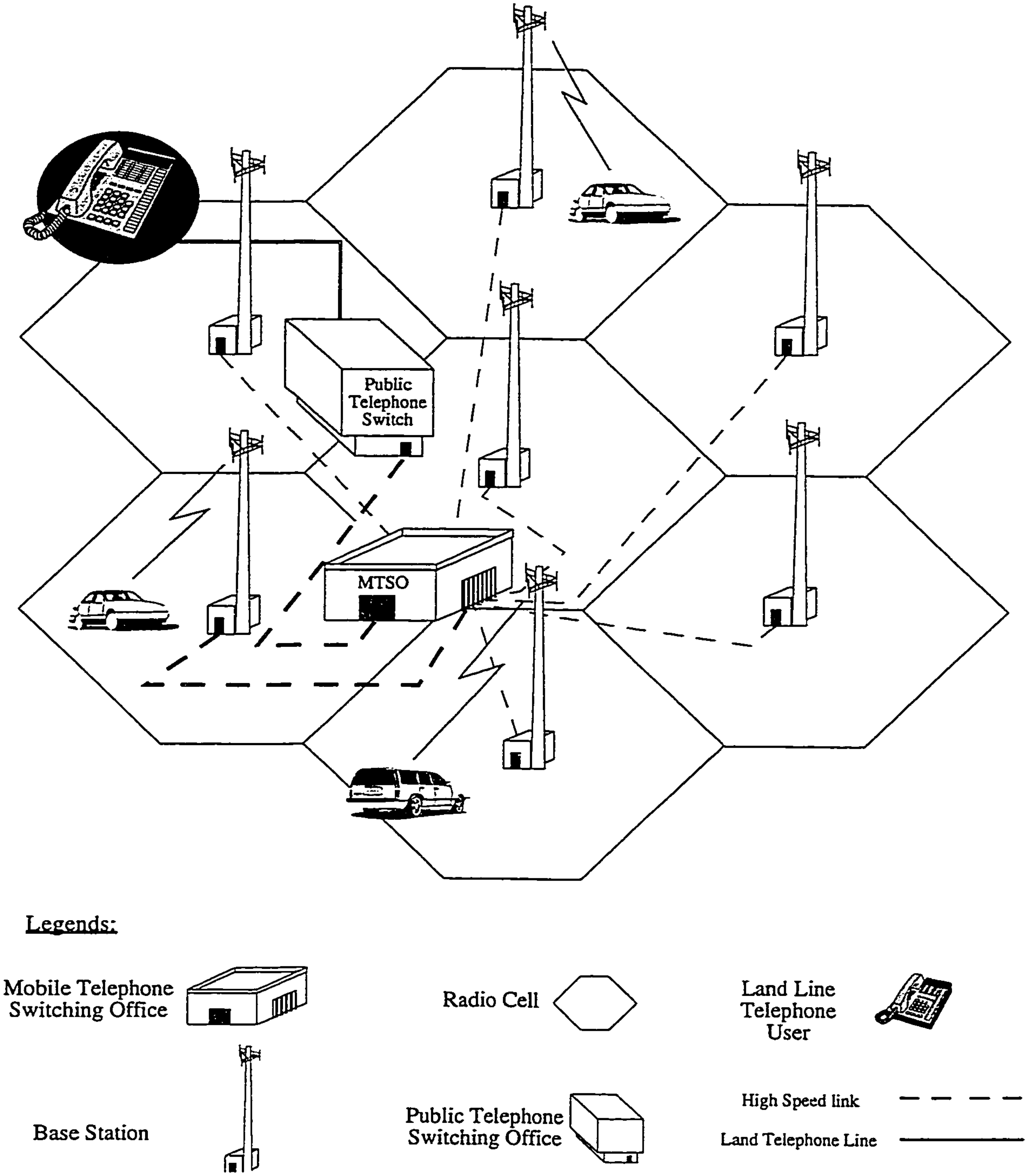


Figure 2.2: The Cellular Concept

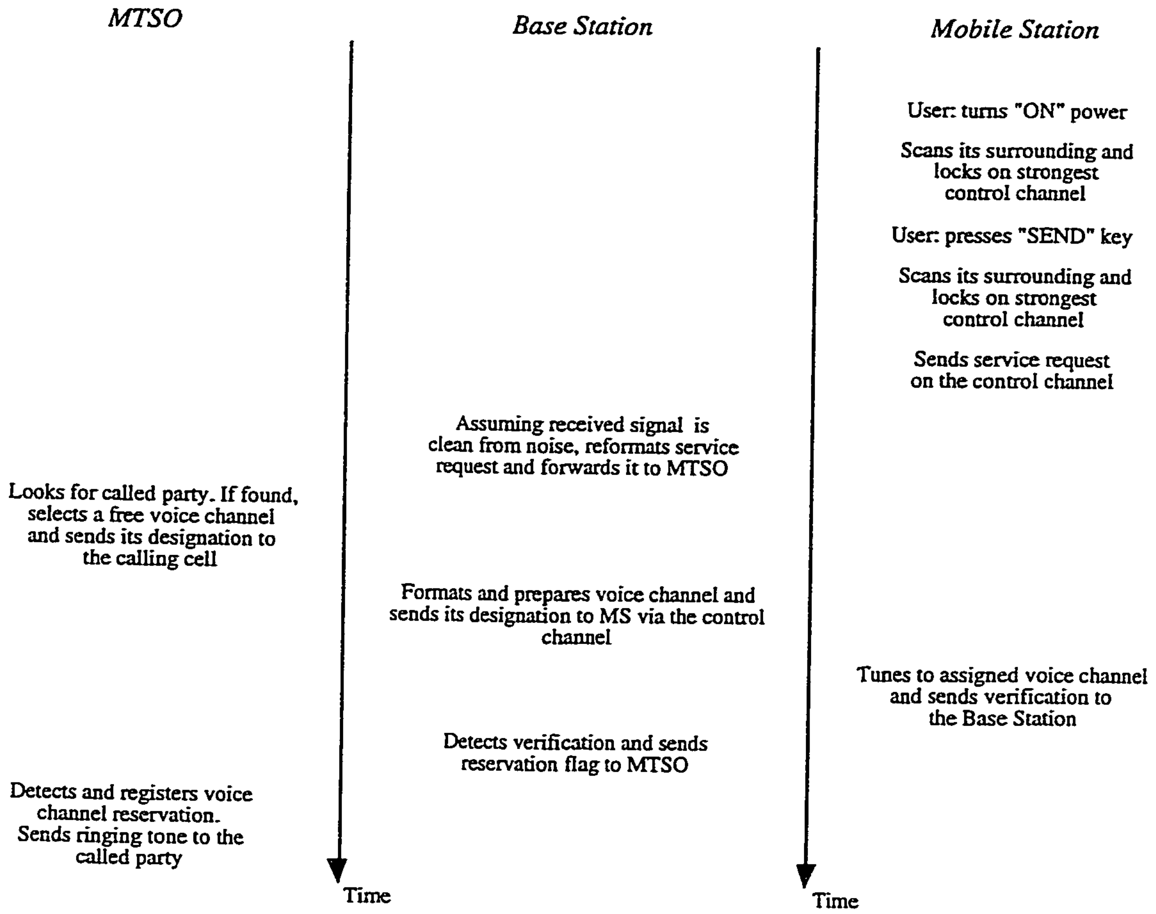


Figure 2.3-a: Establishing a link for an originated call from the MS

During the network originated calls, the land line party dials the MS unit phone number. The telephone company switching office recognizes that the number belongs to an MS and passes the call to the MTSO. The later sends a paging message to set of cell sites based on the MS identification number and a search algorithm using the last time that MS was detected in the network. Each BS broadcasts the paging message on its control channel and waits for a response from the MS. The BS that receives an acknowledgment, informs the MTSO which then assigns a voice channel to the MS, and a communication link is established. Once the communication is terminated, the voice channel is freed by the MTSO and the MS resumes monitoring pages through the strongest control channel in its area.

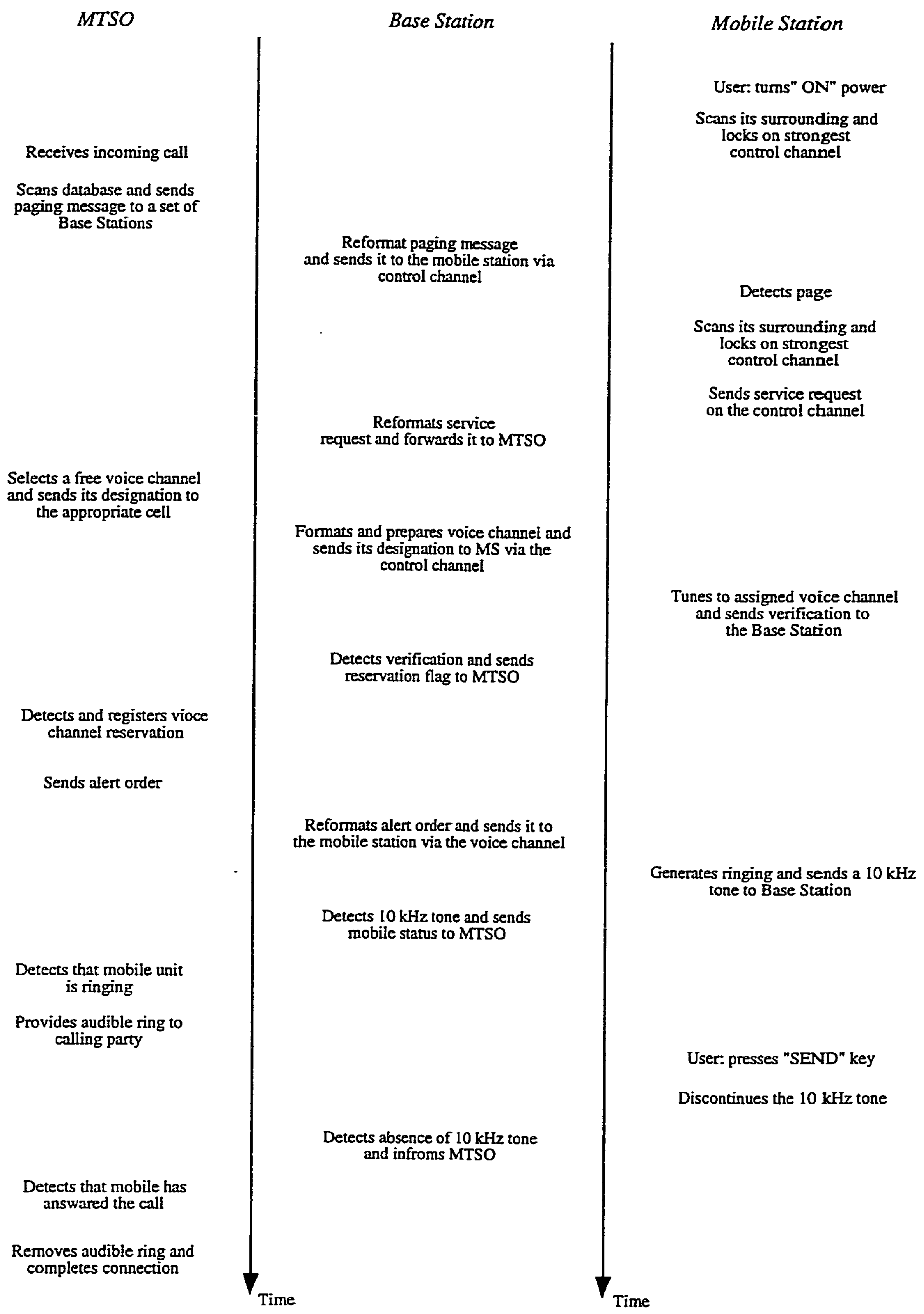


Figure 2.3-b: Establishing a link for a terminated call at the MS

In order to cover larger areas, a frequency reuse system must be incorporated among the cells. This can be achieved by allowing the same frequency to be used in different cells that are separated by a far enough distance to eliminate any radio interference. Figure 2.4 represents the concept of frequency reuse using seven different channel groups.

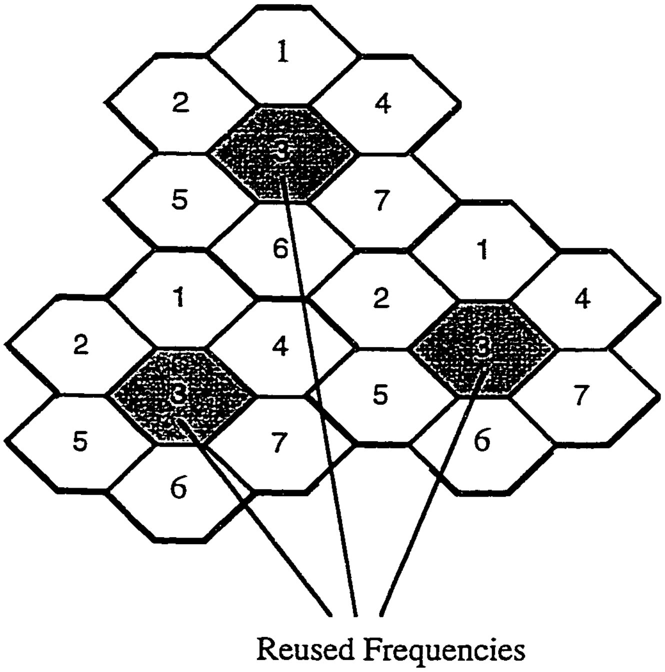


Figure 2.4: Frequency Reuse in a cellular system

A very common scenario occurs when an MS is involved in a voice communication with another party and crosses the boundaries of a cell entering a new one serviced by a new BS with a new set of channels and radio coverage. The new BS therefore sends a request to the MTSO to switch the call to a new frequency channel. This activity should be done without interrupting the user's discussion. This process is known as *handoff.* A simulation study was done to find the probability of requiring a handoff in a 16 kilometers cell while an MS moves randomly between 0 and 360 degrees and travels at a random speed between 8 and 96 kilometers per hour [Lee-83]. The chances of the MS reaching the cell boundary is then dependent on the call holding time. The results showed that for an average call holding time of 1.76 minutes, a handoff probability of 11.3 percent was found. Calls of longer duration are presented in table 2.1.

Table 2.1: Handoff probability in a 16 km cell [Lee-83]

Handoff Probability (percentage)	Call Duration Time (minutes)
11.3	1.76
18.0	3
42.6	6
59.3	9
90.6	25

2.2 History, Background and Evolution of Mobile Cellular Technology

In this section, we present a brief history on mobile communication and it evolution. Most of the information gathered here were extracted from [Gibs2-97].

Throughout history, man has always tried to find more efficient ways to communicate over long distance. Shouting was probably the very first method used to accomplish the task. Then, thoughts and ideas were carried further afield upon the invention of drums using a stretched animal skin; using different sounds and rhythms, more complex ideas were expressed. Light was another tool used for communication. The Greek historian Herodotus reported the use of the sunlight on a polished shield to transport information from one place to another. This method was adapted in 4000 BC all the way up to the nineteenth century. It was refined with the used of a moveable mirror controlled manually. This method of communication was known as a *heliograph* and was used heavily by the army until the invention of the telegraph which is today replaced by the wireless technology.

Fire was another method of communication over far distances and used by the British to spread the news of General Wellington's victory at the battle of Waterloo in 1815. The American Indians devised a system of communication with smoke signals.

Another method of communication was introduced in the early 1800s with the use of pigeons in the city. By putting a piece of paper containing a written message in a capsule and attach it to the bird's leg, the bird is released to fly back home. Buy using its own natural navigation system, the pigeon reaches its destination where the owner of the place would receive the message.

Until 1861, messages and mail were sent from town to town by messengers on horseback, by train and on Ships through the sea.

With the discovery of electricity in the late sixteenth century, it was found that static charges can travel over wires and produce an effect on some objects such as a feather placed at the other end of the line. In May 1844, the electric wire work was developed by Samuel Morse who demonstrated a useable telegraph system using a buried thirty-five miles wire length (running from Washington, D.C to Baltimore, Maryland). The successful transmission of the words "What God hath wrought" was done through a coding system which was later revised and called the *Morse code*. The first transcontinental telegraph line was put into operation in 1861. It was not until 1866 that a cable was installed across the Atlantic ocean and proven successful. Today, there are more than 400,000 miles of undersea cables laid in the oceans around the world.

Even though the telegraph was a successful breakthrough, it had major drawbacks regarding privacy and the availability of a third party individual to translate the Morse code into the local spoken/written language. It had become obvious that a voice communication method was needed. It was not until March, 1876, that Alexander Graham Bell has invented the telephone. Two years later, the first telephone switchboard was installed in New Haven, Connecticut, with thirty-eight subscribers.

About the same time frame, an Italian engineer, Guglielmo Marconi, was conducting a research with the aim to eliminate all the wires needed in the telegraph system. By the year 1895, he had managed to transmit the first wireless signal on record during a demonstration held out on Salisbury Plain in England. In 1897, Morse's code was able to be transmitted through the wireless technology. Seeing the possibilities in this new technology, voice was the next subject to be transmitted via wireless in 1902 by a system developed by Reginald Fessenden. From this point on, wireless communication started to develop and expand into longer distances and better quality.

In 1920, the first recorded mobile radiotelephone service was put into use by the Detroit Police Department. The devices used were known as walki-talkies. After further development, the service expanded in usage and was available for the general public to use for personal and business reasons in 1946. The system was built in St. Louis, United States of America, and installed by AT&T. The band of frequencies operating in the system was in the 150 MHz band. A limited number of channels were available, and all calls to and from mobile subscribers were routed through a special operator. The mobile units used a simplex channel (also referred to "push-to-talk") where the user push the "talk" button to speak through the device and must release it to listen to the other party. This action restricted the user from being able to listen or getting interrupted by the user at the other end of the communication line (a telephone or mobile radio user). One base station radio with high power was used per city in these systems.

After several improvements, AT&T introduced the Improved Mobile Telephone Service (IMTS) in 1964. Now the mobile telephone user can directly get linked to the other end of the line user without the intervention of an operator, and the communication channel is automatically selected by the serving BS. The mobile unit access request delay was also reduced.

With the increasing rate of automobile usage and growing cities populations, the mobile telephone demand became drastically large for business and personal use. This created a lack of available radio frequencies, and a need for higher channel capacity. In 1974, the FCC came out with an allocation of 40 MHz of the 800 MHz band for the commercial cellular radiotelephone system. By 1978, after a remarkable improvement in the cellular technology, the first cellular telephone system, named Advanced Mobile Phone Service (AMPS), was installed in the United States of America, city of Chicago by AT&T, and began operation with test sample subscribers from the business community in that area. The system consisted of ten cells and covered 21,000 square miles, and operated on the 40 MHz of the 800 MHz band. Even though it is not the ideal frequency band for a cellular mobile system, it has been demonstrated that, without exceeding the 800 MHz band, the system can be deployed [Blec-80], [MacD-79].A central computer and switching office was installed to establish the connection of the mobile radios with the telephone network. After the successful operation and minor changes in the system, AMPS was declared to be the analog cellular standard used in North-America. With an increased interest in wireless and mobile communication, by the year 1992, other analog cellular standards were developed and used around the world. Table 2.2 shows some of the popular standards with the different frequency bands and countries in which it is used [Redl-95].

Table 2.2 : Analog Cellular Standards

Standard	Some countries using the Standard
AMPS	United States, Canada, Mexico, Brazil, Argentina, Australia, New Zealand, Taiwan, South Korea, Hong Kong, Thailand
TACS	United Kingdom, Ireland, Spain, Italy, Austria, United Arab Emirates, Kuwait
NMT	Denmark, Finland, Austria, France, Hungary, Spain, Turkey, Switzerland

With the introduction of the Very Large Scale Integrated (VLSI) circuits technology, a large number of functions were built in one transistor chip. This feature allowed manufactures to provide smaller and lighter mobile units and base stations with lower costs and more features. With a rapidly growing market in technology and personal businesses during the 1990's, the popularity of mobile communications became visibly noticed and under high demand. This has put the AMPS under pressure for higher frequency spectrum space and higher quality and better service. With the introduction of digital communication, a new cellular system was put in place operating on the 1900 MHz frequency band with a fully digital operation. The system was previously developed in Europe and was known as GSM (or Global System for Mobile use). GSM technology had proven to be effective in Europe and in other countries having the credibility of probably becoming the international cellular standard in the future. This will create the facility for the subscriber to use the same handset anywhere in the world. Being fully digital, the service offered lighter handsets, a more robust network [Bell-82], an intelligent and flexible system [Smit-85] and more security and privacy. The first PCS system in the United States was installed in Washington/Baltimore area with 300 cells, and came on line in 1995. With its success, other digital mobile cellular standard were being studied in north-America. This lead to the formation of the *dual-mode* AMPS (D-AMPS) standard which is also known as IS-54 (Interim Standard) or the *North American Digital Standard* (NADS). IS-54 was later updated to support more features which led to a new standard known as the IS-136 standard in late 1994.

Another North American dual-mode digital technology has evolved and was published as a standard in 1993. It was known as the *Code Division Multiple Access* (CDMA) system, or IS-95 system.

In the japanese market, a Japanese digital system was developed and published as a standard called the *Japanese Digital Cellular* (JDC) or *Personal Digital Cellular* (PDC) system. This system was and add-on to the Japanese's analog systems in a manner almost identical to GSM, however, confined to Japan.

Another technology that is worth mentioning in the wireless communication systems is the paging systems which began to develop in the early 1930s. The first paging units would transmit an audible signal along with a digital telephone number for the pager holder to call. This one way communication tend to be slow but efficient in case of emergencies or getting in contact with an individual. Today, some of the paging systems have evolved to include short messages displayed on mini-screen attached to the pager. Pagers have been incorporated into wrist watches and laptops. This way the user is able to respond using the computer via the electronic mail facility. This type of paging has become known as two-way paging.

With the ever evolving technology of cellular radios, and the constantly dropping subscription price, we can easily see the cellular handset as an every-home high-tech unit in the future that provides safety and a constant contact with business associates and friends. Based on North American statistics of 1997 [Cons-97], table 2.3 shows the main three reasons people subscribe today for a cellular phone.

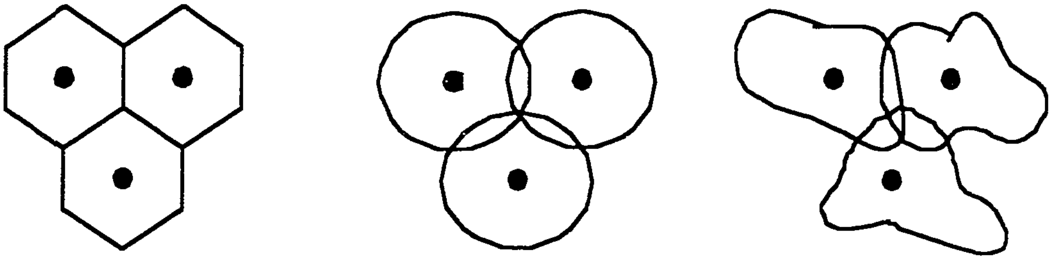
Table 2.3: Cellular Phone Purchase Reason [Cons-97]

Main Purchase Reason	Subscribers Percentage
Safety	45.3
Business use	34.3
Stay in touch with family and friends	20.6

In addition, gathered information in North America [Chic-97], [Comp-96], have shown that 90 percent of cellular phone sales were made in the analog systems and the rest in the digital with a 90 percent of total revenues generated in the United States while the rest was made in Canada and Mexico. In appendix A we present the leading manufacture companies of cellular and portable phones as well as some rough figures of the number of subscribers and cellular system type used in different countries around the world.

2.3 Mobile Cellular Telecommunications Systems

A basic cellular system, as shown in figure 2.2, consists of three major components: a mobile unit, a base station and a mobile telephone switching office. Hexagonal cells are used to represent the radio coverage for each BS. However, these shapes are artificial and cannot be generated in the real world. Engineers use hexagonal shapes over the idle circular ones to simplify design drawings. Figure 2.5 presents the fictitious, ideal and real shapes of radio coverage of a base station. Note the overlap section in the ideal and real shapes. These creates confusions in drawings. Depending on the geography surrounding the BS antenna, the radio coverage takes its shape considering obstacles and land curves.



Fictitious Hexagonal shape Ideal shape Real life shape

Figure 2.5: Shapes of coverage of a cells

Even though circular cells are desired to cover the maximum area possible, it is sometimes required to have *selective cells* of various shapes using a properly designed antenna. These cells are able to narrow the transmitted power into a certain region and exclude power from adjacent areas. Such antennas may be placed at the entrances of tunnels, on the edge of valleys, or at the ends of streets among large buildings. Figure 2.6 presents the most common selective coverage scheme where it is confined to 120 degrees sectors within the same cell. This process is also known as *cell splitting*. More elaboration on cell splitting will be presented at a later stage.

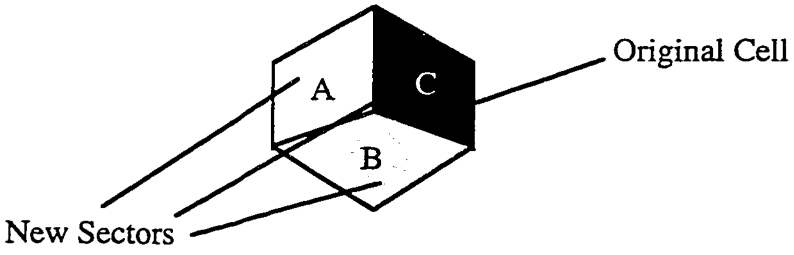


Figure 2.6: Cell splitting into three sectors using directional antenna

2.3.1 Radio Transmission Medium

Considering a single cell, let us present some of the theory regarding the radio transmission medium between the mobile and the base station.

In mobile transmission medium, four type of radio path are considered: the *Direct* path, the *Reflected* path, the *Diffracted* path, and the *Refracted* path. Figure 2.7 shows the difference between the three paths.

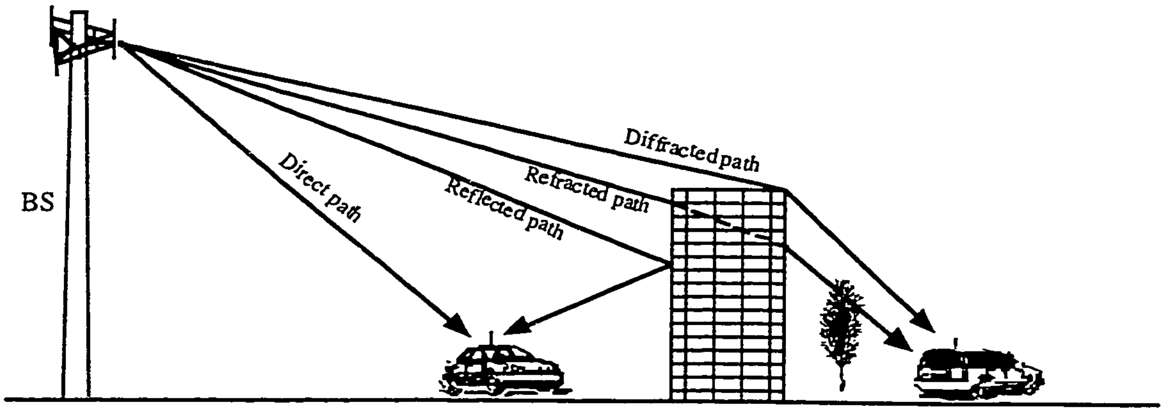


Figure 2.7: Radio transmission path

In any case, a radio signal transmitted over air, suffers of power loss which increases with distance. This is know as the propagation path loss. Considering an antenna height of 30 to 100 meters at the cell site and an MS antenna of 3 meters at a distance of 2 kilometers or further from the BS, it was found that the propagation path loss is of 40 dB/dec [Lee1-82], where "dec" is an abbreviation of *decade*, i.e., a period of 10. This statement simply means that a 40 dB loss of the signal will be observed by the MS as it moves from 1 to 10 km. The received carrier power can therefore be expressed as follows:

$$C = \alpha R^{-4}$$

where C = received carrier power
R = distance between transmitter and receiver
α = constant

A measure of power difference between two distances R_1 and R_2 can be expressed as

$$\frac{C_1}{C_2} = \left(\frac{R_2}{R_1}\right)^4$$

and in decibel

$$\Delta C = C_2 - C_1 = 10\log\left(\frac{C_2}{C_1}\right) = 40\log\left(\frac{R_1}{R_2}\right)$$

When $R_2 = 2R_1$, ΔC = -12 dB. When $R_2 = 10R_1$, ΔC = 40 dB. This 40 dB/dec general rule is easy to remember.

Other types of signal interference are caused by the environment in which the MS and BS are operating. This is known as noise and it can be generated from various sources. Some of the noises include the thermal noise which is proportional to the surrounding temperature and the signal bandwidth. It can be expressed as

$$N = kTB$$

where k = Boltzmann's constant

T = temperature of the surrounding in Kelvin

B = bandwidth (for voice it is equal to 40 kHz)

Other type of noise is the ignition noise which is generated by the vehicle [Spau-74], [Skom-78] and is basically considered only when the mobile cellular is operating in an automobile.

2.3.2 Cellular Network Structure

With the limited number of frequency channels assigned to a cellular system, only so many cells can be created each with a different set of channels. This must be done in order to avoid many users using the same channel in adjacent cells. The interference created from such an act is often referred to *cochannel interference.* Due to the high demand for cellular phone units in a system, a new strategy was developed in the use of the distribution of the frequency channels such that they can be used at the same time by different users. This concept is known as *frequency reuse* , and consist on assigning the same set of channels for tow cells that are separated by distance D large enough to avoid cochannel interference. This act increases the spectrum efficiency of the cellular system, however, if not properly designed, serious interference may occur. The frequency spectrum allocation is divided into K frequency reuse patterns that provides different distribution of the channels. Figure 2.8 shows the frequency reuse concept for K = 4, 7, and 12.

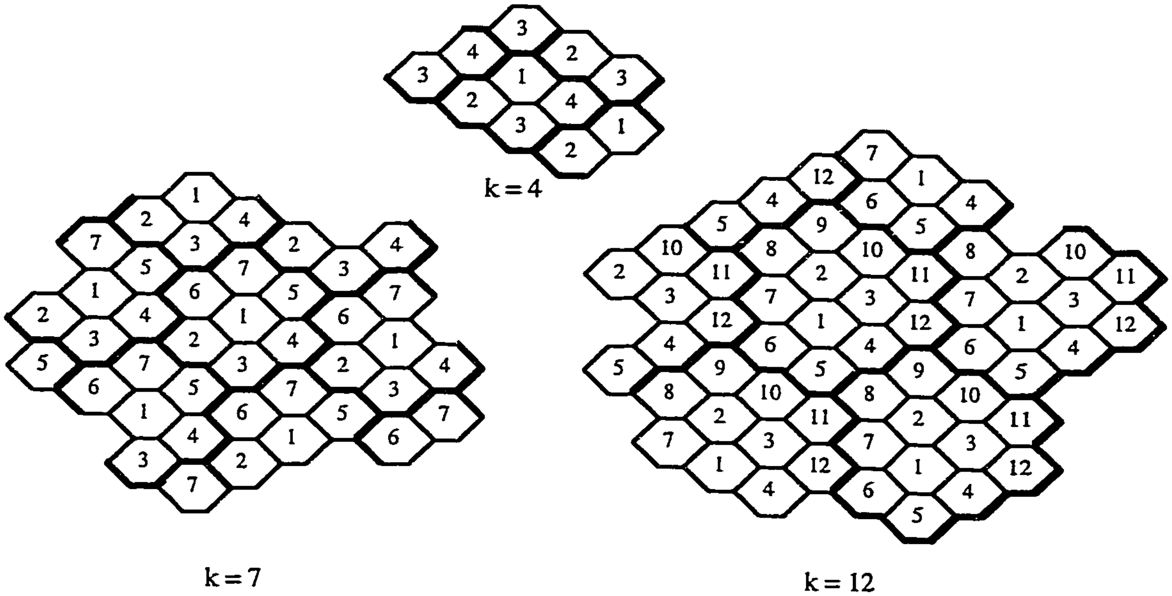


Figure 2.8: Frequency reuse concept

When designing the cellular system, a minimum distance between cells using the same frequencies is required in order to avoid cochannel interference. The distance will depend on the type of geographical contour, antenna height and other factors that will determine the coverage from the BS. Assuming all cells have the same radius in a system, it was determined [MacD-79], [Blec-80], [Bods-84], [Lee-86], that the frequency reuse distance can be found from

$$D = \sqrt{3K} \times R$$

where R is the cell radius and K the frequency reuse pattern as shown in figure 2.8. With this, one can generate the following for D:

$$D = \begin{cases} 3.46R & k = 4 \\ 4.6R & k = 6 \\ 6R & k = 12 \end{cases}$$

It is obvious that, the larger D is, the less cochannel interference is created. This requires larger values of K. However, having limited number of channels, large K implies less channels per cell which implies lower number of users in a cell to avoid congestion problems. Therefore, depending on the system criteria and the traffic load in the cell, the value of K is chosen.

A common method of determining the cochannel interference level is by using a parameter q defined as

$$q = \frac{D}{R}$$

The parameter q is knows as the *cochannel interference reduction factor* [Bell-71]. As q increases, the cochannel interference decreases providing better quality signal.

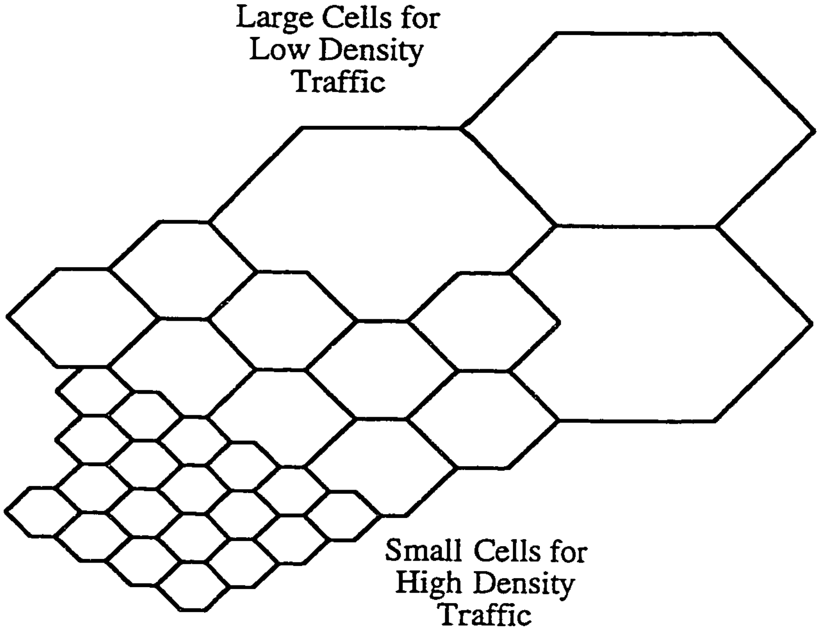


Figure 2.9: Cell Splitting example in a cellular area

Frequency reuse is one method of improving utilization of spectrum efficiency. As the number of subscribers increases, and the number frequency channels in a cell cannot handle enough MS calls, the original cell can be split into smaller cells of usually half the radius. This concept is known as *cell splitting*, and is used in high-density population areas. Figure 2.9 shows an example of this scenario.

Two common methods are used in splitting an existing cell. In the first method, the original cell is eliminated and four new cells of half the radius are created (see figure 2.10a). In the second method, the original cell is replaced with one of smaller coverage and six new cells are created forming a total of seven new cells of radius equals to half the original cell (see figure 2.10b).

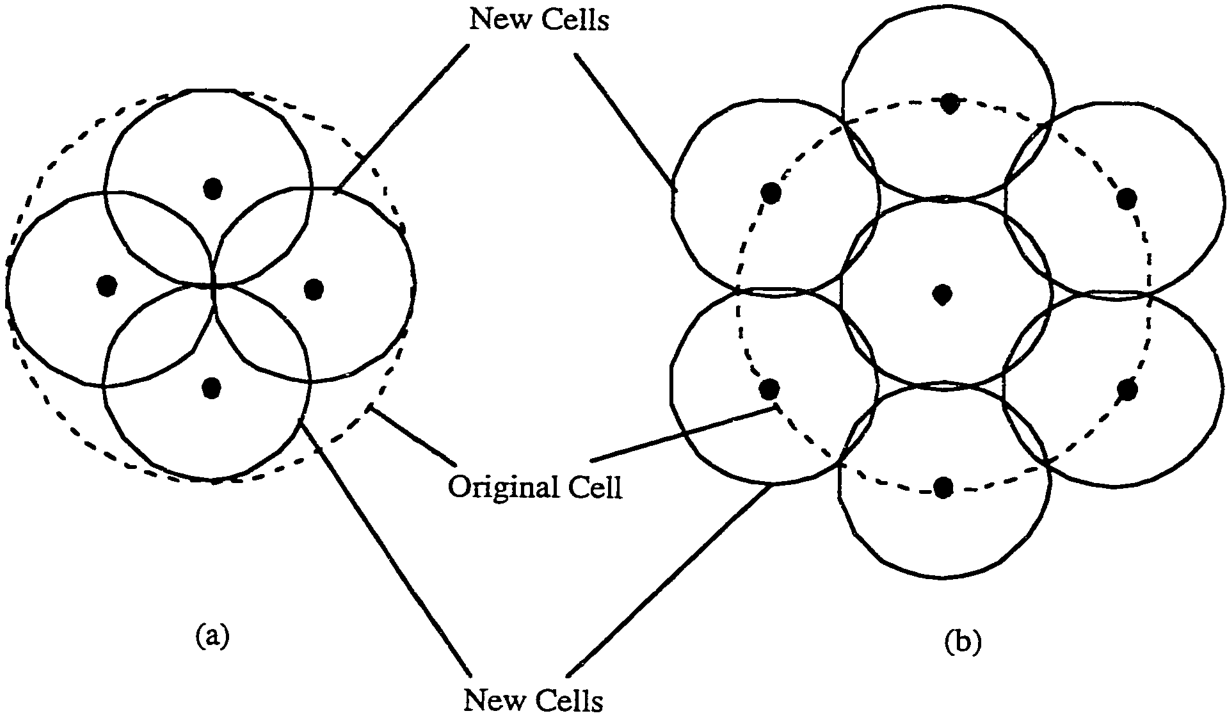


Figure 2.10: Cell splitting: (a) original cell not used; BS removed
(b) original cell reused; BS replaced

Having new cells of radius equals half the radius of the original cell, this leads the new cells to have quarter the area size of the original cell. Assuming that each new cell can handle the same maximum traffic load of the old cell, then, in theory, the new total traffic load per unit area becomes four times the maximum traffic load, if we consider the case in figure 2.10a, and seven times the maximum traffic load, if we consider the case in figure 2.10b.

A drawback in cell splitting is introduced when a mobile cellular is moving at high speed within the region of small cells. This is a common case on freeways crossing cities. This causes a large number of handoffs among the small cells and therefore an extra workload on the system. To avoid this problem, an *Umbrella Cell* is used where power is transmitted at a higher level than it is within the underlying microcells and at a different frequency. Figure 2.11 provides an illustration. A fast moving mobile is detected by the system based on the extensive amount of handoffs, and is handed over to the umbrella cell.

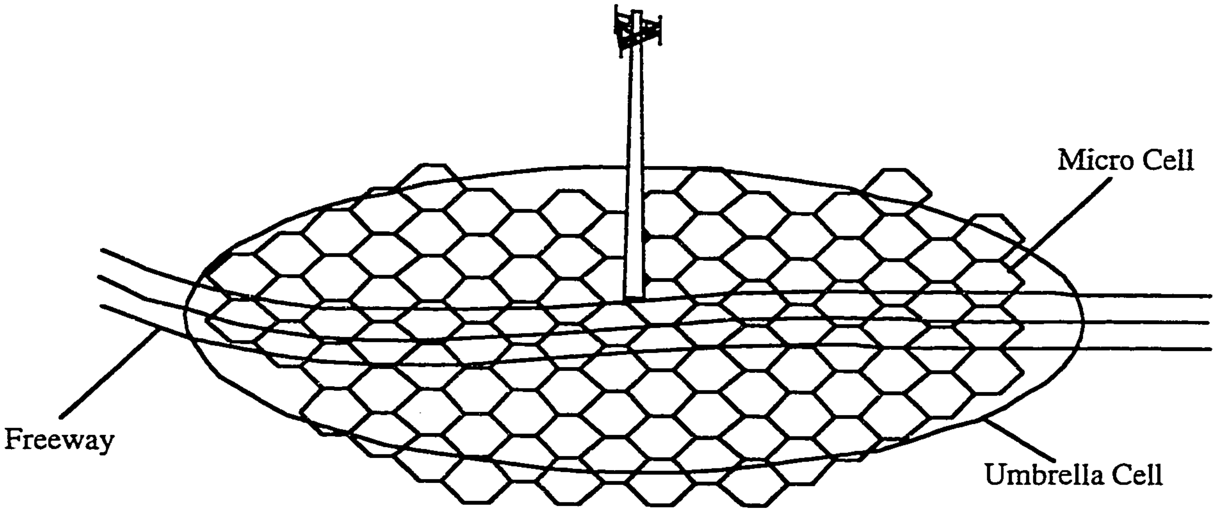


Figure 2.11: Umbrella Cell Illustration

In any cellular system, a frequency management and channel assignment schemes must be available. The frequency management consists of designating and numbering the control and voice channels. This is done by the government. The channel assignment takes care of the allocation of the channels to cells and MS's. A fixed channel assignment is done by assigning a set of channels to a cell, and this is done by the system designers. A temporary channel assignment is given to an MS during a call, and is done by the MTSO. In the overall system, the channel assignment should be based on causing the least interference in the system.

Even though each cell is assigned a set of channels, when a traffic load increases in a given cell, channel of adjacent cells can be shared and used as a short-term relief scheme, or borrowed and handied on a long term basis [Halp-83], [Huff- 85].

As mentioned before, it is the job of the system to ensure that no channel interference must occur when new channel sets are shared or borrowed. The interference can be the cause of using the same frequency channel in a near by cell, or the cause of using two different channels of close frequency levels.

With all the facilities described earlier to help increase the efficiency and capacity of the cellular system, some of the calls can still be blocked (dropped) due to the lack of channel resources in a given cell. Three types of blocking can occur: Set-up channel blockage, Voice channel blockage and End-office Trunk blockage.

