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CDMA DIGITAL CELLULAR COMMUNICATION SYSTEMS

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CERTIFICATE

Certified that this is a bonafied report of the dissertation work done by Major Rakesh Avasthi during the year 1998 inpartial fulfilment of the requirement for the award of the Degree of Master of Technology in Electrical Engineering by the Jawaharlal Nehru University, New Delhi

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III **THEORY OF CELLULAR COMMUNICATION AS APPLIED TO CDMA**

CHAPTER 1

INTRODUCTION TO MOBILE CELLULAR SYSTEMS

1.1 Background

Mobile telecommunications is certainly one of the major breakthroughs. The possibility to make and receive calls through a small wireless handset, wherever you are, has an obvious appeal. Wireline telephony allows us to reach a place, if someone is there to answer. Mobile telephony allows us to reach a particular person, wherever the person is. Mobile telecommunication is not a very recent technology but is a rapidly evolving one. Expensive vehicle mounted sets have been available for 30 to 40 years. A major step was made at the beginning of the 1980's when analog cellular technology was introduced.

The idea of instant communication regardless of distance is part of man's oldest dreams. The first implementation of radio waves for communication were realized in the late nineteenth century for radiotelegraphy. Since then it has been a widely used technique for military communications. The first mobile telephone networks were manually operated, the intervention of an operator was required to connect the call to the wireline network. The terminals were heavy bulky and expensive. The service area was restricted to the coverage of a single cell system ie a single emission and reception site.

Between 1950 and 1980, mobile radio system evolved to become automatic and the costs decreased due to the introduction of semiconductor technology. Capacity increased a little but remained two small compared to potential demand, public telephony remained a luxury product for chosen few. During the 70's, large scale integration of electronic devices and the development of microprocessors opened the door to the implementation of more complex systems. Because the coverage area of one antenna is mainly limited by the transmitting power of mobile stations, systems were devised with several receiving stations for a single transmitting station. They allowed coverage of a larger area at the cost of additional infrastructure complexity. But the real break through came with **cellular systems**, where both transmitting and receiving sites are numerous and whose individual coverage areas partially overlap

The cellular concept was introduced by the Bell Labs, and was studied in various places in the world during the 70's. In the US, the first cellular system, the AMPS (Advanced Mobile Phone Service) became a reality in 1979 in Chicago.Nordic Mobile Telephone (NMT) systems started operations in Sweden in Sep 1981. The TACS derived from AMPS, was put in service in the UK in 1985. Major cellular network in operation in Europe in early 1992 are shown in Table 1.1 within the US the concept of cellular radio was developed primarily by AT & T and Motorola. The comparison of first and second generation Analog and Digital Radio systems are given in Table 1.2 and 1.3.

Table 1.1 - Major Systems in Europe in 1991

Country	Systems	Freq.Band	Date of launch	Subscribers (thousands)
United Kingdom	TACS	900	1985	1200
Scandinavia (Sweden, Norway, Finland, Denmark)	NMT	450 900	1981 1986	1300
France	Radiocom 2000 NMT	450,900 450	1985 1989	300 90
Italy	RTMS TACS	450 900	1985 1990	60 560
Germany	C-450	450	1985	600
Switzerland	NMT	900	1987	180
The Netherlands	NMT	450 900	1985 1989	130
Austria	NMT TACS	450 900	1984 1990	60 60
Spain	NMT TACS	450 900	1982 1990	60 60

TABLE 1.2 : Comparison of First and Second-Generation Cellular Radio Systems: Analog

	System					
Parameter	AMPS' (U.S.Canda)	NAMPS^h (U.S>)	NMT (Scandinavia)	MCS.1.1 MCS-L2^d (Japan)	C450 (Germany) 1985	TACS ETACS (U.K.) 1990
Transmission frequency (MHz)						
Base	869-894	469-894	935-960	870-885	461-466	917-933 935-960
Mobile	824-849	824-849	890-915	925-940	451-456	872-888, 890-915
Duplexing method	FDD	FDD	FDD	FDD	FDD	FDD
Multiple-access method	FDMA	FDMA	FDMA	FDMA	FDMA	FDMA
Channel bandwidth (kHz)	30.0	10.0	25	25.0 12.5	20.0 10.0	25.0
Total channels	832	832 x 3	1999	600 1200	222 444	1000
Voice Modulation Peak deviation (kHz)	 Analog PM ± 12	 Analog PM ± 5	 Analog PM ± 5	 Analog PM ± 5	 Analog PM ± 4	 Analog PM ± 9.5
Control Modulation Peak Deviation (kHz) Channel rate (kbps)	Digital FSK ± 8 10.0	Digital FSK ± 8 10.0	Digital FSK ± 3.5 1.2	Digital FSK ± 4.5 0.3	Digital FSK ± 2.5 5.3	Digital FSK ± 6.4 8.0

TABLE 1.3 Comparison of First-and Second-Generation Cellular Radio Systems: Digital

System					
Parameter	**GSM[a] (Europe)**	**PCN[b] (U.K.)**	**IS-54[c] (U.S., Canada)**	**PCD[d] (Japan)**	**IS-95[e] (U.S.)**
Transmission frequency (MHz Base Mobil	890-915 935-960	1710-1785 1805-1880	869-894 824-849	810-826 940-956	869-894 824-849
Duplexing method	FDD	FDD	FDD	FDD	FDD
Multiple-access method	TDMA	TDMA	TDMA	TDMA	CDMA
Channel bandwidth (kHz)	200.0	200.0	30.0	25.0	1.23 MHz
Traffic Channels per RF Channel	8	16	3	3	60
Total channels	125 x 8	375 x 8	832 x 8		60 x 5
Voice carrier Speech rate (kbps) Modulation Channel rate (kbps)	RPE/LTP-LPC 13.0 GMSK 270.8	RPE/LTP-LPC 13.0 GMSK 270.8	VSELP 8.0 $\pi/4$-DQPSK 48.6	VSELP 11.2 $\pi/4$-DQPSK 42	QCELP 8 DS/CDMA -
Channel coding Base - mobile Mobile-base	Conv. 1/2 1/2	Conv. 1/2 1/2	Conv. 1/2 1/2	Conv. 1/2 1/2	Conv. 1/2 1/3

RPE/LTP-LPC - Residual
Pulse Excited
Linear Prediction Coder
with Long Term Prediction.

1.2 REQUIREMENTS OF MOBILE TELEPHONY

There are four basic problems faced by mobile communications.

(a) How to ensure privacy and intelligibility of communications.

(b) How to provide for the growth in number of users both in density as well as diversity.

(c) How to allow user mobility while in conversation.

(d) How to overcome transmission problems such as noise interference etc.

1.2.1 Ensuring privacy & intelligibility of communication : This is ensured by use of multiplexing/de-multiplexing techniques and using special coding/tokens for users identity. A number of voice/data channels are multiplexed to form the information signal which then modulates a radio frequency carrier.

1.2.2 Problem of Bandwidth vis-a-vis growth in number of users. Given a radio frequency band, the bandwidth required for each channel of communication, and the number of channels forming the multiplex, it would be possible only for limited number of users to communicate simultaneously. Now to see how the problem of growth in number of users can be overcome let us consider two geographical areas spaced far apart. In this case it is possible to re-use the same radio frequency band for communications confined to the respective areas. So, if we notionally divide the geographical area of the network to be served into a number of small zones (called cells) then the available radio frequency band can be subdivided into a number of subbands, and adjacent cells can be allotted non-overlapping sub-bands and cells sufficiently far apart (with no common boundaries) can be allowed to re-use the sub-bands. Some pattern of radio frequency band re-use can be followed..

Thus, so long as the number of actual users within a cell area does not exceed the number of channels of communications permitted by the radio frequency sub-band available for use in the cell, there is no difficulty in providing communication facility over the whole network. The uneven density of telecom users in different parts of the network density of telecom users in different parts of the network can be tackled by the following techniques:

(a) Making the size of cells smaller in dense areas & larger in sparse areas so that number of users per unit cell area never exceeds the allowed limit.

(b) Dividing the radio frequency band so that the number of sub-bands are less but each sub-band is wider thus allowing each cell to accommodate more channels.

(c) Adopting RF band re-use pattern so that the less number of sub-bands are re-used as quickly as possible and the channel interference is not troublesome. Use of digital modulation & channel coding schemes enable this to be realized.

Thus, we arrive at the basic structure of the digital cellular network - a geographical area notionally divided into a number of cells of sizes depending on the traffic and user density.

1.2.3 **Providing mobility to the users** : A cellular network consists of a number of cells with a base station with a transmitter located in each cell and the users communicate using wireless radio communication. In addition, there is a Message Switching Centre (MSC) to enable a user in one cell to be able to communicate with another user located in the same cell or in another cell. The message switching centre does the job of linking (or switching through) the channel of communication (voice band) on the appropriate radio frequency carrier of the caller with the channel of communication of the called party on the latters appropriate radio frequency carrier.

So long as both the parties roam within their respective cell areas there is no problem in maintaining the communication link. Only if one or both parties move into adjacent cells while in conversation then, to maintain uninterrupted communication, the MSC transfers the voice channel from the original radio frequency carrier of the previous cell to an available slot on the radio frequency carriers of the new cell (s). This transfer is effected fast enough compared to the radial speed of movement and information flow rate so that the communicating parties on the move do not feel any interruption.

1.2.4 **Overcoming Transmission Problems** : Additional complications affecting reliable communication arise out of signal disturbances as a result of the environment, radio frequency, sensitivity, range and power level requirements of the sender's instrument and frequency synchronization problems as also in identifying different users. causes of signal disturbances are:-

(a) The signal strength deteriorates as the distance from base station increases - phenomenon is called path loss.

(b) The presence of buildings, hills etc. gives rise to shadowing effects - deteriorating the signal strengths - the phenomenon is called log normal fading.