The set-up channel blockage occurs at the MS when all the set-up channels (the control channels) in the current cell are being used by other subscribers. In this case the MS will follow the a multiple access control scheme well defined by the system in place. Some of the control schemes will allow the MS to retry after a random delay. We will be describing some of the popular multiple access control schemes further in the chapter.

The voice channel blockage occurs at the cell site by rejecting a call request from an MS when there is no voice channel available at the current time. Because voice channel has a larger holding time than the set-up channel, its blocking probability is usually higher. It is up to the cellular system designer to assign enough voice channels for a given cell.

The end-office trunk blockage usually occurs when the call traffic builds up in the trunks connecting the MTSO to the end-office, and the number of trunks becomes inadequate.

In a given system, the sum of all blockage types is considered as the blocking probability in the system. By determining the average holding time per call [Halp-76] and estimating the total number of calls per hour at a given site [Lee2-82], a good estimate of the number of MS units can be found for a pre-defined blocking probability. Studies have led to the generation of some look-up tables that define the number of MS's to meet a certain blocking probability [Lee-89].

2.4 Analog to Digital Transition

With the introduction of digital transmission in the first T-carrier system installed on a telephone trunk line [O'Nei-85], a new wave of data transmission was borne. The process of digital communication presented better speed, more accuracy and higher robustness where the message is converted into digital (or binary form in function of bits where a *bit* can take the value of 1 or 0, each represented by a voltage level) before being modulated then transmitted. This, has led many high-tech organizations to convert there direction towards digital communication by presenting more reliable and effective equipment in the wireline and wireless technology.

There are many methods for digitizing and modulating a message whether it is in the analog or digital form [Stal1-97][Couc-95][Hayk-94][Pear-92][Proa-94][Hayk1-89][Hira-79]. In today's mobile system architecture, many modulation techniques are proposed [Hira-79] [Comm-79][Jage-78][Mura-87][Chun-82][Pasu-79][Webe-78][Muro-81][Sund-83][Suzu-82][Akai-87][Gron-76][Asak-81]. Based on the performance requirements of a system, a modulation and digitization technique is selected at the design stage.

Digital data, having a simple representation with bits of values 1 and 0, provides better chances for the receiver to detect errors in the message, and some of the noise or interference added to the message can often be corrected. This act presents the primary advantage in digital communication and is known as the *regeneration* process of the original signal. A binary signal is regenerated in figure 2.12 with no impairments. If it was to be an analog signal, the human ear, in case of voice data, would recognize impurity but still understand the message. This is one of the ways to prove a better quality signals delivery in digital over analog communication.

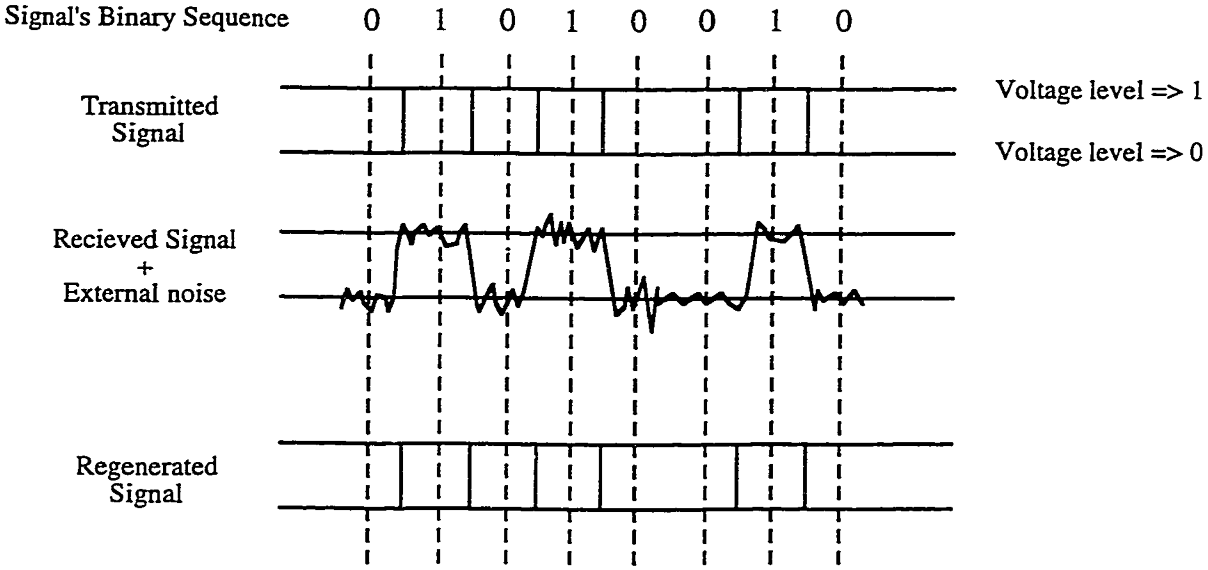


Figure 2.12: Digital signal regeneration after reception

Additionally, many techniques have been developed to detect and control errors introduced in the messages when transmitted over any media [Stal2-97], [Bert-92], [Comr-84] [Mabe-78]. Some of them involve retransmission of part of the data, others include error correction upon reception of the data.

Most wireline communication networks today are digital data oriented. With the introduction of digital cellular systems, data from the cellular radio can be easily transmitted over the networks and integrated with voice and video to present a much efficient use of resources. Along with the many advantages, digital technology offers cost reduction, lower power consumption, and lighter equipment. In mobile cellular systems, these features are highly desirable.

Nowadays, traveling has become a much more common act done by many individuals for business or personal reasons. With the need to be in touch 24 hours a day when traveling around the world, and with the evolving technology of today's fast growing market, a future vision of an international digital cellular system is highly desirable. This system is often referred to as Personal Communication Services or simply PCS. However, due to various political reasons, several digital cellular standards were defined and put in operation independently around the world creating incompatibility in MS operation: a cellular radio purchased in North America would not be operational in Europe. This stage of mobile cellular evolution introduced the second generation cellular systems. The main three standards used around the world today can be listed as:

- ADC American Digital Cellular; developed and used in North America as well as South America. Includes the IS-136 standard, and the IS-95 standard.
- GSM Global System for Mobile communication; developed and used in Europe
- JDC Japanese Digital Cellular

One of the main features in a cellular system is the interface between the MS and the cellular network. On the reverse link, this interface is represented with a well defined *Multiple Access Control* (MAC) protocol. Each of the standards listed above uses different MAC protocols to establish the MS/Wireless network interface to its best performance.

2.5 Multiple Access Schemes

It is no doubt that, in any communication system, the number of users exceed the number of available resources due to the fact that it is highly impossible to have all the users accessing the system at the same time. Such system is know as a *trunking system*. In such system, the users share the resources using a multiple access scheme through which, more than one user may access the system at the same time. This can be achieved by dividing the system into one or more of its operating domains: frequency, space, time or code. In a cellular system, the assigned frequency channels are the resources, and the MS's are the users.

In what follows, we present the concept behind subdividing the communication system in frequency, space, time and code domain creating four distinct multiple access schemes.

2.5.1 Frequency Division Multiple Access

In Frequency division multiple access (FDMA), a number of frequencies are assigned to the system for voice and control channels. Each frequency act as a single channel, and the channels are separated from each other by a certain frequency band to avoid interference. An MS requesting a system access, looks for a free control channel and transmits its request on it. Upon reception of the message at the MTSO, the MS is assigned a voice channel and is reserved for the whole duration of the conversation. If no voice channel is available, the incoming call from the MS is *blocked*, and the MS has to try at later time. Once the conversation is finished, the voice channel becomes available for other MS's in the system.

It is to note that no more than one MS can access the control channel given only one control channel is available per cell. In case where more than one user detect an idle control channel and send their requests, a *collision* occurs and both user's requests are lost and each MS must try again under according to some pre-defined rules.

2.5.2 Space Division Multiple Access

In Space Division Multiple Access (SDMA), more than one MS can use the same frequency channel simultaneously. This is achieved based on the frequency reuse concept described earlier: the same frequency channel is assigned in two different cells located far enough from each other to avoid cochannel interference.

Other methods are used to minimize the distance between the cells assigned the same frequency channels without violating the cochannel interference concerns. Such methods include the microcells technology where the coverage of the BS in the cell is very small, and selective cells where the cell is divided into sectors (120 or 60 degrees sectors) using directional antennas. The sector concept in a cell would concentrate the power of the BS into a certain region minimizing the cochannel interference with a nearby MS situated outside the sector.

With the use of SDMA, the efficiency and capacity of the cellular system increases substantially.

2.5.3 Time Division Multiple Access

Time Division Multiple Access (TDMA) is one of the most popular and widely used multiple access schemes in communication networks today. The basic concept behind TDMA is to subdivide the time axis into time slots. A group of time slots would represent a time frame which is repeated periodically. Figure 2.13 illustrates a TDMA frame structure. During connection set up time, each user is assigned one or more time slots in the time frame. The binary data for a given user is then transmitted on the assigned time slots. A message that does not fit in one time slot is subdivided into smaller sections known as *packets.* The packets are then sent over several time frames, and re-assembled at the receiver site to reconstruct the whole message. Most likely, it is desired to fit a message in a single time slot. However, depending on the operating system requirements, the message length may not be fixed and often requiring more than one time slot for transmission, therefore, more than one slot have to be assigned per user.

In addition, it is important to note that, given that users must transmit in specific time slots, all the users must be synchronized to know at what time they should transmit and for how long.

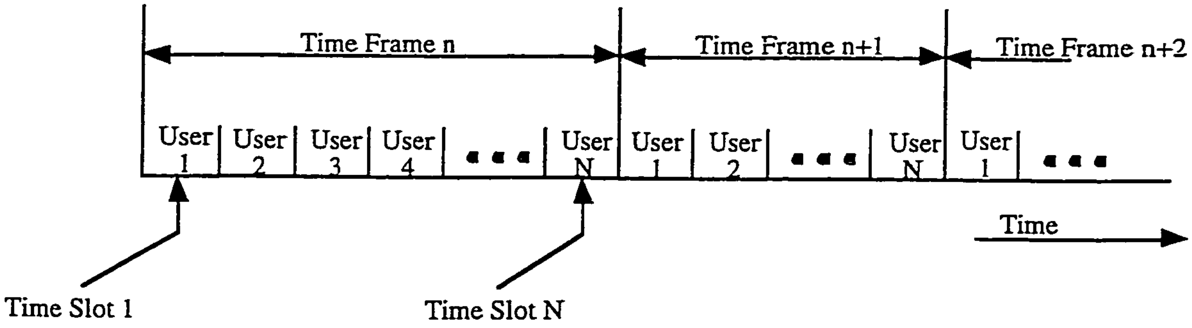


Figure 2.13: TDMA Frame Structure

In a digital cellular radio system, the voice is transformed into binary format. On a single frequency, TDMA scheme is applied creating a time frame in which a time slot is considered a channel. The system therefore, can support more than one user on a single frequency channel, each using one or more time slots to transmit digital voice messages. However, being voice data, the number of slots in a time frame cannot be extended to match the total number of users in a given system. Otherwise, the data will experience significant amount of delay when several frames are used in a conversation.

To increase the system capacity, TDMA is often overlaid on top of an FDMA structure. This is implemented by applying the TDMA scheme for each frequency channel assigned for the cell creating subchannels for each voice channel available. As an example, given a radio cell with 311 frequency voice channels, by applying the TDMA scheme, a time frame of slots can be created. This scenario results in a TDMA system carrying five voice channels per carrier which increases the original system capacity by a factor of five. Figure 2.14 illustrates the situation and the overlaying of TDMA on top of FDMA.

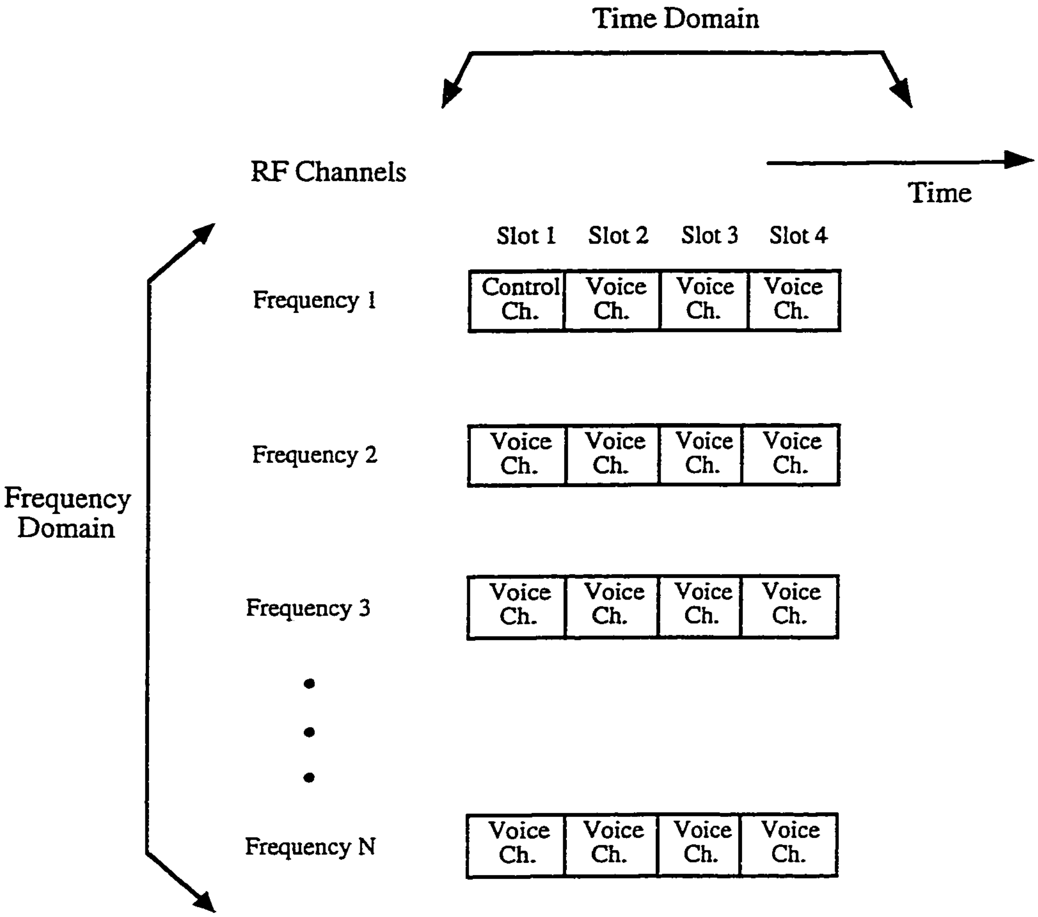


Figure 2.14: TDMA architecture in Digital Cellular System

2.5.4 Code Division Multiple Access

A detailed description of the Code Division Multiple Access (CDMA) scheme can found in [Salm-91] and [Qual-89].

In CDMA, the transmission is based on the spread spectrum concept. Many references can elaborate in more detail about the history and concept of spread spectrum ([Simo-85] [Cook-83] [Pick-82] [Scho-77]), but the main idea is that a communication link is established by using a set of frequencies instead of a single one. Frequency Hopping Spread Spectrum (FHSS) is an excellent example used in military applications where the message is broken into several bursts. Each burst is sent on a different frequency channel based on some pre-defined rule. Given that the enemy may jam some of frequencies, some of the bursts will be lost but most of them will reach the receiver. In order to recover the message correctly, the receiver should be aware of the rules of transmission in terms of frequencies used and in the order with the bursts. [Stal4-97], [Calh-88] and [Dixo-84] are good references on FHSS.

Many valuable advantages for spread spectrum transmission over traditional TDMA or FDMA can be found. The main ones are frequency diversity, noise robustness, low probability of interference and line privacy. However, a drawback in this technology comes in the complexity of the transmitter and receiver design.

For CDMA, all users are set to the same set of frequency channels. Instead of separating the users in time slots as it is done in the TDMA, each user is accompanied by a user-specific high speed code (created as a pseudo random binary sequence) that is superimposed on top of the modulation stage.

In figure 2.15, we present an example of one CDMA channel with two users. Each user sends a 4 bit message using a unique user key. First, the message is added (XOR logic operation) with the key of the user to generate the signals "A" and "B". Because both users are transmitting on the same channel, the *composite* signal will hold the addition of the two signals.

At the receiver end, to decode the message, say of user A, the composite signal is multiplied by the key of the user A. The result is then integrated and therefore generating a new waveform. At the end of every six key bit times, the sign of the waveform is tested. The reading of the sign is the inverse of the original binary data. If the wrong key is used, the wrong output is generated and the result of the decoder would tend to an average of zero volts.

It can be noted that, in order for this concept to work, accurate timing and synchronization are absolutely critical. Non accurate synchronization would result in an error factor that is usually measured with the Signal to Noise ratio. This accuracy requirement adds in the complexity of the system components design.

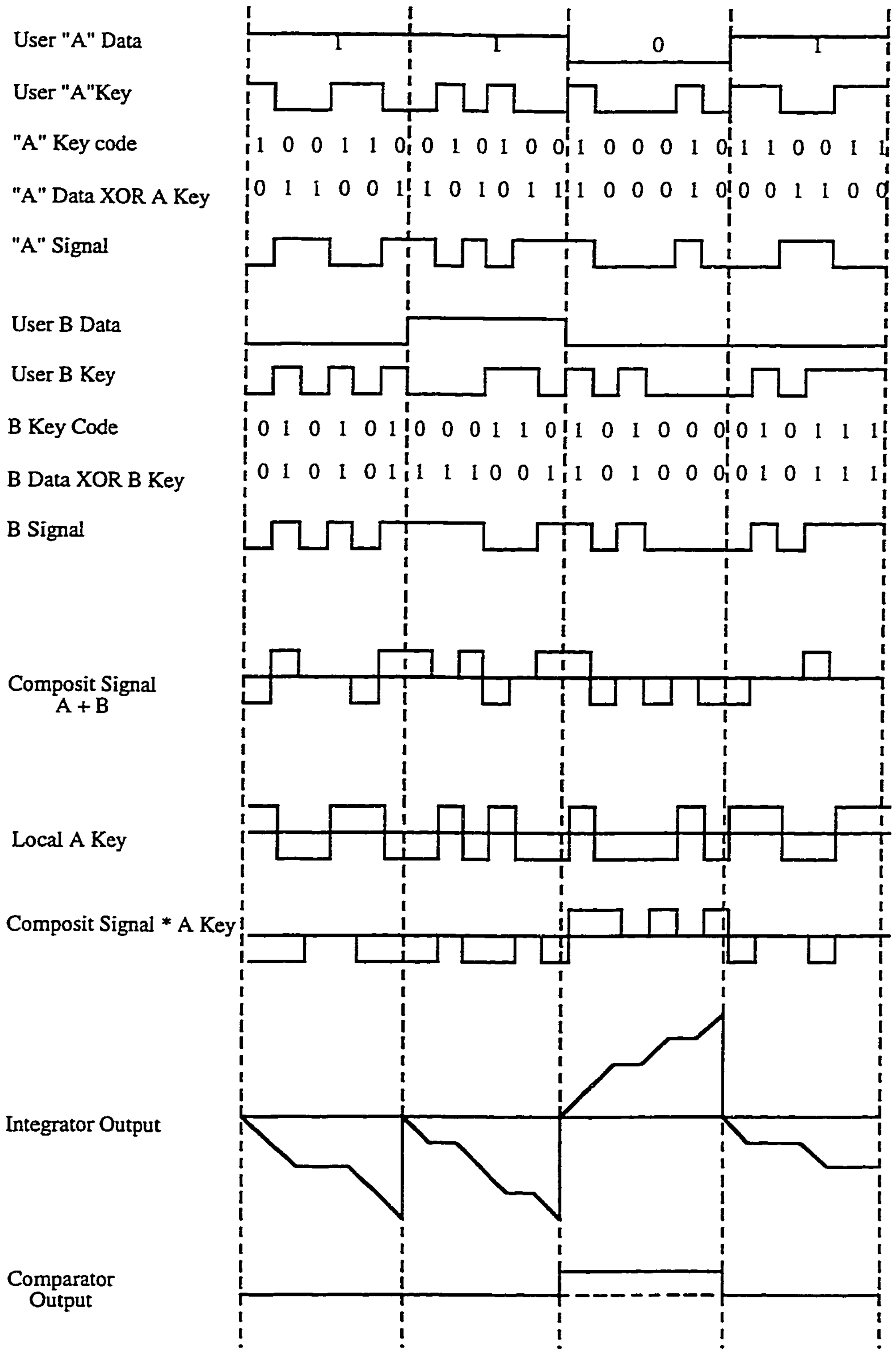


Figure 2.15: CDMA concept and operation with two channels

CHAPTER 3

IS-136-DCCH A North-American Standard for Mobile Cellular Services

3.0 Introduction

The idea of exchanging information at anytime anywhere with anyone on the planet is getting closer to become reality. A North-American standard, and currently being implemented in South America, is currently under improvements with the objective to serve and help reach this goal. The standard referred to is the IS-136 Standard [IS-1STD].

The performance of the IS-136 Digital Control Channel (DCCH) has been chosen to be evaluated in this thesis. In the current chapter, we describe the DCCH and its operation by first presenting the overall system, then move on to describe in particular the main features that will be evaluated in the upcoming chapters.

3.1 IS-136-Digital Control Channel

The Digital Control Channel (DCCH) is composed of a set of logical channels implemented in a Time Division Multiplexing Access (TDMA) scheme. These channels are mainly used for call set-up, information broadcast to all MS's in a given radio cell, and other features that we will cover in this chapter. Note that, it is the responsibility of the MTSO to manage the voice channel pool assigned to a cell. In the case that an MS requires to place a call, an access attempt message is originated from the MS and sent on the DCCH to the BS serving the cell area. After successfully receiving the request message, the MTSO establishes the connection with the called party and assigns a voice channel to the MS.

In addition to voice, a Short Message Service (SMS) was added to IS-136 and is currently fully supported on DCCH allowing the transfer and reception of short text messages.

3.1.1 Logical Channels Definition

Being a TDMA-based system, the IS-136 DCCH channel access mechanism is divided into time frames which in turn are subdivided into a set of logical channels. Figure 3.1 shows the set of the logical channels and their relationship with respect to the Forward (Down-Link) and Reverse (Up-Link) Digital Control Channels.

The reverse DCCH (RDCCH) represents the uplink (MS to BS), and consists of a Random Access Channel (RACH) used by all the MS's serviced under the same BS to send access attempt messages and short messages to the MTSO. The RACH is also used to carry messages from the MS's responding to pages and other signals from the wireless system. The forward DCCH (FDCCH) represents the down-link (BS to MS) in the system, and it is used to deliver messages from the MTSO to the MS's within the coverage area of the serving BS.

Being a control channel, where information about the system configuration and rules for mobile system access are transferred, a Broadcast Control Channel (BCCH) is used for the purpose of broadcasting information to all mobiles within the reach of the BS, MSC and Interworking Function (BMI) unit. Given that the broadcasted information does not share the same level of priority and importance, the BCCH is divided into a fast BCCH (F-BCCH), where the frequently updated information is repeated in every superframe (a superframe is one cycle composed of time slots on the TDMA scheme. Each logical channel is allocated to a portion of the superframe. More details on the superframe structure will be given later), and an extended BCCH (E-BCCH) where other type of information may span over several superframes. The Short Message Service Broadcast Control Channel (S-BCCH) is used to broadcast information regarding the SMS service (S-BCCH is still under development at the time of writing).

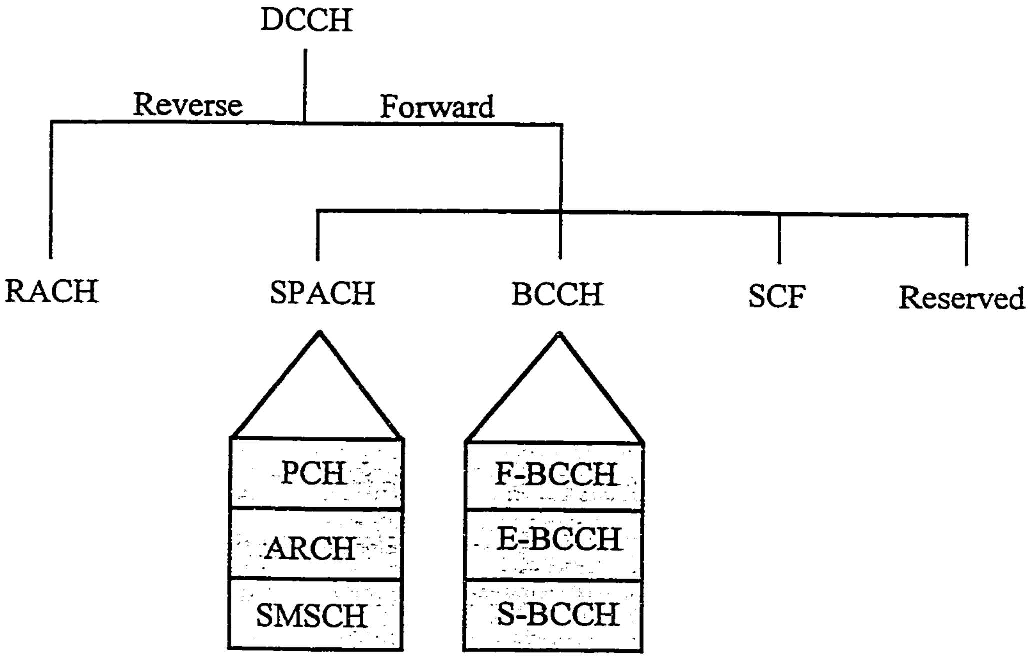


Figure 3.1: IS-136 DCCH Logical Channels

The BCCH is placed at the beginning of the superframe. The other slots are assigned to the SMS, Point-to-Point, Paging and Access Response Channel (SPACH) which consists of the Paging, Access Response and SMS logical channels (PCH, ARCH and SMSCH respectively). The main purpose of PCH is to transfer paging messages originated at the MTSO to a specific MS located under the coverage of the current BMI.

ARCH is used to transfer access response from the BMI to the MS. One type of messages supported on the ARCH would be an acknowledgment for an access attempt message originated from the MS.

SMSCH is used to deliver short text messages and other related signals from the BMI to an MS being serviced in its area.

All three subsets of the SPACH presented above have the attributes of being unidirectional (down-link), point-to-point and shared subchannels.

The Shared Channel Feedback (SCF) is used to support the RACH operation. It is used to provide feedback on the RACH status to all MS's in the current cell. Such feedback includes the RACH subchannels status (the subchannel is Busy, Reserved or Idle), acknowledgment of transmitted message fragments by the MS (burst Received or Not Received) and identification code of the MS that has sent the message fragment.

The reserved channel under the forward DCCH is being reserved for future use.

In what follows, we present in more depth the structure and operation of the forward and reverse digital control channels (FDCCH, RDCCH).

3.2 DCCH Structure

The DCCH structure is better represented in three data layers corresponding to the lower layers of the OSI model. Figure 3.2 shows the message mapping in the forward DCCH through all the three layers. A layer 3 message added with Layer 2 overhead composes a Layer 2 frame which is transferred into a 6.7 ms duration TDMA slot at the physical layer. A TDMA frame is set to be composed of two TDMA Blocks (20 ms each) each consisting of three TDMA slots. As it can be seen from figure 3.2, and as defined by the standard [IS-1STD], only the first slot in a TDMA block is used to carry data on DCCH. The other two are left for other usage. This property also applies in the reverse link. To simplify representation and text reading, we will sometimes refer to the TDMA block as a *slot*. With this convention we say that a Superframe is composed of 32 slots, with each slot having a 20 milli-seconds duration and a unique Superframe Phase (SFP) as depicted in figure 3.2

In what follows, we describe the operation of the three layers. We pay special attention to the random access channel characteristics and operation.

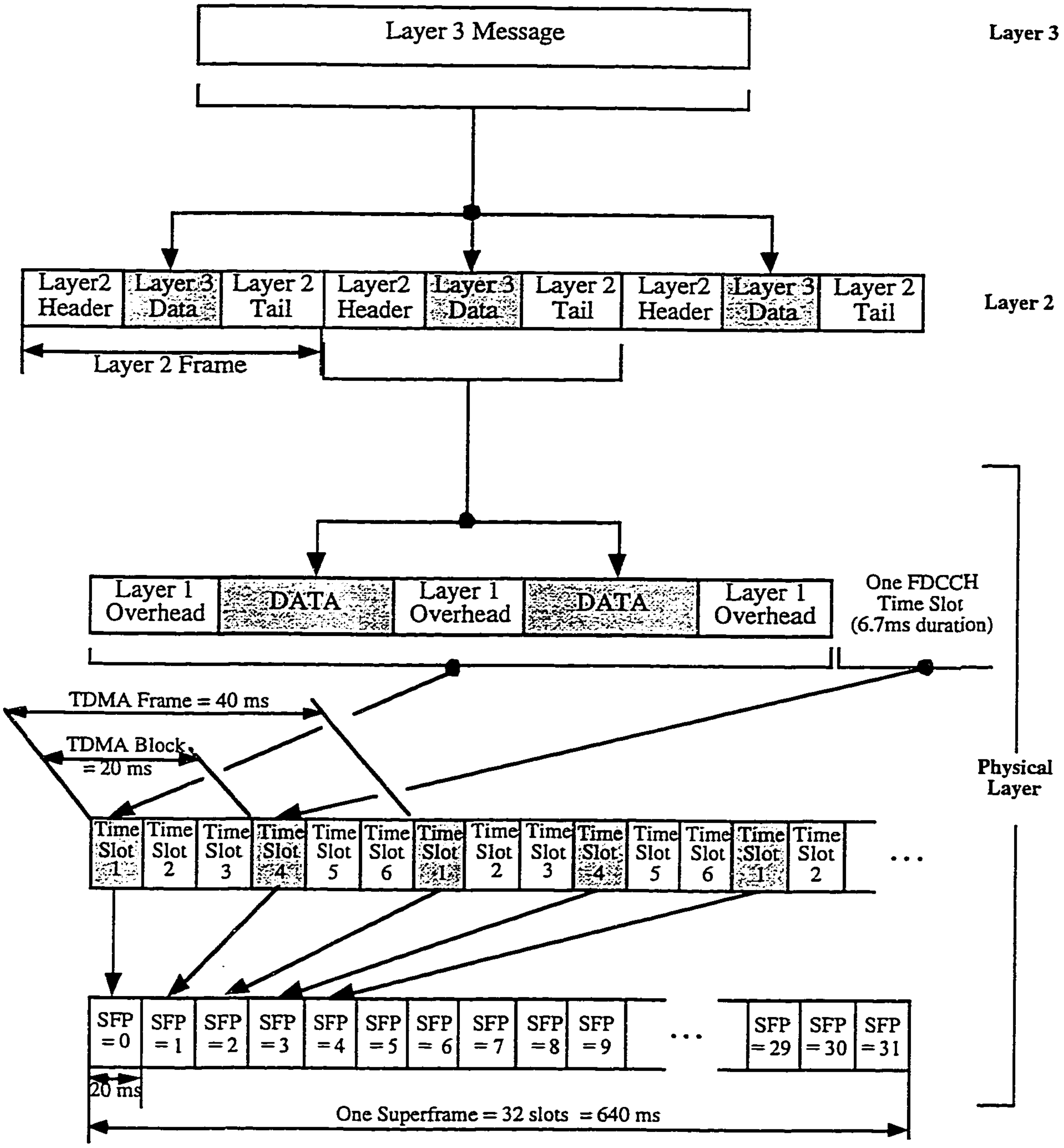


Figure 3.2: FDCCH Message Mapping

3.3 Layer 1 Operation (Physical Layer)

3.3.1 Forward Digital Control Channel

As it was mentioned previously, a message sent on the FDCCH is mapped into the physical layer and transported on a TDMA superframe composed of 32 DCCH slots (or 32 TDMA blocks). A more detailed format of the TDMA frame is presented in figure 3.3.

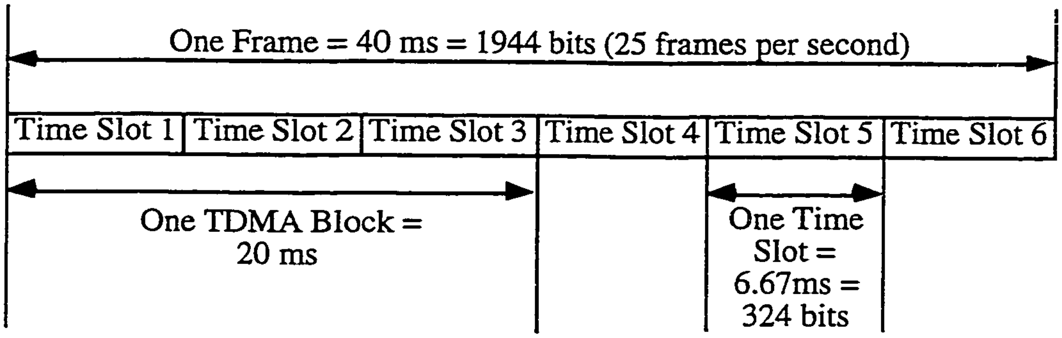
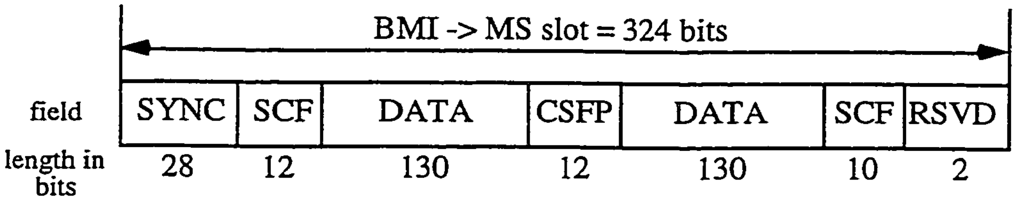


Figure 3.3: TDMA Frame Structure

The TDMA frame is composed of two TDMA blocks, each consisting of three time slots. Each time slot holds 324 bits and has a duration of 6.67 milli-seconds. This leads to a TDMA frame holding 1944 bits and having a 40 milli-seconds duration.

In figure 3.4, the structure of an FDCCH time slot is presented. The bit position of the forward slots/bursts are numbered sequentially from 1 to 324. The first transmitted bit of the SYNC has bit position equals to 1, and the last bit of the RSVD has bit position equals to 324.



field	SYNC	SCF	DATA	CSFP	DATA	SCF	RSVD
length in bits	28	12	130	12	130	10	2

Figure 3.4: FDCCH time slot format (BS to MS)

The SYNC field in the slot consists of 28 bits and is added at the Physical layer and contains information for synchronization purposes.

The SCF field consists of 22 bits distributed in two sections of the slot, and is assimilated at the Physical layer (Layer 1). The field is used to provide feedback to the MS in the cell. The field is comprised of three fields: BRI, R/N and CPE. The BRI (Busy/Reserved/Idle) field is composed of 6 bits used for indicating the status of the current RACH subchannel. The coding of the flag is shown in table 3.1. The R/N (Received/Not-Received) field consists of 5 bits indicating the success or failure of reception at the BMI of a burst previously transmitted by the MS reading the SCF. The coding of the flag into the FDCCH is shown in table 3.2. The CPE (Coded Partial Echo) field occupies 11 bits and holds an abbreviated form of the MS identification number. The CPE is read by the MS after sending a message fragment (or burst) on the RACH in order to make sure that the acknowledgment from the BMI is referring to its transmission status: by comparing the CPE and its identification number, the MS determines if the current SCF is being directed to it.

Being added at the physical layer, the SCF flag is sent on each DCCH slot which adds flexibility to the system by allowing all serviced MS's to get a continuous channel status update of the RACH subchannels read before initiating an access. A more detailed description on the MS reverse channel access mechanism is provided in later sections.

Table 3.1: Bit Mapping and coding of the BRI flag.

	BRI Field					
Channel Status	**BRI5**	**BRI4**	**BRI3**	**BRI2**	**BRI1**	**BRI0**
Busy	1	1	1	1	0	0
Reserved	0	0	1	1	1	1
Idle	0	0	0	0	0	0

The DATA field of the time slot is 260 bits in length and consists of the user data bits (coded information bits) that are mapped from Layer 2 into the DATA field of Layer 1 (Figure 3.2).

Table 3.2: Bit Mapping and coding of the R/N flag.

	R/N Field				
Transmission Status	**R/N4**	**R/N3**	**R/N2**	**R/N1**	**R/N0**
Received	1	1	1	1	1
Not Received	0	0	0	0	0

The CSFP (Coded Superframe Phase) field is 12 bits long and is used to provide information regarding the SFP (superframe phase. See figure 3.2) so that the MS's can identify the beginning of the superframe. The CSFP is added at the physical layer, and therefore accessed by an MS at every DCCH slot of the superframe. The RSVD (Reserved) field of the time slot occupies two bits that are set to "11", and is defined for future use.

In figure 3.5, we present the format of a superframe in the down-link (Forward Digital Control Channel). Each superframe is comprised of an ordered sequence of the DCCH logical channels presented in figure 3.1. The superframe length is 32 slots (or TDMA Blocks) in a full-rate DCCH and 16 slots in a half-rated DCCH. The number of slots designated for each of the logical channels is defined during system set-up stage depending on the system status, for instance, the MS population to be supported with optimum system operation. Table 3.3 [IS-1STD] lay down the options and limits for the logic channels assignment on the superframe. Regardless of the number of possibilities in table 3.3, the total number of slots should always match the length of the superframe in the half or full rate DCCH.

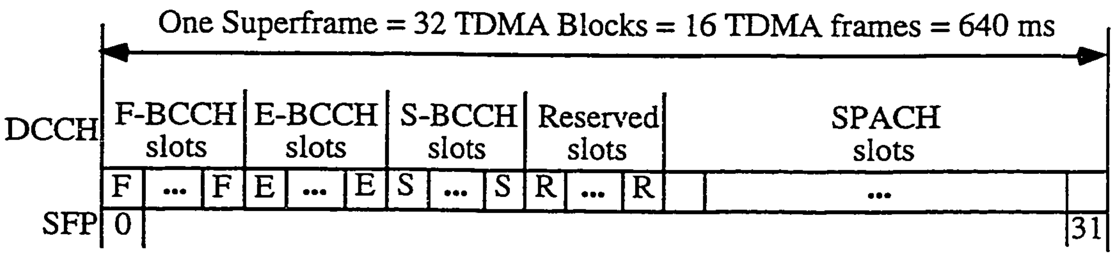


Figure 3.5: Superframe Structure

The Superframe Phase (SFP) increments by one at every slot starting with 0 at the first slot of the F-BCCH of the superframe and ending with the value 31 at the last SPACH slot of the superframe on a full-rate DCCH. On a half-rate DCCH, only the slots with even SFP numbers are used and therefore the superframe will consist of 16 usable DCCH slots.

Table 3.3: Logical channel slots distribution in an FDCCH Superframe

	Full-Rate DCCH		**Half-Rate DCCH**	
Superframe Field	**Min**	**Max**	**Min**	**Max**
F-BCCH	3	10	3	10
E-BCCH	1	8	1	8
S-BCCH	0	15	0	11
Reserved	0	7	0	7
SPACH	2	28	2	12

Combining two superframe cycles lead to the generation of a new term in IS-136 known by a Hyperframe. The hyperframe structure is presented in figure 3.6. In an FDCCH, a hyperframe is composed of two sequential superframes: one primary and the other secondary. The same distribution of logical channels highlighted in figure 3.5 applies for the primary and secondary superframes.

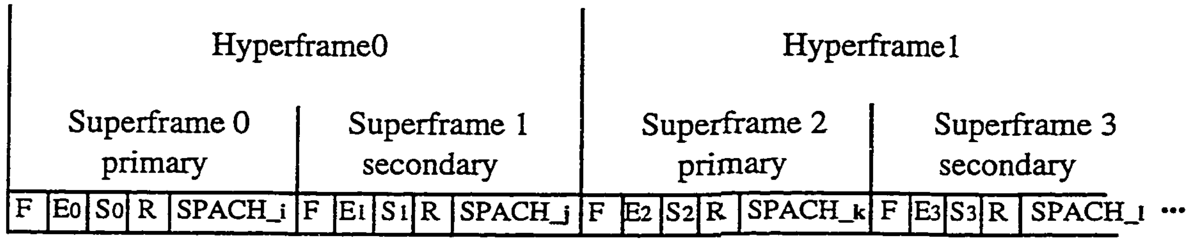


Figure 3.6: Hyperframe Structure

As noted earlier in this chapter (figure 3.1), paging, access response and short messages are transmitted on the SPACH. For notation and terminology sake, each slot of the SPACH is often referred to as a "subchannel" of a given type depending on the type of the message it is holding, for instance in the case of a paging message, it is referred as a PCH subchannel. The subchannel number is the same as the SFP presented in figure 3.5. One of the IS-236 rules is that the information carried on a PCH subchannel in the primary superframe (SF) is always repeated in the secondary SF at the same subchannel number. This is done in case the MS did not receive the PCH message sent on the primary SF. All other SPACH information may be different from one SF to another.

Having higher priority over ARCH and SMS, a PCH subchannel is only allowed to occupy a maximum number of SPACH slots in a superframe (this number is pre-defined and set at configuration phase. However, depending on the DCCH structure and system parameters, the PCH may be allowed to be sent on all the SPACH slots). The main reason for this restriction is to allow some bandwidth for the ARCH and SMS during a heavy load of paging messages. The Non-PCH slots (on which no paging messages can be sent) are located at the end of the SPACH, and the number is defined by the Non-PCH parameter carried on the F-BCCH in the superframe. Figure 3.7 shows the PCH replication in the secondary SF along with the Non-PCH slots on the SPACH. It is important to note that Non-PCH can be set to zero by the BMI as the need arises.

The F-BCCH carries the same information in every SF. This type of information reflects the set-up of the current cell and is the first information that an MS reads when it enters the region serviced by a new BS. The E-BCCH information, on the other hand, can be different from one SF to another as it gets repeated after a certain cycle period which is included in the F-BCCH field.