(c) Because of various reflecting objects of the surroundings signal may reach the receiver following more than one path leading to a number of fade dips as a result of interference of these signals with different phases & amplitude - this is called Rayleigh fading effect. Number and location of these fade dips depends on the carrier radio frequency also.

(d) Reflected signals may arrive after considerable time delay being reflected from a far away object - a phenomenon called time dispersion leading to inter symbol interference.

1.2.5 Techniques Used to Overcome Transmission Problems.

To over come the adverse effects a number of techniques are used. These are:-

(a) Antenna (space) diversity For base station antennas - a gain of 6 db is possible with 5 to 6 meters spacing between two antennas at one BTS.

(b) Frequency hopping. To take advantage of the fact that the fading pattern is frequency dependant, the carrier frequency is changed among a number of frequencies during a call - probability of simultaneous fading of all carriers being very low.

(c) Channel coding and inter leaving

(d) To overcome noise effects and the fact that noise mostly occur in bursts, block coding & convolution coding techniques are used; in addition, interleaving is also resorted to.

(e) To overcome time dispersion effects equalization bit packing technique is adopted.

1.3 CELLULAR NETWORK CONFIGURATION

The functional entities in a typical cellular network that are of particular interest here are:-

(a) Cellular Subscriber Stations (CSS)
(b) Base Stations (BSs)
(c) Mobile Switching Centers (MSCs)
(d) Home Location, Registers (HLRs)
(e) Visitor Location Registers (VLRs)

1.3.1 Cellular Subscriber Stations - CSSs terminate the radio link on the user side of the user-to-network interface. They are also referred to as Mobile Stations (MSs)

1.3.2 Base Stations - The primary role of a BS is to terminate the radio link on the network side of the user-to-network interface. This involves an element of control as well as RF,IF, and base band processing. In some implementations, the controllers are co-located with the transreceivers. In others, a single controller supports multiple remote transreceivers. Regardless of their physical location, however, BS controllers are limited to processing information directly related to the establishment, maintenance, and release of one or more radio links. That is, BS controllers manage channels which are part of connections. CSS registrations and request for service are passed on, essentially as received, to the MSC for processing.

1.3.3 Mobile Switching Centres - In addition to the call processing functions normally performed by a central office, MSCs do the following:

(a) Select and coordinate the broadcast of system level parameters.

(b) Process CSS registrations.

(c) Query Location Registers.

(d) Manage the paging process.

(e) Select the BS best able to handle a call.

(f) Establish connections between the PSTN and the BS assigned to handle the call.

(g) Coordinate handoff activities.

In short, the MSC performs the bulk of the wireless and wired call processing in existing cellular systems. Each CSS is assigned to a home MSC when it is placed in service. Land-line switches route calls placed to a CSS, to the home MSC of the CSS. The home MSC is then responsible for locating the CSS and routing the call.

1.3.4 **Home Location Register** - HLRs are used to support automatic roaming. Each system has one or more HLRs associated with it, each one responsible for maintaining a series of records for a group of CSSs. The HLR entries for each CSS include:

(a) A Mobile Identification Number (MIN) to which the CSS will respond.

(b) The Electronic Serial Number (ESN) burned into the CSS during its manufacture.

(c) The set of features to which the CSS has subscribed (i.e., active/inactive).

(d) Profile settings and data (e.g., call forwarding on/off and forward-to numbers, respectively).

(e) The CSS state (i.e., active/inactive).

(f) A pointer (Point Code and Subsystem Number) to the last VLR to have provided the HLR with registration information concerning the CSS.

Every CSS is assigned to a HLR when it is placed in services and given a MIN. A CSS may have multiple MINs, and as such, may be serviced by multiple HLRs. However, for a given MIN/ESN pair, there is one and only one HLR supporting it. Also, while standards define the interface between a HLR and other components in a cellular system (i.e., MSCs and VLRs) to allow the HLR to operate as a standalone unit on a signaling network, many current implementations have the HLR co-located with an MSC and VLR. This has more to do with how intersystem capabilities are being phased into existing networks than with performance concerns.

1.3.5 Visitor Location Register - VLRs are used in conjuction with HLRs to support automatic roaming. VLRs perform two functions: they assist in locating a CSS for call delivery, and they act as local, temporary repositories for subscriber profiles available locally, reduces traffic on intersystem signalling networks and improves call setup times.

VLRs may operate as stand-alone units, or be co-located with MSCs. Their placement is a trade-off between two factors: to support VLRs as stand-alone units serving multiple MSCs; to support real-time call delivery by providing service profiles to MSCs, it may be advantageous to co-locate VLRs and MSCs.

1.4 OPERATION OF CELLULAR SYSTEM

The cell is an area generally shown in a six sided honey comb shape, because this is the simplest way to illustrate the working of the system and also because it approaches a circular shape that is the ideal power coverage area.

Radio Txn in Cellular System : The radio txn used in a cellular system is narrow band FM. The important characteristic of FM receiver is the capture effect. An FM receiver while detecting two transmissions on the same frequency will ignore the weaker signal and lock onto the stronger one without any real loss in the signal quality. To keep this sort of interference to minimum, the RF power used to transmit the signal between mobile subscriber and the base station is constantly monitored, measured and adjusted to the lowest level of power that will give effective communication. However this is done on another radio channel rather than the voice channel.

1.4.2 CSS Tracking

When an instrument is turned on, it enters into the idle state. In this condition, it is only doing the electronic house keeping routines that are necessary to prepare it to receive or make calls. The receiver scans the designated set up channels and selects the strongest and locks on to it for a certain time. Since each cell is assigned a different set up channel, locking on to the strongest one implies selecting the nearest BS. This eliminates the load on transmission at the cell site for locating the mobile unit. After every 60 seconds, the self location procedure is repeated. This is to cater for the contingency of the CSS moving into another cell.

The BSs forward the registration messages from CSS to an MSC for processing. The serving MSC examines the MIN and forwards the contents of the registration message to its VLR, identifying itself as the serving MSC.

If the CSS has previously registered the VLR merely updates the field used to track the MSC serving the CSS and informs the MSC that the registration has been successfully processed.

If the VLR has no knowledge of the CSS, it notifies the HLR associated with the SCC CSS and MIN of both the SCC's CSS presence and the identity of the serving MSC. It also requests any service profile information for the CSS. After performing the requisite checks, the HLR informs the VLR under what conditions the CSS may be served.

1.4.3 Call Delivery

Calls to a CSS are routed via Public Switched Telephone Network (PSTN) to the home MSC associated with the digits dialed by the calling party. The MSC now sends a location request message to the CSS's HLR seeking guidance as to how to handle the call. The HLR in turn contacts the last VLR from which it received a location update. The VLR contacts the 'Serving' MSC to obtain instructions as to how the call should be delivered.

Before responding the serving MSC checks the busy/idle status of the CSS. If the CSS is idle, the MSC assigns a Temporary Local Directory Number (TLDN) to the call and sends it (via the VLR) to the HLR that had initiated the request, This TLDN is delivered by the HLR to the home MSC which then forwards the call (i.e. establishes voice circuit) to the serving MSC over whatever facilities are available eg PSTN. Finally the serving MSC pages the CSS to determine the serving BS, allocates resources on the trunk connecting the BS with the serving MSC, assigns the CSS to a voice/traffic Channel, and instructs the CSS to alert the subscriber.

When the call has been completed and the CSS hangs up, a particular switching tone is transmitted to the cell site and both sides then free the voice channel.

1.4.4 Hand Off Procedure

As the CSS during a call moves out of a cell site, the signal strength on the existing channel between the BS and CSS, becomes weak and goes below the threshold. This signal is constantly monitored, so the MSC now transfers the call to a vacant channel that will give a better signal either in the same cell or in a adjacent one. At the same time, the BS is directed to tell the mobile unit to switch to the newly assigned channel. The CSS does this automatically and the MSC confirms it. This procedure is called handoff and takes place in less than 2 ms and is accomplished without either party being aware of it.

1.5 BASE STATION HARDWARE

The development of cellular telephony owes its existence to the development of micro and mini computers. The cellular system is a mix of a dedicated processor and a computer in each of its stations. The computer is used at MSC to control the digital switching system and do all other tasks such as billing, traffic analysis and monitoring the operation of all cell sites.

For each voice and date channel there is a module containing a transmitter, a receiver, a control unit and power supply equipment. In addition each base station has a transmitter, combiner and receiver multi-coupler that are designed to allow connecting of a number of transmitters and receivers to the same antenna without creating any interference to each other. The signal receiver measures the strength of the radio signal on any of the channels on the command of MSC. This is done for hand off procedure as and when required.

Control Unit This is a dedicated micro computer and is one for each radio channel. It is responsible for all the communications, both data and voice, with MSC and it controls and monitors the CSS.

Transmitter This consists of a control unit to control the amplification level, frequency generator, the exciter and power amplifier.

Receiver It filters the correct incoming signal, amplifies it, then passes it of the IF unit for further down conversion of the signal. A part of this is fed back to control unit.

Antenna The actual antenna that does the radiating is usually a centre fed collinear type with two or more elements stacked one above the other to provide gain or reinforcement of the signal.

1.6 Sequence of Operation (From Speech to radio waves on the source side)

To understand the sequence of operations in transmitter and receiver side, example of GSM has been taken.

(a) **Channel Coding** introduces redundancy into the data flow, increasing its rate by adding information calculated from the source data, in order to allow the detection or even the correction of signal errors introduced during transmission. The result of the channel coding is a flow of code words; in the case of speech, these code words are 456 bits long.

(b) **Inter leaving** involves mixing up the bits of several code words, so that bits which are close to one another in the modulated signal are spread over several code words. Since the error probability of successive bits in the modulated stream is very much correlated and since channel coding performance is better when errors are decorrelated, interleaving aims at decorrelating errors and their position in code words. After interleaving, the flow of information is succession of blocks - one block for each channel burst.