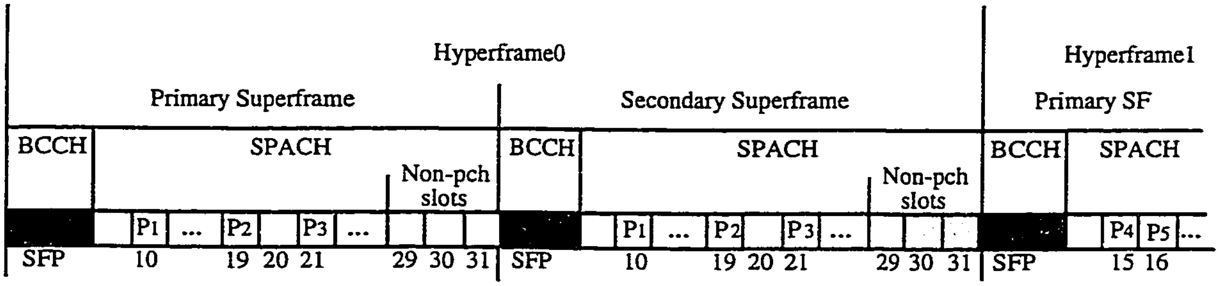


Figure 3.7: PCH allocation on the SPACH

3.3.2 Reverse Digital Control Channel

With reference to figure 3.1, the Reverse DCCH (RDCCH) is comprised of the Random Access Control Channel (RACH) through which information is transferred from an MS to the BMI. One of the main issues in the up-link control channel is the definition of the multiple access control mechanism used on the RACH by the MS's during the call set-up phase. During this phase, the MS's have to compete to gain access to a RACH subchannel.

Having a much lower complexity in the burst type than in the forward DCCH, the RACH message mapping is much simpler: a fixed number of distinct subchannels (constructed in TDMA Blocks) have been defined. Once an MS successfully accesses a RACH subchannel, the BMI returns an acknowledgment of burst reception to the MS in the

SCF flags transmitted on the forward DCCH (figure 3.1). Using the SCF information (R/N, BRI and CPE), the MS can get an update on the outcome of its transmission attempt and the current RACH subchannel status.

To ensure synchronization, the IS-136 standard requires an equal SCF response time from the BMI in the full-rate and the half-rate DCCH. Therefore, the full-rate DCCH has been defined to consist of 6 RACH subchannels, and the half-rate DCCH of 3 RACH subchannels. Figure 3.8 shows the RACH subchanneling for the full-rate DCCH. For the half rate DCCH, only subchannels P1, P3 and P5 are used. The 64.8 ms and 41.8 ms delays are the same for half-rate and full-rate DCCH.

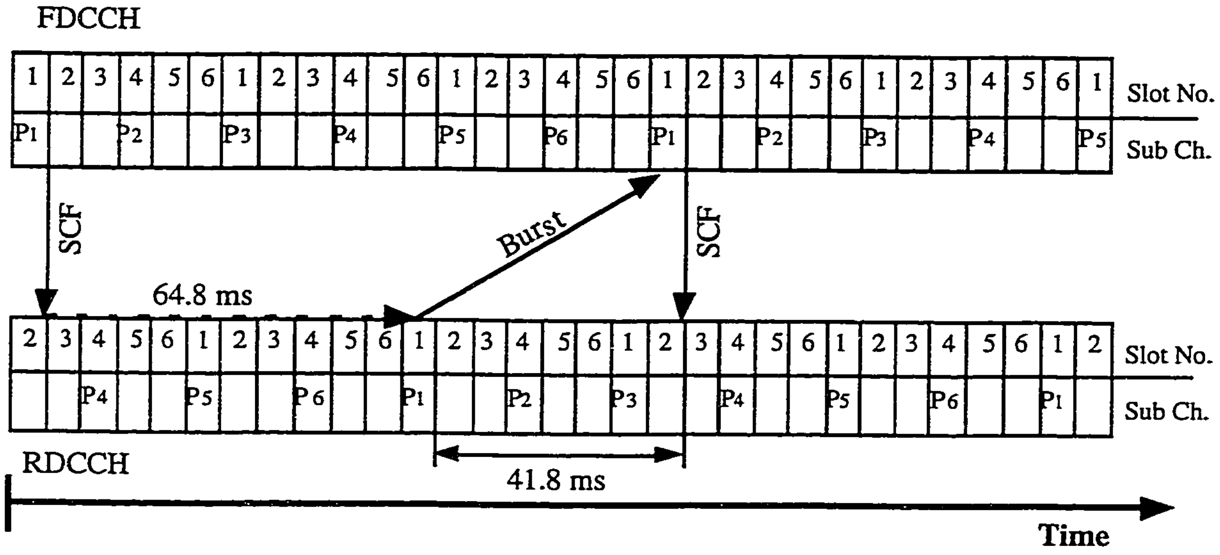


Figure 3.8: RACH subchanneling in Reverse DCCH [IS-1STD]

In figure 3.9 we present a double burst access attempt message from an MS, and we assume no interference by another MS (no collision).

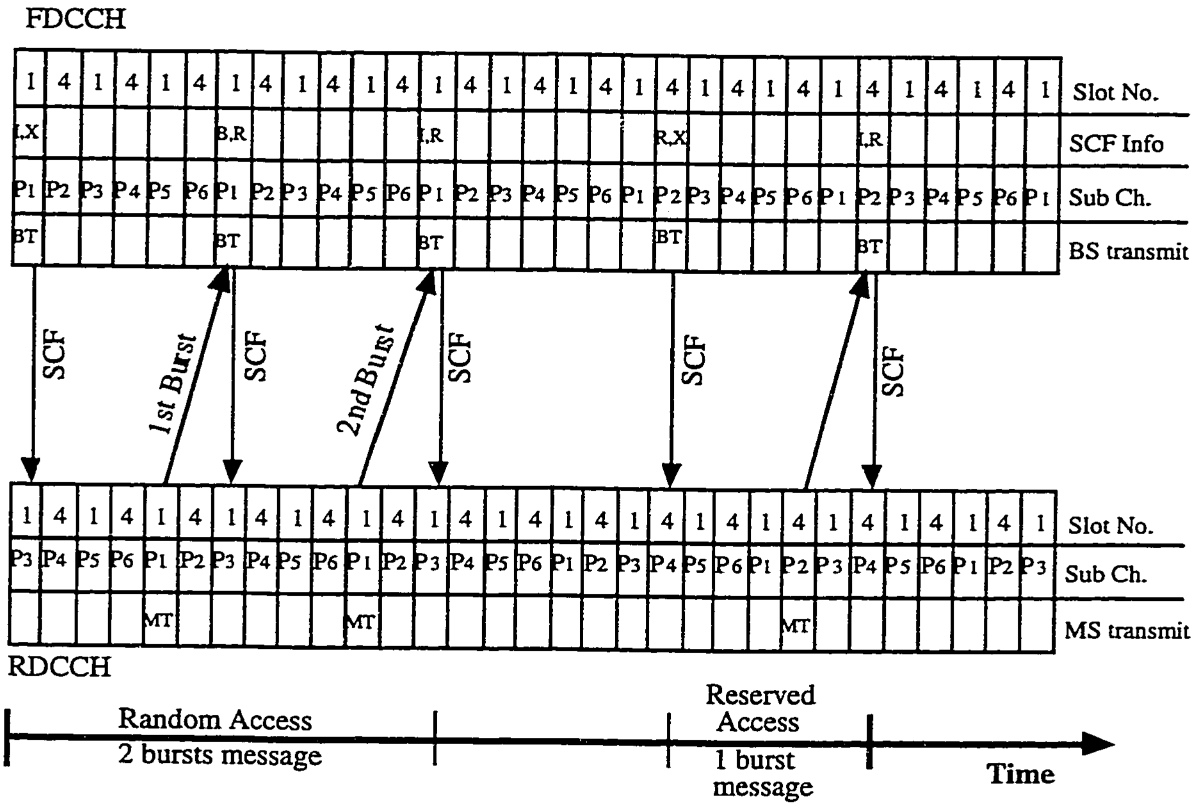


Figure 3.9: RACH Subchannel Dialogue [IS-1STD]

Assuming a full-rate DCCH in figure 3.9 (6 RACH subchannels: P1 to P6), the MS having an attempt willing to gain access on the system, reads the SCF broadcasted by the BMI to determine when to begin its access attempt. Assuming that path 1 in the FDCCH indicates that the next P1 slot in the RDCCH is available (BRI=Idle), the MS begins sending its burst at the next encountered P1 slot (64.8 ms after receiving the full P1 slot containing the SCF) in the FDCCH [IS-1STD]). Once transmitted, the MS will wait for the burst reception acknowledgment from the BMI after allowing some processing time (including propagation delay, typically 41.8 ms after completing the transmission of the burst [IS-1STD]). After reading the SCF, if the previous transmission was successful (R/N = Received), the BMI sets the RACH subchannel to "Busy" (BRI=Busy) and the MS waits for the next P1 (64.8 ms) to transmit the next burst of its message. After allowing some processing time (41.8 ms), the MS reads the SCF to determine the status of the transmission of its second burst. If successful, the dialogue is closed and the MS gets access to the system (in case of a voice channel request, the switch allocates a voice channel to the MS and links it to the required end user specified in the message sent by the MS on the RACH during the random access). In the case that the MS reads an unsuccessful reception of the burst, it follows a collision resolution protocol to retransmit the burst. The collision resolution protocol is implemented by the layer 2 and presented in a later section. If the MS is transmitting a message composed of a single burst, after successfully receiving the burst, the BMI will leave the RACH subchannel free (BRI is not set to busy) and sets the R/N flag to "Received". In this way, other MS's can use the RACH subchannel.

It is very important to note that the SCF information carried on the forward DCCH depends on the physical layer, and has a bandwidth totally independent from that assigned for any FDCCH subchannel (BCCH, PCH, ARCH or SMSCH). This can be clearly seen in figure 3.4 where the SCF flags are shown to be included in all the FDCCH slots.

Another important issue to note is that given that a cell may contain more than one DCCH number, the access paths associated with one DCCH are completely distinct from those associated with any other DCCH. Given that each MS in the cell is assigned to a DCCH, an MS can never use a RACH access path of a DCCH to which it has not been assigned. This guarantees the privileges and the rights for the users associated to a given DCCH.

In the following, we describe the multiple access scheme for the case where two MS's in the same radio cell and assigned to the same DCCH attempt to access the same RACH subchannel. Figure 3.9 illustrates the situation.

Due to the fact that more than one MS in the cell may need to transmit a message on the RACH, after reading SCF with BRI=Idle for a RACH subchannel, several MS's will send the first burst of there message on that subchannel. At the BMI, this situation will be reflected as a collision and all bursts sent on the that RACH subchannel are destroyed. The R/N flag in the SCF in that case remains unchanged and is set to "Not-Received". Detecting a negative acknowledgment (after reading the SCF, R/N flag) the MS's that have transmitted simultaneously on that RACH subchannel will retry the transmission according to a set of rules provided by the MAC protocol at layer 2.

On the other hand, a simultaneous reception of two (or more) bursts at the radio receiver of the BMI may result in having one of the bursts with a larger signal power creating a *packet capture* situation. This leads to a successful reception of one of the bursts and a drop of all the others. The BMI therefore sets the SCF R/N flag to "Received" and the CPE value based on the MSID included in the burst and finally sends the acknowledgment on the forward channel. All the MS's that have participated in the simultaneous transmission will read R/N = Received, but only the MS which identification number matches the CPE in the SCF will know that the "R/N=Received" acknowledgment was directed to it and considers its transmission to be successful. All the other MS's then follow the MAC protocol to retry the transmission of the first burst of their message.

3.4 Random Access Control Channel

In what follows, we present a detailed description of the RDCCH. As it is was shown in figure 3.1, the RACH is what composes the reverse DCCH. In this section, we describe the channel access protocol used by the MS's to gain access to the RACH.

An MS may attempt to gain access to the RDCCH for two main reasons: First, the MS may try to establish a communication link with another end user. This is done through an unsolicited access to the system. Second, the BS may send a message to the MS requiring a response or acknowledgment of reception, for instance an MS should respond to a paging message by sending a *page response* to the BS. Third, during the transmission of a long message (composed of several bursts) from the BS to an MS, the BS may require the MS to send a status message explaining which fragments of the message it has received so far. To guaranty access of that MS on the RACH, the BS will explicitly reserve a RACH subchannel for that MS so that it transmit on it the status message. This type of RACH access is known as the *Reserved Access,* and the request sent by the BS is known as *Automatic Retransmission Request* (ARQ).

An MS may start an unsolicited access on the RACH during the call set-up phase, or if it receives a SPACH message with the SPACH Response Mode (SRM) set to 0 (SRM is set by the BS), or an ARQ frame with the polling indicator (PI) set to 1 and the ARQ response mode (ARM) set to 0 (see figure 3.10).

An MS will start a reserved access if it receives a SPACH message with SRM set to 1, or if it receives an ARQ frame with PI and ARM set to 1 (for more information on the frame format and content, refer to Appendix B).

Due to the fact that more than one MS exist in a given cell and that a DCCH may be assigned to more than one MS, an attempt to access the RACH may result in a success or failure. A successful access attempt would result in the successful transmission of all the bursts composing a message. An access attempt failure would result in aborting the transmission.

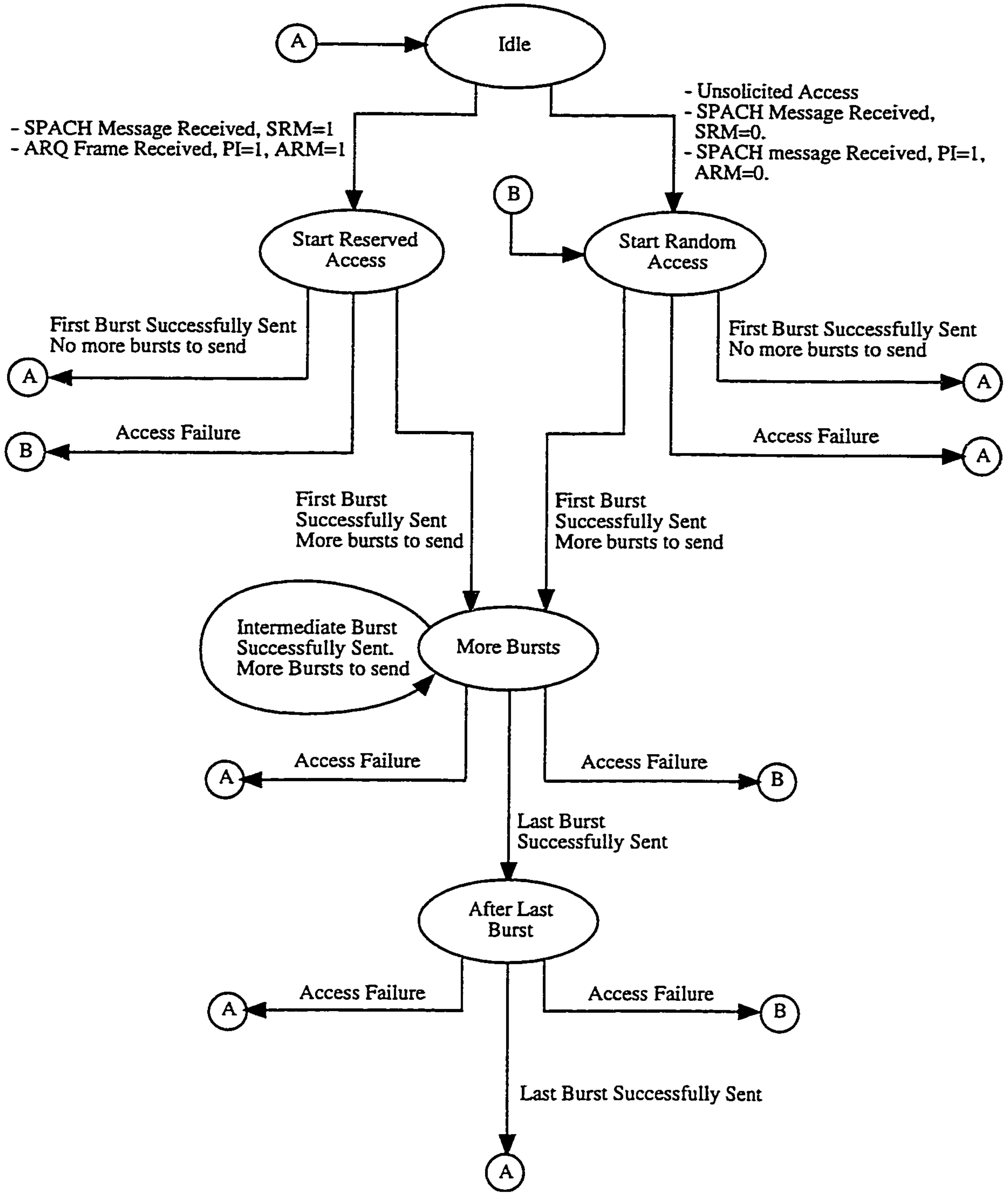


Figure 3.10: Overview of MS states during access on RDCCH

3.4.1 Random Access Procedures

In this section we present the procedures followed during contention or reserved access on the RACH. Table 3.4 summarizes the parameters used by the procedure and their possible values. Note that these access parameters are set-up during installation.

Table 3.4: Random Access Parameters

BCCH Parameter Name	Range of Parameter
Max Busy/Reserved	0, 1
Max Retries	0 - 7
Max Repetition	0 - 3
Max Stop Counter	0, 1

The flow chart of the medium access mechanism is presented in figure 3.12 for the unsolicited and reserved access procedures. The SCF flag notation used is presented in figure 3.11 with six areas each representing a case of the SCF flag value. The top row letters “R”, “B” and “I” refer to the RACH channel status reserved, busy and idle, respectively (BRI field of SCF). The left column letters “N” and “R” refer to the transmission response from the BS as Not-received and Received, respectively (R/N field of SCF). For instance, area 2 in the SCF notation would represent a busy RACH subchannel on which the last transmitted burst was not successfully received by the BS.

SCF	R	B	I
N	1	2	3
R	4	5	6

Figure 3.11 : SCF flag notation

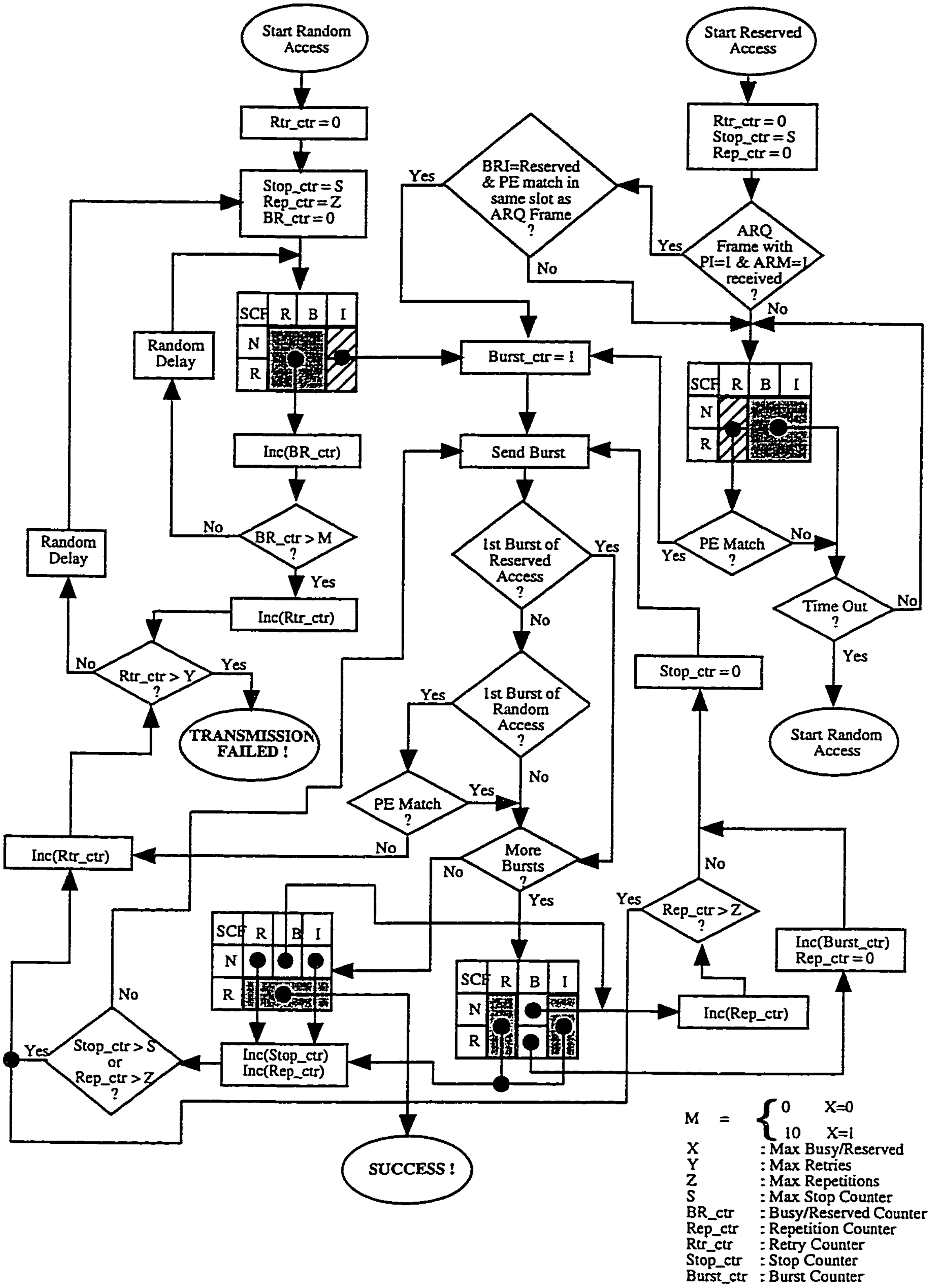
The MS, only after having read the access parameters information on the F-DCCH, can attempt to access the RACH on either a contention or reservation basis.

During a Random Access, the MS starts by looking at the current RACH subchannel by reading the SCF (see figure 3.12). If the SCF BRI is not Idle, the MS would wait for a random delay uniformly distributed between 0 and 6 TDMA blocks with a granularity of 1 TDMA block for a full-rate DCCH or between 0 and 3 TDMA frames with a granularity of 1 TDMA frame for a half rate DCCH before initiating the next attempt. An

MS is allowed to retry up to maximum 10 times if the random access parameter "Max Busy/Reserved" is set to 1, and zero times if "Max Busy/Reserved" is set to 0. If the maximum number of attempts is reached and the MS still has not found a free RACH subchannel, a "Retry Counter" is incremented and the process is repeated after a random delay (the value of the random delay is explained later). The maximum value the retry counter is allowed to reach is defined by the random access parameter "Max Retries". If the "Retry Counter" reaches its maximum value, the current burst is aborted and the message transmission is declared a failure.

The cases where the "Retry Counter" is incremented can be set as follows (figure 3.12):

1. The MS does not read BRI flag as Idle after one attempt (if Max Busy/Reserved access parameter is et to 0) or 10 attempts (if Max Busy/Reserved access parameter is set to 1).
2. The MS does not find a PE match along with R/N = received after sending the first burst of an access attempt.
3. The MS does not successfully send any given burst after the number of retries indicated by Max Repetitions.
4. The MS detects a total of Max Stop Counter + 1 consecutive occurrence of either of the following:
    - BRI is not Busy after sending an intermediate burst of an access attempt.
    - R/N = Not Received and BRI is not Busy after sending the last burst of an access attempt



M = { 0 X=0; 10 X=1

X : Max Busy/Reserved
Y : Max Retries
Z : Max Repetitions
S : Max Stop Counter
BR_ctr : Busy/Reserved Counter
Rep_ctr : Repetition Counter
Rtr_ctr : Retry Counter
Stop_ctr : Stop Counter
Burst_ctr : Burst Counter

Figure 3.12: Mobile Station Random Access Flow Chart

Depending on the value of Max Retries, the IS-136 standard specifies three different possibilities for the MS when one of the four cases presented above occur:

- The random access parameter Max Retries is set to zero. In this case, the MS will drop the burst and declares the message transmission to have failed.
- The random access parameter Max Retries is set to 1. In this case, the MS, before attempting once again, will wait a random delay uniformly distributed between 0 and 20 TDMA blocks with a granularity of 1 TDMA block for a full-rate DCCH, or between 0 and 10 TDMA frames with granularity of 1 TDMA frame for a half rate DCCH.
- The random access parameter Max Retries is set to a value larger than 1. In this case, before making its second attempt, the MS will wait a random delay uniformly distributed between 0 and 6 TDMA blocks with a granularity of 1 TDMA block for a full-rate DCCH, or between 0 and 3 TDMA frames with granularity of 1 TDMA frame for a half rate DCCH. During third and later attempts, the MS will wait a random delay uniformly distributed between 0 and 20 TDMA blocks with a granularity of 1 TDMA block for a full-rate DCCH, or between 0 and 10 TDMA frames with granularity of 1 TDMA frame for a half rate DCCH.

As mentioned earlier, the BS is responsible of setting the SCF and sending it in every slot of the FDCCH. After successfully receiving the first burst from an MS on a given RACH subchannel, judging from the burst condition (collided, very noisy or readable), the BMI sets the R/N and BRI flag in the SCF field accordingly. If the burst is the first burst of the message, and the burst is received successfully, the BMI sets the RACH subchannel to busy and the PE value based on the MSID of the owner MS of the burst. The MS, reading BRI = Busy and a matching PE on the SCF, understands that its first burst was successfully received. The rest of the bursts are then transmitted without a search for a free subchannel on the RACH. However, each burst transmitted on the RACH may experience some error due to external noise or the air channel quality. At the BS, the burst will go through an error check, and if failed, the BS sets the SCF filed R/N to "Not Received" but keeps BRI=Busy. From figure 3.12, the MS will read the SCF, and, if "Rep_ctr" is smaller than the random access parameter "Max Repetitions", re-transmits the last burst immediately. If "Rep_ctr" has exceeded its maximum, the transmission stops and the Retry Counter is incremented. In this case, the BS resets the SCF filed BRI to "Idle" for the RACH subchannel that was used, and the MS retry the transmission of the whole message (if Retry Counter has not reached its maximum) including all the first bursts.

If the message is composed of a single burst, and the burst transmission was successful, the BS sets the SCF field R/N to "received" but keeps BRI to "Idle" so that other MS's can access the RACH subchannel.

It is important to note that during any access attempt, the MS will still listen to the PCH subchannel for registration purposes but does not respond to voice pages.

3.5 Layer 2 and Layer 3 Operations

In this section we take the time to point out some other important features provided by the IS-136 standard, that somewhat make it unique.

In layer 2, the segmentation and assembly of the layer 3 messages are performed to provide features such as the MAC protocol used on the RACH. Based on the SCF information, as described earlier, an MS applies the rules of the MAC protocol to send its message to the serving BS.

Additionally, an improvement in the throughput capacity is introduced at layer 2 by allowing several Mobile Station Identifiers (MSID) to be carried in a single layer 2 frame (up to 4 different MSID's). This efficiently allows up to four layer 3 messages to be directed to four different MS's using only one layer 2 frame. This can viewed as paging 4 MS's during the same time slot.

An additional layer 2 operation consists of indicating to an MS if it should transmit on the RACH using *Reserved* or *Contention* based access. During reserved access, the BS reserves a RACH subchannel for the MS by setting the SCF filed BRI to "Reserved" and the CPE corresponding to the MSID of the MS in question. By doing so, a more reliable delivery of the layer 3 information from the MS is achieved. This request from the BS is mostly used when the BS needs an Automatic Retransmission Request (ARQ) from the MS during the delivery of a long message from the BS to the MS. The MS reply is sent on the reserved RACH subchannel and it contains information on which burst of the message it has received so far. During contention based access, the MS accesses the RACH randomly. This creates the possibility of collisions with other MS's also using contention based access on the RACH.

In Appendix B, we explain in more detail the layer 2 operation implementing the above mentioned features. We also present the layer 3 frame formats and protocols for the forward channel.

At the layer 3 level, most of the operations are related to mobility management and other issues concerning system updates and recovery. Such issues cover mobile registration, mobile location area and radio resource management.

The mobility management main goal is to keep track of the MS location in the cellular network. This is accomplished during registration and call activities. Five types of registration procedures are handled at Layer 3 and can be activated/deactivated from the system [PCS94] :

- Power Up/Power Down registration
- Deregistration
- Periodic Registration
- Geographical Registration
- Forced Registration

Power Up registration is used when the MS comes into the active status and therefore informs the serving BS that it is in the active mode and is ready to receive messages.

Power Down registration informs the system of its power-down status and therefore proper actions are taken by the system like call forwarding, voice mail without having to wait for a time out for the MS response when tried to be reached. For the same reason, a deregistration is activated when the MS changes network type (as an example when moving from a public to a private or residential cellular network).

To improve channel quality and distribute radio resources efficiently, a periodic registration is activated by the MS enabling it to look for a better performance radio resource in its surrounding. It also acts as a reminder for the system of the MS location. The period of registration can be based on a clock at the BS that sends a registration trigger or on an internal clock in the MS.

The geographical registration is activated by the MS when it moves into a new radio cell.

Upon a major system update or system recovery, a forced registration by the network is called for corresponding MS's operating under such system.

One of the major concerns for the MS is to define its geographical area with respect to the surrounding radio cells. This is achieved after a successful registration when the BS sends to the MS a list of area numbers that defines what is known by the Virtual Mobile Location Area (VMLA). During its move, the MS will always read the current area number from the BCCH. If it detects an area number that is not part of its VMLA, it will register with the serving BS which will send a new VMLA to the MS. The area number of the neighboring cells to the VMLA where new registration is required may not be included in the list. This concept is know as "hard" boarders [PCS94]. If avoiding the hard boarders is required, the neighboring cells are included giving the MS a kind of hysteresis area. In figure 3.13 we provide an example to illustrate this concept.

An MS powering up in area 7 gets registered (following the power up registration procedure dictated by the cell). The MS receives the list of all the surrounding areas, i.e., {1,2,8,13,12,11,6}. This list will define its VMLA and it will store its memory. Following the path presented in figure 3.13, the MS, selecting a control channel in area 9, determines that it is necessary to apply a geographical registration since 9 is not part of its current VMLA. Upon a successful registration, the MS then receives a new VMLA defined by the areas list {2,3,4,9,13,12,7}. The MS will then not register when it comes back to area 13 which is now part of its VMLA. This concept eliminates excessive geographical registrations of the MS especially if the MS toggles between two adjacent areas.

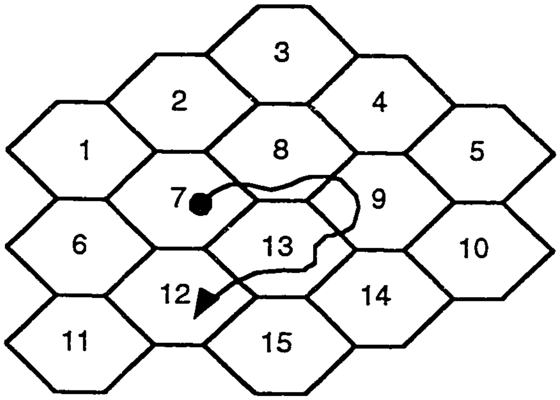


Figure 3.13: Virtual Mobile Location Area concept

Another important feature in IS-136 is the ability for the MS to measure the quality of the traffic channel being used for the conversation and the signal strength on other frequencies covered in its area. This is highly desirable during hand-off and is implemented through the Mobile Assisted Hand Off (MAHO) generating reports evaluating cells that are suitable to make a handover to. MAHO is also used for adaptive channel allocation which allows an automatic traffic channel allocation to the cell based on the traffic in it and interference conditions on the different channels. This specific feature eliminates the need of manually planing the frequencies in the cells and has proved successful in increasing the system capacity by a factor of two [Almg-93]. The feedback on the control channel quality is provided by the MS using the Mobile Assisted Channel Allocation function (MACA) activated upon the BS command. This feature can also be used for system supervision.

In a true hierarchical cell structure, an MS may move into a microcell imbedded within a macrocell (see figure 3.14). An MS usually will select the cell with the strongest control channel which in most cases lies in the macrocell. This only creates a waste of resources and capacity in the microcell and a high traffic load in the macrocell. The trivial solution would be to have high power in the microcell increasing the control channel strength so that it is preferred by the MS under its umbrella. IS-136 avoids this problem by broadcasting on the BCCH information used by the MS to select cells based on other criteria than the strongest signal. In figure 3.14, we present some of the methods that are used.

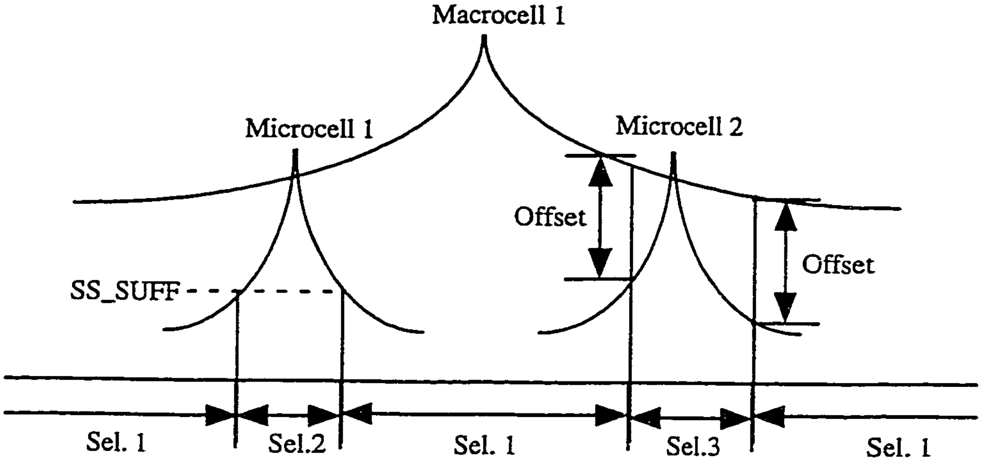


Figure 3.14: Cell selection concept in IS-136

In microcell 1, a preferred cell indicator is used when the cell is selected if the signal strength happen to be higher than a value SS_SUFF. In microcell 2, offset values between the macrocell and the microcell are broadcasted on the BCCH. An MS situated in "Sel.3" as shown in figure 3.14, will read 2 signal power levels: macrocell 1 and microcell 2. If the signal power level of microcell 2 plus the offset value read from BCCH is larger than the signal power level of macrocell 1, microcell 2 is selected. With the application of this rule, a larger selection area for the microcells is achieved when compared to the case where the MS will chose the cell with the strongest signal power.

A summary of some mandatory messages broadcasted on the BCCH is available in Appendix B (section B2).

CHAPTER 4

DCCH Simulations and Analysis

4.0 Introduction

In this chapter, we present a performance evaluation of the channel access mechanism used in the reverse link of the DCCH. To do so, a simplified model of a cellular system operating under the IS-136 standard, digital control channel, was simulated and used to generate statistics with regards to the issues of interest focused around the RACH in the reverse link (or up-link). The main objectives of this study is to provide guidelines for setting the RACH access parameters with and without the support of SMS in order to achieve optimum performance on the air link and at the base station site. We also present performance projections of the system under various air channel qualities. This information can be used by a base station designer to understand the limitations of the air link and the delay that can be afforded at the base station in an optimum system operation.

In the remaining of the chapter we present the model of the up-link along with the assumptions and simulation methodologies followed to generate the required statistics. The simulation results for the system behavior are presented and discussed against different set-ups of the system parameters.

4.1 Performance Analysis Approach

With the main objectives in mind, the study was composed of three phases. In the first phase, we find the maximum system capacity that can be achieved with support of SMS messages as part of the traffic load on the RACH. From this phase of the study, the contributions that can be extracted will present the system throughput analysis for two settings of the MAC protocol and the effect each setting is creating on the queuing space required at the BS and the message end-to-end delay.

Once we know the system limitations with regards to traffic load (traffic load with which maximum throughput is achieved), we can monitor in phase two of the study the RACH performance under various air channel qualities under what is considered a *"safe"* high traffic load; this can be chosen from the phase one results in such way that if the system would have to be pushed to its limits, it will not collapse. From this phase of the study, the contribution that can be extracted is the measure of the air interface integrity with respect to the channel quality. In other words, we should be able to define the level in the channel quality after which the RACH performance starts to decrease.

In the last phase of the study, we vary the RACH access parameters and fix the traffic load as well as the channel quality on the air. The contributions from this phase will consist of the settings for the access parameters such that the system throughput, end-to-end message delay and memory space requirements at the BS are of optimum values.

4.2 Simulation Tool Selection

Discrete-event simulations have been widely used to design new communications systems and improve existing ones. This is due to the increased number of telecommunication networks in existence. By representing the network in a software model that acts and behaves in a similar manner to a real network, a design group can evaluate the network performance under various conditions even before deploying it. This has proven to reduce model development and analysis time considerably. A general reference for the basics of simulation can be found in [Law-91].

The simulation tool OPNET release 3.0B [OPNT97] was used to develop our simulation models and generate the required results. Some of the key features to look for in a simulation tool were modeling flexibility, ease of model development and fast model execution speed [Law-94]. OPNET offered the flexibility in simulation modeling and development. The tool is event driven and allows the user to run simulation outside the OPNET user interface in the form of executable files.

4.3 Random Access Channel on RDCCH

4.3.1 Simulation Perspective

The main objective in this task is to provide guidance on optimum settings of the various IS-136 random access parameters for the RDCCH under various system conditions. Following the standard features presented in chapter 3, the MS access on the RACH is modeled in OPNET. In order to focus the simulation around the objective of the study, unnecessary features of the RACH were not considered. Following is a list of the main features of the reverse DCCH modeled in the simulator:

- Full rate DCCH. This allows the usage of six RACH subchannels on the reverse link from the MS to the BS.
- Mobile contention based access on the RACH. This would cover delay of transmission of the mobile message when a channel is not available as well as the SCF monitoring at MS.
- SCF field.
- Multiple bursts messages generated by the MS. These messages require more than one time slot to be transmitted. The message types will include voice call request and SMS messages.
- Noise and signal fading on the air link which may cause message losses or disturbance.
- Simultaneous transmission of multiple mobiles on the same RACH subchannel.
- Collision detection at the BS radio receiver.

With the above features being simulated, the major components are modeled to provide a performance evaluation of the RACH in the contention based access mode of the MS.

4.3.2 Assumptions

It is important to clarify all assumptions and considerations applied in the simulation so that the results can be understood with respect to corresponding system set-ups.

For the RACH modeling, a simplified cellular system was implemented using a single BS surrounded by one hundred MS units placed randomly over an area of 2.5x1.5 kilometers cell on a flat ground. A single DCCH channel is used in the system, and no propagation delay over the air is modeled during message transmission from any MS. The noise and signal fading through the air interface is modeled by simply generating a Burst Error Rate (BER) (usually 9% according to common practices in the industry) of burst failure at the BS radio receiver. Since channel propagation model is not considered, it does not matter whether mobiles are moving or not.

At the BS radio receiver, no packet capture concept is modeled: if two bursts overlap at the BS radio receiver, a collision is produced and both bursts are destroyed.

The message content is of no concern in this simulation. The Layer 3 message length however, is used to find the number of bursts needed to transmit it on the physical layer (more elaboration on this in the next section).

4.3.3 Simulation Model Architecture and Parameters

A high level view of the simulation system model is presented in figure 4.1. The model consists of two main features: the *Mobile Station* and the *Base Station*. All the models and features were built from scratch and implemented in OPNET.

In the Mobile Station, the modeled features cover the *System Traffic Load, RACH Channel Multiplexing* and *Multiple Access Control Protocol* scheme

The system traffic load at the input of the BS, as mentioned earlier, is generated by all the MS's, and therefore represented by independent message sources (following a Poisson process) each located in an MS object model. One of the main features of the model is that it takes into account the actual message mapping from L3 to L1 as specified by the IS-136 standard [IS-1STD]. Therefore, all messages created by the Poisson sources represent Layer 3 messages that are mapped into the physical layer as predefined by the protocol (see Chapter 3).

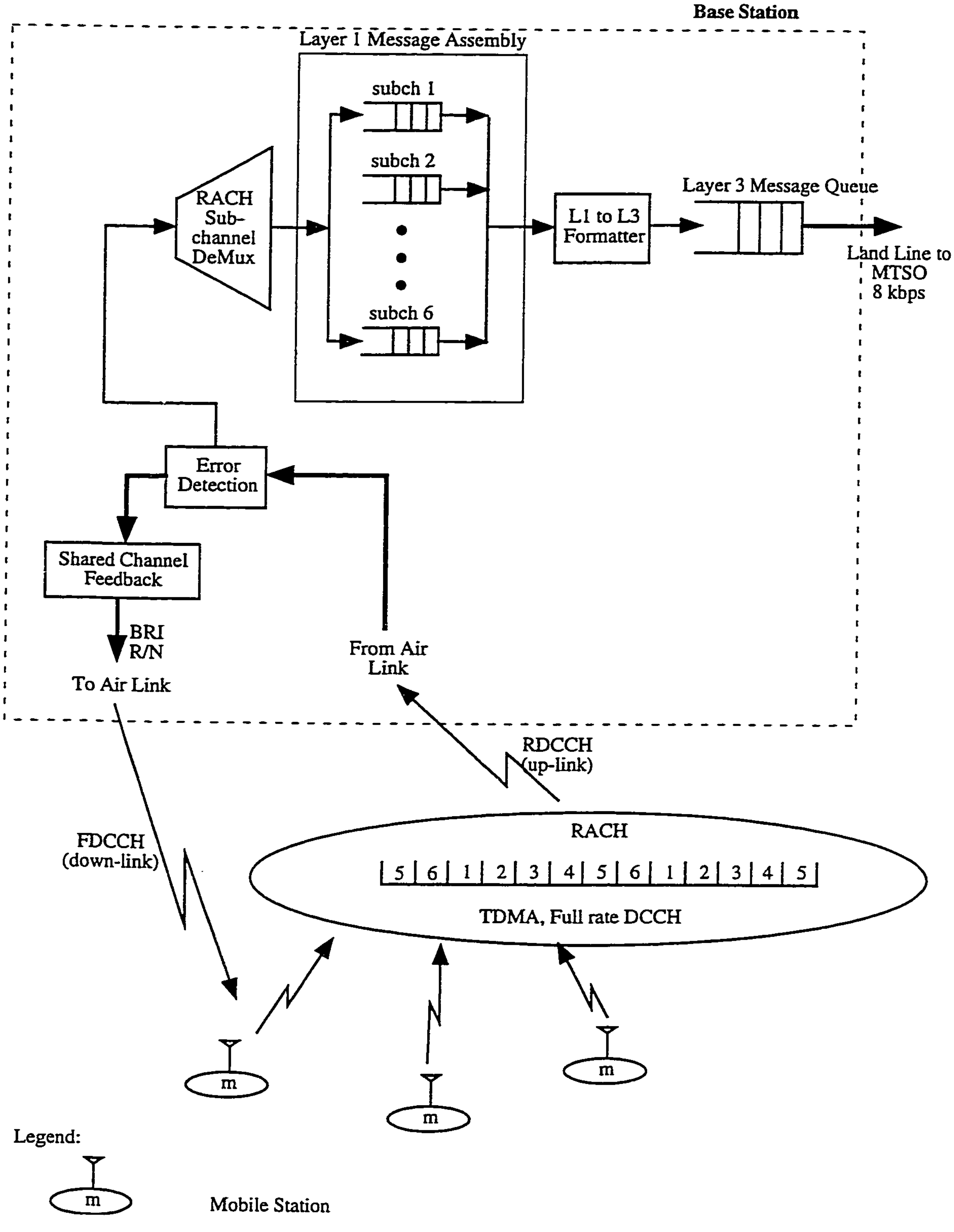


Figure 4.1: Simulation System Model for the RACH

According to the standard, two types of L2 frames can be used on the RACH to hold the L3 information: the *normal length* and the *abbreviated length* frame. In our study, the normal length frame format will be used with an MSID type MIN. In Appendix B, Figure B.4, a BEGIN L2 frame of normal length can hold up to 50 bits of L3 information, and a CONTINUE frame up to 97 bits. The 122 bits L2 frame is then duplicated and appended with L1 header information to form the 324 bits Normal slot format at the physical layer (see figure 4.2).