(c) **Ciphering** modifies the contents of these blocks through a secret recipe known only by the mobile stations and the base transreceiver station.

(d) **Burst Formatting** adds some binary information to the ciphered blocks in order to help synchronization and equalization of the received signal, the output of this stage consists of binary information blocks.

(e) **Modulation** transforms the binary signal into an analog signal at the right frequency and at the right moment using multiple access rules. The signal is then transmitted as radio wave.

1.7 Sequence of operations on the receiver side

(a) **Demodulation** Radio waves are captured by the antenna. The portion of the received signal which is of interest to the receiver is determined by the multiple access rules. This portion undergoes demodulations with the help of the additional information introduced during burst formatting. The result may consist in a succession of binary information blocks. More sophisticated demodulator, however are able to deliver an estimated probability of correctness of each bit; this is called soft decision".

(b) **Deciphering** modifies those bits, by reversing the ciphering recipe, since this recipe is a bit-by-bit "exclusive or" with a ciphering sequence, it may be performed just as well when a soft decision process is applied.

(c) **De-interleaving** puts the bits of the different bursts back in order to rebuild the code words.

(d) **Channel Decoding** Channel decoding tries to reconstruct the source information from the output of the demodulator, using the added redundancy to detect or correct possible errors in the output from the demodulator. This operation is much more efficient when the demodulator indicates a priori error likelihood of each bit.

1.8 Consideration for Further Study

In this Chapter emphasis has been to understand the functioning of a Cellular Communication system in general and the background which laid the foundation for development of modern day multiple access mobile digital communication systems.

Having done this we will now graduate to familiarise with spread spectrum signals and theory of CDMA to pursue the intended study.

CHAPTER 2

THEORY OF SPREAD SPECTRUM SIGNALS AND CDMA

2.1 Introduction

In digital communications the effort is always on efficient utilization of bandwidth and power. Notwithstanding the importance of these two primary communication resources. There are situations where it is necessary to sacrifice the efficient utilization of bandwidth in order to meet certain other design objectives such as provision of secure communication. The signalling technique used for this is called spread-spectrum modulation.

2.2 Definition of Spread-Spectrum Modulation. It can be stated in two parts

(a) Spread Spectrum is a means of transmission in which the data sequence occupies a bandwidth in excess of the minimum bandwidth necessary to send it.

(b) The spectrum spreading is accomplished before transmission through the use of a code that is independent of the date sequence. the same code is used in the receiver (operating in synchronism with the transmitter) to despread the received signal so that the original data sequence may be recovered.

Application of spread spectrum modulation. The spread spectrum modulation was originally developed for military applications, where resistance to jamming is of major concern. It is also used to provide multipath rejection in a ground-based mobile radio environment. It finds application in *multiple-access* *communication* in which a number of independent users are required to share a common channel without an external synchronizing mechanism as in a ground based mobile radio environment involving mobile vehicles that must communicate with a central station.

2.3 Important Elements Employed in the Design of Spread Spectrum Signals

(a) Coding and

(b) Pseudo - randomness

(a) **Coding** Spread spectrum signals have their bandwidth, W much greater than the information rate, R in bits/sec. The bandwidth expansion factor $B_e = W/R$ for a spread spectrum signal is much greater than unity. The large redundancy inherent in spread spectrum signal is required to overcome the severe levels of interference that are encountered in the transmission of digital information. Since coded waveforms are also characterized by a bandwidth expansion factor greater than unity and since coding is an efficient method for introducing redundancy, **coding** is, therefore, an important element in the design of spread spectrum signal.

(b) **Pseudo Randomness** Second important element employed in the design of spread spectrum signals is **pseudo-randomness**, which makes the signals appear similar to random noise and difficult to demodulate by receivers other than the intended ones.

2.4 The Uses of Spread Spectrum Signals

These are

(a) Combatting or suppressing the detrimental effects of interference due to jamming, interference arising from other users of the channels and self interference due to multipath propagation.

(b) Hiding a signal by transmitting at low power and thus making it difficult for an unintended listner to detect in the presence of background noise.

(c) Achieving message privacy in the presence of other listners.

2.5 What is CDMA Technique ?

In multiple access communication system a number of users share a common channel bandwidth. At any given time, a subset of these users may transmit information simultaneously over the common channel to corresponding receivers. Assuming that all the users employ the same code for encoding and decoding of their respective information sequences, the transmitted signal in this common spectrum may be distinguished from one another by superimposing a different pseudo-random pattern, also called a code in each transmitted signal. Thus, a particular receiver can recover the transmitted information intended for it by knowing the pseudo-random pattern ie the key, used by the corresponding transmitter. This type of communication technique, which allows multiple users to simultaneously use a common channel for transmission of information is called **code division multiple access** (CDMA).

2.6 Model of Spread Spectrum Digital Communication System

The block diagram shows the basic elements of a spread spectrum digital communication system with a binary information sequence at its input at the transmitting end and at its output at the receiving end. The channel encoder and decoder and the modulator and demodulator are basic elements of the system. There are two identical pseudo-random pattern generators, one that interfaces with the modulator at the transmitting end and a second that interfaces with the demodulator at the receiving end. The generators generate a pseudo-noise (PN) binary valued sequence, which is impressed on the transmitted signal at the modulator and removed from the received signal at the demodulator.

Synchronization of the PN sequence generated at the receiver with the PN sequence generated at the receiver with the PN sequence contained in the incoming received signal is required in order to demodulate the received signal. Initially, prior to the transmission of information, synchronization may be achieved by transmitting a fixed pseudo-random bit pattern that the receiver will recognize in the presence of interference with a high probability. After time synchromisation of the generator is established, the transmission of information may commence.

Interference is introduced in the transmission of the information-bearing signal through the channel. The characteristics of the interference depend to a large extent on its origin. It may be categorized as being either broad-band or narrowband relative to the bandwidth of the information-bearing signal and either continuous or pulsed (discontinuous) in time. For example, a jamming signal may consist of one or more sinusoid in the bandwidth used to transmit the information. The frequencies of the sinusoids may remain fixed or they may change with time according to some rule.

The interference generated in CDMA by other users of the channel may be either broadband or narrowband, depending upon the type of spread spectrum signal that is employed to achieve multiple access. It is broadband, it may be characterized as an equivalent AWGN.

2.7 Modulation techniques

Two types of modulations are used - PSK and FSK.

(a) PSK is appropriate in applications where phase coherence between the transmitted signal and the received signal can be maintained over a time interval that is relatively long compared to the reciprocal of the transmitted signal bandwidth. The PN sequences generated at the modulator is used in conjunction with the PSK modulation to shift the phase of the PSK signal pseudo-randomly. The resulting modulated signal is called a **direct sequence (DS) or Pseudo-noise (PN) spread spectrum signal**.

(b) FSK modulation is appropriate in applications where phase coherence cannot be maintained due to time-variant effects on the communication link. The PN sequences when used in conjunction with binary or M-ary ($M > 2$) FSK, the pseudo-random sequence selects the frequency of the transmitted signal pseudo-randomly. The resulting signal is called a **frequency-hopped (FH) spread spectrum signal**

2.8 Direct Sequence Spread Spectrum Signals

In the model shown in Fig.2.1. we assume that the information rate at the input to the encoder is R bits/s and the available channel bandwidth is W Hz. The modulation is assumed to be binary PSK. In order to utilize the entire available channel bandwidth, the phase of the carrier is shifted pseudorandomly according to the pattern from the PN generator at a rate W times/s. The reciprocal of W, denoted by T_c, defines the duration of a rectangular pulse, which is called a *chip* while T_c,is called the *chip interval.* The pulse is the basic element in a DS spread spectrum signal.

If we define $T_b = 1/R$ to be the duration of a rectangular pulse corresponding to the transmission time of an information bit, the bandwidth expansion factor W/R may be expressed as

$$B_e = \frac{W}{R} = \frac{T_b}{T_c} \tag{2-1}$$

In practical systems, the ratio T_b/T_c is an integer,

$$L_c = \frac{T_b}{T_c} \tag{2-2}$$

which is the number of chips per information bit. That is, L_c is the number of phase shifts that occur in the transmitted signal during the bit duration $T_b = 1/R$. Figure 13-2.1(a) illustrates the relationships between the PN signal and the data signal.

Suppose the encoder takes k information bits at a time and generates a binary linear (n.k) block code. The time duration available for transmitting the n code elements is kT_b. The number of chips that occur in this time interval is kL_c. Hence, we may select the block length of the code as $n = kL_c$. If the encoder generates a binary convolutional code of rate k/n, the number of chips in the time interval kT_b is also $n = kL_c$. Therefore, the following consideration applies to both block codes and convolutional codes.

One method for impressing the PN sequence on the transmitted signal is to alter directly the coded bits by modulo-2 addition with the PN-sequence. Thus, each coded bit is altered by its addition with a bit from the PN sequence. If b represents the *i*th bit of the PN sequence and c is the corresponding bit from the encoder, the modulo-2 sum is

$$a_i = b_i \oplus c_i \tag{2-3}$$

Hence, $a_i = 1$ if either $b_i = 1$ and $c_i = 0$ or $b_i = 0$ and $c_i = 1$: also $a_i = 0$ if either $b_i = 1$ and $c_i = 1$ or $b_i = 0$ and $c_i = 0$. We may say that $a_i = 0$ when $b_i = c_i$ and $a_i = 1$ when $b_i \neq c_i$. The sequence $\{a_i\}$ is mapped into a binary PSK signal of the form $s(t) = \pm \mathrm{Re}\,[g(t)e^{i2\pi f_c t}]$ according to the convention

$$g_i(t) = \begin{cases} g(t-iT_c) & (a_i = 0) \\ -g(t-iT_c) & (a_i = 1 \end{cases}$$

where g(t) represents a pulse of duration T_c s and arbitrary shape.

The modulo - 2 addition of the coded sequence $\{c_i\}$ and the sequence $\{b_i\}$ from the PN generator may also be represented as a multiplication of two waveforms. To demonstrate this point suppose that the elements of the coded sequence are mapped into a binary PSK signal according to the relation.

$$c_i(t) = (2c_i - 1)\, g(t - iT_c) \tag{2-5}$$

Similarly, we define a waveform $p_i(t)$ as

$$p_i(t) = (2b_i - 1)\, p(t - iT_c) \tag{2-6}$$

where $p(t)$ is a rectangular pulse of duration T_c. Then the equivalent lowpass transmitted signal corresponding to the *i*th coded bit is

$$\begin{aligned} g_i(t) &= p_i(t)\, c_i(t) \\ &= (2b_i - 1)(2c_i - 1)\, g(t - iT_c) \end{aligned} \tag{2-7}$$

This signal is identical to the one given by (2-4), which is obtained from the sequence $\{a_i\}$. Consequently, modulo-2 addition of the coded bits with the PN sequence followed by a mapping that yields a binary PSK signal is equivalent to multiplying a binary PSK signal generated from the coded bits with a sequence of unit amplitude rectangular pulses, each of duration T_c, and with a polarity which is determined from the PN sequence according to (2-6). Although it is easier to implement modulo-2 addition followed by PSK modulation instead of waveform multiplication, it is convenient, for purposes of demodulation, to consider the transmitted signal in the multiplicative form given by (2-7). A functional block diagram of a four-phase PSK DS spread spectrum modulator is shown in Fig.2.2 (b).

The received equivalent lowpass signal for the *i*th code element is

$$r_i(t) = p_i(t)c_i(t) + z(t), \quad iT_c \leq t \leq (i+1)T_c$$

$$= (2b_i - 1)(2c_i - 1)g(t - iT) + z(t) \qquad (2\text{-}8)$$

where z(t) represents the interference or jamming signal corrupting the information-bearing signal. The interference is assumed to be a stationary random process with zero mean.

If z(t) is a sample function from a complex-valued gaussian process, the optimum demodulator may be implemented either as a filter matched to the waveform g(t) or as a correlator, as illustrated by the block diagrams in Fig. 2.3. In the matched filter realization, the sampled output from the matched filter is multiplied by $2b_i - 1$, which is obtained form the PN generator at the demodulator when the PN generator is properly synchronized. Since $(2b_i - 1)^2 = 1$ when $b_i = 0$ and $b_i = 1$, the effect of the PN sequence on the received coded bits is thus removed.

In Fig. 2.3, we also observe that the cross-correlation can be accomplished in either one of two ways. The first, illustrated in Fig. 2.3 (b), involves premultiplying r_i (t) with the waveform p_i (t) generated from the output of the PN generator and then cross-correlating with g^* (t) and sampling the output in each chip interval. The second method, illustrated in Fig.2.3(c), involves cross-correlation with g^* (t) first, sampling the output of the correlator and, then, multiplying thus output with $2b_i - 1$, which is obtained from the PN generator.

If z(t) is not a gaussian random process, the demodulation methods illustrated in Fig.2.3 are no longer optimum. Nevertheless, we may still use any of these three demodulator structures to demodulate the received signal. When the statistical characteristics of the interference z(t) are unknown a priori, this is certainly one possible approach. An alternative method, utilizes an adaptive filter or correlator to suppress narrowband interference.

2.8.1 The Processing Gain and Jamming Margin

An interpretation of the performance characteristics for DS spread spectrum signal is obtained by expressing, the signal energy per bit $\mathscr{E}_b$ in terms of average power.

That is $\mathscr{E}_b = P_{av} T_b$, where P_{av} is the average signal power and T_b is the bit interval.Let us consider the performance obtained in the presence of CW jamming for the rectangular pulse. When we substitute for $\mathscr{E}_b$ and J_o into , the equation for probability of a code word error for CW jamming ie $P_M \le \sum_{m=2}^{M} Q(\sqrt{2\frac{\mathscr{E}_b}{J_0}R_c w_m}$

We get,

$$P_M \le \sum_{m=2}^{M} Q\left(\sqrt{\frac{2P_{av}}{J_{av}}\frac{T_b}{T_c}R_c w_m}\right) = \sum_{m=2}^{M} Q\left(\sqrt{\frac{2P_{av}}{J_{av}}L_c R_c w_m}\right) \qquad (2\text{-}9)$$

where L_c is the number of chips per information bit and P_{av}/J_{av} is the signal-to--jamming power ratio.

An identical result is obtained with broadband jamming for which the performance is given by $P_m \le \sum_{m=2}^{M} Q(\sqrt{2r_b R_c w_m}$ For the signal energy per bit, we have

$$\mathscr{E}_b = P_{av} T_b = \frac{P_{av}}{R}$$

where R is the information rate in bit/s. The power spectral density for the jamming signal may be expressed as

$$J_o = \frac{J_{av}}{W} \tag{2-10}$$

Using the relation in (2-9) and (2-10), the ratio $\mathcal{E}_b/J_o$ may be expressed as

$$\frac{\mathcal{E}_b}{J_o} = \frac{P_{av}/R}{J_{av}/W} = \frac{W/R}{J_{av}/P_{av}} \tag{2-11}$$

The ratio J_{av}/P_{av} is the jamming-to-signal power ratio, which is usually greater than unity. The ratio $W/R = T_b/T_c = B_e = L_c$ is just the bandwidth expansion factor, or, equivalently, number of chips per information bit. This ratio is usually called the *processing gain* of the DS spread spectrum system. It represents the advantage gained over the jammer that is obtained by expanding the bandwidth of the transmitted signal. If we interpret $\mathcal{E}_b/J_o$ as the SNR required to achieve a specified error rate performance and W/R as the available bandwidth expansion factor, the ratio J_{av}/P_{av} is called the *jamming margin* of the DS spread spectrum system. In other words, the jamming margin is the largest value that the ratio J_{av}/P_{av} can take and still satisfy the specified error probability.

The performance of a soft-decision decoder for a linear (n,k) binary code, expressed in terms of the processing gain and the jamming margin, is

$$P_M \leq \sum_{m-2}^{M} Q\left(\sqrt{\frac{2W/R}{J_{av}/P_{av}} R_c \omega_m}\right) \leq (M-1)Q\left(\sqrt{\frac{2W/R}{J_{av}/P_{av}} R_c d_{\min}}\right) \tag{2-12}$$

In addition to the processing gain W/R and J_{av}/P_{av}, we observe that the performance depends on a third factor, namely, $R_c w_m$. This factor is the *coding gain*.

A lower bound on this factor is $R_c d_{min}$. Thus the jamming margin achieved by the DS spread spectrum signal depends on the processing gain and the coding gain.

If a repetition code is used it gives no. coding gain but results in a processing gain of W/R ie a binary repetition code provides a margin against an interference or jamming signal but yields no coding gain. An improvement in performance can be obtained by replacing the repetition code by a more powerful code that will yield a coding gain in addition to the processing gain. This is accomplished by using code concatenation.

Effect of Pulsed Interference an DS Spread Spectrum

The effect of continuous interference of jamming on a DS spread spectrum signal can be overcome through processing gain and coding gain. There is another jamming signal which consists of pulses of spectrally flat noise that covers the entire signal bandwidth W. This is called pulsed interference or partial-time jamming. Interleaving of the coded bits prior to transmission over the channel is resorted to. This makes the coded bits that are hit by the jammer statistically independent. The block diagram of the digital communication system with interleaving and deinterleaving is shown (Fig 2.4).

2.8.2 Some Applications of DS Spread Spectrum Signals

The use of coded DS spread spectrum signals can be made for three specific applications. One is concerned with providing immunity against a jamming signal. In the second, a communication signal is hidden in the background noise by transmitting the signale at a very low power level. The third application is concerned with accommodating a number of simultaneous signal transmission on the same channel. i.e, CDMA.

Code Division Multiple Access The enhancement in performance obtained from a DS spread spectrum signal through the processing gain and coding gain can be used to enable many DS spread spectrum signals to occupy the same channel bandwidth provided that each signal has its own distinct PN sequence. Thus, it is possible to have several users transmit messages simultaneously over the same channel bandwidth. This type of digital communication in which each user (transmitter-receiver pair) has a distinct PN code for transmitting over a common channel bandwidth is called either code division multiple access (CDMA) or spread spectrum multiple access (SSMA).

In the demodulation of each PN signal, the signals from the other simultaneous users of the channel appear as an additive interference . The level of interference varies, depending on the number of users at any given time. A major advantage of CDMA is that a large number of users can be accommodated if each transmits messages for a short period of time. In such a multiple access system, it is relatively easy either to add new users or to decrease the number of users without disrupting the system.

We determine the number of simultaneous signals that can be supported in a CDMA system. For simplicity, we assume that all signals have identical average powers. Thus, if there are N_u simultaneous users, the desired signal-to-noise interference power ratio at a given receiver is

$$\frac{P_{av}}{J_{av}} = \frac{P_{av}}{(N_u - 1)P_{av}} = \frac{1}{N_u - 1} \tag{2-13}$$

Hence, the performance for soft-decision decoding at the given receiver is upper-bounded as

$$P_M \leq \sum_{m=2}^{M} Q\left(\sqrt{\frac{2W/R}{N_u - 1} R_c \omega_m}\right) \leq (M-1) Q\left(\sqrt{\frac{2W/R}{N_u - 1} R_c d_{\min}}\right) \tag{2-14}$$

In this case, we have assumed that the interference from other users is gaussian.