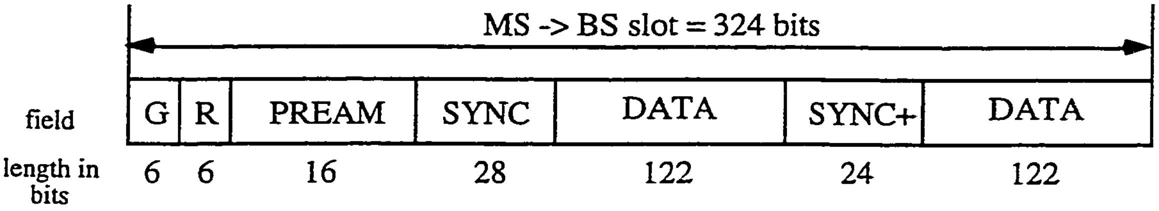


Figure 4.2: L1 Normal Slot Format MS to BS on DCCH

The number of L1 bursts needed for a given Layer 3 message is then found by the following calculation:

$$\textit{Number of L1 bursts} = \mathrm{FLOOR}\left(\frac{(L3\_bit\_length-50)}{97}+1.5\right)$$

where FLOOR[X] represents the closest integer smaller or equal to X.

It can be noted that the number of bursts composing a message transmitted on the physical layer depends on the L3 message length which varies with the message type. For all origination messages (requesting a voice channel), the L3 message length can vary from 30 bits covering only the mandatory information elements, up to 470 bits including optional elements such as message encryption, call display and other features. This means that the message length varies between 1 and 6 bursts. Currently and in the near future, additional features will become more affordable and used. Therefore, we choose to have a higher message rate for all origination messages with optional information elements than the ones with only the mandatory information.

The SMS messages are by far the longest, and without doubt the ones that will be using the RACH capacity for the longest time. According to the IS-136 standard [IS-1STD], the maximum L3 message length is 255 bytes (2040 bits). Based on the calculation method of the L1 bursts presented earlier, 2040 bits will require 22 L1 bursts to be sent on the RACH. Given that the SMS message is not always of maximum length, a thousand bits L3 message was chosen to represent the average SMS message length in the simulation model.

To cover the different messages described above, three message types are defined in the simulation model each with an average length and a generation rate. Table 4.1 presents the message types and their characteristics. We will also have the opportunity to change message rate depending on what message types are included in the simulation (see upcoming sections).

Table 4.1: Sample of message types created at an MS.

Message type	L3 Message length (bits)	Number of bursts required on the RACH	Message rate (percentage)
Type 1	30	1	30
Type 2	200	3	50
Type 3	1000	11	20

The message rate represents the percentage of the total number of messages created by each MS. The type 3 message rate was defined with the assumption that users will mostly use the service to establish telephone calls than for sending short text messages.

Throughout the text, we will be using the notation {A, B, C bursts} to describe the message types used in each run. For instance, the representation {1,3,11 bursts} for a message population will state that during the simulation run, the MS's have generated messages of length 1, 3 and 11 bursts.

The TDMA channel has been modeled as consisting of 6 RACH subchannels of a full-rate DCCH on the reverse link. When a message is available at an MS, the first burst is transmitted at the beginning of the slot corresponding to a free RACH subchannel. Each burst is sent independently on the same RACH subchannel. The message is reconstructed at the BS once all the bursts belonging to the message have been received.

The channel access control used on the RACH (see chapter 3) has been fully modeled. The four random access parameters provided in the IS-136 standard for the MS access on the RACH are listed in table 4.2 together with the range of values as defined in the standard [IS-1STD]. It is important to note that when "Max Busy/Reserved" parameter is set to 0, the access protocol restricts the MS to only one attempt for finding a free RACH subchannel before incrementing the "Retry Counter", and 10 attempts when "Max Busy/Reserved" is set to 1 (see Chapter 3).

Table 4.2: Random Access Parameters on the RACH

Random Access Parameter	**Range**
Max Busy/Reserved	0,1
Max Retries	0-7
Max Repetitions	0-3
Max Stop Counter	0,1

Given that we are studying only the random access procedure on the RACH, the access parameter "Max Stop Counter" will not be considered in our simulations. This parameter is only effective when the MS makes use of a reserved access on the RACH (see Chapter 3 for more details).

In the BS model, the simulated features consist of *Message Queueing, Message Reception Rules, Layer 3 Message Reconstruction* and *Output Wireline Link.* Figure 4.1 depicts the queueing model at the BS. All queues are of type FIFO (First In First Out). In the RACH subchannel demultiplexer, the Layer 1 bursts are stored in their corresponding RACH subqueue. When all the bursts of a message are received, the Layer 3 message is reconstructed and stored in the BMI queue before being delivered to the MTSO via the land link.

The land link is a model of the physical connection between the BS and the MTSO in a cellular network. In the simulation model, we have used an 8 kbps data link at the output of the BMI queue.

The radio receiver of the BS simulates the message reception criteria and the BS reaction upon the reception of a message frame. Based on the BER and collision status, the BS updates the SCF flag which is read by the MS 41.8 ms after sending a message burst on the RACH (see chapter 3). Figure 4.3 summarizes the SCF settings in all scenarios of message burst reception.

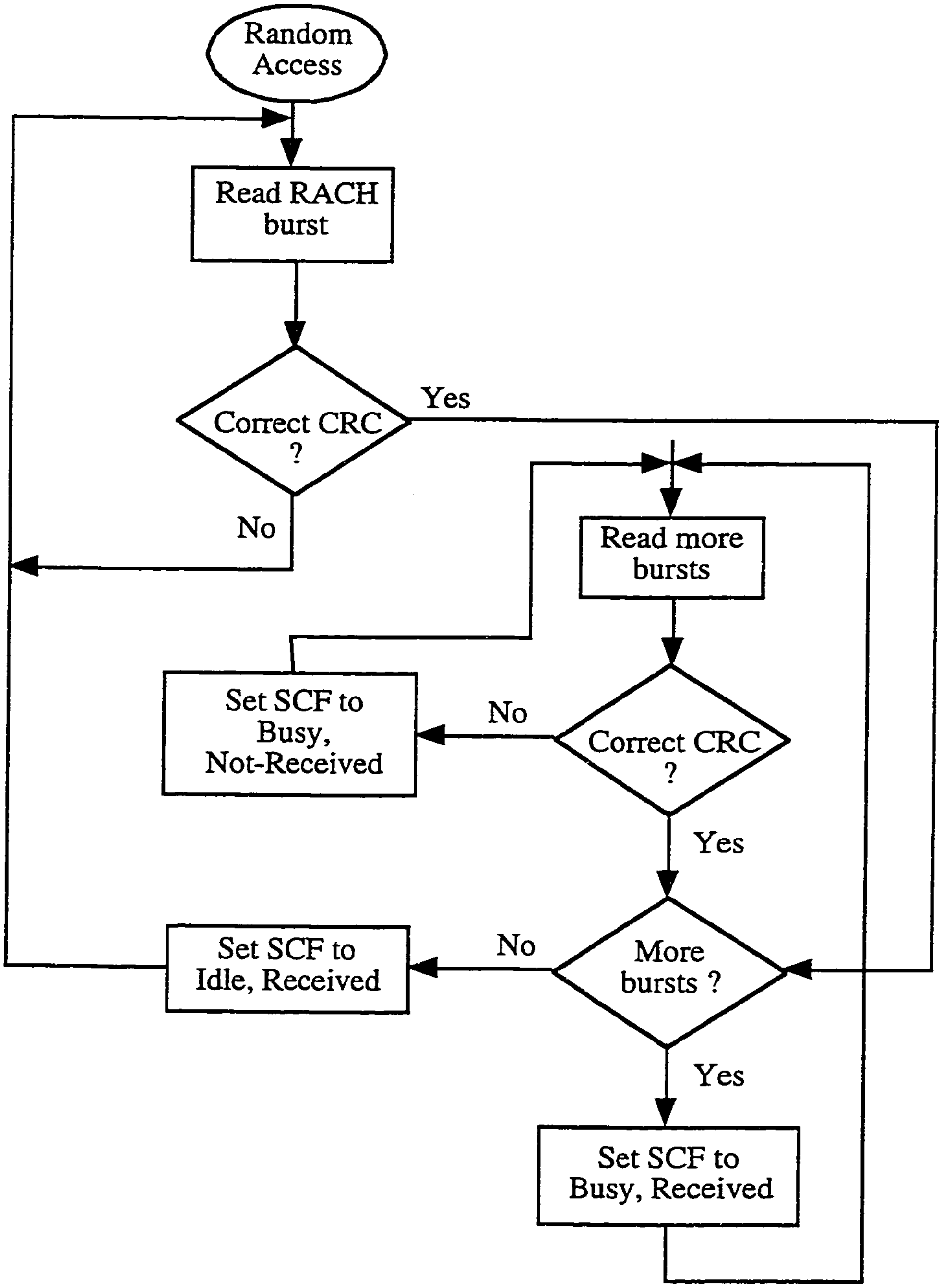


Figure 4.3: SCF Processing Flow Chart at the BS

4.3.4 Simulation Set-up

In Appendix C we explain the details on setting up each simulation run and how the error margin was controlled using what is known by the *confidence interval.*

In our simulations, three runs (each with a different initial simulation seed) are used to generate each point with a pre-defined warm-up period. The mean value of statistical results created by the three seeds for a given case is shown in the graphs with a 90 percent confidence interval. A sample of the confidence interval in our simulation results can be seen in figure 4.12. The other graphs do not show the error margin because it is too small.

The simulation run was stopped after 100,000 messages were successfully received at the BS rather than by the amount of seconds in simulation run time. This was found to be a better strategy knowing that a long simulation duration varies with input system parameters whereas, the number of messages received at BS remains the same.

In addition, each MS contains a message source with the characteristics of a Poisson process. This is achieved by having a process whose inter-arrival times $\{A_n\}$ are exponentially distributed with a rate parameter λ [Cinl-75]:

$$P\{A_n \le t\} = 1 - e^{-\lambda t}$$

We take a moment at this stage of the study to define the metrics used in our study, their functionalities in the simulation model and how they where measured.

"*System Load on the RACH*" or simply "*System Load* refers to the number of messages generated by all the MS's in the cellular partition per second. From simulation perspectives, we generate this load by dividing it by the number of MS used in the system, and assigning to the message source of each MS the corresponding inter-arrival time. For instance, if a 5 messages per second system load is required, using 100 MS in our simulation model, each MS will generate 0.05 messages per second, in other words, a message source in the MS will generate messages with 20 seconds inter-arrival time exponentially distributed. More elaboration on traffic modeling can be found in [Fors-94].

The *"Burst Load on the RACH"*, or *"RACH Load"* is defined and calculated in a simulation run as:

$$\frac{\textit{total number of bursts sent on the RACH}}{\textit{total number of RACH subchannels occurred during the simulation}} \times 100$$

The total number of bursts sent on the RACH includes all bursts that have attempted transmission on the RACH. Given that the system does not provide feedback to the MS telling it to stop transmitting because the RACH is too busy, the MS will keep generating messages trying to get access until it times out with respect to the access protocol. This leads to have a burst load on the RACH that could be higher than 100 percent with increasing system loads. The burst load metric will give us an idea on how many bursts the RACH can handle with respect to a required performance.

Another metric used is the *"Collision Rate on the RACH"*. With the SCF being broadcasted on the physical layer, multiple MS's can read "BRI=Idle" for a given RACH subchannel and therefore transmit simultaneously on it leading to a collision on the RACH. The collision rate in a simulation run is measured as

$$\frac{\textit{total number of collisions on the RACH}}{\textit{total number of RACH access attempts}} \times 100$$

and can reach a maximum of 100 percent rate in which case all bursts attempting transmission on the RACH will experience a collision.

The *"channel access delay on the RACH"* is another important metric when evaluating the performance of the system. This metric represents the average delay to successfully access a RACH subchannel on the uplink. It is measured from the moment a message was ready to be transmitted by the MS until the first burst of the message is successfully sent on the RACH. Note that, an MS would not know if the burst transmission was successful until it reads the SCF=*Received* 41.8 milliseconds after sending the burst on the air. The delay period while an MS is waiting for the SCF is not included in the access delay. Furthermore, the messages that have failed the transmission or failed accessing a RACH subchannel are not included in the access delay statistics.

During a simulation run, the average channel access delay metric is collected from the traffic created by all the MS's for all messages successfully transmitted on the RACH and is calculated as follows:

$$\text{Average RACH Access Delay} = \frac{1}{n}\sum_{i=1}^{n} T_i$$

where T_i is the access delay of the current message that has successfully been transmitted on the RACH, and n is the total number of messages successfully transmitted on the RACH during the simulation run.

The *"message transmission delay"* is another metric used in our study. It defines the time delay measured from the moment a message is ready to be transmitted from the MS until the last burst of the message is successfully received at the BS. Again note that, the delay period while the MS is waiting for the SCF for the last burst of the message is not included in the measurement. The metric was measured only for successfully transmitted messages.

The *"message transmission failure rate"* is another metric used in the study. This metric is measured independently for each message type used in the simulation and is defined as

$$\frac{\textit{number of messages having failed transmission}}{\textit{number of messages attempting transmission on the RACH}}\times 100$$

where a message is declared to have failed having attempted transmission according to the rules of the access protocol on the RACH. The number of messages attempting transmission on the RACH includes messages successfully and unsuccessfully transmitted on the RACH.

At the BS side, we monitor the BS queue length and queue delay. The mean queue length and queue delay are expressed in terms of the *"sample mean value"*. During a simulation run, for each measure, each of the value update is done at every arrival and departure of a message from the queue. The *Sample Mean value* is collected as the sum of all the update values divided by the number of updates occurring in the simulation.

Another term used to measure the queue length was also considered. The *"time average value"* is collected considering the interarrival time of messages at the input of the queue. Again, reading an update at every arrival and departure in the queue, the time average value is performed assuming a "sample-and-hold" behavior of the data set; each value is weighted by the amount of time separating it from the following update and the sum of all the weighted updates is divided by the width of the simulation time. As an example, let us consider the set of updates in table 4.3 where the simulation run is done from time 0 to time 10 seconds. The mean queue length would be

$$\frac{1+0+1+0}{4}=0.5 \qquad \text{(messages)}$$

and the time average queue length would be

$$\frac{\left(\frac{0}{1}+\frac{1}{2}+\frac{0}{1}+\frac{1}{6}\right)}{10} = 0.0667 \qquad \text{(messages)}$$

Table 4.3: BS queue length updates example in a simulation run

Simulation Time (seconds)	Queue length update (messages)
1	1
3	0
4	1
10	0

By measuring the time average value of the queue length, we take into consideration the message arrival time at the input of the queue and its utilization factor. These factors are not always included in the mean value. For example, assuming that we stop a simulation after serving 2 messages at the queue and that the service time takes 1 second. With a message arrival sequence at 2 and 9 seconds, the mean value of the queue length is 0.5 and the time average value is 0.2. Now considering a message arrival sequence at 1 and 4, the mean value of the queue length stays 0.5 and the time average value becomes 0.4. A higher time average queue length explains a higher queue utilization.

Some abbreviations listed in table 4.4 are used in the upcoming sections to facilitate text readings.

Table 4.4: Parameters abbreviation

Parameter	Abbreviation Symbol
Max Busy/Reserved	X
Max Retries	Y
Max Repetitions	W
Burst Error Rate	BER (normalized to unity)
System Load on the RACH	L (messages/second)

4.4 Simulation Results

4.4.1 System Load Variation Effect

In the first part of the study, we monitor the system behavior under different loads created by the MS's with a BER of 0.09 on the air link (uplink). It was decided to use a non-perfect air channel in order to make the simulation as close as possible to operation conditions. However, we will also show statistical results for a zero BER.

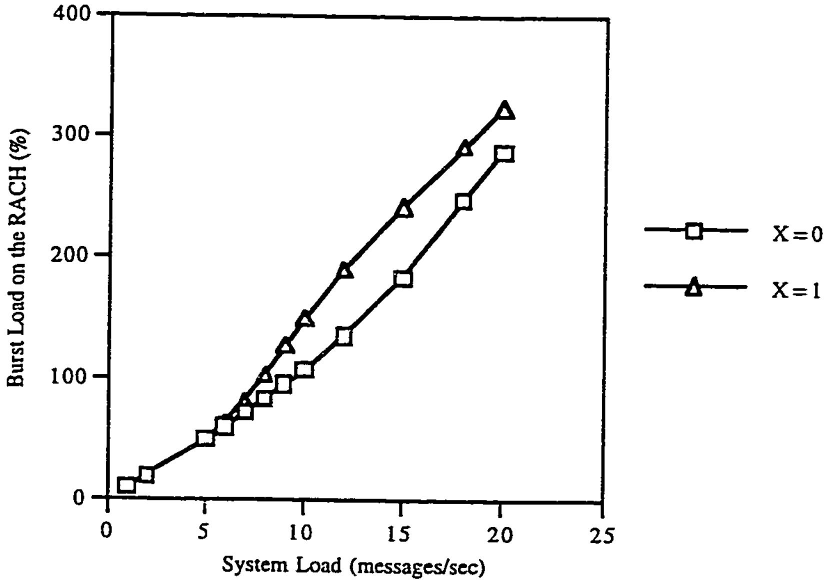


Figure 4.4: Burst Load on the RACH vs System Load.
Message Population = {1,3,11 bursts}
Y=7,W=3, and BER = 0.09.

Looking at figure 4.4, we note that the burst load on the RACH steadily increases rapidly with the message system load. We can also note that, when "Max Busy/Reserved" (or X) is set to 1, the burst load becomes higher than the case of X=0 for system load larger than 6 messages per second. By setting X to 1, the MS is given more chances (see RACH access protocol in chapter 3) to insist on the transmission of the message which means more attempts on the RACH from all MS's and therefore a larger the number of bursts is sent on the RACH compared to the case of X=0.

As mentioned earlier, given that the system does not protect itself by telling the MS's to stop transmitting when the RACH is heavily loaded, the MS population will keep generating messages and a higher than 100 percent burst load on the RACH is seen in figure 4.4 with increasing system load.

By increasing the system message load, one can see from figure 4.5 that the collision rate increases rapidly then converges towards 100 percent; at system load of 20 messages per second, one can see that a free RACH subchannel will be used by more than one MS most of the times. Based on the RACH access protocol described in Chapter 3, collided bursts are retransmitted and therefore creating a larger burst load on the RACH. When a mobile is transmitting a new burst that has not yet experienced a collision, this transmission has to compete with other new bursts and the ones that are in the retransmission process from other mobiles. With X=1, an MS is given 10 attempts, instead of only one for X=0, to find a free subchannel before incrementing the "Retry Counter". This generates a larger number of attempts on the RACH and therefore a higher collision rate.

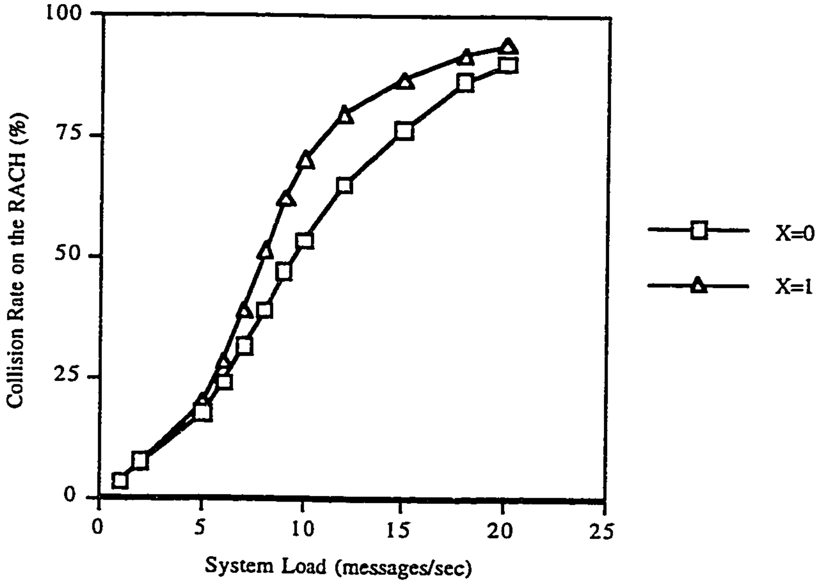


Figure 4.5: Collision rate on the RACH vs System Load
Message Population = {1,3,11 bursts}
Y=7,W=3, and BER = 0.09.

As the system load increases, it can be noted that the settings of X does not really make a big difference as the collision rate of both X=0 and X=1 converges towards the same value. This is because, as the load on the RACH becomes almost unbearable, an MS attempting to transmit a new burst will collide with others most of the time or will never find a free subchannel.

In figure 4.6, we present simulation results for the access delay for different system loads. For both cases of X=0 and X=1, the average access delay steadily increases rapidly with the system load on the RACH. This is simply due to the unavailability of RACH subchannels as more burst traffic need to be sent with increasing system load. The unavailability of the RACH subchannels becomes more evident with X=1 for system loads larger than 5 messages per second. This is caused by a higher burst load and collision rate on the RACH as seen in figures 4.4 and 4.5 respectively.

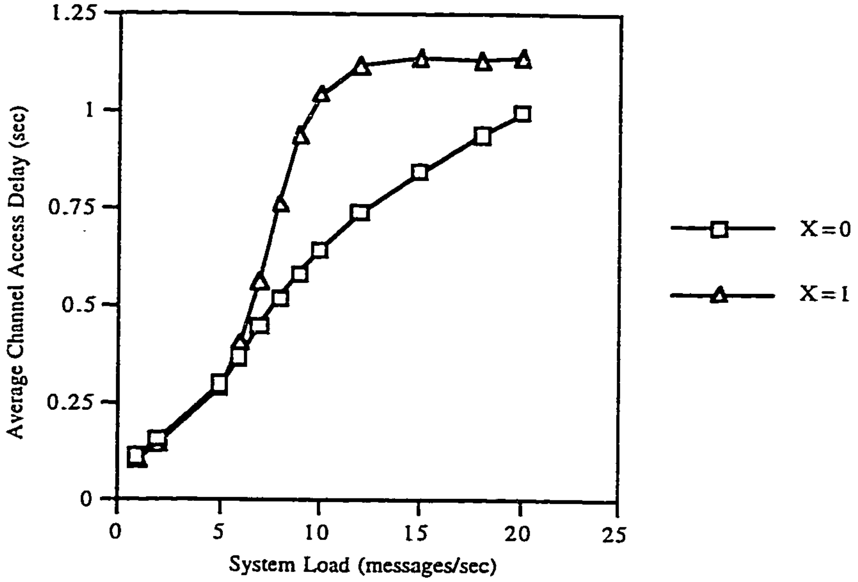


Figure 4.6: Average RACH subchannel Access Delay vs System Load
Message Population = {1,3,11 bursts}
Y=7,W=3, and BER = 0.09.

Additionally, with X=1, the message is granted $Y \times 10 = 70$ trials before declaring message transmission failure and aborting the message. With X=0, only $Y \times 1 = 7$ trials are allowed. Therefore, when X is set to 1, more chances are given to messages to look for a free subchannel but suffering a longer access delay on the RACH. This explains the much higher access delay experienced for X=1. Note that for X=1, the average access delay for successfully transmitted messages converges to a constant; the variation in the delay is minimal for system loads larger than 12 messages per second. This is because, for X=1, the collision rate for system loads > 10 messages per second, is not increasing rapidly when compared to system loads < 10 messages per second. Therefore, the messages that are successfully transmitted will suffer almost the same access delay for system loads > 10 messages per second.

As it was presented in the previous graphs, the collision rate on the RACH and the average channel access delay experienced an increase with the system message load. It is only correct to expect an increase in the number of attempts ending in failure for each of the message types used in the study (1, 3 and 11 busts messages). These results are presented in figures 4.7, 4.8 and 4.9 for the message type 1, 2 and 3 respectively. With increasing system load, the messages failure rate slowly increases at first where the system adapts to the change, then as the system load becomes high enough to push the system, the failure rate steadily increases rapidly converging towards 100 percent.

Given that each burst transmitted on the RACH experiences a BER, we can find the probability that a message, after successfully having accessed a RACH subchannel, will be successfully transmitted. When W=0, given that each burst transmission is independent from other bursts in the message, the probability of transmitting the message successfully is be given by:

$$\text{Prob}\begin{bmatrix}\text{Successful MessageTransmission}\\ \text{on the Current RACH Subchannel}\end{bmatrix} = (1 - BER)^{L}$$

where L is the number of bursts composing the message. With that, we can see that longer messages will face higher failure rate on a given RACH subchannel.

Let us first look at the failure rate for long messages of length 11 bursts in figure 4.9. By setting X to 1, we can see the result reflected in a smaller transmission failure rate on the RACH when compared to the case of X=0. As mentioned earlier, when X=1, we are giving the MS more chances to look for a free RACH subchannel. By doing so, the MS will not abort the transmission early and will insist more on the transmission of the current message in hand. The price to pay for this advantage is a longer channel access delay as it was present in figure 4.6.

Looking at the message failure rate for the "3 bursts" message in figure 4.8, we see the same behavior as the "11 bursts" message for system loads < 10 messages per second. For higher system loads, the message failure rate is almost the same for the cases X=0 and X=1.

For the "1 burst" message, the failure rate in figure 4.7 presents the same behavior as the "11 bursts" message for system loads < 8.5 messages per second. For higher system loads, the "1 burst" message actually experiences higher failure rate when X=1 than when X =0.

Let us focus on the system under system loads > 8.5 messages per second. When X=1, we have seen that the long messages benefit from the RACH access protocol settings to allow the MS to insist strongly on finding a free subchannel (70 trials instead of only 7 when X=0). This means that, with higher system loads, the transmission of the "11 burst" message will take longer time due to the higher burst load on the RACH which requires a longer search for a free subchannel. Additionally, given that the probability of sending the

"11 burst" message successfully on a current RACH subchannel is lower than the "1 burst" message, the "11 bursts" message will have more chances of being retransmitted on a different RACH subchannel. This also applies for the "3 burst" message. Given that long messages represent 70% of the population (see table 4.1), they will occupy the RACH for much more time than in the case of X=0. Therefore, for system loads > 8.5 messages per second with X=1, the "3 burst" and "11 burst" message transmissions will penalize the "1 burst" message which is put under a higher failure rate than what it is in the case of X=0. For system loads < 8.5 messages per second, all the messages will be sent with a lower failure rate when X=1 because the system load is not high enough to create the situation described above.

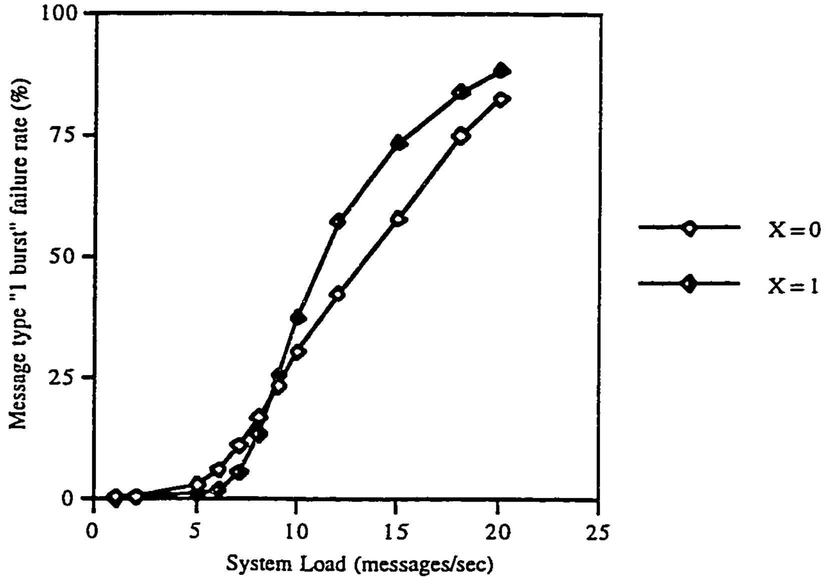


Figure 4.7: Message Type 1 transmission failure rate on the RACH vs System Load
Message Population = {1,3,11 bursts}
Y=7,W=3, and BER = 0.09.

Another observation can be extracted from our analysis noticing almost the same message transmission failure rate for all three messages (despite their burst length) at a given system load when X=1. This is due to the large amount of chances given to an MS to find a free RACH subchannel. In the case X=0, the message transmission failure rate is higher for longer messages due to the limited number of trials to finding a free RACH subchannel.

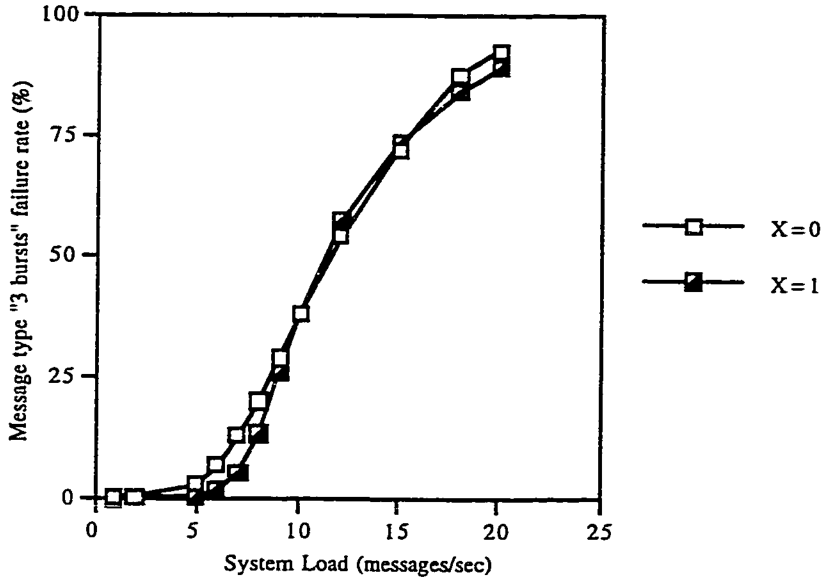


Figure 4.8: Message Type 2 transmission failure rate on the RACH vs System Load
Message Population = {1,3,11 bursts}
Y=7,W=3, and BER = 0.09.

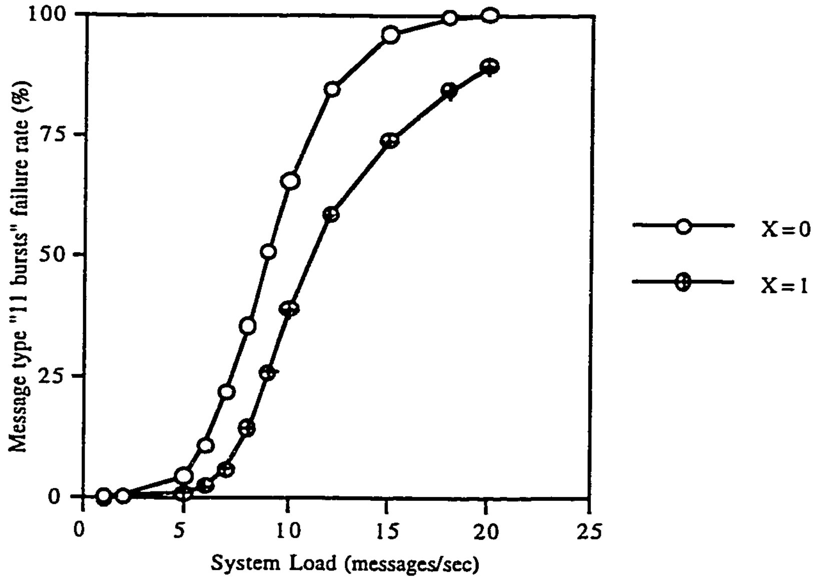


Figure 4.9: Message Type 3 transmission failure rate on the RACH vs System Load
Message Population = {1,3,11 bursts}
Y=7,W=3, and BER = 0.09.

Looking at the BS side, we monitor the BS message queue length and delay. These two metrics will be affected by the service time of the queue (which is linked to the land line, and in our case is 8 kbps. See figure 4.1) and the message arrival time at the input of the queue (which is directly proportional to system load generated by all the MS's in the system).The mean queue length of the BS queue in messages is given in figure 4.10 with respect to the system message load for the two cases X=0 and X=1.

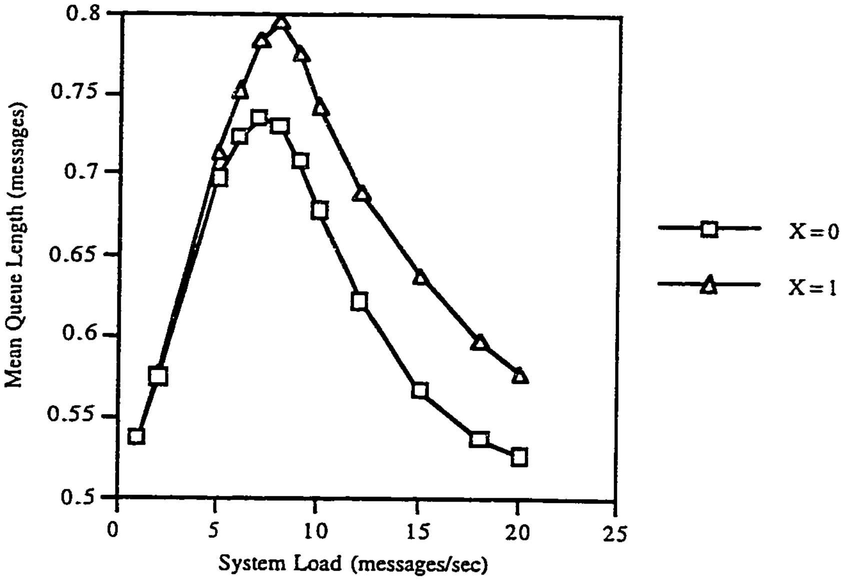


Figure 4.10: Mean Queue Length at BS vs System Load
Message Population = {1,3,11 bursts}
Y=7,W=3, and BER = 0.09.

We can see that the mean queue length behavior follows a bell shape by increasing with system load to a peak value then decreasing towards a minimum. As it was shown earlier, an increase of the system load generated high rate collision on the RACH which led to an increase in the message transmission failure rate. When the load on the RACH hits the point where most of the messages experience collision during transmission, less and less messages actually make it to the BS as the system load increases. Therefore, the BS queue (see figure 4.1) becomes less loaded due to the low traffic entering the BS. By setting X=1, the message failure rate decreases for some message types as shown in figures 4.7, 4.8 and 4.9, and therefore increasing the traffic load at the input of the BS. This obviously increases the message arrival time at the BS queue and in turn increases the mean queue length. Using this reasoning, we know that, the higher the average queue length, the more messages are successfully making it to the BS, and therefore the higher the system throughput. Referring to figure 4.10 and figure 4.11, it can be noted that for X=1, higher average queue length is reached with a higher system load. This shows that with X=1, the system can support more: the average queue length does not start decreasing until after 8 messages per second system load, whereas when X is set to 0, it starts its descent after 7 messages per second.

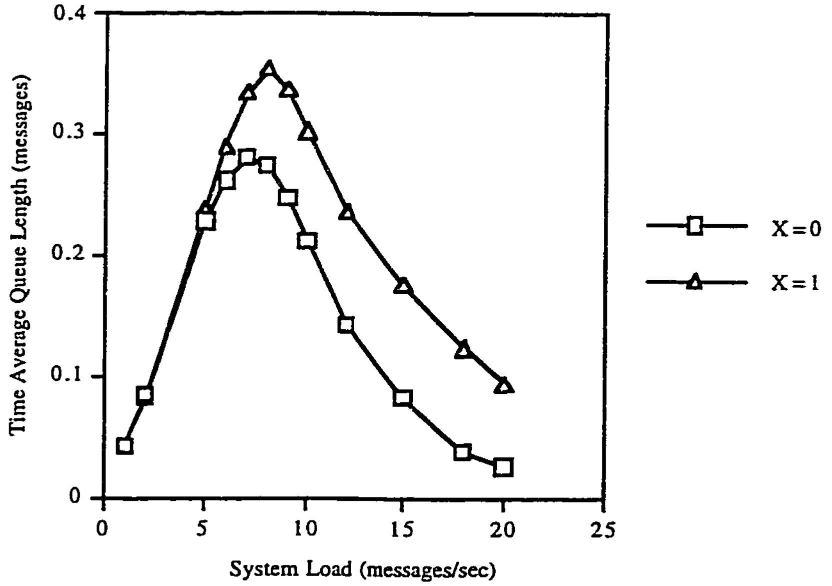


Figure 4.11: Time Average Queue Length at BS vs System Load
Message Population = {1,3,11 bursts}
Y=7,W=3, and BER = 0.09.

The same observation on the average queue length can be done when monitoring the maximum queue length reached during the simulation period in figure 4.12. However being a statistic collected in one moment of time during the simulation run, the accuracy of the result can vary visibly between different initial seeds. However, for X=0, it is clear that the maximum BS queue length is reached under the same system load (7 messages/sec) where the maximum average queue length is obtained (figure 4.11). For X=1, judging from the behavior in figure 4.12, the maximum BS queue length presents a close correlation with the average queue length in figure 4.11.

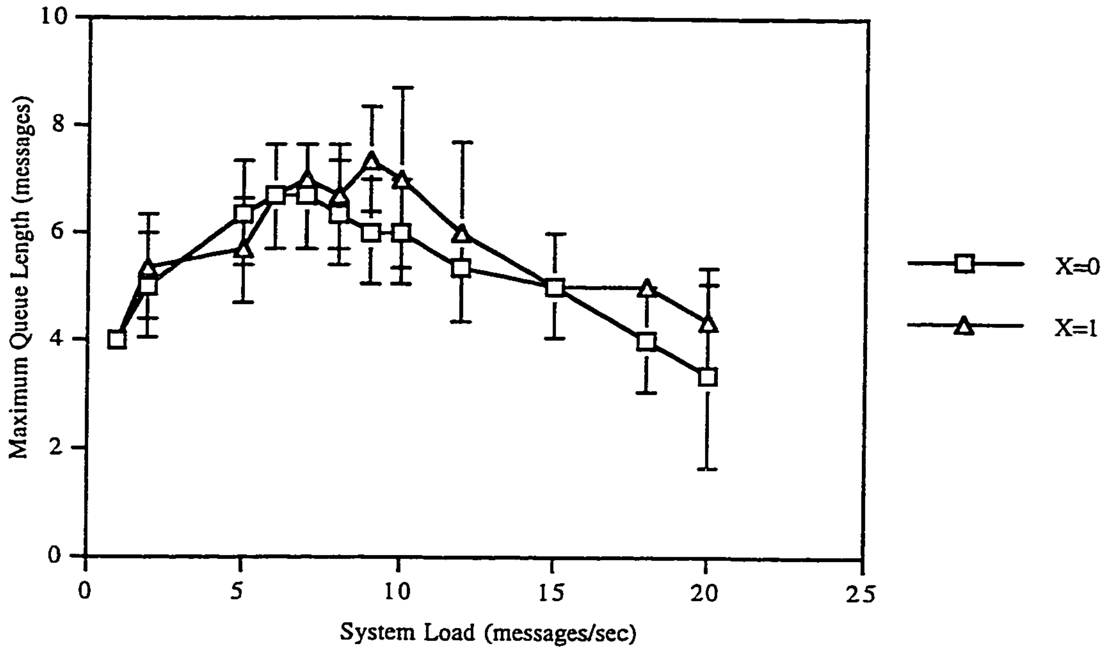


Figure 4.12: Maximum Queue Length at BS vs System Load
Message Population = {1,3,11 bursts}
Y=7,W=3, and BER = 0.09.

An additional statistic gathered during the simulation is the average queue delay shown in figure 4.13. This metric is important for a system engineer having an interest in the end-to-end message delay measuring the total time an MS message takes to reach the MTSO. This factor plays a major contribution in the time delay a user will suffer to get a voice channel after dialing a call. The average queue delay was obtained by measuring the time delay a message experiences when going through the BS queue. This delay is measured from the time the message enters the queue until it leaves the server of the queue onto the land line link (see figure 4.1). Given that the service rate at the queue is constant (introduced as an assumption to be 8 kbps), the message delay will depend on the message arrival rate at the tail of the queue. By increasing the system load on the RACH, the traffic load increases at the input of the BS queue leading to longer queue delays. Note that the average queue delay start decreasing after a system load of 8 messages per second for X=1, and 7 messages per second for X=0. This outcome is in perfect agreement with the observation done on the average queue length in figures 4.10 and 4.11.