As an example, suppose that the desired level of performance (error probability of 10^{-6}) is achieved when

$$\frac{W/R}{N_u - 1} R_c d_{\min} = 20$$

Then the maximum number of users that can be supported in the CDMA system is

$$N_u = \frac{W/R}{20} R_c d_{\min} + 1 \tag{2-15}$$

If $W/R = 100$ and $R_c\ d_{\min} = 4$, as obtained with the Golay (24, 12) code, the maximum number is $N_u = 21$. If $W/R = 1000$ and $R_c\ d_{\min} = 4$, this number becomes $N_u = 201$.

In determining the maximum number of simultaneous users of the channel, we have implicitly assumed that the PN code sequence are mutually orthogonal and the interference from other users adds on a power basis only. However, orthogonality among a number of PN code sequences is not easily achieved, especially if the number of PN code sequences required is large. In fact, the selection of a good set of PN sequence for a CDMA system is an important aspect, and requires due attention.

2.9 Frequency-Hopped Spread Spectrum Signals

In a frequency-hopped (FH) spread spectrum communications system the available channel bandwidth is subdivided into a large number of contiguous frequency slots. In any signaling interval, the transmitted signal occupies one or more of the available frequency slots. The selection of the frequency slot(s) in each signaling interval is made pseudo-randomly according to the output from a PN generator. Figure 2.5 illustrates a particular frequency-hopped pattern in the time-frequency plane.

A block diagram of the transmitter and receiver for a frequency-hopped spread spectrum system is shown in Fig.2.6. The modulation is usually either binary or M-ary FSK. For example, if binary FSK is employed, the modulator selects one of two frequencies corresponding to the transmission of either a 1 or a 0. The resulting FSK signal is translated in frequency by an amount that is determined by the output sequence from the PN generator, which, in turn, is used to select a frequency that is synthesized by the frequency synthesizer. This frequency is mixed with the output of the modulator and the resultant frequency-translated signal is transmitted over the channel. For example, m bits from the PN generator may be used to specify $2^m - 1$ possible frequency translations.

At the receiver, we have an identical PN generator, synchronized with the received signal, which is used to control the output of the frequency synthesizer. Thus, the pseudo-random frequency translation introduced at the transmitter is removed at the receiver by mixing the synthesizer output with the received signal. The resultant signal is demodulated by means of an FSK demodulator. A signal for maintaining synchronism of the PN generator with the frequency-translated received signal is usually extracted from the received signal.

Although PSK modulation gives better performance than FSK in an AWGN channel, it is difficult to maintain phase coherence in the synthesis of the frequencies used in the hopping pattern and, also, in the propagation of the signal over the channel as the signal is hopped from one frequency to another over a wide bandwidth. Consequently, FSK modulation with noncoherent detection is usually employed with FH spread spectrum signals.

In the frequency-hopping system depicted in Fig.2.6. the carrier frequency is pseudo-randomly hopped in every signaling interval. The M information-bearing tones are contiguous and separated in frequency by $1/T_c$, where T_c is the signaling interval. This type of frequency hopping is called *block hopping*.

Another type of frequency hopping that is less vulnerable to some jamming strategies is independent tone hopping. In this scheme, the M possible tones from the modulator are assigned widely dispersed frequency slots. One method for accomplishing this is illustrated in Fig. 2.7. Here, the m bits from the PN generator and the information bits are used to specify the frequency slots for the transmitted signal.

The frequency-hopping rate is usually selected to be either equal to the (coded or uncoded) symbol rate or faster than that rate. If there are multiple hops per symbol, we have a fast-hopped signal. On the other hand, if the hopping is performed at the symbol rate, we have a slow-hopped signal.

Fast frequency-hopping is employed in AJ applications when it is necessary to prevent a type of jammer, called a *follower jammer*, from having sufficient time to intercept the frequency and retransmit it along with adjacent frequencies so as to create interfering signal components. However, there is a penalty incurred in subdividing a signal into several frequency-hopped elements because the energy from these separate elements is combined noncoherently. Consequently, the demodulator incurs a penalty in the form of a noncoherent combining loss.

2.9.1 FH signal vs DS spread spectrum signal

FH spread spectrum signals are used primarily in digital communications systems that require AJ protection and in CDMA, where many users share a common bandwidth. In most cases, a FH signal is preferred over a DS spread spectrum signal because of the stringent synchronization requirements inherent in DS spread spectrum signals. Specifically, in a DS system, timing and synchronization must be established to within a fraction of the chip interval $T_c = 1/W$. On the other hand, in an FH system, the chip interval is the time spent in transmitting a signal in a particular frequency slot of bandwidth $B << W$. But this interval is approximately $1/B$, which is much larger than $1/W$. Hence the timing requirements in a FH system are not as stringent as in a PN system.

2.10 A CDMA System Based on FH Spread Spectrum

It is also possible to have a CDMA system based on FH spread spectrum signals. Each transmitter-receiver pair in such a system is assigned its own pseudo-random frequency-hopping pattern. Aside from this distinguishing feature, the transmitters and receivers of all the users may be identical in that they may have identical encoders, decoders, modulators, and demodulator.

CDMA system based on FH spread spectrum signals are particularly attractive for mobile (land, air, sea) users because timing requirements are not as stringent as in a PN spread spectrum signal. In addition, frequency synthesis techniques and associated hardware have been developed that make it possible to frequency-hop over bandwidth that are significantly larger than those currently possible with DS spread spectrum systems. Consequently, larger processing gains are possible with FH. The capacity of CDMA with FH is also relatively high. Viterbi (1978) has shown that with dual-k codes and M-ary FSK modulation, it is possible to accommodate up to $\frac{3}{8}W/R$ simultaneous users who transmit at an information rate R bits/s over a channel with bandwidth W.

2.11 Other Types of Spread Spectrum Signals

DS and FH are the most common forms of spread spectrum signals used in practice. There are other methods which may be used to introduce pseudo-randomness in a spread spectrum signal. Time hopping (TH) is one method which is analogous to FH. In TH, time interval, which is selected to be much larger than the reciprocal of the information rate, is subdivided into a large number of time slots. The coded information symbols are transmitted in a pseudo-randomly selected time slot as a block of one or more code words. PSK modulation may be used to transmit the coded bits.

2.12 Consideration for further study

The aspects studied in chapter 1 and 2 will form a back-ground for understading the theory of cellular communication as applied to CDMA and analysis of various CDMA digital communication systems developed and in vogue in the various parts of the globe.

CHAPTER - 3

THEORY OF CELLULAR COMMUNICATION AS APPLIED TO CDMA

3.1 Introduction

The analysis and design of CDMA digital cellular systems is quite complex as the analysis requires knowledge of mobile radio channels, methods of implementing diversity, cellular system topology and spread spectrum techniques. Certain analytic tools are required to analyze and design a CDMA digital cellular communication system.

3.2 Fundamentals of Cellular Radio Systems

Cellular radio systems - macro and microcellular, analog and digital, conventional and CDMA - have a number of fundamental characteristics, as summarized in the following:

a) As shown in Figure 3.1, the geographical area is broken up into smaller geographic areas. To simplify the analysis uniform-area polygons that tessellate the plane (i.e. cover the area without overlap or missed areas) are often assumed to represent the cells. Although triangles and squares have been used in some analysis, the hexagon is most frequently employed, as has been shown in the figure. Base stations are located either in the middle of the cell ("center illumination") or at the corner of the cell ("corner illumination").

b) By the cellular construction in characteristic (a) above. it is assumed that communication with a mobile in a given cell is made to the base station that serves the cell. This implies that the signal strength of the serving cell exceeds the signal strength of the base station in surrounding cells. The power of both the base station transmitter and the mobile station transmitter is intentionally limited to that which is required to communicate within the cell area.

c) Because of the power limitation described above and propagation characteristics of radio waves, frequencies may be reused within the overall geographic area. The **spectral efficiency** of the systems is, therefore, increased by a factor equal to the number of times a frequency may be reused within a geographical area. To minimize cochannel interference, the total available allocation of channels is divided into N disjoint subsets, with each subset assigned to one cell of a group of N cells. The number N is the frequency-reuse factor of the cellular system and is dependent on the co-channel interference immunity of the modulation, diversity, and coding methods employed, the antenna pattern characteristics, and the characteristics of radio propagation in the area. Figure 3.2 shows a cellular system **frequency reuse** of 78 (a so-called seven-cell pattern).

d) As a mobile proceeds from one cell to another during the course of call, a central controller automatically reroutes the call from the old cell to the new cell without noticeable interruption, in a process known as **handoff.**

e) As demand for the radio channels within a given cell increases beyond the capacity of the cell, measured in terms of the number of supportable calls that may occur simultaneously, the overloaded cell is "**split**" into smaller cells, each with its own base station and central controller, as shown in Fig.3.3 The radio-frequency allocations of the original cellular system are then reallocated to account for the smaller cells.

For cellular systems, the base-to-mobile and mobile-to-base communication paths are allocated in pairs of frequencies separated by a fixed bandwidth. Such an approach is known as **frequency division duplex (FDD)**.

3.2.1 **Sector in a cell** : Specific cellular systems often exhibit additional system characteristics.One additional characteristic that is often employed is the concept of sectors in a cell. Rather than using omnidirectional antennas at the base station, a cell may be split into equal-area sectors through the wise of directional antennas. Directional antennas often permit the use of smaller frequency-reuse factors and therefore a reduction in geographic separation between sites. For example, a 12-cell-site repeat pattern employing omnidirectional antennas can be shown to be equivalent to a seven-cell pattern employing 120° sectors in terms of cochannel rejection performance. For spread-spectrum systems, a sectorized cell pattern can lead to a significant increase in system capacity.

3.2.2 **Power Control** : Another system concept that is often employed in some cellular systems is that of power control of the transmitter in the uplink (mobile to base) as well as sometimes in the downlink (base to mobile). Power control in the uplink tends to minimize co-channel interference within a cellular system. Because mobiles are restricted to transmit at the minimum amount of power (or a quantized step size thereof) required to achieve acceptable performance with the serving base station, interference into surrounding cells is minimized. Furthermore, power control is absolutely required for any degree of operation in certain types of CDMA digital cellular systems.