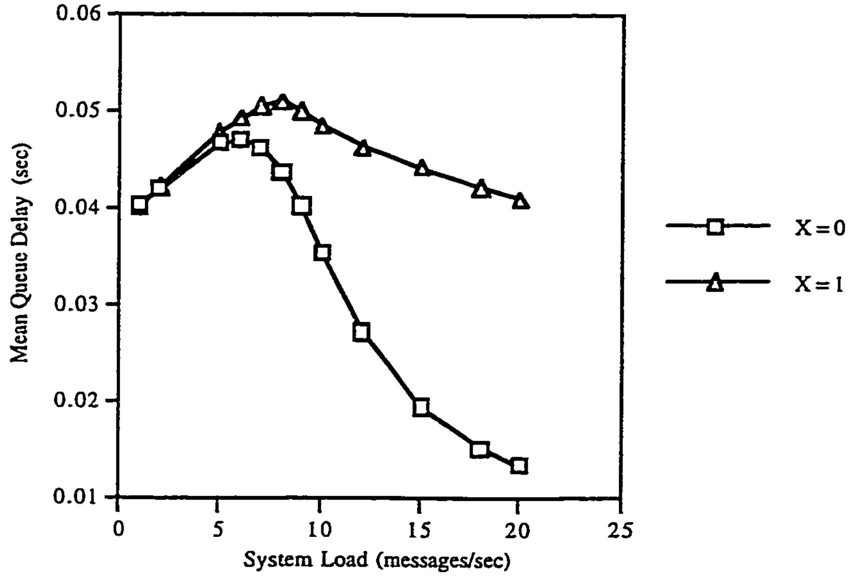


Figure 4.13: Mean Queue Delay at BS vs System Load
Message Population = {1,3,11 bursts}
Y=7,W=3, and BER = 0.09.

One of the last metrics that we monitor is the system throughput variation against the system input message load. Under the pre-mentioned assumptions and messages construction, we measured the normalized throughput and presented it in figure 4.14. The throughput variation is measured with relation to its maximum which is set to unity. Note that 1 in the graph does not mean a 100 percent system throughput but the maximum throughput obtained.

As expected from our discussion on the BS queue length (figures 4.10, 4.11), we can see from the throughput graph that the maximum is reached for a system message load of 7 messages per second for X=0 and 8 messages per second for X=1.

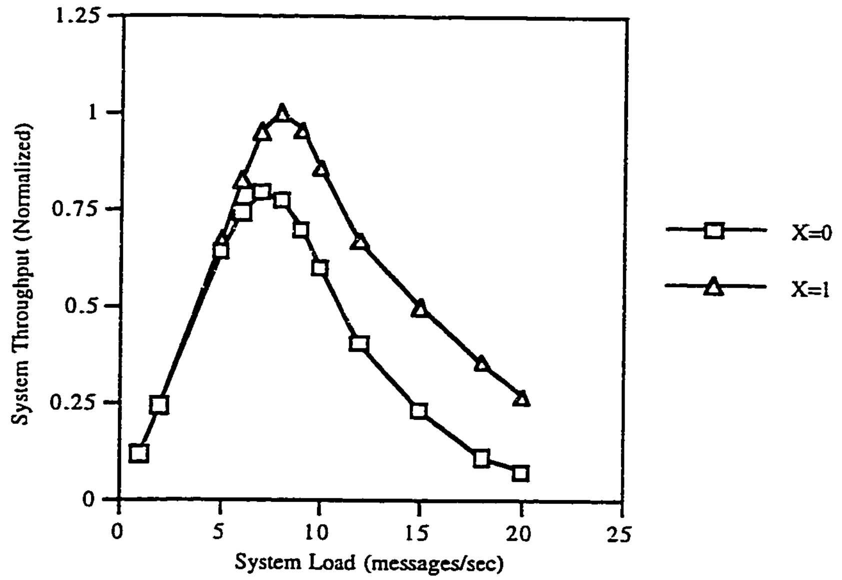


Figure 4.14: System Message Throughput vs System Load
Message Population = {1,3,11 bursts}
Y=7,W=3, and BER = 0.09.

4.4.2 Transmission Channel Quality Effect

Given all the information obtained above, in this section we investigate our modeled cellular system under various channel conditions. To do so, we fix the system load and vary the BER. To work in a safe environment without having the system to crash if pushed to its limits, we operate the system under a load of 5 messages per second judged from the system throughput in figure 4.14.

In this study, three message classes were used to understand the behavior of the system with increasing BER. Each class consists of specific message population generated by all the MS's in the simulated cellular partition. In table 4.5, we present the message types generated in the system within different message classes.

Table 4.5: Message types and rates created at Mobile Stations.

Message Type	1 burst Message	3 bursts Message	11 bursts Message	Message Population Type
Rate	20 %	30 %	50 %	{1,3,11 bursts}
	40 %	60 %	0 %	{1,3 bursts}
	100 %	0 %	0 %	{1 burst}

As table 4.5 shows, for each message type, a generation rate is specified out of the total messages generated during a simulation run. For example, for the message population {1,3 bursts}, 40% of messages created by the MS's are "1 burst" length messages, and the remaining 60% are "3 bursts" length messages. As mentioned earlier, with a fixed system message load of 5 messages per second, the message rates and types follow the notations in table 4.5.

In order to evaluate the impact of the BER on the system, we set X to 0. By doing so, we should be able to see a difference in the message failure rate with relation to BER. By increasing the BER on the RACH, a message being transmitted will fail with a high probability in a first attempt and will try to be re-transmitted on a new RACH subchannel which leads to more transmission retries in the system and therefore a higher burst load on the RACH. In order to see this effect in our simulation results, we set Y to 7 and W to 3. By doing so, we also give more chances for messages to make it through the RACH and see a change in the transmission delay statistics given that we only collect that statistic for successfully transmitted messages. With this, a burst would have 3 chances to be re-transmitted on the same RACH subchannel, and a message would have 7 chances to be re-transmitted on a different RACH subchannel before the MS declares a transmission failure of the message.

With the above set-up, we first monitor the burst load on the RACH as a function of the BER. As mentioned earlier, with higher BER on the RACH, less chances are provided for a burst to reach the BS successfully, and therefore, given that W=3, more retransmissions of a burst are done on the same RACH subchannel and often the message must be re-transmitted on a different RACH subchannel. This scenario obviously leads to a larger burst load on the RACH. Figure 4.15 illustrates this situation. Note that for the message populations {1,3,11 bursts} and {1,3 bursts}, the burst load converges almost towards the same value with higher BER. This is because, at high BER, each burst will suffer a high risk of failure when sent on the RACH, and as the number of attempts for a given burst is bounded, the total burst load will be limited because the message will eventually either be dropped or transmitted.

It is obvious that as the RACH load increases, a smaller amount of free subchannels is available, and therefore the probability of collision increases as BER increases. For the same reason described in the burst load on the RACH, the collision rate for the three message population types converges toward the same value. Figure 4.16 shows that the collision rate exhibits the same behavior as the burst load.

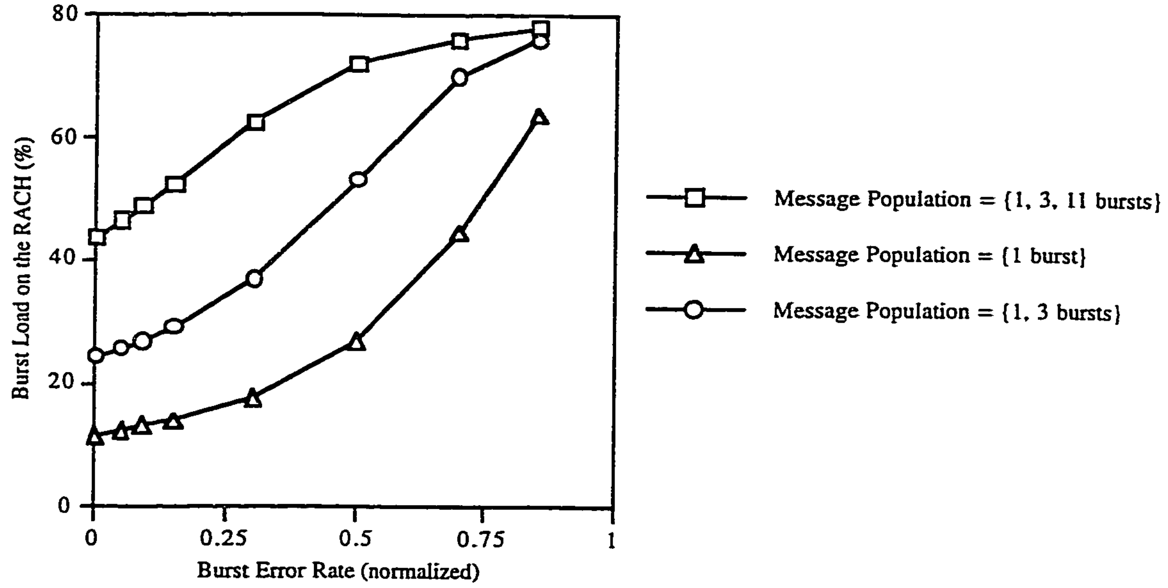


Figure 4.15: Burst Load on the RACH vs Air Channel BER
X=0,Y=7,W=3, and L = 5 messages/sec.

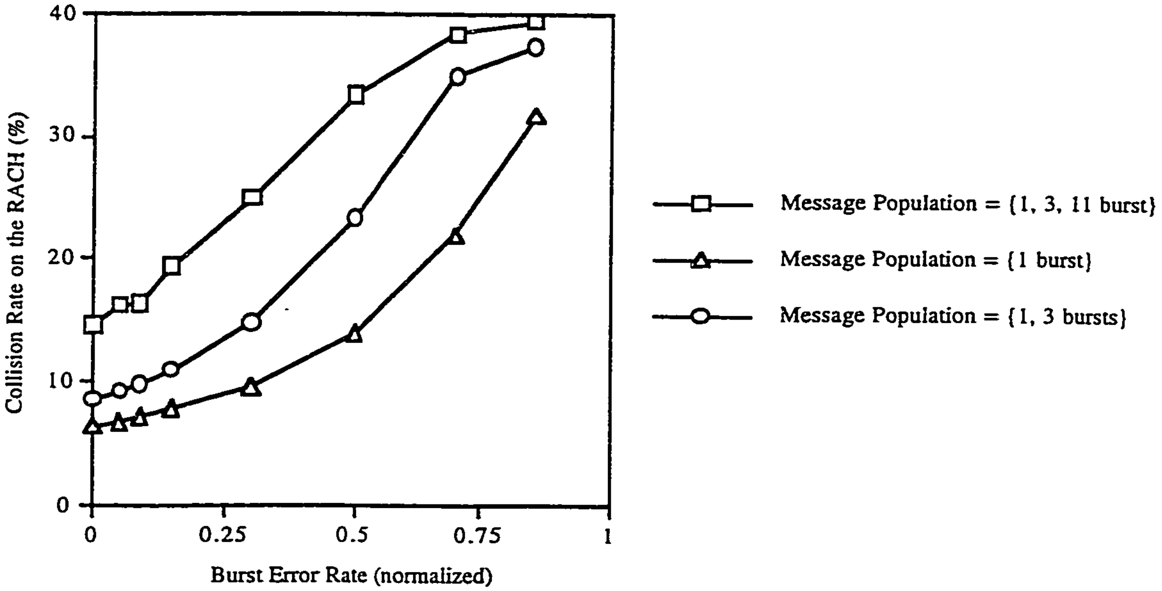


Figure 4.16: Collision rate on the RACH vs Air Channel BER
X=0,Y=7,W=3, and L = 5 messages/sec.

For the message population {1 burst}, the transmission of a message requires to use a RACH subchannel only once. This is done during the access attempt as the MS sends the first burst of its message on a free RACH subchannel, and if successfully received at the BS, the transmission of the message is completed and the RACH subchannel is not even reserved. Under these conditions, a small message failure rate is achievable because the RACH subchannel is not used for a long time. This is shown in the message failure rate graph in figure 4.18. Therefore, it can be easily noted that, for message populations composed of shorter messages, a lower burst load is obtained on the RACH simply due to a lower message failure rate, but obviously increasing with larger BER.

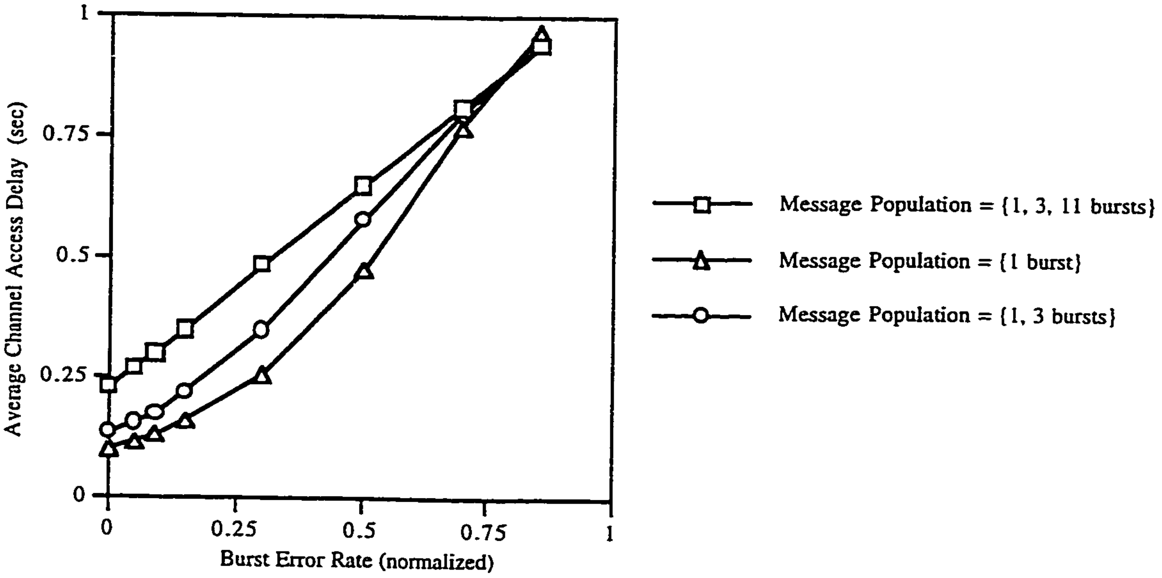


Figure 4.17: Average RACH subchannel Access Delay vs Air Channel BER
X=0,Y=7,W=3, and L = 5 messages/sec.

Looking at the average channel access delay on the RACH, due to the higher collision rate and burst load on the RACH, a longer RACH access delay is shown in figure 4.17 for higher BER. Given that the transmission of longer messages on the RACH requires a longer reservation time of the subchannel, we can note a smaller access delay in message populations containing shorter messages due to the shorter RACH occupancy time. However, for high BER values, all bursts in any of the three message populations considered will suffer a very high BER, and the RACH access delay will heavily depend mainly on the RACH channel quality and not on the burst load excess caused by higher BER. With this, the RACH access delay (measured only for successfully transmitted messages) becomes the same regardless of the message population considered.

Regarding the message transmission failure rate, figure 4.18 shows an increase for each message type. However, as the BER comes closer to the maximum (100 percent burst rejection at the BS), the failure rate converges towards 100 percent.

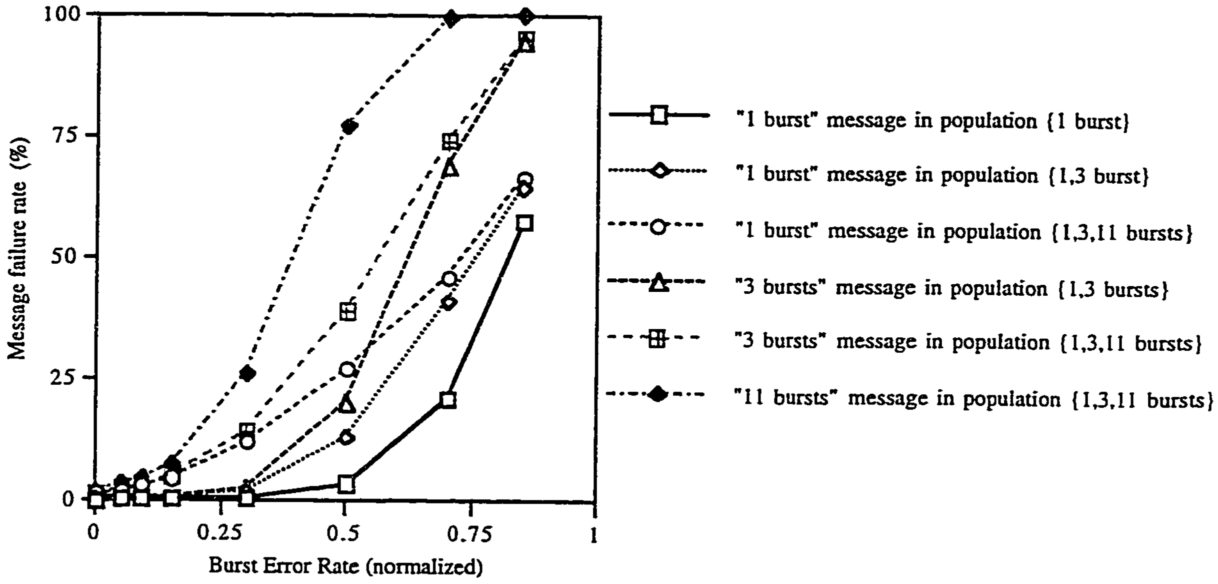


Figure 4.18: Message transmission failure rate vs Air Channel BER X=0,Y=7,W=3, and L = 5 messages/sec.

By looking at the burst load and the collision rate on the RACH (figure 4.15 and 4.16), an agreement in the message failure rate can be seen that, for a given message type, a larger failure rate is obtained when the message shares the RACH with other message types of larger length. This can be clearly seen in figure 4.18 for the "1 burst" message in the message populations {1 burst}, {1,3 bursts} and {1,3,11 bursts} where in the {1 burst} message population, the failure rate is smaller. This effect is simply produced due to the longer RACH subchannel reservation time when longer messages are being transmitted. It can also be seen in the failure rate of the "1 burst" message in the population {1,3,11 bursts} where for BER less than 0.54, the failure rate is larger than the one for the "3 bursts" message in the population {1,3 bursts}.

Another interesting observation can be made when looking at the failure rate of the "3 bursts" message in the population {1,3 bursts}. For BER higher than 0.54, the failure rate for "3 bursts" messages becomes higher than the one for the "1 burst" message in the population {1,3,11 bursts}. This explains that even though a high population of "3 burst" and "11 bursts" messages are sharing the RACH with the "1 burst" message, the latter suffer a smaller failure rate than the "3 bursts" message in a shorter messages population ({1,3 bursts}). This explains the robustness of the "1 burst" message in a very noisy environment: with a BER of 85 percent, 34% of "1 burst" messages still make it to the BS while the other messages only offer a maximum of 5% success. The main reason behind the robustness of the "1 burst" message is its short length which requires only a single time slot for its transmission.

At high BER, all bursts in a message suffer a high failure rate during transmission, and a successful transmission does not depend any more on the burst load on the RACH but mainly on the BER. However, longer messages will definitely suffer a higher failure rate due to their length. Therefore, disregarding the message population type, the failure rate for the same message type converges toward the same value in figure 4.18.

We now move on to monitor the message transmission delay. As longer channel access delay and higher collision rate are presented with higher BER, a longer transmission delay is experienced. Figure 4.19 illustrates the situation.

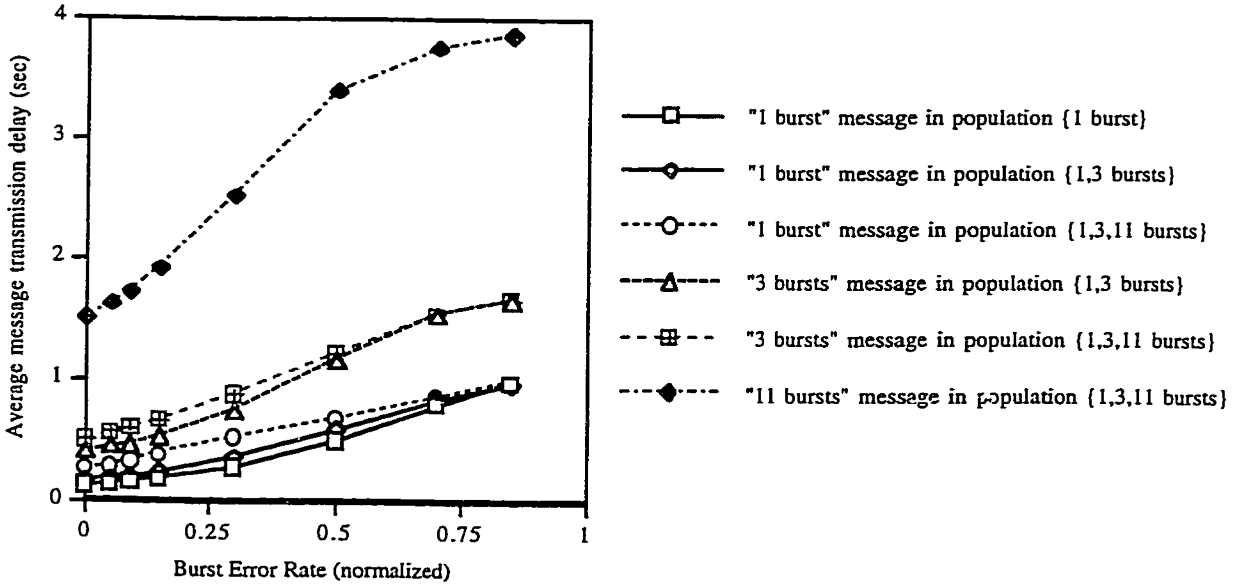


Figure 4.19: Average message transmission delay vs Air Channel BER
X=0,Y=7,W=3, and L = 5 messages/sec.

Having measured the transmission delay only for the successfully transmitted messages, for each message type, the transmission delay converges towards a constant value. Due to lower failure rates (figure 4.18), shorter messages will experience smaller transmission delays. Even that the message failure rate of "3 bursts" message is in some cases smaller than the "1 burst" message (see figure 4.18), figure 4.19 shows that the "3 burst" message still experience a longer transmission delay due to its larger length. If one burst fails transmission on a given subchannel, all bursts of the message must be retransmitted on a new RACH subchannel including the ones that may have been successfully transmitted in the first trial.

It can be noted that for a given message type, disregarding the message population considered, the message transmission delay in all the three message populations converges toward the same value. This is due to the same reasons explaining the message failure rate in figure 4.18 and the RACH access delay in figure 4.17.

Figure 4.20 and 4.21 depict the BS queue length as a function of the BER. Since the message failure rate for each message type increases as a function of the BER and converges towards a 100 percent value (figure 4.18), it is obvious that less messages reach the BS queue. This translates into a shorter BS queue length with higher BER. Figure 4.20 and 4.21 present the mean and time average queue length of the BS queue respectively as a function of the BER.

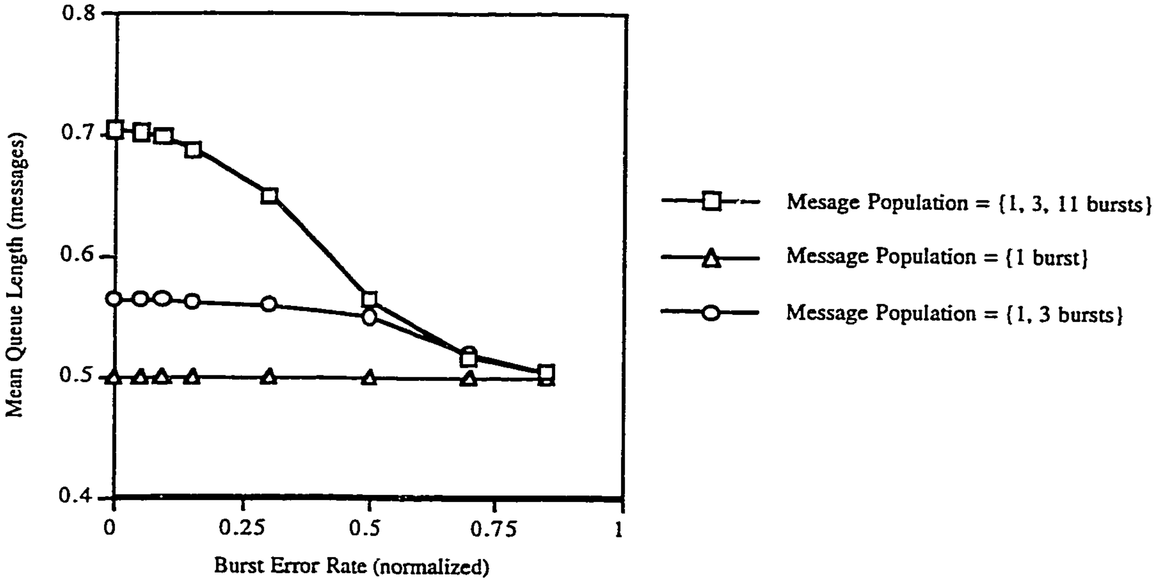


Figure 4.20: Mean Queue Length at BS vs Air Channel BER
X=0,Y=7,W=3, and L = 5 messages/sec.

A valid observation can be done when looking at the queue length in the message population {1,3,11 bursts} with a BER of 70%. Note that the queue length is actually smaller than when the system is operating in a message population {1,3 bursts}. It has already been shown that by adding the "11 burst" message in the message population, a longer processing time is required at the queue to get the message out of the BS into the land line. This results in a larger waiting time to all other messages in the queue leading to a larger average queue length. This can be seen in figure 4.20 for a BER of less than 65%. From figure 4.18, we have that almost 100 percent of "11 burst" messages fail to reach the BS for BER values larger than 70%. Under these conditions, the effect of the "11 bursts" message on the BS queue no longer exist and the message population can be treated as {1,3 bursts} at the BS queue given that most of the "11 bursts" messages did not make it. Comparing the message failure rate for "1 burst" and "3 bursts" messages for BER larger than 70%, we find a higher failure rate in the population {1,3,11 bursts} than in the {1,3 bursts} population (see figure 4.18). With a higher failure rate, less "1 burst" and "3 bursts" messages make it to the BS leading to a smaller average queue length in the BS for the message population {1,3,11 bursts} than the one obtained for the message population {1,3 bursts}. The time average queue length in figure 4.21 shows a clearer view of the scenario.

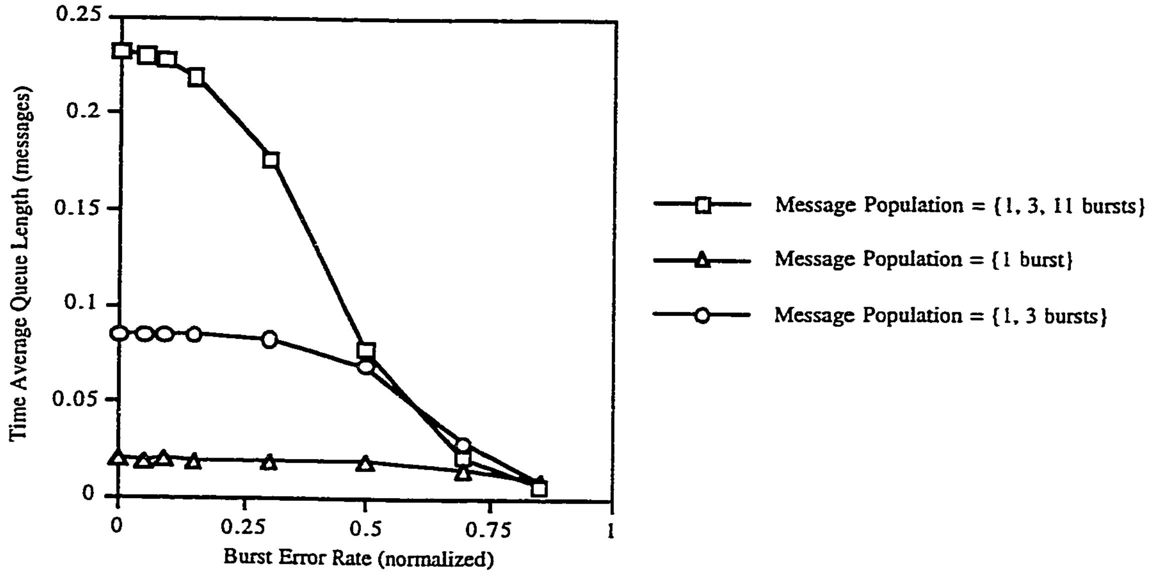


Figure 4.21: Time Average Queue Length at BS vs Air Channel BER
X=0,Y=7,W=3, and L = 5 messages/sec.

As the BER becomes larger, the failure rate of "1 burst" and "3 burst" messages in {1,3,11 bursts} and {1,3 bursts} populations converges to the same value (figure 4.18). This leads to a common average queue length for both cases.

From figure 4.18, a BER of 70% generated 99.23% failure rate for the "11 burst" message delivery in the {1,3,11 bursts} population. Given that some of the messages still make it through and must be processed at the BS queue, the mean queue delay at the BS would show a higher value for the {1,3 bursts} population case. For other values of BER, the mean queue delay shows a decrease in value as BER becomes larger except in the case of {1 burst} population where the value remains constant (figures 4.22). This is due to the short length of the message that requires minimal processing time at the BS queue. This again, proves the robustness of the "1 burst" message where the BS queue characteristics do not severely change with the RACH quality.

In the cases of message populations {1,3 bursts} and {1,3,11 bursts}, as BER increases, the mean queue delay converges toward the same value due to the common message failure rate (figure 4.18).

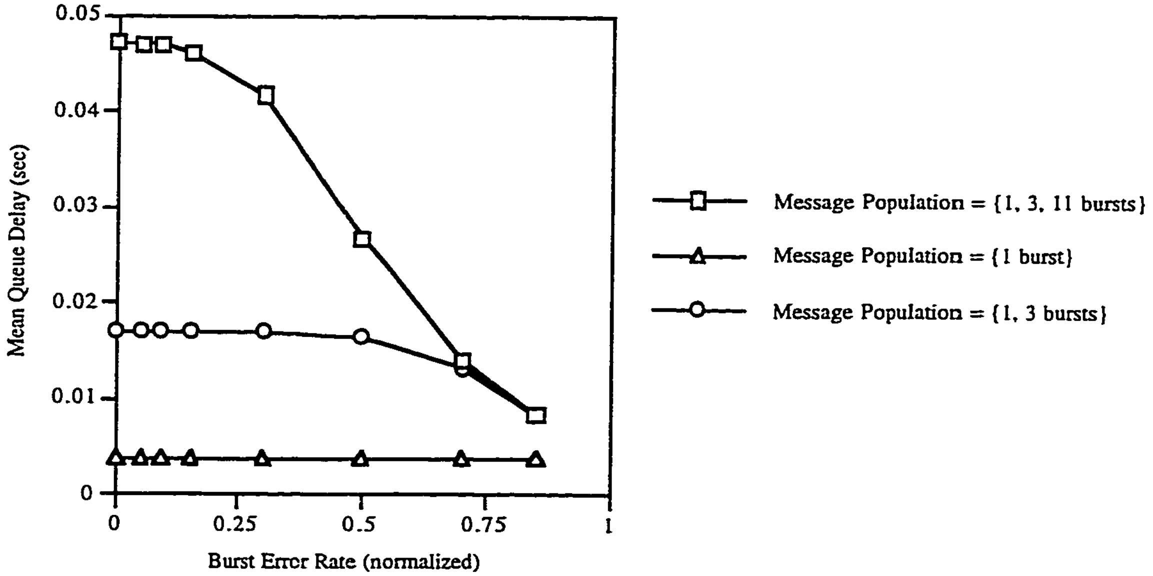


Figure 4.22: Mean Queue Delay at BS vs Air Channel BER
X=0,Y=7,W=3, and L = 5 messages/sec.

4.4.3 Random Access Parameters Effect

Having looked at the behavior of the system under different message loads and channel conditions, we shift our interest to study the effect of varying the random access parameters within the limits defined by the IS-136 standard [IS-1STD].This is crucial since the access parameters are to be set by the cellular service provider in order to meet optimum performance operations in the given operational region.

The main idea is to monitor the changes applied by the access parameters and analyze the results. To cover more ground, we look at the system behavior as a function of the access parameter "Max Retry" (Y for abbreviation. See table 4.4) while varying other parameters and traffic characteristics. To do so, we subdivide this section into three parts where in the first, we focus on the effect of "Max Repetitions" (W) and the second part we vary the message population on the RACH. In the last part, we study the effect provided by "Max Busy/Reserved" (X).

For all the system configurations, we fix the system load to 5 messages per second and the BER to 0.09 on the reverse link.

4.4.3.1 Maximum Repetition Parameter Effect

While studying the effect of W and Y on the system, it is best to have a message population of {1,3,11 bursts} sent on the RACH. By allowing the system to support various message types, we can point out any positive or negative behavior from the system regarding the message type supported.

We first look at the system by varying the "Max Retries" parameter (Y) while setting the "Max Repetitions" parameter to the extreme ends (W= 0,3). To see the effect of Y and W , we set X to 0. As a reminder from the access protocol, Y defines the maximum number of times a message can be retransmitted on a different RACH subchannel, and W defines the maximum number of times a burst can be retransmitted on the same RACH subchannel. When W limits are exceeded, Y counter is incremented by one and W counter is reset to 0.

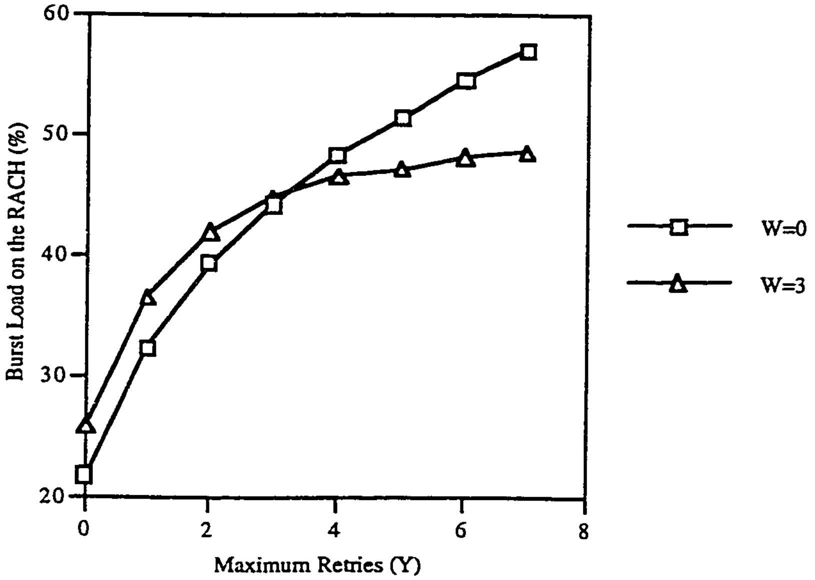


Figure 4.23: Burst Load on the RACH vs Maximum Retries
Message Population = {1,3,11 bursts}
X=0, BER = 0.09, and L = 5 messages/sec.

Figure 4.23 presents the burst load on the RACH as a function of "Max Retries" with W=0 and W=3. With increasing Y, we allow more chances for a message to be retransmitted on a different RACH subchannel after having failed on a current subchannel. By doing so, we increase the burst load on the RACH. This is due to the retransmission of some bursts (belonging to a message) that may have already been successfully sent. By forbidding the retransmission of a burst on the same subchannel after a failure (by setting W to 0), the whole message is declared to have failed on the current subchannel as soon as one of its bursts fails to be received at BS. The MS must then look for a different RACH subchannel if the number of retries is still within the maximum boundaries defined by Y.

Considering the case of Y=0 in figure 4.23, when W=0, each burst in a given message has no chance to be retransmitted on the current subchannel if failed, and given that Y=0, the message cannot be retransmitted on a different subchannel. In this case, the MS abort the transmission. With W set to 3 and Y to 0, if the same situation is to occur, the failed burst will be retransmitted on the same subchannel up to 3 times if necessary before declaring the message transmission a failure. This puts more burst load on the RACH leading as well to a higher collision rate as shown in the figures 4.23 and 4.24 respectively.

As the number of allowed attempts on a different subchannel is increased (by increasing Y), the number of retransmitted bursts also increases causing to have a larger burst load on the RACH with W=0 than in the case of W=3. This is because, by setting W to 3, we reduce the chances of retransmitting some of the bursts that have already been transmitted. This is seen in figure 4.23 for Y values larger than 3. We can therefore say that, setting W to 3 works for the advantage of the system with a reduction in the burst load on the RACH for Y values larger than 3.

With higher burst load on the RACH, higher collision rate is obtained as shown in figure 4.24, and being directly proportional to the burst load on the RACH, the collision rate presents a similar behavior for the same reasons.

From figure 4.23, we have seen a difference in the load between setting W to 0 and 3 for all values of Y. However, in figure 4.25, we can note that for any W, the channel access delay is almost the same when Y is less than 4. This is mainly due to the burst load on the RACH being not high enough to occupy most of the RACH subchannels in order to produce a significant difference in the access delay when compared for W=0 and W=3. This is proven by noticing a difference due to a higher burst load for Y larger than 3. As a result, we can note that the average channel access delay becomes affected by the settings of W for values of Y larger than 3.

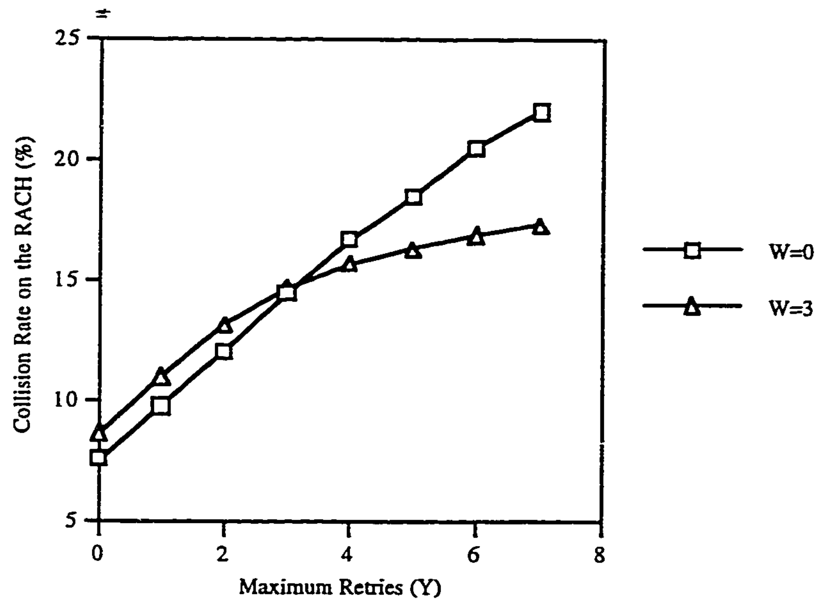


Figure 4.24: Collision Rate on the RACH vs Maximum Retries
Message Population = {1,3,11 bursts}
X=0, BER = 0.09, and L = 5 messages/sec.

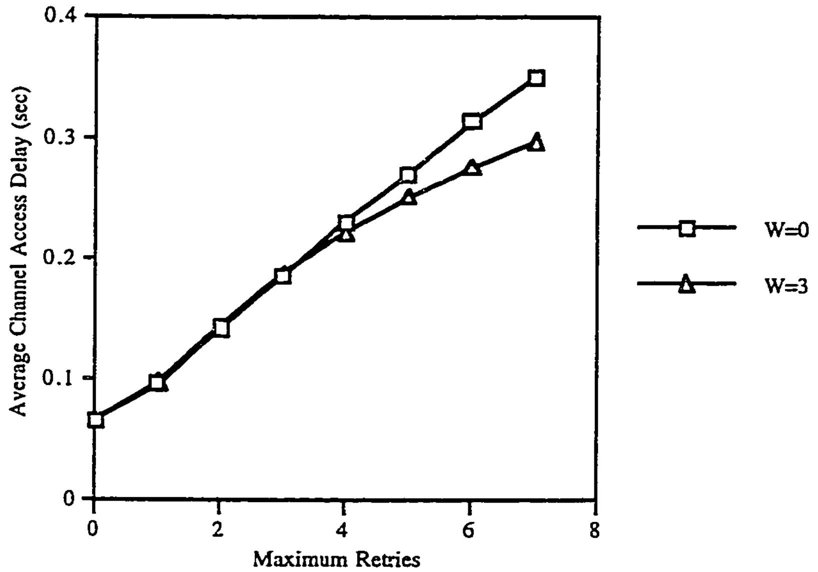


Figure 4.25: Average RACH subchannel Access Delay vs Maximum Retries
Message Population = {1,3,11 bursts}
X=0, BER = 0.09, and L = 5 messages/sec.

Figure 4.26 depicts the transmission failure rate for each of the message types. From the figure, we obtain better results for all messages when W is set to 3 for all values of Y except for the "1 burst" message. Being a message composed of only 1 burst, the transmission of the first burst of the message results in a successful transmission of the whole message. But in order for this to happen, the MS must access a free subchannel before sending the burst on the RACH. If failed, the MS should look for a different RACH subchannel if the value of Y allows it. This simply means that a burst in the "1 burst" message cannot be retransmitted on the current subchannel. Therefore, the "1 burst" message failure rate does not depend on the value of W but on the RACH subchannel availability which is directly proportional to the burst load. With W=3, a larger burst load is shown in figure 4.23 for Y<4 when compared to the case of W=0. This reason leads to a higher failure rate of the "1 burst" message in figure 4.26. However, because the burst load with W=3 becomes smaller for Y>3 (when compared with the case W=0), so the "1 burst" message failure rate.

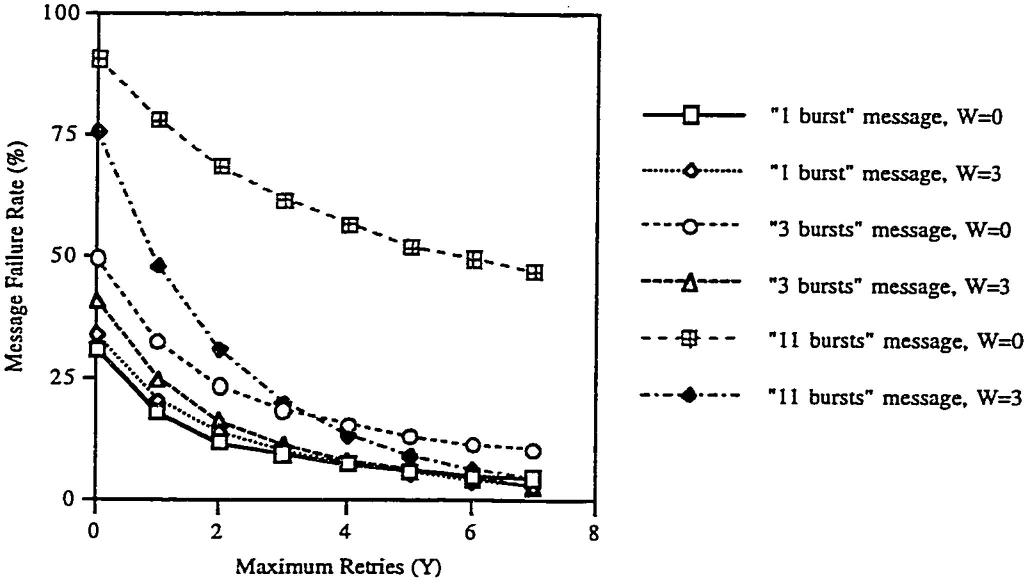


Figure 4.26: Message Transmission Failure Rate vs Maximum Retries
Message Population = {1,3,11 bursts}
X=0, BER = 0.09, and L = 5 messages/sec.