3.2.3 Co-channel Interference Protection Prediction

The cell repeat pattern N is a function of a number of parameters, which in turn determine the co-channel interference (C/I) properties of a particular cell system design. There are two approaches toward estimating the C/I protection factor of a particular cell system design.

3.2.4 Method 1 : Geometrical Approach to C/I Protection Prediction

Define an area equivalent hexagon (AEH) to be a hexagon whose area is equal to the area of a group of N cells in a reuse pattern. Let R be defined to be the distance from the center of the AEH to a corner of the AEH. Then by the geometrical properties of hexagons, it may be shown that

$$\text{area} \quad (\text{AEH}) = \frac{3\times\sqrt{3}}{2}R^2 \tag{3-1}$$

Similarly, it may be readily seen that if D is the distance between similar cells in adjacent patterns, D is related to R by

$$D = \sqrt{3}\,R \tag{3-2}$$

and hence

$$\text{area(AEH)} = \frac{\sqrt{3}}{2}D^2 \qquad (3\text{-}3)$$

Letting r be the diameter of each of the (small) cells that constitute the AEH, the area of the AEH in terms of the cell diameter r is

$$\text{area} \quad \text{(AEH)} = \frac{3\sqrt{3}}{2}r^2 = \frac{\sqrt{3}}{2}D^2 \qquad (3\text{-}4)$$

or

$$\frac{D}{r} = \sqrt{3N} \qquad (3\text{-}5)$$

Now assuming a propagation path loss of the form kd^{-4} and using as a worst-case interference mobile, a mobile located at the vertex of the central cell, the signal power received at a target mobile from its base station is proportional to Akr^{-4} for some transmitter power A. To a first approximation, the distance between the target mobile and an interfering base station is (D-r) hence the interference power is proportional to $Ak(D-r)^{-4}$. The co-channel interference protection ratio for the target mobile is thus

$$\frac{C}{I} = \left[\frac{r}{D-r}\right]^{-4} \qquad (3\text{-}6)$$

or, in terms of decibles,

$$\frac{C}{I}(\text{dB}) = 40\log_{10}\frac{D-r}{r} = 40\log_{10}\sqrt{3N} - 1) \qquad (3\text{-}7)$$

where (3-5) has been used. For example, an N = 12 all pattern should achieve a C/I protection ratio of approximately 28 dB.

This approach completely neglects, the effects of lognormal shadowing. Nonetheless, it does yield a simple rule of thumb in relating cell-reuse pattern size to C/I protection ratio. As shown here, the co-channel interference protection ratio increases as a function of the cell-reuse pattern size. To optimize the communication ink quality, N should therefore be large. However, as N increases, the number of available frequencies in each frequency set decreases, and the overall capacity of the system measured in terms of users per area per megahertz decreases.

3.2.5 Method 2 : Monte Carlo Approach to C/I Protection Prediction : The simple geometrical approach to C/I protection prediction in a cellular system neglects the lognormal shadowing effects. Hence the geometrical approach is commonly used only in first-pass designs of cellular systems. More commonly, a Monte Carlo approach is employed.

In the Monte Carlo approach to C/I protection prediction, a probability distribution function of the required C/I over some fraction of the area, also known as the **location reliability**, is calculated via a simulation approach. For calculation of the uplink C/I protection ratio, a target mobile is randomly placed in the serving cell. Interfering mobiles are randomly located in each of the possible interfering cells. Shadowing is accounted for by assigning a lognormal random variable with a fixed σ to each of the randomly placed mobiles. Using a fixed propagation path-loss equation, the signal received at the base from the target mobile is computed where the path loss is equal to the path loss predicted from the propagation equation plus the path loss due to the lognormal random variable. Next, the interference power at the base due to each of the interfering mobiles is computed in a similar manner. Then the C/I ratio is computed from the simulated signal power and sum of the interference power received at the base. The target mobile is then randomly moved and the interterers are again randomly placed with new lognormal shadowing losses drawn randomly. A new C/I value is computed and the process is repeated many times. A histogram of the C/I values obtained is computed and a probability distribution function is then calculated from the histogram. A "typical" distribution resulting from the Monte Carlo approach is shown in Figure 3.4, which plots the distribution function of C/I as a function of the cell pattern size for a lognormal shadowing σ of 6 dB, and .the Hata model is employed as the propagation model. An approach similar to the above may be used to predict the downlink location reliability.

The Monte Carlo method can be made quite exact by properly accounting for the shadowing model, the propagation model, path correlation models, power control, handoff algorithms is and the antenna patterns employed.

3.3 Cellular System Design Process

The goal of cellular systems design is to maximize spectral efficiency through the use of frequency reuse. In designing a cellular system, a trial design might begin with a choice of a multiple-access method, a choice of a modulation/coding method and a choice of diversity method(s). The performance of the radio link subsystem as a function of co-channel interference is then evaluated using analysis and simulation. A minimum performance requirement as a function of (C/I is established based on the system requirements - for a digital system this may be a required decoded probability of error or a required block error probability. Next, a trial cellular system design is attempted by selection of the reuse factor N, the sectorization factor, and the system coverage reliability goals.Using either the geometric approach or the Monte Carlo simulation approach, the resulting C/I coverage protection is computed, for a given reliability in the latter case. Next, the radio subsystem performance is compared to the C/I protection requirement prediction. If the radio subsystem performance exceeds the C/I protection requirement, the system design is deemed permissible. Finally, system capacity goals and frequency allocation goals must be compared with the corresponding calculated parameters. Often a number of iteration are required to complete the system design.

3.4 CDMA Digital Cellular Systems

3.4.1 **General Aspects** :CDMA digital cellular systems share most of the attributes of analog and narrow-band digital cellular systems, that is, they are governed by the same basic principles of cellular systems discussed earlier in this chapter. Hence the modulation/ coding/diversity methods employed determine the cochannel interference immunity of the system, and the cell system topology/propagation model/sectorization determines the cochannel protection available to the system. To the extent that the modulation method combined with coding and diversity can overcome the cochannel interference provided in the cell system, measured in terms of operation above some threshold, communication within a CDMA digital cellular system is possible.

CDMA digital cellular systems also have some unique attributes. From the beginning, CDMA digital cellular systems were designed to offer improvements over analog cellular system designs in the following two areas:

a) An improvement in capacity/spectral efficiency over analog cellular systems.

b) An improvement in quality, measured in terms of improved speech quality and/or improved system reliability, which in turn is measured in terms of number of '**dropped**' calls, interference rejection capability, and so on.

3.4.2. Systems for Capacity Spectral Efficiency of Cellular Systems

Approach 1: Relative Spectral Efficiency

The relative spectral efficiency η (relative to a 30-kHz channel-spacing AMPS system) of a cellular radio system was defined to be

$$\eta = \frac{U}{F_r}\,\frac{30\text{kHz}}{W} \tag{3-8}$$

where U is the average number of users/cell. W the bandwidth required for one-way transmission, and F, the frequency reuse factor, defined as N in para II. The relative spectral efficiency thus provides a measure of the number of users per cell per 30 kHz of bandwidth. The relative spectral efficiency metric has been employed by a number of authors. For reference purposes, the relative spectral efficiency of an analog AMPS system employing a 12-cell reuse design with omnidirectional antennas is given by

$$\eta_{\text{AMPS}} = \frac{1}{12} = 0.0833\,\% \tag{3-9}$$

Approach 2 : CDMA System Capacity : For CDMA digital cellular systems that employ power control such that all uplink (mobile-to-base) signals are received at the same power level, and all users are spread (via either direct-sequence or frequency-hop spread spectrum) over the total available bandwidth W, a simple equation for capacity may be developed as follows.

Assuming that a cell has a total of N mobile users, the comosite uplink receive signal at the base site will consist of the desired signal with power S and N-1 interfering users, each also having power S, by the power control constraint.

The signal-to-interference ratio at the base is thus $S/I = S/(N-1)S = 1/(N-1)$. The energy/bit to interference power spectral density E_b/I_0 may be derived similarly. The energy/bit is just the signal power S divided by the information bit rate R (i.e.$E_b = S/R$). The interference power spectral density is the interference power divided by the spreading bandwidth W (i.e. $I_0 = S(N-1)/W$]. Hence the expression for E_b/I_0 becomes

$$\frac{E_b}{I_0} = \frac{S/R}{(N-1)S/W} = \frac{W/R}{N-1} \qquad (3\text{-}10)$$

solving (3-10) for N yields the capacity of the cell in terms of user channels/bandwidth W:

$$N = 1 + \frac{W/R}{E_b/I_0} \qquad (3\text{-}11)$$

which for N large is

$$N \cong \frac{W/R}{E_b/I_0} \qquad (3\text{-}12)$$

The derivation above for the number of users N per bandwidth W assumes that each interferer is transmitting continuously. In fact, for voice (and some data) information sources, in a two way conversation, the percentage of time that a speaker is active (i.e. talking) ranges from 35 to 50%. The interference in (3-12) is thus reduced by the voice activity factor d. In addition, provided that a single cell-reuse pattern, yields acceptable performance, the number of users in (3-12) may be increased by the sectorization factor g. This implies that a cell may be "split" into g cells determined by the sectorization approach used. Finally,because the interference at a base station will come from both within a cell, as has already been noted, as well as outside the cells, a term f accounting for an increase in interference power due to interfering users outside the target cell must be factored into the capacity equation.

Taking all of these elements into account, the modified equation for capacity is given by

$$\text{capacity,} \quad N = \frac{W/R}{E_b/I_0}\left[\frac{1}{d}\right] gf \qquad (3\text{-}13)$$

where E_b/I_0 is the required energy/bit to interference spectral density necessary to achieve a given level of performance. This equation was first developed by Cooper and Nettleton and was subsequently embraced by Gilhousen et al.

Equation (3-13) was derived for the uplink (mobile to base); a similar calculation for the downlink (base to mobile) yield the same result.

3.4.3 <u>**Power Control**</u> : In the derivation of the equation for capacity, (3-13), it was assumed that the mobile transmitter power was controlled in such a manner that the received power at the base from each of the users was identical. Without very good power control, in direct-sequence (and certain types of frequency hopping) CDMA cellular systems, multiple access communications is impossible. Assume, for example, that a cellular system has two mobiles each trying to communicate with the base with the same transmit power. One mobile is located near the base station, the other near the cell boundary. From considerations of the path-loss equations, a 60-dB or more signal power difference at the base station between the two mobiles is quite possible. At the base station, the near-in mobile appears as a wideband jammer with 60dB more power than the far-out jammer. Unless very wideband spreading is used the far-out mobile will never be received by the base station. This is the familiar *near-far* problem of spread-spectrum multiple-access communications systems. The solution to overcoming the near-far problem is the use of stringent power control in the uplink. This is a challenging engineering problem. The near-far problem does not exist in the downlink path as the base station can transmit all signals with equal power, thereby ensuring that none of the multiple access signals are dominant jammers.

Power control may also be used in the downlink. In this case, power control is usually used for allocation of power to users in fringe areas (near cell boundaries, for example). Power control of the downlink requires significantly less dynamic range than that required in the uplink. Note that perfect downlink power control creates a near-far problem at the mobile.

3.4.4 Voice Activity Factor : The modified equation for capacity given above includes a term (1/d) to accommodate a voice activity factor. This equation is correct if it is assumed that all the interference comes from a single interferer with voice activity factor d. The interference due to the other users is a binomially distributed random variable. In a CDMA digital cellular system with N+ 1 users, each having a voice activity factor d, a given link experiences interference from n other channels at a given instant of time, where n is distributed according to

$$P_r\{n\} = \begin{bmatrix} N \\ n \end{bmatrix} d^n (1 - d)^{N-n} \quad n = 0,1,2,\ldots,N$$

which has a mean of E{n} = dN. In figure 3.5, the probability density function of n is shown plotted for N = 60 for three different values of d. As expected, the mode of each of these curves occurs near the mean of n, but there is a wide distribution of values around the mean. This indicates that the simple (1/d) factor in (3-13) must be decreased in value to accommodate a higher level of interference than that predicted in the analysis given above.

3.4.5 **Sectorization** : The modified equation for capacity above includes a multiplier term for the capacity which accounts for sectorization. Just as interference from adjacent cells is accounted for in the capacity equation. so must interference from adjacent sectors be accounted for in the capacity equation. Interference from adjacent sectors is due to both (1) radio propagation from adjacent cells and (2) nonideal sectorization antennas. The nonideal sectorized antenna patterns are accounted for by defining the equivalent uniform beam width of the antenna as the beam-width of a rectangular function enclosing the same area as that of the original antenna. For the simplified capacity equation given above, the loss from ideal sectorization may be accounted for in a reduced value for g (or f).

3.5 Special Aspects of CDMA Ditigal Cellular Systems : CDMA digital cellular systems have certain common additional attributes discussed in previous chapter. We will brush them up again as several digital cellular system take advantage of these attributes.

3.5.1 Direct-Sequence CDMA Digital Cellular Systems : In direct-sequence CDMA digital cellular systems and in certain frequency-hopped CDMA digital cellular systems, the signals are assumed to occupy the full allocated bandwidth all the time. Interferers are therefore assumed to come from all directions, not just a few directions as is the case with narrow band cellular systems. The large number of interferers leads to the concept of interference averaging in treating interference. That is, interference is assumed to obey the law of large numbers - hence the interference is equated to the mean level of interference observed with no dominant interferers. The *interference averaging* concept then allows, for example, interference to be treated as a Gaussian random process, large code cross correlation peaks to be ignored, and so on.

3.5.2 **Slow-frequency-Hop CDMA Digital Cellular Systems** : Slow-frequency hopped (SFH) CDMA digital cellular systems can benefit from two means of performance improvements over non-frequency hopped systems. First, at slow vehicle speeds, slow frequency hopping provides a form of frequency diversity through exploitation of frequency selectivity over the system bandwidth. From hop to hop the fading process is decorrelated either over the span of an interleaver or over the duration of long fades. This frequency diversity results in improved performance, which is independent of vehicle speed, provided that the hopping dwell period is sufficiently small.

Secondly, by careful assignment of small correlation frequency-hopping patterns, a given source of interference can affect the interference only a small portion of time. This interference reduction effect has been termed *interferer diversity*. Interferer diversity causes the interference experienced by any user to be reduced, as the interference experienced by the user comes not from a single dominant interferer, as is the case in analog cellular systems, but from the aggregate of all users, each sampled one at a time. Provided that coding with adequate interleaving is employed in the SFH system, individual samples of extreme interference may be corrected in the decoding process.

Several systems take advantage of both of these attributes of SFH systems.

3.5.3 **Consideration for Further Study** : Having gone through the theory of cellular communication in the next chapter some of the CDMA Digital communication systems will be studied and analysed.

CHAPTER - 4

CASE STUDIES

4.1 Introduction

There are a number of cellular communication system operative in the different parts of the world. Till now we have discussed the fundamentals of cellular systems, CDMA technique and the spread spectrum signals.

That spread spectrum and CDMA are the same is a frequent but incorrect assumption, FDMA and TDMA techniques can be used with any type of modulation, including spread-spectrum signals. however CDMA applies only to modulation techniqes associated with a code, specifically spread-spectrum modulation techniques. Spread-spectrum signals can be used with or without CDMA, the employment of CDMA requires spread-spectrum signals.

Qualcomm's spread-spectrum CDMA system was optimized under existing US mobile cellular system constraints. Its analysis shows that CDMA system can achieve about 10 to 20 times the capacity of the existing analog FDMA system and about 3 to 7 times then the new digital TDMA standard system. The key to this increase in capacity is the ability of the CDMA system to reuse the same frequency in all cells, with capacity defined as the total number of active mobile users in a large area with many cells.

4.2 Case Studies of Digital Cellular Standards

In this chapter we will carry out a study of the following ditigal cellular systems.

a. DS-CDMA Digital cellular system (IS-95)

b. Cooper and Netteleton DPSK-FHMA System

c. Bell Labs Multilevel-FSK frequency-HOp System

d. SFH 9000 System (Slow Frequency Hop - 900 System

d. GSM-SFH Digital Cellular System

4.3 Overview of the CDMA Digital Cellular System (IS-95)

The IS-95 digital cellular system operates in the same band as the current U.S. analog cellular band (AMPS) in which full-duplex operation is achieved by using frequency division duplexing (FDD) with 25 MHz in each direction, with an uplink of 869-894 MHz mobile-to-cell band and a downlink of 824-849 MHz cell-to-mobile band. For AMPs, each analog cellular signal occupies 30 kHz in each direction in a standard FDMA system. In IS-95, the 25 MHz in each direction is divided into 20 FDMA bands. In each 1.25 MHz band (each direction), direct-sequence spread spectrum signal are used in a CDMA system. The implementation strategy is to introduce this higher-capacity IS-95 system one CDMA system (1.25-MHz band) at a time, using the dual-mode (AMPS and CDMA) mobile units.

Among the modulation and coding features of this system are the following:

a. Direct-sequence spreading with QPSK modulation

b. Nominal data rate of 9600 bps

c. Chip rate of 1.25 MHz

d. Filtered bandwidth of 1.25 MHz

e. Convolutional coding with Viterbi decoding

f. Interleaving with 20 msec span

Details for the modulation and coding differ for the uplink and downlink channels. Pilot signals transmitted by each cell site aid the mobile radios in acquiring and tracking the cell site down link signals. The strong coding enables these radios to operate effectively at Eb/N_o in the 5-dB to 7-dB range.

To minimize mutual interference, this CDMA system uses power control and voice activation circuits. Voice activation occurs in the form of a variable-rate vocoder that operates from a high of 8 kbps down to 4 kbps, 2 kbps and a minimum of 1 kbps, depending on the level of voice activation. With the decreased data rate, the power control circuits can reduce the transmitter power for the lower data rates to achieve the same bit error rate performance. Tight power control, along with voice activation circuits, is critical for avoiding excessive transmitter signal power, which contributes to the overall interference level in this interference-limited CDMA system. It is estimated that in a typical two way conversation, the average data rate is 3 kbps, which, with power control increases the battery life of mobile radios.

To overcome rapid mulitipath fading and shadowing, a time interleaver with a 20 msec span is used with the error-control coding. The time span used is the same as that in the time frame of the voice compression algorithm. Also a RAKE processor is used in these radios to take advantage of multipath delays greater than 1 μ sec, which are common in large cellular networks.

Key IS-95 system features for each 1.25 MHz band CDMA system are as follows:

a) All signals use an unmodulated "carrier", a direct-sequence binary phase-shift-keying (BPSK) signal using a 15-state pseudorandom (PN) sequence with a 32,768-chip period, with each cell using a different phase (time shift) of this PN sequence. Thus, each cell has its own unique PN carrier, which is used as a common carrier by all radios active in the cell.

b) A downlink pilot channel consists of the cell's unique PN carrier, which helps mobile units acquire and track cell-site signals. The mobile unit essentially acquires the strongest unmodulated direct-sequence BPSK signal it finds by ranging over the time shifts of the PN code.

c) Each cell also transmits a low-bit-rate, low-power synchronization channel, which allows mobile radio to time-synchronize to the network.

d) Each CDMA downlink supports upto 62 paging and traffic channels.

e) The downlink channels use orthogonal Walsh codewords assigned uniquely to each mobile unit active in the cell. These codewords, further modulated by coded data bits, are superimposed on the PN carrier for the cell.

f) Each active uplink mobile radio signal uses a unique non-orthogonal PN code of 2^{42} chips on top of the PN carrier

g) Taking advantage of the RAKE processer, fake multipath signals transmitted from two cell sites allow mobile radios to conduct "soft handoffs" from one cell site to another.