Another observation can be made on the "11 bursts" message failure rate for Y>3 with W set to 3. It can be noted that the failure rate is smaller than the one for "3 bursts" message when W=0. This proves the efficiency of setting W to 3 for Y larger than 3.

A last comment can be made by observing the failure rate converging to the same value regardless of the message length at Y=7 with W set to 3. This observation is in perfect agreement with the previously obtained results when varying the system message load in figures 4.7, 4.8 and 4.9.

In figure 4.27, we look at the effect of W on the message transmission delay for each message type. The "1 burst" message experiences the same delay for all Y less than 4. Being a message composed of a single burst, the transmission delay is the same as the access delay which is the same for all Y less than 4 as depicted in figure 4.25. The other message types experience a smaller transmission delay for Y less than 2 with W set to 0, but larger value for Y larger than 1. The same reasoning as for the burst load on the RACH in figure 4.23 applies.

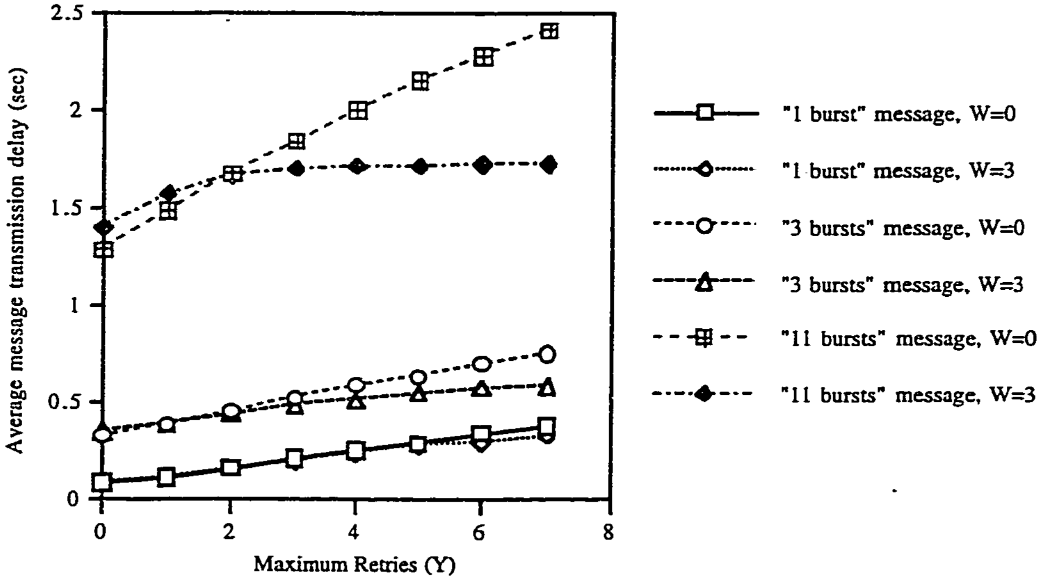


Figure 4.27: Average Message Transmission Delay vs Maximum Retries
Message Population = {1,3,11 bursts}
X=0, BER = 0.09, and L = 5 messages/sec.

It can be noted that, for W=3, the average transmission delay for each message type tends to settle at a constant value especially in the "11 bursts" message case. This is due to the same behavior of the burst load on the RACH depicted in figure 4.23, and knowing that the message transmission delay is directly proportional to the burst load.

With the knowledge of decreasing failure rate as higher values are given to Y, it is obvious that the queue length at the BS will increase with Y in the reverse direction of the message failure rate due to the higher number of messages successfully reaching the BS. This is clearly shown in the mean and time average queue length simulation statistics in figures 4.28 and 4.29 where the queue length converges towards a constant value for both boundaries of W.

Given that the processor in the BS queue will process any message waiting in the queue, the queue length is directly proportional to the message arrival rate at its input. The latter is inversely proportional to the message transmission failure rate over the RACH. From figure 4.26, we note a higher message failure rate with W set to 0 for most of the message types. The BS queue length being reversibly proportional to the message failure rate will present an inverse behavior resulting in smaller values for W=0 when compared to the case of W=3. Figures 4.28 illustrates the situation. The same analysis can be applied on the mean queue delay presented in figure 4.30.

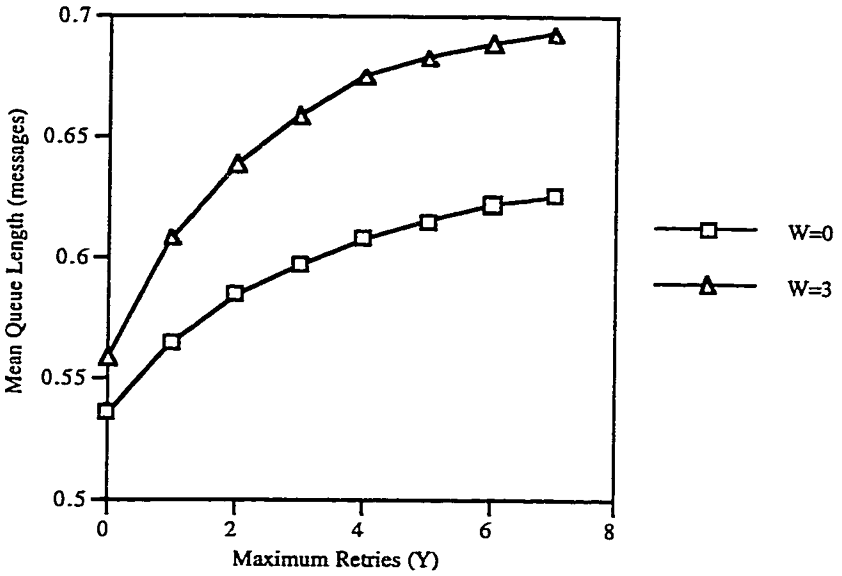


Figure 4.28: Mean Queue Length at BS vs Maximum Retries
Message Population = {1,3,11 bursts}
X=0, BER = 0.09, and L = 5 messages/sec.

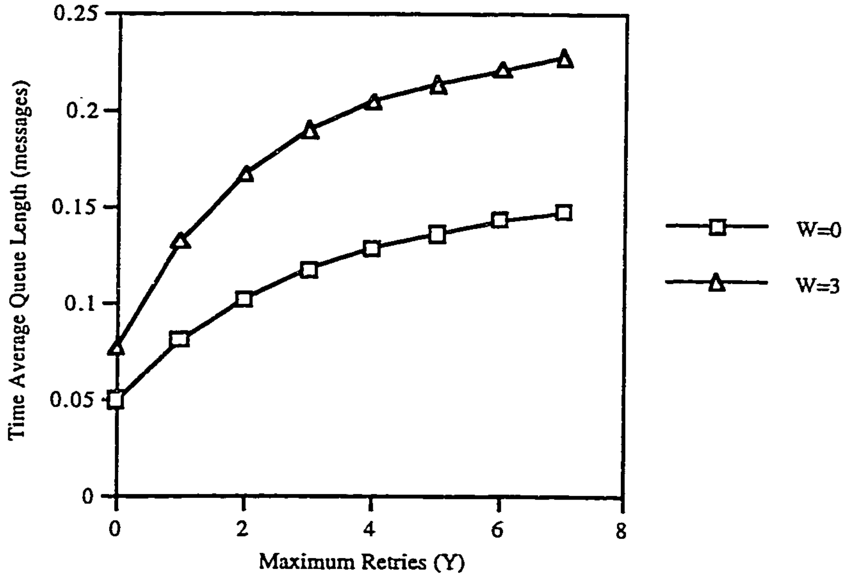


Figure 4.29: Time Average Queue Length at BS vs Maximum Retries
Message Population = {1,3,11 bursts}
X=0, BER = 0.09, and L = 5 messages/sec.

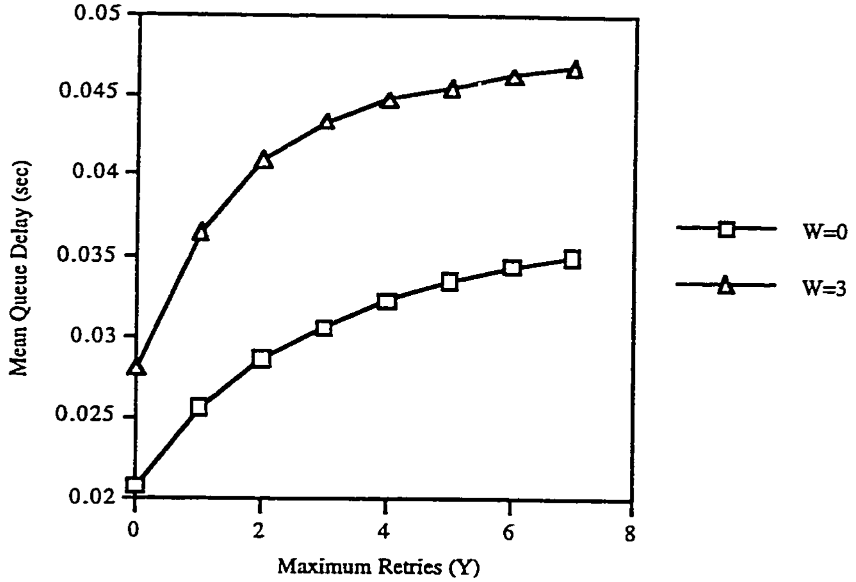


Figure 4.30: Mean Queue Delay at BS vs Maximum Retries
Message Population = {1,3,11 bursts}
X=0, BER = 0.09, and L = 5 messages/sec.

4.4.3.2 Message Population Effect

In this section, we study the effect of the message population content while varying "Max Retry" (Y). We will investigate the system with and without the support for long messages (i.e., with and without the "11 bursts" message).

By comparing the burst load on the RACH for the message population {1,3 bursts} and {1,3,11 burst}, we can note from figure 4.31 the same behavior but at different load amplitudes. Due to the need to send longer messages on the RACH, it is obvious in the case of {1,3,11 busts} population that a higher burst load is submitted to the system. By increasing the Maximum Retry limit (Y), it can be noted that the burst load for the message population {1,3 bursts} converges to a constant level for Y > 3. This is due to having almost the same message failure rate for all Y larger than 3 (see figure 4.34); the common message failure rate for Y>3 implies a non-increasing number of retries during the transmission of a message, and therefore the same burst load on the RACH is delivered to the system. For the message population {1,3,11 bursts} however, the message failure rate keeps decreasing with Y and converges towards the same value at Y=7. This leads to having a slightly increasing burst load on the RACH for Y>7.

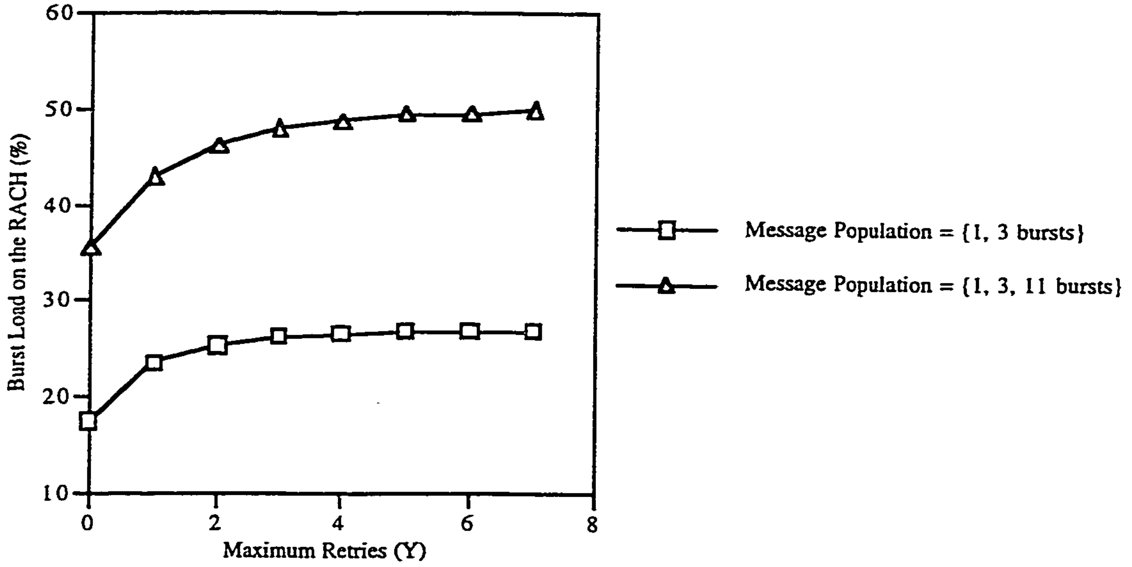


Figure 4.31: Burst Load on the RACH vs Maximum Retries
X=0, W=3, BER = 0.09, and L = 5 messages/sec.

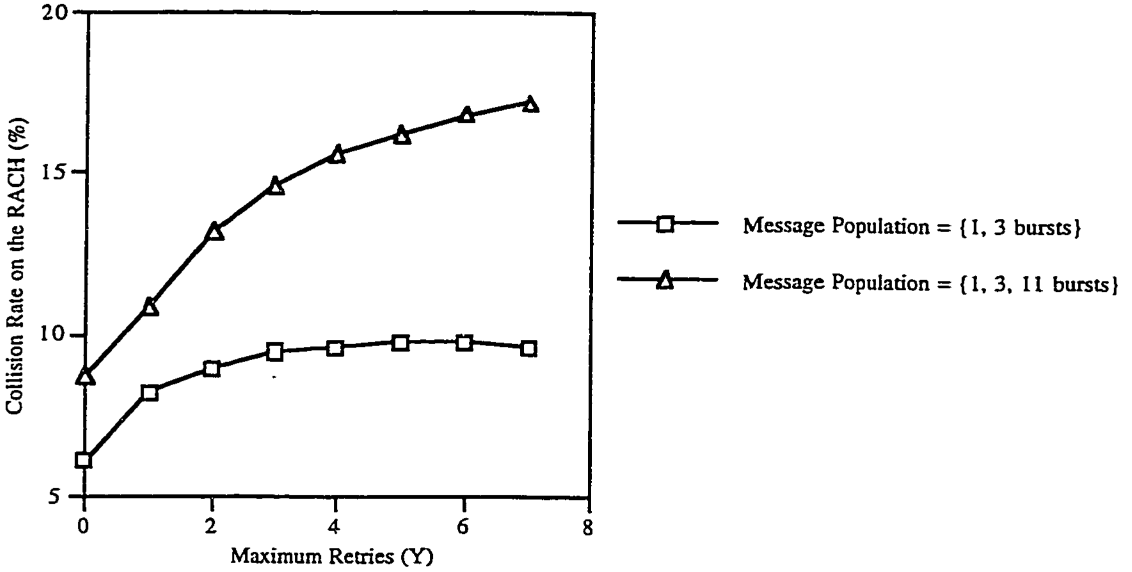


Figure 4.32: Collision Rate on the RACH vs Maximum Retries
X=0, W=3, BER = 0.09, and L = 5 messages/sec.

The load variation described above for the two types of message populations is reflected in the collision rate on the RACH in figure 4.32 which depicts a direct relationship to the burst load: a constantly increasing collision rate with larger Y occurs with the message population {1,3,11 burst} whereas for message population {1,3 bursts}, the collision rate levels off and becomes almost the same for values of Y larger than 3.

Due to the increasing collision rate on the RACH for the message population {1,3,11 burst}, it is normal to see in figure 4.33, the same behavior with the average channel access delay. For the message population {1,3 bursts}, the access delay levels off around Y=5, but slows down its increment rate at Y=3 just as seen in the collision rate.

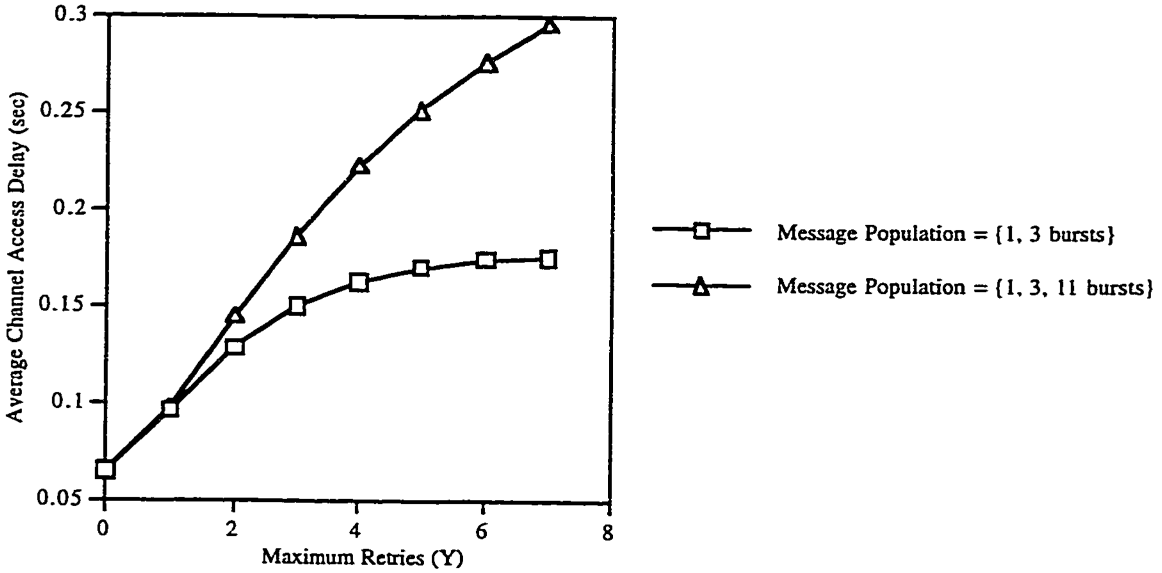


Figure 4.33: Average RACH Subchannel Access Delay vs Maximum Retries X=0, W=3, BER = 0.09, and L = 5 messages/sec.

An additional observation can be seen for Y values less than 2 where the channel access delay is the same for both message populations. Because the collision rate in these cases of Y does not have a big difference for both message populations used, and due to the minimal burst load on the RACH, the probability of finding a free RACH subchannel is high and tend to be the same for both message populations. As the burst load and collision rate increase on the RACH with larger Y, the channel access delay in the message population {1,3 bursts} becomes smaller than in the message population {1,3,11 bursts} due to the smaller burst load on the RACH.

By allowing a message to attempt retransmission on a different RACH subchannel (achieved by increasing Y), from previous analysis presented in this chapter, we can predict a decrease in the message failure rate in the system. Figure 4.34 illustrates the situation.

Looking first at the message population {1,3 bursts}, the "1 burst" message, due to its shorter length, offer a smaller failure rate for Y values less than 3. For larger values of Y, the failure rate of the "1 burst" and "3 burst" messages is almost the same, and obviously decreasing with higher Y. This is because the collision rate and the burst load on the RACH offer the same rate for theses values of Y.

The same behavior is presented in the message population {1,3,11 bursts}, except that the failure rate for "1 burst" and "3 bursts" messages doesn't become the same until for Y values larger than 4.

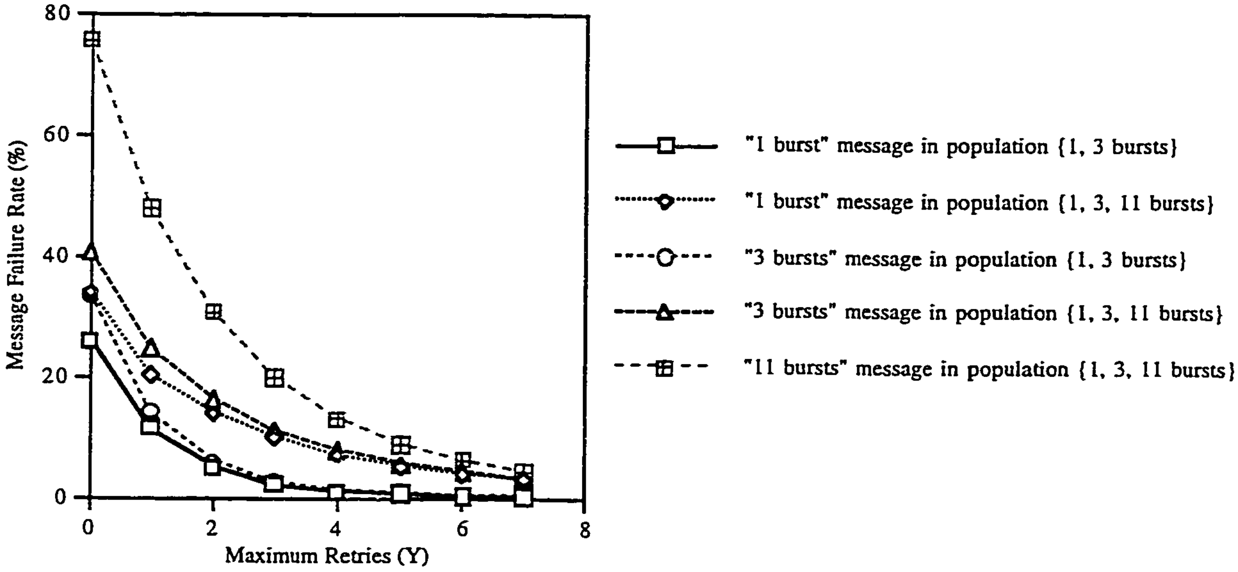


Figure 4.34: Message Transmission Failure Rate vs Maximum Retries
X=0, W=3, BER = 0.09, and L = 5 messages/sec.

With a system load of 5 messages per second created by all the MS's, setting Y to 7, the message failure rate converges towards the same value, therefore becoming independent of the message population or message length due to the sufficient number of retries of message transmission. This result has also been observed in this chapter when studying the cellular system under different system loads (figures 4.7, 4.8 and 4.9).

Given that the message transmission delay depends on the message length and the burst load on the RACH, a similar behavior as the burst load is observed in figure 4.35 where the transmission delay increases at a slower rate as Y becomes larger for the message population {1,3,11 bursts}. However, in any case of Y, the longer the message length, the higher is the transmission delay.

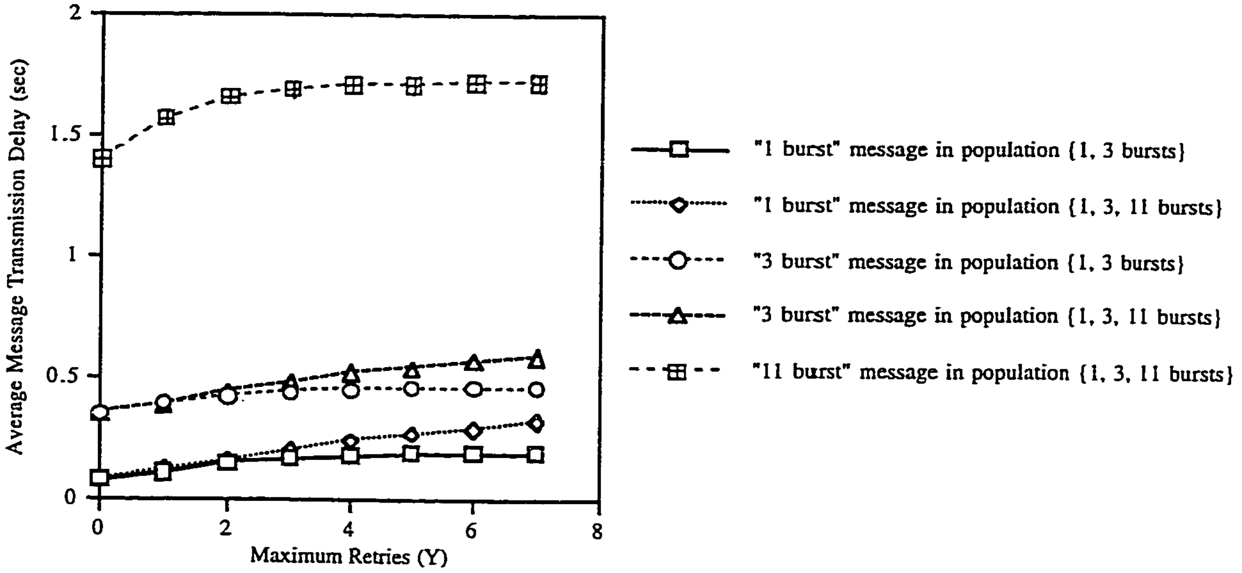


Figure 4.35: Average Message Transmission Delay vs Maximum Retries
X=0, W=3, BER = 0.09, and L = 5 messages/sec.

For the message population {1,3 bursts}, the message transmission delay offer almost the same value for Y larger than 3. This is a reflection of the load presented in figure 4.31.

We can conclude that the longer the message length, and the higher the message population, the longer is the message transmission delay.

As the failure rate decreases with higher Y, more messages reach the BS queue therefore providing a higher input message rate at the input of the queue. For the message population {1,3,11 bursts}, the BS input message rate increases for every larger Y due to constantly decreasing failure rate, whereas in the message population {1,3 bursts}, the message failure rate becomes the same for Y values higher than 3 leading to a constant BS queue input message rate.

The BS queue, having a constant service rate, the queue length and queue delay will depend on the message length and the message arrival rate. Being inversely proportional to the message failure rate, the BS time average queue length in figure 4.36 reads the same value for Y>3 in the message population {1,3 bursts} and increases at a faster rate in the message population {1,3,11 burst}. In figure 4.37, the mean queue delay presents the same behavior except that in the message population {1,3 bursts}, the queue delay increase is not significant (when compared to the population {1,3,11 bursts}). This is due to the short service time of short messages.

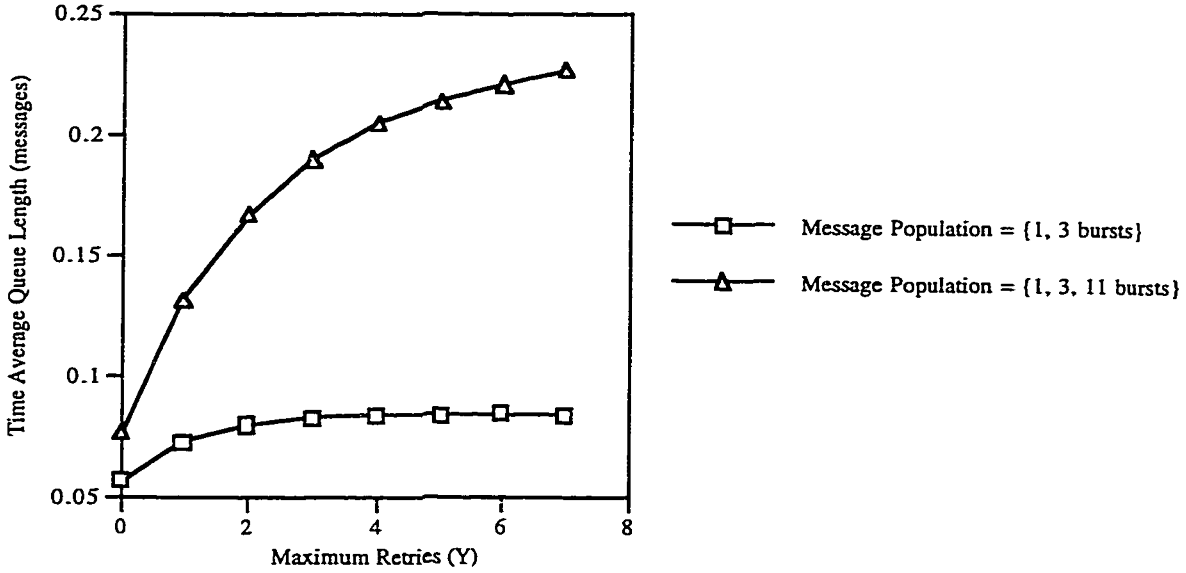


Figure 4.36: Time Average Queue Length vs Maximum Retries
X=0, W=3, BER = 0.09, and L = 5 messages/sec.

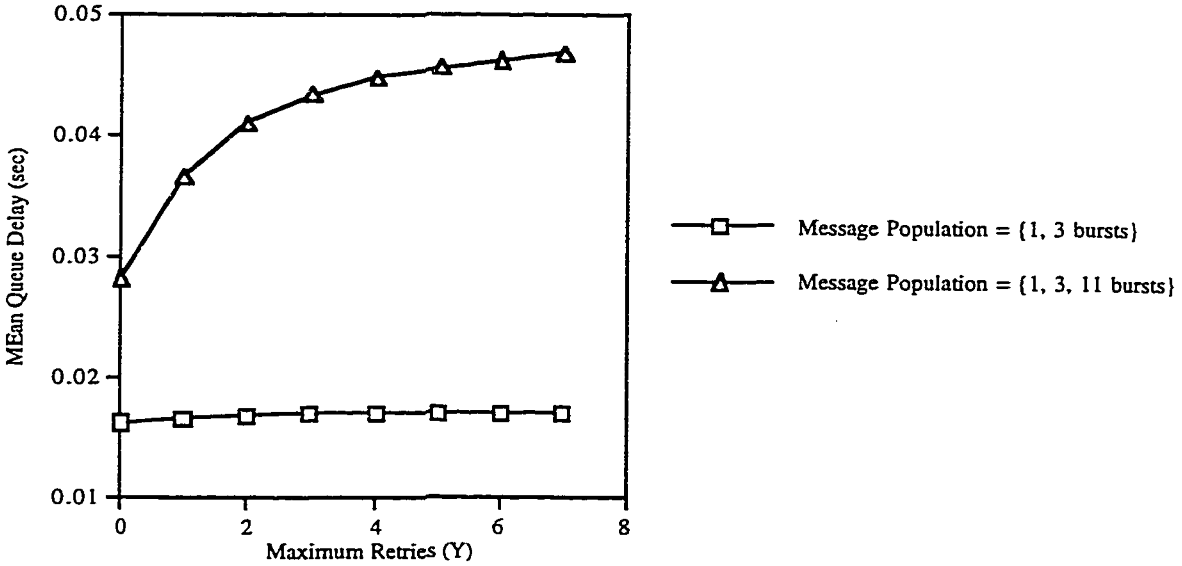


Figure 4.37: Mean Queue Delay vs Maximum Retries
X=0, W=3, BER = 0.09, and L = 5 messages/sec.

4.4.3.3 Maximum Busy/Reserved Parameter Effect

We now switch our attention to study the effect of the parameter "Max Busy/Reserved" (X) while varying "Max Repetition" (Y). Note that setting X to 1 will allow the MS 10 attempts to look for a free RACH subchannel before incrementing "Max Retry" counter (see RACH access protocol in chapter 3) therefore incrementing the number of attempts on the RACH.

Figure 4.38 presents the burst load on the RACH as a function of Y for X=0 and X=1. For Y=0 and X=0, the burst load on the RACH is due to the system message load (5 messages/second) and retransmissions. An extra burst load is added to the RACH when X=1 because the MS's insist more on finding a free subchannel before dropping the message. This means that more messages will attempt to access the RACH, therefore a higher burst load is submitted to the system.

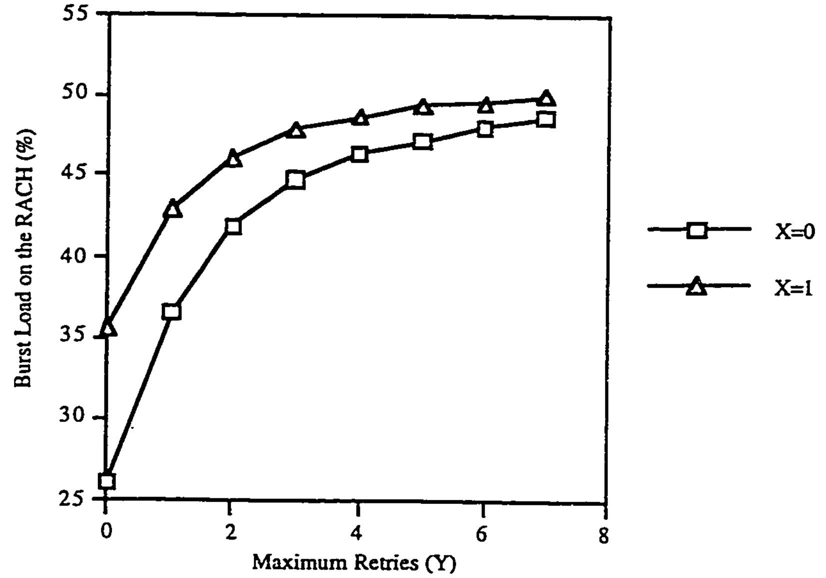


Figure 4.38: Burst Load on the RACH vs Maximum Retries
Message Population = {1,3,11 bursts}
W=3, BER = 0.09, and L = 5 messages/sec.

As the number of allowed attempts of the message transmission on a different RACH subchannel is increased (by increasing Y), additional burst load on the RACH is created and more messages successfully reach the BS therefore decreasing the transmission failure rate as seen in figure 4.39.

For X=1, at a given value of Y, we can note that the message failure rate is almost the same for any message type. This is due to the increasing number of attempts to look for a free RACH subchannel.

For X=0, however, given the limited number of attempts to find a free subchannel, the message transmission failure rate becomes more dependent on Y and the BER on the RACH. Given that longer messages have a higher probability of failing on one subchannel and must try to use another (due to BER factor), the message failure rate will depend on the message length and Y. However, as more retransmission attempts are allowed (by increasing Y), the transmission failure rate of the three message types will converge toward the same value.

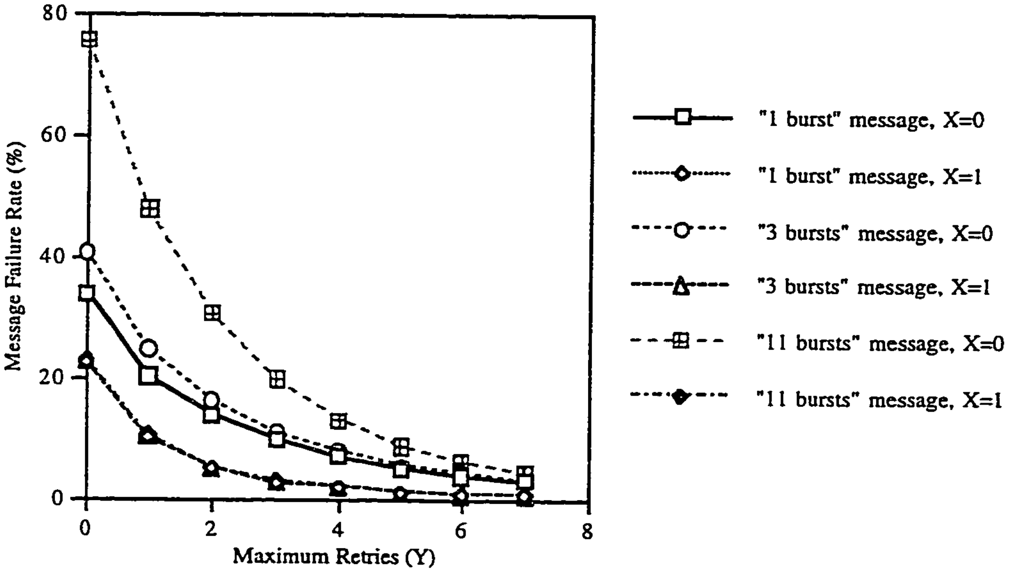


Figure 4.39: Message Transmission Failure Rate vs Maximum Retries
Message Population = {1,3,11 bursts}
W=3, BER = 0.09, and L = 5 messages/sec.

For both settings of X, an increase in the burst load with higher values of Y was observed in figure 4.38. Being proportional to the burst load, the message transmission delay exhibits the same behavior in figure 4.40.

Considering the case at Y=0, with X=0, in order to transmit a message successfully, an MS must be able to transmit all the bursts of the message over the same subchannel, and a free RACH subchannel must be found the moment where the MS starts looking for one. Otherwise, the message is dropped. With X=1 however, 10 attempts are allowed for the MS to find a free RACH subchannel, therefore a lower transmission failure rate is obtained (as seen in figure 4.39) but a higher transmission delay is required due to the longer search time for a free RACH subchannel.

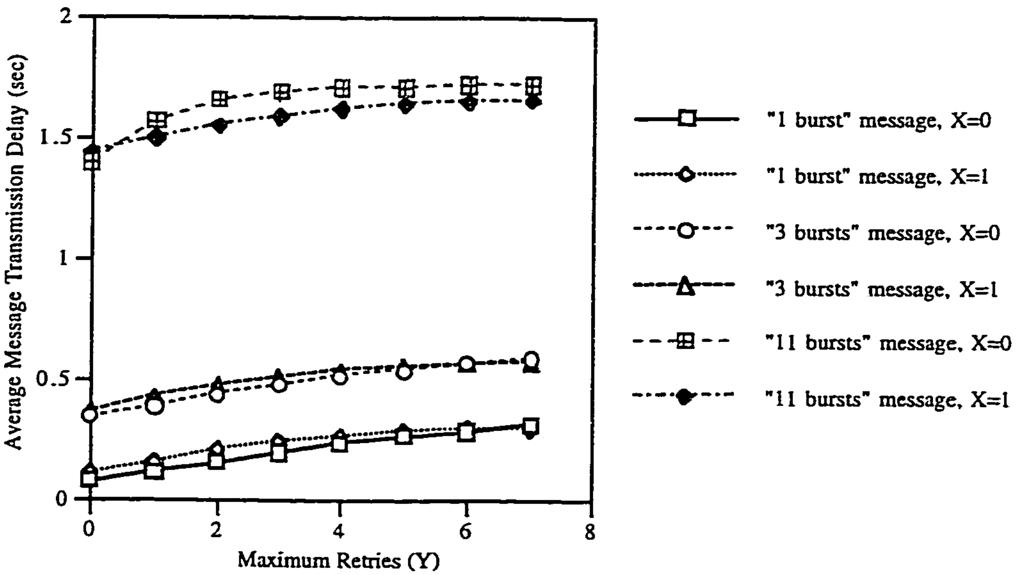


Figure 4.40: Average Message Transmission Delay vs Maximum Retries
Message Population = {1,3,11 bursts}
W=3, BER = 0.09, and L = 5 messages/sec.

Based on the RACH access protocol described in chapter 3, the MS experiences two types of random delays that waits for before taking the next action. Let us call them X-delay (created from using the access parameter X) and Y-delay (created from using the access parameter Y). If X=1, the X-delay is started when the MS does not read a free RACH subchannel and must try to transmit at a later time. The X counter in this case is incremented by one after every trial. The X-delay ranges between 0 and 6 TDMA Blocks (or 0 to 120 ms). If X=0, the X counter and X-delay are not used. The Y-delay is started when the message transmission fails on a given RACH subchannel (or MS fails to find a free subchannel) and the MS must try to transmit the message on another subchannel. The Y counter in this case is incremented by one at each attempt. The Y-delay ranges between 0 and 20 TDMA Blocks (or 0 to 400 ms) if Y=1, and 0 to 6 TDMA Blocks the first trial, and 0 to 20 TDMA Blocks for all others when Y>1.

In the case of lower values of Y, lower burst loads on the RACH are obtained, and most message retransmissions will be caused by the BER on the RACH. Given that longer messages are more affected by the BER, the number of message retransmission on a different subchannel in their case is higher (compared to short messages), therefore the Y counter is used more often.

When X=0, the Y counter is used (if Y>0) by the MS to look for a free subchannel and to retry the message transmission on another subchannel. Given that the Y delay is larger than the X delay, the message will experience longer transmission delays when the X counter is not used (X=0). This is illustrated in figure 4.40 for the "11 bursts" message.

For shorter messages however (3 bursts and 1 burst length), the BER effect is not as high as it is for long messages (during lower burst loads on the RACH), and the Y counter is not used as much. Therefore, the main effect on the transmission delay comes from the attempts to find a free subchannel. By allowing more attempts to find a free subchannel (setting X to 1), a higher collision rate is obtained on the RACH (compared to X=0) due to the higher burst load submitted (figure 4.38). In that case, the MS insist more on finding a free subchannel therefore a longer transmission delay is obtained than in the case of X=0 where the collision rate is not as high.

As Y is set to higher values, the burst load on the RACH converges toward the same value in both cases of X=0 and X=1. The collision therefore provides the same behavior, and the Y counter is used more creating a slightly longer transmission delay when X=0 for the short messages (3 and 1 burst messages).

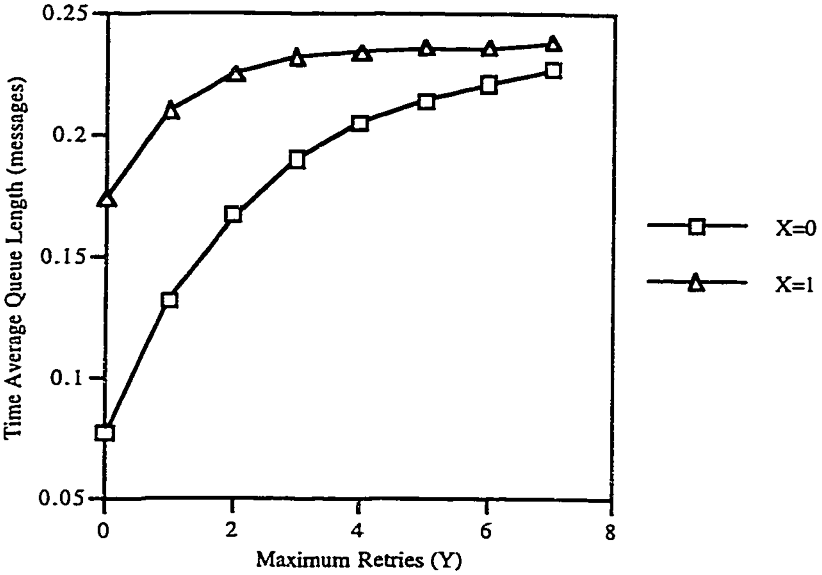


Figure 4.41: Time Average Queue Length vs Maximum Retries
Message Population = {1,3,11 bursts}
W=3, BER = 0.09, and L = 5 messages/sec.

Being directly proportional to the message rate at the input of the BS queue, the queue length and queue delay increases with Y exhibiting the reverse behavior of the message transmission failure rate for both setting of X. The results are presented in figures 4.41 and 4.42 for the time average queue length and mean queue length respectively.

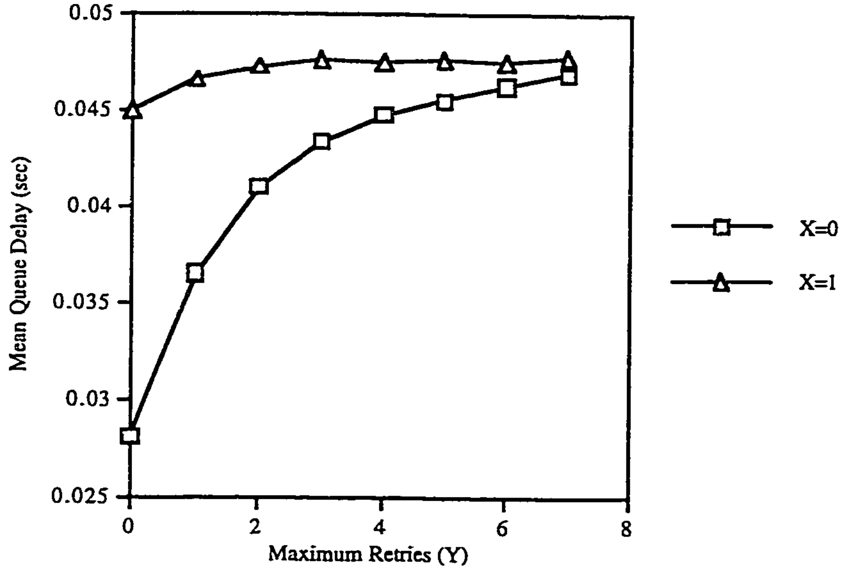


Figure 4.42: Mean Queue Delay vs Maximum Retries
Message Population = {1,3,11 bursts}
W=3, BER = 0.09, and L = 5 messages/sec.

4.4.4 Message Transmission Delay Analysis

One last study was done on the system with focus on the message transmission delay given that this parameter will mostly affect the quality of service perceived by the user. For different values of "Maximum Repetitions" (W), the message transmission delay for the "11 burst" message was measured against various channel conditions. The results are depicted in figure 4.43.

As we have seen earlier in this chapter, the "11 bursts" message failure rate and transmission delay increase with higher BER. In figure 4.43, we can see the effect of W on the transmission delay for values of BER < 0.2, the transmission delay decreases with larger W. This is because the system allows less attempts to the MS's to retransmit bursts that were already successfully transmitted. We can also say that this effect causes the failure rate to decrease (see section of maximum repetition parameter effect of this chapter). For each case of W in figure 4.43, as BER increases, the transmission delay increases until a situation occurs where a large number of the "11 burst" messages need more time than allowed by the access protocol to be transmitted, and therefore the message transmission is aborted. After that, due to the high transmission failure rate and the load on the RACH, the only messages that will actually make it through are the ones that are able to be sent in shorter times. That is if it would had to take slightly more time to get through, it would have failed the transmission and not included as part of the measured statistics. Therefore, the threshold allowed for the transmission delay of successfully transmitted messages becomes smaller as the BER increases and therefore allowing less and less "11 bursts" messages to make it through. In cases of W=0 and W=1, for BER larger than 0.5 and 0.7 respectively, no statistics are available due to the 100% message transmission failure rate (for the "11 bursts" messages in the message population {1,3,11 bursts}), and a decrease in the transmission delay explains a display of only the "11 bursts" messages with shorter transmission delay.

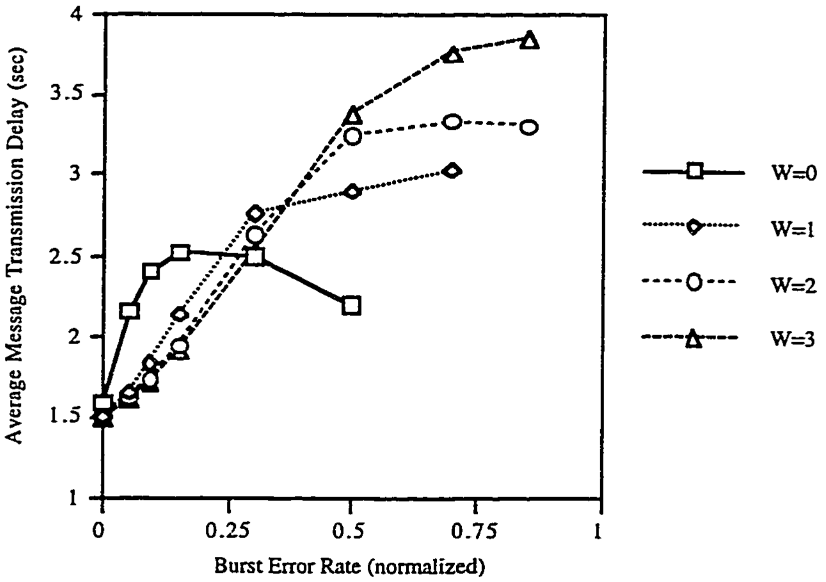


Figure 4.43: Average Message Transmission Delay vs Air Channel BER
Message Population = {1,3,11 bursts},
Message type = "11 bursts", X=0, Y=7, and L = 5 messages/sec.

Even though the above analysis results in a non-effective behavior when W is set to zero, it is important to keep in mind that it is highly unrealistic to have a system operating on an air link that produces extremely high BER. If this case ever occurs, the MS normally tries to scan for a better DCCH in its surrounding.

4.5 Summary and Discussion

In this chapter, we have studied the performance of the RACH of DCCH of the IS-136 standard used for the air interface to transmit messages from mobile stations in a cellular partition to the BS serving the area. Along with the RACH we have extended the study to monitor the statistics of the BS queue that stores L3 messages before sending them out on the land line to the MTSO. All the features simulated for the evaluation purposes were modeled according the north-American standard IS-136, revision A [IS-1STD].
In this section we gather the results of our study to provide guidelines to design this set-up of IS-136 based communication systems.

In order to provide a broad coverage of the study on the system, we created a variation in the message traffic on the reverse link. The variation was in the message length and rate of creation in a given message population. To simulate a system closer to real life, a transmission channel quality was modeled using an error rate (BER) on every burst transmitted on the RACH, and we considered a message population by varying the message length and message arrival rate.

By setting BER and the system load on the RACH, we varied the random access input parameters of the RACH as allowed by the standard, and stretched the parameters to their limits monitoring the system behavior in each case. In the following, we summarize the results of our study from the different setups modeled in this chapter.

In the first part of the study, we looked at the modeled cellular system under various system message loads. From the results obtained, we found the maximum achievable system throughput. Table 4.6 summarizes the results (refer to table 4.4 for the abbreviations of the random access parameters of the RACH).

Table 4.6: System peak throughput performance results.
Message population = {1,3,11 bursts},
Y=7, W=3, BER=0.09.

Value of Random Parameter X	System Load at Peak Throughput (messages/sec)	Average Channel Access Delay (sec)	Time average BS Queue Length (messages)	Mean BS Queue Delay (sec)
0	7	0.44583	0.27886	0.04619
1	8	0.76	0.35216	0.050859

Note that, in practice, the system load applied on the RACH depends on the MS population in the cellular partition. With an estimate of the call attempt rate of an MS in a real setup (for example an MS can be estimated to make 2 calls per hour) the designer can predict the maximum number of MS that the system can support by using the information in table 4.6 under the conditions applied therein.

As it can be seen from table 4.6, by setting X to 1, we achieve a higher system throughput of the system, 20.82% higher than the case for X=0 as seen in figure 4.14, but at the expense of a higher message end-to-end delay. The end-to-end delay is increased when setting X to 1 by a longer RACH access delay and a longer waiting time at the BS queue. It is up to the designer to decide if this drawback is affordable in the system. An alternative of course would be to split the cell and add an additional BS. This new cellular structure will provide a higher capacity, and therefore the system is able to support more subscribers that may come aboard in the future.

Given the nature of the access protocol, the system throughput drops for system loads higher than 7 messages per second when X=0 and 8 messages per second for X=1. It is therefore not recommended to operate the system under higher system loads, and to leave a margin for variation in the MS population and call attempt rate, the system must be designed under system loads smaller than the ones generating maximum throughput.

Another observation was made in the case of X=1 where the message transmission failure rate is almost the same for all messages despite their burst length but depends rather on the system load. This proves the effectiveness of allowing the MS to insist more on finding a free RACH subchannel under heavy system loads. For X=0 however, the message failure rate depends on the system load and the message length. We can also say that, in general, when X=1, the system generates a smaller message transmission failure rate than when X=0 for system loads < 8 messages per second.

In the next phase, we evaluated the system under various transmission channel qualities and varied the message population type in each case. The system message load was fixed to 5 messages per second to avoid collapsing the system if stretched over the limit (figure 4.14).

Focusing on getting the message successfully to the BS, we monitor the message transmission failure rate. For different message types in different message populations, we increased the BER on the RACH, and monitored the message transmission failure rate. At a certain value of BER, the message failure rate start rising reflecting the inability of the system to adapt to such bad conditions on the RACH. That BER value can act as a benchmark for the system integrity and the message type robustness. Table 4.7 summarizes some results. (notation used in the message type and population column are the same ones described in table 4.5).

Table 4.7: System maximum integrity in worst affordable BER.
X=0,Y=7, W=3, L=5 messages/sec.

Message Type and Population	**Maximum BER before break-up of the system (normalized)**	**Average Message Transmission Delay at Max. BER (sec)**	**Time average BS Queue Length at Max. BER (messages)**	**Mean BS Queue Delay at Max. BER (sec)**
"1 burst" in {1 burst}	0.5	0.4868	0.0182	0.00375
"1 burst" in {1,3 bursts}	0.3	0.3593	0.0824	0.0168
"1 burst" in {1,3 11 bursts}	0.09	0.3125	0.227	0.0467
"3 burst" in {1,3 bursts}	0.3	0.7265	0.0824	0.0168
"3 burst" in {1,3 11 bursts}	0.09	0.5836	0.227	0.0467
"11 burst" in {1,3 11 bursts}	0.09	1.7144	0.227	0.0467

By increasing the BER on the RACH, the system tries to adapt to the new conditions with the objective to keep the message failure rate to the minimum. It does so by increasing the message transmission delay due to the increased number of retransmissions. The system break-up can also be seen in the BS queue as its time average length starts to drop for BER values larger than the maximum that the system can handle.

With the above summary, we conclude that without the support of the "11 burst" message, the system can keep the same performance for all BER values < 30% provided that a larger message transmission delay is affordable. The system presents even a better performance for a message population {1 burst} where the performance does not decrease dramatically until for BER values > 50%.

By choosing a fixed BER and a 5 messages per second system load, our next analysis consisted on varying the random access parameters. The main objective when monitoring the system is to find correct settings for the parameters that leads to minimum message transmission failure rate with an affordable end-to-end delay. As described earlier, each random access parameter, plays a role in increasing the number of retransmissions in case a transmission attempt fails; the larger the value of the parameter, the more the number of allowed retries. This setup will compensate for higher system loads and higher BER when introduced in the system. The main drawback in setting a parameter to a higher value is a longer transmission delay for the message and a larger queue length at the BS. Given that a maximum value for each parameter is defined by the standard [IS-1STD], it is important to look in the results analysis for the smaller value of the parameter in favor of the minimum transmission failure, transmission delay, and queue length at the BS. By doing so, we leave a margin for expanding the network with an increase in system load and therefore number of MS serviced. We summarize the results in table 4.8, but first let us state what was concluded from the study.

In the first phase of the study we looked at the effect of the "W" parameter and varied Y. By choosing W=0, the message transmission failure rate was too high, even with Y set to 7, compared to the case of W=3. In all cases of W, Y must be set to its maximum (value = 7) in order to achieve minimum transmission failure rate. This leads to a higher transmission delay and queue length at the BS. It was also noted that by increasing W and fixing Y, we decrease the transmission failure rate as well as the transmission delay, however, larger queue length is required at BS. Given that Y should be set to 7, one way to reduce the queue length at the BS is to choose 0 < W < 3 with an affordable transmission failure rate (results for the end extremes of W were presented earlier).

Table 4.8: Random Access Parameters Outcome (BER=0.09, L=5 messages/second).

	Message population			
	{1,3,11 bursts}			**{1,3 bursts}**
	W (X=0)		**X (W=3)**	**X=0, W=3**
	0	**3**	**1**	
Minimum Y in favor of minimum transmission failure rate, transmission delay and queue length at the BS.	7	7	4	3
Average Transmission Delay (sec)	1.1736	0.87	0.803	0.298
BS queue length (messages)	0.1475	0.227	0.233	0.0824
Average transmission failure rate (%)	20.354	3.32	1.634	2.393

Looking at different message population types we fixed W and X, and varied Y. In case of message population without long messages (no "11 bursts" messages), the transmission failure rate becomes roughly the same for Y>3. This simply means that no changes happen in the system performance by setting Y to larger values than 3. The message transmission delay and queue length also show no change in behavior for Y>3. This gives an opportunity to increase the capacity on the RACH and therefore a larger number of MS's in the partition can be supported.

By adding the "11 burst" message to the message population, the system performance increases with Y and does not reach its maximum until Y=7. Therefore, in order to support the message population {1,3,11 bursts}, Y should be set to its maximum for a minimum message transmission failure rate. This means that an expansion in the system load leads to higher transmission failure rate (this can also be seen in the results presented when we were varying the system load at the beginning of the study).

To observe the effect of X on the system, we fixed W and the message population type. With X=1, no changes happen in the system performance by setting Y to larger values than 4. This was seen in the similarity of the transmission failure rate, queue length and transmission delay for Y>4. However, when X=0, the transmission failure rate decreases with increasing Y and does not reach the minimum until Y=7. This case explains the efficiency of setting X to 1 in favor of transmission failure rate but presents a drawback in the channel access delay and the queue delay in the BS. Table 4.8 presents a general summary of the results.

Note that for system loads higher than 5 messages per second, the study has shown that, when X=1, a larger channel access delay is required than when X=0 (see figure 4). This behavior should be kept in mind during parameters setup.

CHAPTER 5

Conclusions

5.0 Introduction

In this chapter we conclude our study by present some final remarks. Furthermore, we provide insights on any future work that can be conducted using the work presented in this thesis to take this study to the next step.

5.1 Final Remarks

In this thesis, we took the opportunity to look at one of the North-American cellular standards that is actually a small part of the broad world of wireless communication as we know it today and the possibilities the wireless industry is exploring for the future. From what was presented in chapter 1 and chapter 2 of this thesis, it can be seen why wireless communication is expanding so fast and becoming more in demand by the day. In chapter 2, we touched on the cellular concept and presented some of the current standards used today in the MAC protocols between the mobile stations and the serving base station. With focus on IS-136, we presented a more detailed description of the standard in chapter 3 with concentration on the RACH model in DCCH being the main focus of the investigation in this thesis.

Having presented the protocol and its operation in a cellular system, we took the opportunity to take a closer look at the RACH in chapter 4 by modeling one cellular partition and simulating the operation according to the rules specified by the IS-136 standard. Under certain conditions, the performance evaluation of the RACH was done using two types of access attempt messages (different in length) and one type of data message for SMS applications (11 bursts long message) with the objective to provide guidance to a cellular system designer in the settings of the random access parameters for the RACH and their effect on the performance. The performance proved the system to be most effective with short messages but adapting to the introduction of long messages with a drawback of a longer end-to-end delay in the message transmission.

In the first phase of the study, it was found that under high system message loads (more than 8.5 messages per second), long messages penalize the short messages transmission when the MAC protocol allow the MS to insist more on finding a free RACH subchannel (maximum Busy/Reserved access parameter set to 1). From this phase of the study, the contributions that can be extracted are the system throughput analysis for two settings of the MAC protocol and the effect each setting is creating on the queuing size required at the BS and the message end-to-end delay when SMS is supported.

In the second phase of the study, the RACH was evaluated against different channel quality measures under heavy traffic and the system integrity in terms of throughput was monitored. From this phase, the RACH robustness with respect to transmission channel quality can be measure for a given set-up of the MAC supporting SMS.

In the last phase of the study, we monitored the system performance by varying the RACH access parameters for a fixed traffic load and a channel quality on the air interface. The contributions from this phase consisted of the settings for the access parameters such that the system throughput, end-to-end message delay and memory space required at the BS are of optimum values with and without SMS support.

From designer point of view, all the performance results presented in chapter 4 can be used as a presentation of the system behavior and BS requirements when the RACH characteristics vary from one end to the other. This will give the designer a clear understanding of the system behavior when pushed to its limits whether in message load capacity, integrity with respect to air channel quality or best performance that can be obtained with variation of the RACH access parameters.

With this, we like to close our study by saying that wireless communication is one of the most evolving technology today, and has been for the last 10 years. With a daily increasing number of subscribers, the MAC protocol acting as the interface between the end user and the wireless network would become required to provide highest capacity possible, and becomes one of the main issues in today's wireless development.

5.2 Future Work

From all the results presented in this study, new doors were opened for research with questions and concerns that may lead to a better outcome.

Given that data messages (long in length to support SMS applications) create the most noticeable impact on the system, it is a good idea to investigate furthermore the way to deal with these messages with the objective to minimize the transmission failure rate of all messages as well as the RACH utilization. One way of doing so is to use reserved access for long messages originated at the MS when the reverse path is under heavy traffic. The RACH subchannel will be reserved by the BS by setting the SCF accordingly after receiving a one burst signal from the MS in question. The "1 burst" message, being very robust as seen from our study, should have a high rate of success reaching the BS under heavy traffic. With a probability "*P*", the BS should decide if a RACH subchannel will be reserved for the MS in question or random access should be used, and send the decision to the MS on the forward path. The analysis of this new feature will be based on the probability *P* which is to be defined.

An additional study could be done in the system with the focus to find the maximum number of users that can be supported given a limited number of voice channels available at the MTSO. By assigning and holding a voice channel for each successful access attempt by an MS, one can measure the rate of failure to find a free voice subchannel and the average delay required for the MS before successfully being assigned a voice channel.

Also, the mobility of the mobile stations can be studied under different traffic models in a multi-cell cellular system. By introducing several cells in the system, a mobile station coming into a new cell must register under the new base station coverage and its traffic model is now transferred to the new cell. This behavior introduces a variation in population and traffic load functionalities in the cells. A performance evaluation could be done on the whole system rather than only in one cell.

5.3 Contributions

We would like to note that a paper consisting of some of the work presented in this thesis has been accepted to be presented at ICC'99 conference in Vancouver, Canada. The paper is entitled *"Performance Evaluation of the IS-136 DCCH Reverse Access Channel Mechanism"* and it covers phase three of this study where the RACH performance was evaluated under heavy traffic load with and without SMS support, and optimum settings for the RACH access parameters were recommended.

APPENDIX A

Cellular Standards and Subscribers Worldwide

In this Appendix, we take the opportunity to prove the cellular business global popularity by presenting a *World Report* on the systems available in many countries along with the number of subscribers in each of the countries. The upcoming statistics were retrieved from [Cell-97]. Due to the large amount of available data, some of the countries were not included in this Appendix, however, we believe that the presented information is more than enough to prove cellular networks popularity around the world.

Prior to providing the world report, we introduce a list of principal cellular radio systems that can be found today [Maca-97]:

NMT	Nordic mobile telephone (followed by a number referring to the frequency band)
AMPS	Advanced mobile phone system (North America)
TACS	Total access communication systems (United Kingdom)
E-TACS	Extended TACS, offering more channels by additional frequency assignment
GSM	Global system for mobile communications — specified by CEPT (committee of European Posts and Telecommunications)
JTACS	Japanese total access communications system, similar to TACS
JDC	Japanese digital cellular; a TDMA system
ADC	American digital cellular (similar to JDC; works within the AMPS frequency plans)
D-AMPS	New name for ADC, i.e. digital AMPS
DCS 1800	GSM system operating at 1800 MHz
PCS 1900	The DCS 1800 system, or D-AMPS system at 1900 MHz in America

PHS	Japanese PCS system, known as personal handy-phone system; operates at 1900 MHz
DECT	Digitally enhanced cordless telecommunication; operates at 1800 MHz

We now present the world report on cellular phones usage and popularity in table A.1.

Table A.1: World Report on Cellular Systems

(*: Information not available as of press time.)

Country	System	Startup	Number of subscribers	Suppliers
Albania	900-GSM	5/96	1,200	Alcatel
Algeria	900-NMT	12/89	6,900	Nokia
Argentina	800-N-AMPS	11/89	250,000	Motorola
	800-AMPS/800-TDMA	3/93	180,000	Ericsson
	800-AMPS	10/94	125,000	Astronet/Lucent/Plexsys
	800-AMPS/800-TDMA	3/96	65,000	Ericsson/Octel
	800-AMPS/800-TDMA	3/96	35,000	Ericsson
American Republic	900-GSM	12/96	*	*
Aruba	800-AMPS/800-TDMA	1993	*	Nortel
	800-N-AMPS	1995	*	Motorola
Australia	800-AMPS	12/86	2,700,000	Ericsson
	900-GSM	4/93	900,000	Ericsson
	900-GSM	5/93	650,000	Nokia/Nortel/Matra
	900-GSM	9/93	250,000	Ericsson
Austria	450-CNETZ	11/84	29,800	Motorola
	900-TACS	7/90	258,850	Motorola
	900-GSM	12/93	268,870	Alcatel/Motorola/Nortel/Siemens
	900-GSM	7/96	10,000	Siemens
Bahamas	800-AMPS/800-TDMA	1988	3,000	Nortel
Bangladesh	800-AMPS	8/93	4,100	Motorola
Barbados	800-AMPS	1990	2,500	Nortel
Belgium	450-NMT	7/87	39,000	Nokia
	900-GSM	1/94	350,000	Various
	900-GSM	8/96	70,000	Alcatel/Motorola/Nortel
	MOB-II	*	42,200	Nokia
Belize	800-AMPS/800-TDMA	11/93	1,850	Nortel
Bermuda	800-AMPS/800-TDMA	2/87	5,000	Nortel
	800-AMPS	7/97	*	Phoenix Wireless
Bosnia	900-GSM	11/96	400	Ericsson
Brazil	800-AMPS	8/90	1,185,000	Various
Bulgaria	450-NMT	12/93	26,000	Ericsson
	900-GSM	9/95	12,500	Siemens
	900-GSM	1997	*	Ericsson
Burundi	800-AMPS	1992	1,000	Plexsys
Cameroon	900-GSM	10/93	2,500	Philips/Siemens

Country	System	Startup	Number of subscribers	Suppliers
Canada	800-AMPS/800-D-AMPS	7/85	946,300	Nortel
	800-AMPS/800-TDMA	1/86	1,049,000	Ericsson/NovAtel/ Nortel
	900-GSM	12/96	*	*
Central Africa Rep.	800-AMPS	11/95	450	Plexsys
Chile	800-AMPS/800-TDMA	3/89	86,020	Ericsson/NEC
	800-AMPS/800-TDMA	5/89	93,200	Nortel
	800-AMPS	6/91	35,850	Motorola
	800-AMPS	1991	40,900	Motorola/Plexsys
China, PR	900-TACS	1989-95	3,554,640	Ericsson/Motorola/ Nortel
	800-AMPS	1993-95	7,000	AT&T/Motorola
	900-GSM	1994-97	20,000	Various
	800-E-TDMA	1994	*	Alcatel/Hughes Networks
	900-GSM	1995	50,000	Ericsson
Colombia	800-AMPS/800-TDMA	6/94	100,000	Nortel
	800-AMPS/800-TDMA	6/94	11,000	LCC/Nortel
	800-AMPS/800-TDMA	4/94	120,000	Nortel
	800-AMPS/800-TDMA	7/94	60,000	Ericsson
	800-AMPS/800-TDMA	1994	40,000	Ericsson
	800-AMPS (A band)	9/94	12,000	Ericsson
Cuba	800-AMPS	2/93	2,000	Ericsson
Denmark	450-NMT	9/81	28,820	Ericsson
	900-NMT	12/86	505,000	Ericsson
	900-GSM	7/92	490,000	Ericsson
	900-GSM	7/92	460,000	Nokia
Dominica	800-AMPS	*	*	Plexsys
Egypt	MATS	5/87	12,000	Matsushita
	900-GSM	11/96	*	Alcatel
ElSalvador	800-AMPS/800-N-AMPS	1/93	15,000	Ericsson
	800-AMPS	1996	*	*
Ethiopia	900-GSM	7/97	*	*
Finland	450-NMT	12/81	193,000	Ericsson
	900-NMT	12/86	440,950	Ericsson
	900-GSM	1/92	250,000	Nokia/Siemens
	900-GSM	6/92	490,000	Ericsson/Nokia
	900-GSM	1/97	*	*
France	RC2000	11/85	185,000	Alcatel/Matra
	450-NMT	4/89	125,000	Alcatel/Nokia
	900-GSM	7/92	1,211,900	Alcatel/Ericsson/Matra
	900-GSM	4/93	715,000	Alcatel/Lucent
	1800-PCS	1/96	73,000	Dassault/Ericsson/Matra/ Nokia
Georgia	800-AMPS	7/94	*	Plexsys
	900-GSM	8/95	*	Motorola/Siemens
	900-GSM	12/96	*	Ericsson

Country	System	Startup	Number of subscribers	Suppliers
Germany	450-C-NETZ	5/86	583,300	Siemens
	900-GSM/D1	6/92	2,050,000	Alcatel/Motorola/Philips/ Siemens
	900-GSM/D2	6/92	2,240,000	Ericsson/Siemens
	1800-DCS	5/94	450,300	Ericsson/Nokia/Siemens
Greece	900-GSM	7/93	238,000	Ericsson/Italtel
	900-GSM	7/93	225,300	Ericsson/Italtel
Greenland	900-NMT	11/92	5,250	*
Haiti	800-AMPS	1997	*	*
Hong Kong	900-TACS	1/84	40,000	NEC
	900-TACS	1/89	64,000	Ericsson/Motorola
	800-AMPS	6/85	63,000	Motorola
	900-E-TACS	8/89	61,800	Ericsson
	800-TDMA	10/92	125,530	Ericsson
	CDMA	9/95	50,000	Motorola
	900-GSM	1/93	235,000	Ericsson/Nokia
	900-GSM	7/93	360,000	Nokia
	900-GSM	5/95	145,000	Motorola/Siemens
	900-GSM	1/97	*	*
Hungary	450-NMT	10/90	73,550	Ericsson/Nokia
	900-GSM	3/94	140,000	Ericsson/Nokia
	900-GSM	4/94	205,000	Ericsson
Iceland	450-NMT	7/86	22,700	Ericsson
	900-GSM	8/94	22,000	Ericsson
India	900-GSM	7/95	55,000	Motorola/Siemens
	900-GSM	7/95	11,600	Motorola/Siemens
	900-GSM	8/95	12,500	Nokia
	900-GSM	9/95	67,000	Ericsson/Motorola
	900-GSM	6/95	12,000	Motorola/Nokia
	900-GSM	10/95	34,500	Motorola/Siemens
	900-GSM	11/95	48,500	Ericsson/Motorola
	900-GSM	1995	12,000	Ericsson
	900-GSM	12/96	500	Ericsson
	900-GSM	12/96	200	Lucent
	900-GSM	1995-97	700	Various
Indonesia	450-NMT	4/86	30,000	Ericsson/Nokia
	800-N-AMPS	8/91	12,000	Motorola
	800-AMPS	8/91	85,000	Lucent/Motorola
	800-AMPS	2/93	11,000	*
	900-GSM	9/94	150,000	Ericsson/Motorola/Siemens
	900-GSM	11/94	190,000	Alcatel/Siemens
	900-GSM	6/96	*	Ericsson
	NMT-450	1/97	21,000	Nokia
Iran	900-GSM	6/94	24,000	Nokia
	900-GSM	3/95	*	*
	900-GSM	*	*	*
Ireland	900-TACS	12/85	124,000	Ericsson
	900-GSM	7/93	125,200	Ericsson
	900-GSM	1/97	*	*

Country	System	Startup	Number of subscribers	Suppliers
Israel	800-N-AMPS	3/86	300,000	Motorola
	800-AMPS/800-TDMA	12/94	350,000	Nortel
Jamaica	800-AMPS	8/91	22,500	NEC
Japan	NTT	12/79	2,260,000	NEC
	NTT	12/88	278,000	NEC
	JTAC	4/89	750,000	Motorola
	JTAC	10/91	600,000	Motorola
	800-PDC	1993	7,399,000	Ericsson/Motorola/NEC
	PDC	4/94	235,600	Motorola/NEC
	1500-PDC	4/94	164,000	Ericsson/Toshiba
	PDC	5/94	120,000	Ericsson
	PDC	6/94	138,400	Motorola/NEC
	PDC	7/94	111,700	Motorola/NEC
	PDC	7/94	*	Ericsson
	PDC	2/96	25,000	Motorola
	PDC	1/96	90,000	Ericsson
	1500-PDC	1994	832,800	Ericsson/NEC
	1500-PDC	1994	1,308,000	Motorola
	PDC	1996-97	*	*
Jordan	900-GSM	7/95	23,400	Motorola
	900-GSM	11/98	*	*
Kenya	900-E-TACS	1993	2,600	NEC
	900-GSM	4/96	*	Siemens
Korea	800-AMPS	4/84	2,260,000	Lucent/Motorola
	CDMA	3/96	458,000	*
	CDMA	4/96	200,000	Lucent
Lebanon	800-AMPS	7/91	10,000	Nortel/NovAtel
	900-GSM	5/95	85,000	Ericsson
	900-GSM	5/95	80,000	Motorola/Siemens
Libya	900-GSM	11/96	*	Ericsson
Luxembourg	450-NMT	6/85	100	Ericsson
	900-GSM	4/93	42,500	Philips/Siemens
Madagascar	800-AMPS	7/94	2,590	Celcore/Motorola
Mali	800-AMPS	9/96	2,000	Harris Wireless/NovAtel
Mexico	800-AMPS	10/89	460,000	Ericsson/Motorola/Nokia/Toshiba
	800-AMPS/800-TDMA	11/89	230,000	Nortel
	800-AMPS	1990	*	Various
	800-AMPS	11/90	19,000	Motorola
	800-AMPS	11/90	18,000	Motorola/Nortel
	800-AMPS	11/90	25,000	Motorola
	800-AMPS	11/90	25,000	Motorola/Nortel
	800-AMPS	1990	14,000	Motorola
Monaco	900-GSM	*	*	*
Mongolia	900-GSM	3/96	*	Alcatel
Morocco	450-NMT	1989	35,000	Ericsson
	900-GSM	4/94	4,000	Motorola/Siemens
Namibia	900-GSM	4/95	6,700	Ericsson/Motorola/Siemens
North Africa	900-GSM	1996	*	Ericsson

Country	System	Startup	Number of subscribers	Suppliers
Norway	450-NMT	7/81	190,400	Ericsson/Mitsubishi/Nokia
	900-NMT	12/86	288,600	Ericsson/Matra/Mitsubishi/ Nokia
	900-GSM	5/93	464,900	Ericsson/Nokia
	900-GSM	9/93	260,000	Motorola/Nokia/Siemens
Pakistan	800-AMPS	11/90	32,500	Ericsson
	800-AMPS	12/90	13,000	Ericsson
	900-GSM	8/94	20,000	Motorola/Siemens
Peru	800-AMPS/800-TDMA	4/90	40,000	Lucent/Nortel/NovAtel
	800-AMPS/800-TDMA	7/91	41,870	Motorola/Nortel
	800-AMPS/800-TDMA	1993	*	Nortel
	CDMA	12/96	*	Motorola
Romania	450i-NMT	4/93	14,300	Ericsson
	900-GSM	1996	*	Alcatel
	900-GSM	1997	*	*
Russia	450-NMT	6/91	162,000	Ericsson/Nokia
	450-NMT	12/91	17,980	Benefon/Ericsson/Motorola/ Nokia
	450-NMT	1991-96	7,850	AT&T/Ericsson/Nokia
	D-AMPS	1993	2,550	Hughes Network
	800-AMPS/800-D-AMPS	6/94	32,000	Ericsson/Motorola/Plexsys/ Telular
	800-N-AMPS	1995	3,000	Motorola
	800-AMPS	1994-96	51,350	Various
	900-GSM	1993-96	45,000	Various
Saudi Arabia	450-NMT	8/81	20,000	Ericsson/Philips
	900-GSM	1/96	180,000	Lucent/Philips
	900-GSM	*	*	Motorola/Siemens
South Africa	450-CNETZ	5/86	10,000	Siemens
	900-GSM	6/94	412,000	Alcatel/Motorola/Siemens
	900-GSM	6/94	330,000	Ericsson
Spain	450-NMT	6/82	13,500	Ericsson/Philips
	900-TACS	4/90	1,397,800	Lucent/Motorola
	900-GSM	7/95	750,000	Lucent/Ericsson
	900-GSM	10/95	430,000	Ericsson/Siemens
Switzerland	900-NMT/Natel C	9/87	314,600	Ericsson/Philips
	900-GSM	3/93	345,500	Ericsson/Lucent/Motorola/ Philips
	1800-DCS	10/95	5,000	Ericsson/Nokia/Philips
Taiwan	800-AMPS	5/89	600,000	Ericsson
	900-GSM	7/95	315,600	Nortel
	900-GSM	1997	*	Various
Turkey	450-NMT	10/86	114,000	Motorola/Nokia
	900-TACS	1993	*	*
	900-GSM	2/94	127,000	Alcatel/Motorola/Siemens
	900-GSM	3/94	550,000	Ericsson

Country	System	Startup	Number of subscribers	Suppliers
Uganda	900-GSM	12/94	1,750	Motorola/Siemens
United Kingdom	900-E-TACS	1/85	1,975,200	Motorola
	900-E-TACS	12/87	1,880,000	Ericsson
	900-GSM	7/92	1,108,000	Ericsson/Nokia/Orbitel
	1800-DCS	9/93	500,000	Ericsson/Nortel
	900-GSM	1/94	802,000	Ericsson/Motorola/Nokia/ Siemens
	900-GSM	6/94	5,580	Alcatel
	1800-DCS	*	620,000	Nokia/Nortel
	900-GSM	6/94	5,580	Alcatel
United States	800-AMPS/800-TDMA	10/83	44,100,000	Multiple Suppliers
Venezuela	800-AMPS/800-TDMA	10/88	310,000	Ericsson
	800-AMPS/800-N-AMPS	1991	340,000	Motorola
	900-GSM	1997	*	*
Vietnam	800-AMPS	5/92	22,000	Ericsson
	900-GSM	4/94	32,000	Alcatel/Ericsson
	900-GSM	7/95	14,370	Alcatel/Ericsson
	900-GSM	6/96	*	Motorola/Siemens
West Africa	900-GSM	3/96	*	*
	900-GSM	3/96	*	*
Yemen	900-TACS	5/92	7,500	Motorola
Zaire	800-AMPS	1987	11,500	Motorola/Plexsys
	800-AMPS	1994	*	Motorola
	900-TACS	1994	*	Motorola
	900-GSM	*	*	*

APPENDIX B

DCCH Layer 2 Operations

B.1 Layer 2 Operation

In this section we present some of the frame formats that are used at Layer 2 in the Forward and Reverse DCCH: in the forward channel we present the E-BCCH, F-BCCH and SPACH protocols and in the reverse channel we present the RACH protocol. We also present a summary of the fields comprising the layer 2 protocol frames.

B.1.1 F-BCCH Protocol

This protocol is used whenever a message carrying F-BCCH information is transmitted on a TDMA slot. The first F-BCCH slot of a superframe has the SFP value set to zero and that a full cycle of F-BCCH information (a set of layer 3 messages) always start at the beginning of the superframe and is completed in the same superframe.

According to the IS-136 standard [IS-1STD], the F-BCCH frame is constructed to fit in a 125-bit envelope and an extra 5-bits are added as tail bits resulting in a 130-bit F-BCCH burst. A sample set of the frames and a summary of the layer 2 protocol frame for F-BCCH is presented below in figure B.1.

Figure B.1 : F-BCCH frame formats

Frame Number	Field 1	Field 2	Field 3	Field 4	Field 5	Field 6	Field 7	Field 8	Field 9
1	BC = 0 (1 bit)	FC (1 bit)	EC (1 bit)	L3LI (8 bits)	L3DATA	BI = 0 (1 bit)	FILLER	CRC (16 bits)	-
2	BC = 0 (1 bit)	FC (1 bit)	EC (1 bit)	L3LI (8 bits)	L3DATA	BI = 1 (1 bit)	L3LI (8 bits)	L3DATA	CRC (16 bits)
3	BC = 1 (1 bit)	FC (1 bit)	EC (1 bit)	CLI (7 bits)	L3DATA	BI = 0 (1 bit)	FILLER	CRC (16 bits)	-

Table B.1 present a mapping between the frame number in figure B.1 and its types as known in the standard.

Table B.1 : F-BCCH Layer 2 protocol frame type

Frame Number	Type
1	BEGIN Frame (1 complete message)
2	BEGIN Frame (2 Layer 3 messages with the second Layer 3 message continued)
3	CONTINUE Frame (message ending)

The BEGIN frame is used to start the delivery of one or more layer 3 messages on the F-BCCH. If the layer 3 message data is shorter than one frame, the Begin Indicator (BI) flag is added after the "L3DATA" field. If BI = 0, the receiver would understand that the remaining space in the frame before the CRC field is padded with FILLER. If BI = 1, a new layer 3 message is started in the frame. If the first Layer 3 message sent on the frame ends with less than 9 bits remaining in the frame and another layer 3 message is to be sent, BI is set to 0, the rest of the frame is padded with filler and the new layer 3 message is sent on a new BEGIN frame. However, if the first layer 3 message sent on the frame needs more than on frame, no BI field is used, and the remaining of the message is sent on a CONTINUE frame.

In case where there is no layer 3 message to be sent in the frame, the frame will have "L3LI" set to 0 and the L3DATA field padded with FILLER.

The CONTINUE frame is used to transmit the remaining of a started layer 3 message in the previous frame. The CLI field in the frame indicates the number of bits of the frame that belong to the continued message. The same concept of the BI field usage in the BEGIN frame is applied in the CONTINUE frame.

With this observation, we can see an increase in the capacity of the fast broadcast channel (F-BCCH) where a layer 3 message can begin transmission in the same frame where a previous layer 3 message has finished. This key feature of the protocol, known by message concatenation, offer a high throughput capacity with the knowledge that a consecutive layer 3 message does not have to wait for another frame to be transmitted.

In table B.2, we present a more in depth description of the F-BCCH layer 2 protocol fields summary.

Table B.2 : F-BCCH Layer 2 protocol field summary

Field Name	Length (bits)	Value(s)
BC = Begin/Continue	1	0 = Begin 1 = Continue
FC = F-BCCH Change	1	Toggles to indicate a change in the F-BCCH. This would make the mobile read the whole message and therefore react to the new status.
EC = E-BCCH Change	1	Toggles to indicate a change in the E-BCCH.
CLI = Continuation Length Indicator	7	Number of bits in the current L2 frame used to carry information from a previously initiated L3 message.
L3LI = Layer 3 Length Indicator	8	Variable length layer 3 messages supported from 0 up to 255 octets.
L3DATA = Layer 3 Data	Variable	Contains a portion (some or all) of the layer 3 message having an overall length as indicated by L3LL The portion of this field not used to carry layer 3 information id filled with zeros.
BI = Begin Indicator	1	0 = No additional layer 3 message present 1 = additional layer 3 message present.
FILLER = Burst Filler	Variable	All filler bits are set to zero.
CRC = Cyclic Redundancy Code	16	Used for error detection of SPACH messages received at the mobile station.

B.1.2 E-BCCH Protocol

This protocol is applied on all TDMA bursts carrying E-BCCH information and transmitted on the E-BCCH field of a superframe. It should be noted that, unlike F-BCCH, a full cycle of E-BCCH information (a set of layer 3 messages) does not have to be aligned to start in the first E-BCCH slot of a superframe and may span multiple superframes.

According to the standard [IS-1STD], an E-BCCH layer 2 protocol frame is constructed to fit in a 130 bits envelope including a 5 bits reserved for use as tail bits. In figure B.2 we present some of the frames and their formats.

Figure B.2 : E-BCCH frame formats

Frame Number	Field 1	Field 2	Field 3	Field 4	Field 5	Field 6	Field 7	Field 8	Field 9
1	BC = 0 (1 bit)	ECL (8 bits)	L3LI (8 bits)	L3DATA	BI = 0 (1 bit)	FILLER	CRC (16 bits)		-
2	BC = 0 (1 bit)	ECL (8 bits)	L3LI (8 bits)	L3DATA	BI = 1 (1 bit)	L3LI (8 bits)	L3DATA	CRC (16 bits)	
3	BC = 1 (1 bit)	RSVD=0 (1 bit)	CLI (7 bits)	L3DATA	BI = 0 (1 bit)	FILLER	CRC (16 bits)		-

Table B.3 presents a maping between the frame number in figure B.2 and its type as known in the standard.

Table B.3 : E-BCCH Layer 2 protocol frame type

Frame Number	Type
1	BEGIN Frame (1 complete message)
2	BEGIN Frame (2 Layer 3 messages with the second Layer 3 message continued)
3	CONTINUE Frame (message ending)

The BEGIN frame is used to start the delivery of one or more layer 3 messages comprising a full cycle of E-BCCH information. The first L3 message is set in the first L3DATA filed of the frame (field 4). As in F-BCCH, the same protocol is applied with the use of the Begin Indicator (BI) field:

If the layer 3 message data is shorter than one frame, the Begin Indicator (BI) flag is added after the "L3DATA" field. If BI = 0, the receiver would understand that the remaining space in the frame before the CRC field is padded with FILLER. If BI = 1, a new layer 3 message is started in the frame. If the first Layer 3 message sent on the frame ends with less than 9 bits remaining in the frame and another layer 3 message is to be sent, BI is set to 0, the rest of the frame is padded with filler and the new layer 3 message is sent on a new BEGIN frame. However, if the first layer 3 message sent on the frame needs more than on frame, no BI field is used, and the remaining of the message is sent on a CONTINUE frame.

In case where there is no layer 3 message to be sent in the frame, the frame will have "L3LI" set to 0 and the L3DATA field padded with FILLER.

The same purpose and rules of the F-BCCH layer 2 CONTINUE frame apply on the one in E-BCCH. It is used to transmit the remaining of a started layer 3 message in the previous frame. The CLI field in the frame indicates the number of bits of the frame that belong to the continued message. The same concept of the BI field usage in the BEGIN frame is applied in the CONTINUE frame.

Again, the layer 3 message concatenation feature in this protocol offer the high throughput capacity of the broadcast channel.

In table B.4, we present a more in depth description of the E-BCCH layer 2 protocol fields summary.

Table B.4 : E-BCCH Layer 2 protocol field summary

Field Name	Length (bits)	Value(s)
BC = Begin/Continue	1	0 = Begin 1 = Continue
ECL = E-BCCH Cycle Length	8	This field indicates the total number of Layer 2 frames required for the current E-BCCH Cycle.
RSVD = Reserved	1	Reserved field set to 0.
CLI = Continuation Length Indicator	7	Number of bits in the current L2 frame used to carry information from a previously initiated L3 message.
L3LI = Layer 3 Length Indicator	8	Variable length layer 3 messages supported from 0 up to 255 octets.
L3DATA = Layer 3 Data	Variable	Contains a portion (some or all) of the layer 3 message having an overall length as indicated by L3LI. The portion of this field not used to carry layer 3 information id filled with zeros.
BI = Begin Indicator	1	0 = No additional layer 3 message present 1 = additional layer 3 message present.
FILLER = Burst Filler	Variable	All filler bits are set to zero.
CRC = Cyclic Redundancy Code	16	Used for error detection of SPACH messages received at the mobile station.

B.1.3 SPACH Protocol

The SPACH layer 2 protocol is used whenever a slot is used to carry point-to-point SMS, paging, or ARCH message. According to the IS-136 Standard Revision A [IS-1STD], a single SPACH layer 2 frame shall be constructed to fit in a 125-bit envelope. An additional 5 bits are reserved for use as tail bits resulting in a total of 130 bits carried in each slot on the SPACH. Figure B.3 presents some of the SPACH headers and frame formats.

Figure B.3 : SPACH Headers and Frame formats

Frame Number	Field 1	Field 2	Field 3	Field 4	Field 5
1	BU (3 bits)	PCON (1 bit)	BCN (1 bit)	PFM (1 bit)	RSVD = 0 (1 bit)
2	BT (3 bits)	IDT (2 bits)	MM (1 bit)	SRM (1 bit)	-
3	MEA (2 bits)	MEK (2 bits)	RSVD = 0 (1 bit)	-	-
4	Header A (BU=000) (7 bits)	GA (1 bit)	FILLER = 0...0 (101 bits)	CRC (16 bits)	-
5	Header A (BU=101) (7 bits)	MSID1 (34 bits)	MSID 2 (34 bits)	MSID3 (34 bits)	CRC (16 bits)
6	Header A (BU=110) (7 bits)	IDT = 01 (2 bits)	MSID1 (24 bits)	MSID2 (24 bits)	MSID3 (24 bits)
7	Header A (BU=001) (7 bits)	MSID1 (20 bits)	MSID2 (20 bits)	MSID3 (20 bits)	MSID4 (20 bits)(
8	Header A (BU=111) (7 bits)	Header B (BT = 000) (7 bits)	EHI = 0 (1 bit)	MSID	L3LI (8 bits)
9	Header A (BU=011) (7 bits)	Header B (BT = 000) (7 bits)	EHI = 1 (1 bit)	Extension Header (5 bits)	MSID
10	Header A (BU=011) (7 bits)	Header B (BT = 001) (7 bits)	EHI = 0 (1 bit)	MSID1	MSID2
11	Header A (BU=011) (7 bits)	Header B (BT = 001) (7 bits)	EHI = 0 (1 bit)	MSID1	MSID2
12	Header A (BU=011) (7 bits)	Header B (T = 100) (7 bits)	L3DATA1	L3DATA2	FILLER = 0...0
13	Header A (BU=011) (7 bits)	Header B (BT=010,MM=1) (7 bits)	EH = 0 (1 bit)	MSID1	MSID2
14	Header A (BU=011) (7 bits)	Header B (BT=011,MM=0) (7 bits)	EH = 0 (1 bit)	MSID1 (20 bits)	MSID2 (20 bits)
15	Header A BU=011) (7 bits)	Header B (BT = 100) (7 bits)	L3DATA	FILLER = 0...0	CRC (16 bits)
16	Header A (BU=100) (7 bits)	Header B (BT = 101) (7 bits)	EH = 0 (1 bit)	MSID	PEA (7 bits)
17	Header A BU=100) (7 bits)	Header B (BT = 110) (7 bits)	PEA (7 bits)	RSVD = 00 (2 bits)	PI (1 bit)

Figure B.3 (continued) : SPACH Headers and Frame formats

Frame Number	Field 6	Field 7	Field 8	Field 9	Field 10	Field 11
1	-	-	-	-	-	-
2	-	-	-	-	-	-
3	-	-	-	-	-	-
4	-	-	-	-	-	-
5	-	-	-	-	-	-
6	MSID4 (24 bits)	FILLER = 0...0	CRC (16 bits)	-	-	-
7	MSID5 (20 bits)	FILLER = 0...0	CRC (16 bits)	-	-	-
8	L3DATA1	FILLER = 0...0	CRC (16 bits)	-	-	-
9	L3LI1 (8 bits)	L3DATA1	FILLER = 0...0	CRC (16 bits)	-	-
10	L3LI1 (8 bits)	L3LI2 (8 bits)	L3DATA2	FILLER = 0...0	CRC (16 bits)	-
11	L3LI1 (8 bits)	L3LI2 (8 bits)	L3DATA1	CRC (16 bits)	-	-
12	CRC (16 bits)	-	-	-	-	-
13	MSID3	L3LI (8 bits)	L3DATA	CRC (16 bits)	-	-
14	MSID3 (20 bits)	MSID4 (20 bits)	L3LI1 (8 bits)	FILLER (6 bits)	CRC (16 bits)	
15	-	-	-		-	-
16	RSVD = 00 (2 bits)	PI (1 bit)	ARM (1 bit)	L3LI (8 bits)	L3DATA	CRC (16 bits)
17	ARM (1 bit)	FRNO (5 bits)	L3DATA (79 bits)	CRC (16 bits)	-	-

Table B.5 : SPACH Layer 2 protocol frame type

Frame Number	Type
1	SPACH Header A
2	SPACH Header B
3	Extension Header
4	Null Frame
5	Hard Triple Page Frame (34-bit MIN, PCH)
6	Hard Quadruple Page Frame (24-bit TMSI, PCH)
7	Hard Penta Page Frame (20-bit TMSI, PCH)
8	Single MSID Frame (PCH)
9	Single MSID Frame (ARCH)
10	Double MSID Frame (ARCH)
11	Double MSID Frame with Continuation (ARCH)
12	CONTINUE Frame Type I (ARCH)
13	Triple MSID Frame (ARCH, 1 Layer 3 message for 3 MSIDs)
14	Quadruple MSID Frame with Continuation (ARCH)
15	CONTINUE Frame Type II (ARCH)
16	ARQ Mode BEGIN Frame (SMSCH)
17	ARQ Mode CONTINUE Frame (SMSCH)

Table B.5 presents a maping between the frame number in figure B.3 and its type as known in the standard.

Let us provide a brief description of the frame types presented above.

SPACH Header A

This header is included in all frame type. It contains information and flags for managing mobile stations in sleep mode and indicate changes in the BCCH. This type of indication will trigger the mobile to read the next BCCH and update it knowledge of its surrounding or react to the BMI accordingly.

SPACH Header B

This header block exist if header A indicates a burst usage of type PCH, ARCH or SMSCH. It contains supplementary information on the layer 2 frame and layer 2 access mode (contention or reservation) to be used in the next access attempt made by the receiving mobile.

Extension Header

This header holds information about the encryption methodology used on the layer 3 message. The header block confirm its presence by a set-up of the EHI field to 1.

Null Frame

This frame is sent by the Base Station (BMI) when there is no information to transmit on the SPACH.

Hard Triple Page Frame

This frame is used to page three mobiles at once. It holds three 34-bit MINs.

Hard Quadruple Page Frame

This frame is used to page four mobiles at once. It holds four 20 or 24-bit MSID ad determined by the IDT field.

Hard Penta Page Frame

This frame is used to page five mobiles. I holds five 20-bit TMSIs.

Single MSID Frame

This frame is used to send first bursts of a single ARCH or SMSCH layer 3 messages in non-ARQ mode. The frame can also be used to send non-ARQ PCH layer 3 messages.

Depending on the length of the layer 3 message sent in the frame, FILLER information are padded at the end of frame in case of short message, or CONTINUE frames Type II are used in case of a long message.

Double MSID Frame

This frame is used for starting the delivery of two ARCH messages in non-ARQ mode or two PCH layer 3 messages. The number of MSIDs is indicated in the BT field of Header B.

If any required L3LI fields cannot fit entirely within the frame, the frame is padded with FILLER and the remaining L3LI fields are then included immediately prior to the L3DATA field in the subsequent CONTINUE frame [IS-1STD].

It is necessary to note that, depending on the value in the MM field of the header B in the frame, one instance of L3LI and L3DATA is considered for one instance of MSID (when MM = 0) or for multiple MSID's (when MM = 1). An example of MM = 0 is shown in the Double MSID Frame with Continuation; assuming that L3DATA1 does not completely fit in the frame, the CONTINUE frame Type I is used to continue the transmission of the two L3 messages. In this case, L3DATAn is directed to MSIDn.

If MM = 1, only one field of L3LI will be used, and the rest of the frame is occupied by L3DATA. If the L3 message is too big for the frame, a CONTINUE frame Type II is used to continue the transmission.

Triple MSID Frame

This frame is used for starting the delivery of three ARCH layer 3 messages in no-ARQ mode or three PCH L3 messages. The number of MSIDs is indicated in the BT field of Header B.

Same rules for frame continuation in the Double MSID Frame apply for both cases of MM = 0 and MM = 1. Frame 13 in figure B.3 represents the case of MM = 1.

Quadruple MSID Frame

This frame is used for starting the delivery of four ARCH layer 3 messages in no-ARQ mode or four PCH L3 messages. The number of MSIDs is indicated in the BT field of Header B.

Same rules for frame continuation in the Double MSID Frame apply for both cases of MM = 0 and MM = 1. Frame 14 in figure B.3 represents the case where MM = 0 with continuation. The CONTINUE frame type I is used with the fields L3LI2, L3LI3 and

L3LI4 placed prior the fields L3DATA1, L3DATA2, L3DATA3, L3DATA4. The CRC field is still placed the last.

CONTINUE Frame Type I

This frame is used for continuation of L3 message that are too long to fit into one frame. This type is used when MM = 0. There can be one or more L3DATA fields.

CONTINUE Frame Type II

This frame is used for continuation of L3 message that are too long to fit into one frame. This type is used when MM = 1. Only one field of L3DATA is present in this structure.

ARQ Mode BEGIN Frame

This frame is always sent to initiate an ARQ mode L3 message delivery on the SMSCH or ARCH. It contains only one MSID within its L2 header. If the message is too long to fit in a single frame, an ARQ mode CONTINUE frame is used.

ARQ Mode CONTINUE Frame

This frame is used to continue transmission of L3 messages only in ARQ mode.
The frame number (FRNO field) keeps track of the number of frames sent to complete the message transmission. It increments by one for every CONTINUE frame and remains unchanged if a frame was re-sent due to an error encounter at the receiver end.

Following is a more in depth description of the SPACH layer 2 protocol fields summary.

Table B.6 : SPACH Layer 2 Protocol Field Summary

Field Name	Length (bits)	Value(s)
BU = Burst Usage	3	000 = Null 001 = Hard Penta Page (20-bit MSID) 010 = Reserved 011 = ARCH Burst 100 = SMSCH Burst 101 = Hard Triple Page (34 bit MSID) 110 = Hard Quadruple Page (10 or 24-bit MSID) 111 = PCH Burst
PCON = PCH Continuation	1	0 = No PCH Continuation 1 = PCH Continuation
BCN = BCCH Change Notification	1	Transitions whenever there is a change in F-BCCH or E-BCCH information.
PFM = Paging Frame Modifier	1	0 = Use Assigned PFC

		1 = Use one higher/lower than Assigned PFC.
BT = Burst Type	3	000 = Single MSID Frame 001 = Double MSID Frame 010 = Triple MSID Frame 011 = Quadruple MSID Frame 100 = CONTINUE Frame 101 = ARQ Mode BEGIN 110 = ARQ Mode CONTINUE 111 = User Group Frame
IDT = Identity Type	2	00 = 20-bit MSID/UGID 01 = 24-bit MSID/UGID 10 = 34-bit MSID/UGID 11 = 50-bit MSID/UGID
MSID = Mobile Station Identity	20/24/34/50	20-bit TMSI 24-bit TMSI 34-bit MIN 50-bit IMSI
MM = Message Mapping	1	0 = One instance of L3LI and L3DATA per instance of MSID 1 = One instance of L3LI and L3DATA for multiple MSIDs.
L2LI = Layer 3 Length Indicator	8	Variable length layer 3 messages supported up to a maximum of 255 octets.
L3DATA = Layer 3 Data	Variable	Contains a portion (some or all) of the layer 3 message having an overall length as indicated by L3LI. The portion of this field not used to carry layer 3 information id filled with zeros.
PEA = Partial Echo Assigned	7	the 7-bit partial echo value used by a mobile station during an ARQ mode transaction.
PI = Polling Indicator	1	Indicates whether or not the BMI is soliciting a response (ARQ STATUS FRAME) from the mobile station. 0 = ARQ STATUS Frame not required 1 = ARQ STATUS Frame required.
SRM = SPACH Response Mode	1	Indicates how a mobile station is to respond once it has received all frames associated with a given SPACH message. 0 = Next access attempt made on RACH to be contention based. 1 = Next access attempt made on RACH to be reservation based.
EHI = Extension Header Indicator	1	0 = Extension Header not present 1 = Extension Header present
MEA = Message Encryption Algorithm	2	00 = Reserved 01 = Reserved 10 = Reserved 11 = Reserved for SOC/BSMC specific signaling.
MEK = Message Encryption Key	2	00 = Reserved

		01 = Reserved 10 = Reserved 11 = Reserved for SOC/BSMC specific signaling.
RSVD = Reserved	1/2	Set to zero
ARM = ARQ Response Mode	1	Indicates how a mobile station is to respond once it has received an ARQ frame with PI set to 1. 0 = Send SPACH ARQ STATUS frame on contention basis. 1 = Send SPACH ARQ STATUS frame on reservation basis.
FRNO = Frame Number	5	Uniquely identifies specific frames sent in support of an ARQ mode transaction.
GA = Go Away	1	Indicates if the DCCH is barred 0 = DCCH is not barred 1 = DCCH barred
FILLER = Burst Filler	Variable	All filler bits are set to zero.
CRC = Cyclic Redundancy Code	16	Used for error detection of SPACH messages received at the mobile station.

B.1.4 RACH Protocol

A RACH frame sent on the RDCCH as a TDMA burst follows a RACH layer 2 protocol defined by the IS-136 standard [IS-1STD]. A RACH layer 2 frame can have a normal length or an abbreviated length which reduce the size in bits of the data filed in the frame. The base station (BMI) would broadcast the necessary information to the mobiles indicating which type of frame should they use on the RDCCH. The BMI, being at a constant awareness of the system status, would make the decision with the objective of keeping the system at its optimum performance.

A RACH protocol layer 2 frame is constructed to fit within a 122/100 (normal/abbreviated) bits of information including a 5 bits as tail bits. Figure B.4 shows examples of some of the frame formats.

Figure B.4 : RACH normal/abbreviated length frame format

Frame Number	Field 1	Field 2	Field 3	Field 4	Field 5	Field 6	Field 7	Field 8	Field 9
1	BT=000	IDT=00	EHI=0	MSID	NL3M = 000	L3LI	L3DATA	CRC	-
bit length: normal	3	2	1	20	3	8	64	16	
abbreviated	3	2	1	20	3	8	42	16	
2	BT=000	IDT=10	EHI=0	MSID	NL3M =	L3LI	L3DATA	CRC	-

					000				
bit length: normal	3	2	1	34	3	8	50	16	
abbreviated	3	2	1	34	3	8	28	16	
3	BT=000	IDT=11	EHI=0	MSID	NL3M = 001	L3LI1	L3LI2	L3DATA	CRC
bit length: normal	3	2	1	50	3	8	8	26	16
abbreviated	3	2	1	50	3	8	8	4	16
4	BT=001	CI	L3DATA	CRC	-	-	-	-	-
bit length: normal	3	1	97	16					
abbreviated	3	1	75	16					
5	BT=010	RSVD=0	L3DATA + FILLER	- (combined with L3DATA)	CRC	-	-	-	-
bit length: normal	3	1	97		16				
abbreviated	3	1	75		16				
6	BT=011	IDT=10	EHI=0	MSID	NL3M = 000	L3LI	L3DATA + FILLER	- (combined with L3DATA)	CRC
bit length: normal	3	2	1	34	3	8	50		16
abbreviated	3	2	1	34	3	8	28		16
7	BT=100	PEA	RSVD= 00	FRNO MAP	FILLER = 0...0	CRC	-	-	-
bit length: normal	3	7	2	26	63	16			
abbreviated	3	7	2	26	41	16			

Table B.7 presents a maping between the frame number in figure B.4 and its type as known in the standard.

Table B.7 : RACH Layer 2 protocol frame type

Frame Number	Type
1	BEGIN frame (MSID type TMSI)
2	BEGIN frame (MSID type MIN)
3	BEGIN frame (MSID type IMSI and two Layer 3 messages)
4	CONTINUE frame
5	END frame
6	BEGIN and END frame (MSID type MIN
7	SPACH ARQ STATUS frame

Note that the layer 3 data field length changes based on the MSID used (different types of MSIDs have different bit length) and the type of frame used (normal/abbreviated). Nest is a brief usage description of the frames.

BEGIN Frame

The BEGIN frame is always sent first at the beginning of a random access transaction. The number of concatenated L3 messages is indicated by NL3M field content.

If any required L3LI fields cannot fit entirely within the frame, the frame is padded with FILLER and the remaining L3LI fields are then included immediately prior to the L3DATA field in the subsequent CONTINUE frame [IS-1STD].

CONTINUE Frame

This frame is sent if the L3 message is too long to fit in the previous frame. The CONTINUE frame is always sent as intermediate frame of a random access transaction. The first CONTINUE frame sent would contain a CI value set to 0. The mobile station then toggles the CI field for every initial transmission of a CONTINUE frame. For a repeated CONTINUE frame, the CI field remains unchanged. The frame is repeated if the mobile station reads a "Not-Received" from the R/N flag of the SCF field transmitted from the base station on the FDCCH.

END Frame

This frame is sent at the end of a random access transaction closing the message transmission if the MS receives an acknowledgment from the base station (R/N flag of SCF reads "Received").

BEGIN and SEND Frame

This frame is used when a random access transaction requires only one frame for its completion.

SPACH ARQ STATUS Frame

This frame is sent to report to the base station a partial or complete status of the ARQ based transmission received by the MS on the SPACH. The frame is sent after receiving an ARQ Mode BEGIN or CONTINUE frame on the SPACH where PI field is set to 1.

In table B.8 we present the RACH layer protocol field summary

Table B.8 : RACH Layer 2 Protocol Field Summary

Field Name	Length (bits)	Value(s)
BT = Burst Type	3	000 = BEGIN 001 = CONTINUE 010 = END 011 = BEGIN and END 100 = SPACH ARQ STATUS 101...111 = Reserved

RSVD = Reserved	1/2	Set to Zero.
CI = Change Indicator	1	Starts at 0, toggles for every new transmitted frame. Stays the same for every repeated frame.
EHI = Extension Header Indicator	1	0 = Extension Header not present 1 = Extension Header is present
IDT = Identity Type	2	00 = 20-bit TMSI 01 = 24-bit TMSI 10 = 34-bit MIN 11 = 50-bit IMSI
MSID = Mobile Station Identity	20/24/34/50	20-bit TMSI 24-bit TMSI 34-bit MIN 50-bit IMSI
NL2M = Number of Layer 3 Messages	3	000 = 1 layer 3 message 001 = 2 layer 3 messages 010 = 3 layer 3 messages 011 = 4 layer 3 messages ... ... 111 = 8 layer 3 messages
L3LI = Layer 3 Length Indicator	8	Variable length layer 3 messages supported from 0 up to a maximum of 255 octets.
L3DATA = Layer 3 Data	Variable	Contains a portion (some or all) of the layer 3 message having an overall length as indicated by L3LI. The portion of this field not used to carry layer 3 information id filled with zeros.
PEA = Partial Echo Assigned	7	the 7-bit partial echo value used by a mobile station during an ARQ mode transaction.
MEA = Message Encryption Algorithm	2	00 = Reserved 01 = Reserved 10 = Reserved 11 = Reserved for SOC/BSMC specific signaling.
MEK = Message Encryption Key	2	00 = Reserved 01 = Reserved 10 = Reserved 11 = Reserved for SOC/BSMC specific signaling.
FRNO MAP = Frame Number Map	26	A partial or complete bit map representation of the receive status of an ARCH or SMSCH ARQ mode transaction (1 = Frame Received, 0 = Frame not received).
FILLER = Burst Filler	Variable	All filler bits are set to zero.
CRC = Cyclic Redundancy Code	16	Used for error detection of SPACH messages received at the mobile station.

B.2 BCCH Messages

In this section we provide a set of some mandatory messages that are broadcasted on the BCCH in the forward channel.

Table B.9 : BCCH Mandatory Messages

BCCH Message	F-BCCH	E-BCCH	S-BCCH
DCCH Structure	X		
Access Parameters	X		
Control Channel Selection Parameters	X		
Registration Parameters	X		
System Identity	X		
Neighbor Cell		X	

The DCCH Structure message will hold information about the superframe format being used for the current DCCH.

The Access Parameters message will define the access parameters values for the mobile to use during a random access attempt on the uplink (RACH access).

The Control Channel Selection Parameters message provides the mobile with the necessary information to be used when looking for a better DCCH.

The Registration Parameters message provide rules of registration for the mobile. The System Identity message provide information on the network type being used, protocol versions and system identification number.

The Neighbor Cell message the mobile with a list of surrounding TDMA control channels in neighbor cells.

B.2.1 DCCH Structure

One of the important broadcasted messages on the Fast BCCH (F-BCCH) is the DCCH structure message. It provides the mobile station with information regarding its allocated PCH, the format of the superframe and other system features. In table B.10, we list some of the mandatory elements provided in the DCCH structure message. This message is implemented on Layer 3.

Table B.10: DCCH Structure Message on F-BCCH

Information Element	**Length (bits)**
Message Type	6
Number of F-BCCH slots	3
Number of E-BCCH slots	3
Number of S-BCCH slots	4
Number of Reserved slots	3
Hyperframe Counter	4
Primary Superframe Indicator	1
MAX-SUPPORTED_PFC	3
PCH_DISPLACEMENT	3
PFM_DIRECTION	1
Number of Non_PCH Subchannel slots	2

APPENDIX C

Simulation Set-up and Confidence Interval Calculations

In this appendix, we take the chance to explain the simulation set-up and how an error margin was controlled in the simulation results presented in this thesis by considering what is known by the warm-up period and the confidence interval.

In order to generate reliable accurate simulation results, each simulation set was run three times with different initial seed values.

Another important issue to consider before running the simulation is perhaps one of the most common mistakes that simulator designers do by collecting simulation data before the system enters the steady state. In order to converge simulation results generated by different initial seeds, the user is forced to run the simulations for long time, enough to compensate the useless statistics collected at the beginning of the run. This increases the cost of the simulation runtime, amount of data collected, and inaccuracy in the results. To avoid this waste of time and resources, statistics should be collected once the system is in steady state. To do so, one should invest the time before running the simulation to define what is known by the *Warm-up Period.* The latter covers all fluctuations and large variances occurring in the software model at the beginning of the simulation. In our simulation model, several simulations were run with the same seed and several warm-up periods. Starting with a zero value and then increasing it, the system is known to be in the steady state when the simulation results of the current warm-up period setting is the same as the ones of a smaller one. The latest warm-up period, therefore, becomes the benchmark for starting to collect the simulation statistics. It is important to note that, the simulation duration should be long enough to pass all fluctuations happening at the beginning of the simulation. Several attempts in measuring the warm-up period is the optimum method to use.

It can be noted that, a direct proportion exists between the simulation duration and the accuracy of the simulation output statistics: the longer the simulation duration, the more precise are the results. However, running simulations with long duration takes a tremendous amount of real time and a lot of computing resources. The alternative would be to use several initial seeds and a warm-up period that will eliminate most of the inaccuracy in the output statistics. With that, for every statistic point collected, a confidence interval can be obtained.

By calculating the average value of an extremely large number of samples with different seeds, one can obtain the *true mean value*. Limiting the number of samples to N, we can generate a *mean value* $\bar{x}$. A confidence measure could be thought of as assigning a probability to the condition that the true mean value μ is within a particular distance of the mean value $\bar{x}$ as shown below:

$$Prob\left[\bar{x}-z_\alpha\left(\frac{\sigma}{\sqrt{N}}\right)<\mu<\bar{x}+z_\alpha\left(\frac{\sigma}{\sqrt{N}}\right)\right] = \alpha$$

where σ is the standard deviation, N the number of samples and z_α a standardized normal variable for which the standard deviation is unity and the mean is zero.

$$z_\alpha = \frac{\left(\bar{x}-\mu\right)}{\sigma_{\bar{x}}}$$

This statement introduces the notion of confidence interval for μ: with a probability of α, μ is defined to be in the interval $\left[Q_{lower}, Q_{upper}\right]$. For instance, if $\alpha = 0.9$, then the interval is called 90% confidence interval for μ. The confidence interval limits can therefore be defined as:

$$Q_{lower} = \bar{x} - z_\alpha\left(\frac{\sigma}{\sqrt{N}}\right) \qquad Q_{upper} = \bar{x} + z_\alpha\left(\frac{\sigma}{\sqrt{N}}\right)$$

α is often referred to as the confidence level. For instance, for a confidence level of 90%, the confidence interval $\left[Q_{lower}, Q_{upper}\right]$ is defined based on the value of z_α. Table C.1 shows the value of z_α for a few common confidence levels used in simulations. These measures were extracted from [OPNT2-97], page "Datan-23".

Table C.1: z_α for different confidence levels.

Confidence Level α	z_α
99%	2.575
98%	2.327
95%	1.96
90%	1.645
80%	1.282

Note that the above expressions rely on the knowledge of the true standard deviation σ which is not always known, and an extremely large number of samples is required to estimate the true mean μ. For cases where the true variance is not known and only few samples are affordable, the sample variance s^2 can be used instead of the true variance σ^2, and t_α is used instead of z_α. The new confidence interval becomes

$$Q_{lower} = \bar{x} - t_\alpha\left(\frac{s}{\sqrt{N}}\right) \qquad Q_{upper} = \bar{x} + t_\alpha\left(\frac{s}{\sqrt{N}}\right)$$

where t_α is provided in table C.2 [OPNT2-97].

Table C.2: t_α for different confidence levels and number of samples

Confidence Level α	t_α, N=3	t_α, N=5	t_α, N=10	t_α, N=20
99%	9.925	4.604	3.250	2.861
98%	6.965	3.747	2.821	2.539
95%	4.303	2.776	2.262	2.093
90%	2.920	2.132	1.833	1.729
80%	1.886	1.533	1.383	1.328

By comparing table C.1 with table C.2, it can be shown that by considering more samples, the t distribution converges to the z distribution.

Bibliography

[Cell-97] “Cellular Business: The Journal of Cellular Telecommunications”, World Report ‘97, April, 1997, pp. 27-48

[Chic-97] “Chicago Tribune”, February 26, 1997, p. 3-1.

[Cons-97] “Consumer Reports”, February 1997, p. 11, from MTA-EMCI.

[Gibs1-97] Stephen W. Gibson, “Cellular Telephones and Pagers: An Overview”, Newnes, 1997, Chap. 1.

[Gibs2-97] Stephen W. Gibson, “Cellular Telephones and Pagers: An Overview”, Newnes, 1997, Chap. 2.

[Gibs3-97] Stephen W. Gibson, “Cellular Telephones and Pagers: An Overview”, Newnes, 1997, Chap. 3.

[Maca-97] Raymond C. V. Macario, “Cellular Radio; Principles and Design”, Second Edition, McGraw-Hill, 1997, p. 267.

[OPNT97] Mil-3 Inc., OPNET MODELER/RADIO, Release 3.0B, 1995.

[OPNT2-97] Mil-3 Inc., OPNET MODELER/RADIO, OPNET Modeling Manual, Volume 2, Release 3.0B, 1995.

[Stal1-97] William Stallings, ‘Data and Computer Communications: Fifth Edition”, Upper Saddle River, NJ: Prentice Hall, 1997, Chap. 4.

[Stal2-97] William Stallings, ‘Data and Computer Communications: Fifth Edition”, Upper Saddle River, NJ: Prentice Hall, 1997, Chap. 6.

[Stal4-97] William Stallings, ‘Data and Computer Communications”, Fifth Edition, Upper Saddle River, NJ: Prentice Hall, 1997, p.129.

[Comp-96] “Computer Reseller News”, December 23, 1996, p.23, from Frost & Sullivan Inc.

[Couc-95] Couch L., “Modern Communication Systems: Principles and Applications”, Englewood Cliffs, NJ: Prentice Hall, 1995.

[IS-1STD] IS-136.1 DCCH standard ‘TDMA Cellular/PCS - Radio Interface - Mobile Station - Base Station Compatibility - Digital Control Channel, Rev. A”, 1995.

[Redl-95] Siegmund H. Redl, Matthias K. Weber, Malcolm W. Oliphant, “An Introduction to GSM”, 1995, Artech House Inc., p. 5.

[Fors-94] Victor S. Forst and Benjamin Melamed, “Traffic Modeling for Telecommunications Networks”, IEEE Communications Magazine, March 1994, pp. 70-81.

[Hayk-94] Haykin S., “Communication Systems”, New York: Wiley, 1994.

[Law-94] A. M. Law and Michael G. McComas, “Simulation Software for Communications Networks: The State of the Art”, IEEE Communications Magazine, March 1994, pp 44-50.

[PCS94] Hakan Andersson and Anders Hoff, “PCS support in IS-54C”, IEE, International Conference on Universal Personal Communication, Third Annual ,1994.

[Almg-93] Almgren M., Andersson H., Wallstedt K., “Capacity enhancement features in a TDMA system”, Proc. IEEE VTC’93, May 1993, pp. 277-280.

[Bert-92] Bertsekas D. and Gallager R., “Data Networks”, Englewood Cliffs, NJ: Prentice Hall, 1992.

[Pear-92] Pearson J., “Basic Communication Theory”, Englewood Cliffs, NJ: Prentice Hall, 1992.

[Law-91] A. M. Law and W. D. Kelton, “Simulation Modeling and Analysis”, Second Edition, McGraw-Hill, 1991.

[Salm-91] A. Salmasi, K. S. Gilhousen, “On the System Design Aspects of Code Division Multiple Access (CDMA) Applied to Digital Cellular and Personal Communications Networks”, Proceedings of IEEE Vehicular Technology Conference, VTC-91, St. Louis, USA, May 1991, pp. 57-63

[Hayk1-89] Haykin S., “An Introduction to Analog and Digital Communications”, New York: Wiley, 1989, Chap. 7.

[Lee-89] W. C. Y. Lee, “Mobile Cellular Telecommunications Systems”, McGraw-Hill Book Co., 1989, p. 49.

[Qual-89] Qualcomm, Inc. and Pactel, “CDMA Cellular”, 1989.

[Calh-88] George Calhoun, “Digital Cellular Radio”, Artech House Inc., 1988, pp. 344-351.

[Akai-87] Yoshihiko Akaiwa and Yoshinori Nagata, “Highly Efficient Digital Mobile Communications with a Linear Modulation Method”, IEEE Journal on Selected Areas in Communications, Vol. SAC-5, June 1987, pp. 890-895.

[Mura-87] Flavio Muratore and Valerio Palestini, “Features and Performance of 12PM3 Modulation Methods for Digital Land Mobile Radio”, IEEE Journal on Selected Areas in Communications, Vol. SAC-5, June 1987, pp. 906-914.

[Lee-86] W. C. Y. Lee, "Mobile Communications Design Fundamentals", Howard W. Sams & Co., 1986, p.141.

[Huff- 85] D. L. Huff, "AT&T Cellular Technology Review", Conference Record of 1985 IEEE Military Communications Conference, October 1985, Boston, pp. 490-494.

[O'Nei-85] E. F. O'Neill, ed., "A History of Engineering and Science in the Bell System: Transmission Technology (1925-1975)", AT&T Bell Laboratories, 1985, p. 562.

[Simo-85] Marvin K. Simon, Jim K. Omura, Robert A. Scholtz, and Barry K. Levitt, "Spread Spectrum Communications: Volume I", Rockville, Maryland: Computer Science Press, 1985, p.80.

[Smit-85] David R. Smith, "Digital Transmission Systems", New York: Van Nostrand Reinhold, 1985, pp. 223 ff., p. 552.

[Bods-84] D. Bodson, G.F. McClure, and S. R. McConoughey (eds), "Land-Mobile Communications Engineering", IEEE Press, 1984, Part III.

[Comr-84] R. A. Comroe and D. J. Costello, Jr., "ARQ Schemes for Data Transmission in Mobile Radio Systems", IEEE Transactions on Vehicular Technology, Vol. VT-33, August 1984, pp. 88-97

[Dixo-84] Dixon R., C., "Spread Spectrum Systems: 2nd edition", New York: Jhon Wiley and Sons, 1984.

[Cook-83] Charles E. Cook and Howard S. Marsh, "An Introduction to Spread Spectrum", IEEE Communications Magazine, March 1983, pp. 8-16.

[Halp-83] S. W. Halpren, "Reuse Partitioning in Cellular Systems", 33rd IEEE Vehicular Technology Conference Record, Toronto, May 1983.

[Lee-83] W. C. Y. Lee and H. Smith, "A Computer Simulation Model for the Evaluation of Mobile Radio Systems in the Military Tactical Environment", IEEE Transactions on Vehicular Technology, Vol. VT-32, May 1983, pp. 177-190.

[Oett-83] J. Oetting, "Cellular Mobile Radio—An Emerging Technology", IEEE Communications Magazine, Vol. 21, No. 8, November 1983. pp. 10-15.

[Sund-83] C. E. Sundberg, "Continuous Phase Modulation in Cellular Digital Mobile Radio Systems", Bell System Technical Journal, September 1983, pp. 2067-2086.

[Bell-82] John C. Bellamy, "Digital Telephony", New York: Wiley, 1982, p. 71.

[Chun-82] K. S. Chung and L. W. Zegers, "Generalized Tamed Frequency Modulation", Philips Journal of Research, Vol. 37, 1982, pp. 165-177.

[Lee1-82] W. C. Y. Lee, "Mobile Communications Engineering", McGraw-Hill Book Co., 1982, p. 104.

[Lee2-82] W. C. Y. Lee, "Mobile Communications Engineering", McGraw-Hill Book Co., 1982, p. 390.

[Pick-82] Raymond L. Pickholtz, Donald L. Schilling, and Laurence B. Milstein, "Theory of Spread Spectrum Communications: A Tutorial", IEEE Transactions on Communications, Vol. COM-30, May 1982, pp. 855 ff.

[Suzu-82] Hiroshi Suzuki and Kenkichi Hirade", System Considerations of Mary PSK Land Mobile Radio for Efficient Spectrum Utilization", The Transactions of the IECE of Japan, Vol. E 65, No. 3, March 1982, pp. 159-165.

[Asak-81] S. Asakawa and F. Sugiyama. "A Compact Spectrum Constant Envelope Digital Phase Modulation", IEEE Transactions on Vehicular Technology, Vol. VT-30, August 1981, pp. 102-111.

[Muro-81] K. Murota and K. Hirade. "GMSK Modulation for Digital Mobile Radio Telephony", IEEE Transactions on Communications, Vol. COM-29, July 1981, pp. 1044-1055.

[Blec-80] F. H. Blecher, "Advanced Mobile Phone Service", IEEE Transactions on Vehicular Technology", Vol. VT-29, May 1980, pp. 238-244.

[Bell-79] "Advanced Mobile Phone Service", special issue, Bell System Technical Journal, Vol. 58, January 1979

[Comm-79] "Single-Sideband Mobile Radio: A Review and Update", IEEE Communications Magazine, March 1979, pp. 25-28.

[Hira-79] K. Hirade and K. Murota, "A Study of Modulation for Digital Mobile Telephony", 29th IEEE Vehicular Technology Conference Record, Arlington Heights, Illinois, March 27-30, 1979, pp. 13-19.

[MacD-79] V. H. MacDonald, "The Cellular Concept", Bell System Technical Journal, Vol. 58, January 1979, pp. 15-42.

[Pasu-79] Subbarayan Pasupathy, "Minimum Shift Keying: Spectrally Efficient Modulation", IEEE Communications Magazine, July 1979, pp. 14-22.

[Jage-78] F. de Jager and C. B. Dekker, "Tamed Frequency Modulation, a Novel Method to Achieve Spectrum Economy in Digital Transmission", IEEE Transactions in Communications, Vol. COM-26, May 1978, pp. 534-542.

[Mabe-78] P. J. Mabey, "Mobile Radio Data Transmission-Coding for Error Control", IEEE Transactions on Vehicular Technology, Vol. VT-27, August 1978, pp. 99-109.

[Skom-78] E. N. Skomal, "Man-Made Radio Noise", Van Nostrand Reinhold Co., 1978, Chap. 2.

[Webe-78] W. J. Weber, "A Bandwidth Compressive Modulation System Using Multiamplitude Minimum Shift Keying (MAMSK)", IEEE Transactions on Communications, Vol. COM-26, May 1978, pp. 543-551.

[Scho-77] Robert A. Scholtz. "The Spread Spectrum Concept", IEEE Transactions on Communications, Vol. COM-25, August 1977, pp. 748-755.

[Gron-76] S. A. Gronemeyer and A. L. McBride, "MSK and Offset QPSK Modulation", IEEE Transactions on Communications, Vol. COM-24, August 1976, pp. 809-820.

[Halp-76] S. W. Halpren, "Techniques for Estimating Subjective Opinion in High-Capacity Mobile Radio", Microwave Mobile Symposium, Boulder, Colorado, 1976.

[Cinl-75] E. Cinlar, "Introduction to Stochastic Processes", Prentice-Hall, 1975.

[Spau-74] A. D. Spaulding and R. T. Disney, "Man-Made Radio Noise, Part I", U.S. Department of Commerce, Office of Technical Services Report 74-38, June 1974.

[Bell-71] Bell Laboratories, "High-Capacity Mobile Telephone System Technical Report", December 1971, submitted to FCC.

IMAGE EVALUATION
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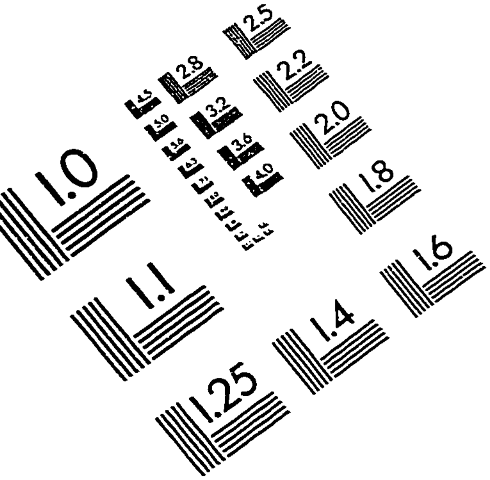

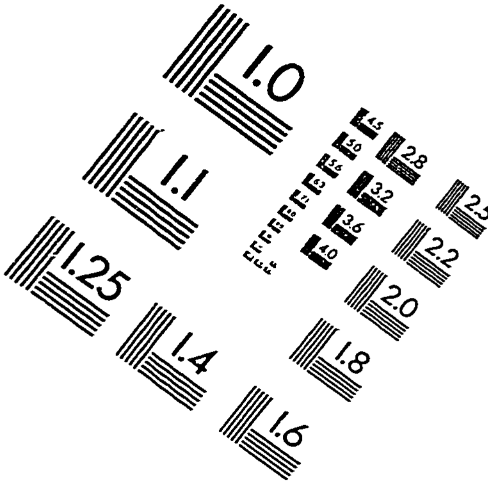

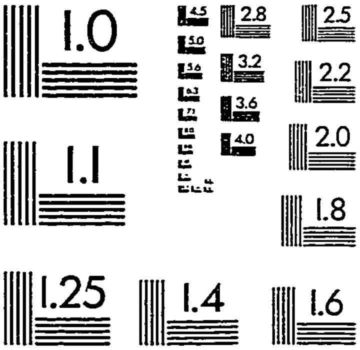

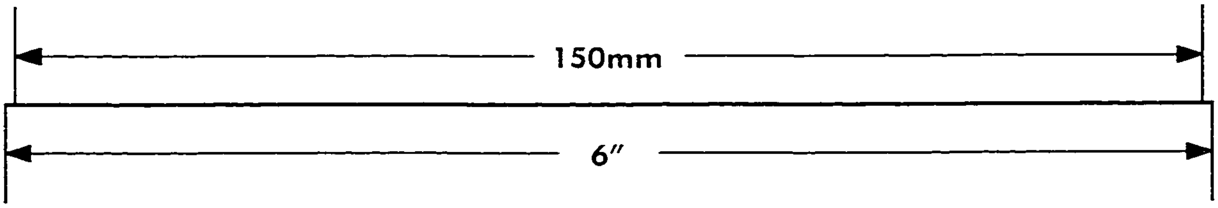

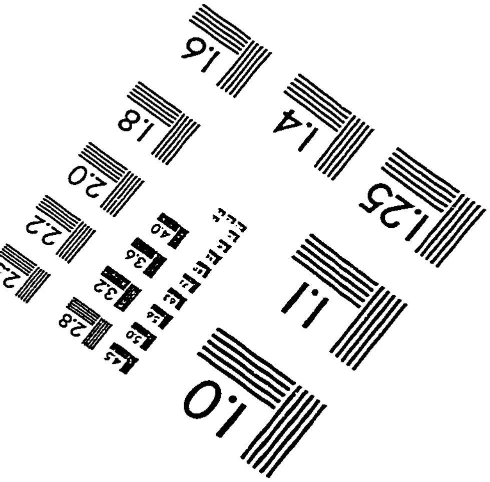

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