Although much more complex, this system is inherently more robust than conventional narrowband radios using traditional FDMA and TDMA approaches. Perhaps most important is its robustness against multipath fading. It also allows more flexibility in the application of antennas for sectorization being able to use fixed and adaptive multibeam antennas to increase capacity dramatically and further reduce radio power requirements. Fig. 4.1 gives the conceptual block diagram of IS-95 for forward link and reverse link. Its parameters are summarsed in Table 4.1

Parameter	Forward Link	Reverse Link
Frequency band (MHz)	869-894	824-849
Access method	DS/CDMA-FDMA	DS/CDMA-EDMA
Cell reuse pattern	Sinle-vector reuse	Single-sector reuse
Modulation	BPSK with Walsh orthogonal covering	64-ary orthogonal signaling
DS spreading	QPSK sread, period 2^1 with modualtion shaping	OQPSK spread, period $= 2^{15}$ with modualtion shaping
Chip-rate (Mchips/s)	1.228	1.2288
FEC	Rate ½ k = 0 convolutionate code	Rate 1/3 k 9 convolutional code
Interleaving	Block Interleaver, duration = 20 ms	Block interleaver, duration = 20 ms
Scrambling	Decimated 2^{42}-1 length user sequence	2^{42} -1 length user sequence
Receiver structure	Three-branch Rake receive	Four-branch Rake receiver
Speech coder.Method data rates	QCELP 9,6, 4,8 2,4, 1.2 kbps, rate determined by VAD	QCELp 9.6, 4.8 2.4, 1.2 kpbs, rate determined by VAD
Frame duration (ms)	20	20
Diversity methods	Frequency diversity:wideb and signal Time diversity: interleaving Path diversity: multipath Rake	Frequency diversity; wideband signal Time diversity: interleaving path diversty: multipath Rake + antenna diversity

4.4.4 Comparison of IS-95, IS-54 and GSM

The first U.S. digital cellular standard, IS-54, and the European digital cellular standard, GSM, are both based on narrow band modulations,with TDMA as the basic multiple-accessing technique. The second U.S. digital cellular standard, IS-95, differs fundamentally in its use of direct-sequence spread-spectrum modulation, using CDMA for multiple access. All three systems overlay these basic access systems with further channelization using FDMA. Table 4-2. Summarizes the key features of these three digital cellular standards.

Like existing analog cellular systems, these digital cellular systems use separate uplink and downlink frequency bands, with frequency division duplexing (FDD) to achieve full duplex operation. Some level of power control is used by all three systems but the IS-95 systems uses the tightest dynamic power control since power control plays a more critical role in CDMA systems. Dynamic power control means that the average transmit power of the IS-95 handsets can be less than that in IS-54 and GSM hand sets. All three systems also employ convolutional coding with Viterbi decoding. The IS-95 system, however, uses stronger constraint length K = 9 convolutional codes, with rate ½ in the cell-to-mobile channel and rate $\frac{1}{3}$ in the mobile-to-cell channel.

All three digital cellular systems require some level of synchronization among all adjacent cells in a given area. The IS-95 system uses GPS receivers to provide master clocks for each cell. GPS is another widely used commercial application of spread-spectrum radios.

Overall capacity is the most important feature of the three digital cellular systems. Owing to so many parameters and other performance issues, it is very difficult to show clearly which system offers to greatest overall capacity. For example, the soft handoff feature of the IS-95 system enhances performance but sacrifices some capacity on the less critical downlink. It is clear, however, that the spread-spectrum CDMA system differs fundamentally from the TDMA systems and possesses three key properties that can greatly increase overall system capacity; 100 percent frequency of reuse, flexible antenna applications, power control and voice activation.

Table 4.2

<u>Comparison of digital cellular systems</u>

Feature	IS-54	GSM	IS-95
Multiple access	TDMA	TDMA	CDMA
Frequency band	Unites States	Europe	United States
Uplink (MHz)	869-894	935-960	869-894
Downlink (MHz)	824-849	890-915	824-849
Channel spacing	30 kHz	200kHz	1.25 MHz
Modulation	DQPSK	GMSK	BPSK/QPSk
Maximum Tx power (mobile handset)	600 mW	1 W	600 mW
Average Tx power	200 mW	125 mW	Variable
Speech rate	8 kbps	13 kbps	1-8 kbps
Number of channels	3	8	Variable
Channel bitrate	48.6 kbps	270.3 kbps	1.25 Meps

4.5 Cooper and Nettelton DPSK-FHMA System

It is a fast frequency hop CDMA system. The modulation employed is differential PSK hence system is called DPSK- FHMA system. Parameters of DPSK - FHMA system are in the table below.

Table 4-3

Parameters of DPSK-FHMA System

Frequency	825-845 MHz mobile transmit 870-890 Mhz base transmit
Total occupied bandwidth. W	20 MHz
Speech coder rate. R	31.25 kbps
Channel coding	Hadamard orthogonal code, k = 5
Modulation method	DPSK
Access method	Fast-frequency-hop CDMA
Diversity approach	Frequency diversity
Number of branches	32
Channel spacing	200 kHz
Cell reuse pattern	Single Cell

4.5.1 Transmitter

The DPSK-FHMA system is a fast-frequency hop CDMA system. Speech data coded at approximately 32 kbps is fed to a Walsh or Hadamard block orthogonal channel coder of dimension 5. Thus data are encoded with a rate (5/32) block code which increases the symbol rate by 32/5 relative to the information rate. The output of the channel coder is then binary differentially encoded using a conventional DPSK encoder but with a delay element equal to one Walsh symbol time (5 information bits or 32 coded symbols). DPSK is used because the multipath nature of the channel (as well as the fast-hopping rate) destroys any phase coherence in the received signal. Each coded symbol is then mixed to a frequency determined by an M-ary FSK generator (or FH synthesizer). where M = 32. For 31.25 kbps information rate, the frequency-hopping rate of the synthezier is

$$f_{hop} = 31.25\text{kbps}.\frac{32\text{coded symbols}}{5\text{ informatin bits}} = 200\text{kbops/s} \tag{4-1}$$

This is truly a fast-hopping system since there are 32/5=6.4 hops per information bit, each hop of duration t_1 = 1/200 khops/s = 5 μs. The fast-hopping rate allows the system to use frequency diversity to overcome the effects of Rayleigh fading, as well as permitting the use of "good" FH sequences. Because of the fast-hopping rate, Cooper and Nettleton termed each dwell period a 'chip," by analogy with direct-sequence spread spectrum.

The frequency-hopping patterns are assumed to be selected from a much larger set of frequencies in a manner such that the signals have a low aperiodic correlation among themselves. Hence no two frequency sequences are identical. Specifically, Cooper and Nettleton psoposed the use of the Yates-Cooper sequences, a set of sequences that has the one coincidence property; that is, when a frequency-hop sequence is shifted in time by one dwell period with respect to any other frequency-hop sequence in the set, there will be at most one dwell period for which two sequences will occupy the same frequency. The Yates-Cooper sequences are all of the form

$$f_i^k = f_0 + a_i^k f_1 \qquad i = 1,2,..,m \qquad k = 1,2...,m \qquad (4\text{-}2)$$

where f_i^k is the ith frequency for user k, the set $\{a_i^k\}$ the set of integers asociated with the kth FH sequence, f_1 the minimum frequency shift, and f_0 the nominal carrier frequency.

The desired property of the sets of frequency-hopping sequences is that collectively, the sequences will occupy the entire W = 20 MHz bandwidth with minimal cross correlation between sequences of different users. To minimize the interference level between usrs, the mobile transmitter is assumed to have power control on the uplink such that at the base station, each user is received with equal power.

4.5.2 Receiver

The receiver must frequency dehop the signal, differentially decode the dehopped signal, and perform frequency diversity combining to ovecome the effects of multipath. Figure 4.2 shows a receiver structure to perform all these operations. Rather than constructing a receiver to perform all these operations in serial. Cooper and Nettleton advocated the use of a parallel receiver architecture. Specifically, the receiver shown employs 32 bandpass filters, corresponding to the 32 frequencies used in the frequency-hop sequence. Each bandpass filter is assumed to be matched to a rectangular chip of duration t_1 and thus has a noise equivalent bandwidth of $1/t_1$. A tapped delay line is used to align in time the chips of the received sequence for each Walsh codeword. Thus all of the 32 chips in the FH sequence (or Walsh

Codeword) pass through each of the filters simultaneously. The output of each of the matched bandpass filters is then followed by a DPSK decoder and a loss-pass filter (to remove second harmonic terms).

The outputs of the lowpass filters are then fed to a combiner and decoder circuit. The function of the combiner is to combine the appropriate outputs of the low-pass filter in a manner that will correspond to a possible transmitted codeword. Since the transmitter employed a Walsh-Hadamard block encoder, the receiver may use the corresponding decoding matrix to perform the combining function. Alternatively, from the previous discussion of the IS-95 system, a fast Hadamard transform could be used in the receiver to perform the combining function in order to minimize combiner complexity. After combining, the decoder selects the combiner output that yields the greatst amplitude, performs a mapping from the combiner output index to decoded bits, and outputs the decoded bits.

4.5.3 Performance

The system was analysed by Henry. He began with the observation that for a system consisting of the mobile users occupying a bandwidth W. assuming that the transmitters were uncorrelated, for large M the received interference to a single user was approximately equivalent to white Gaussian noise with a one sided power density of

$$S(f) = p\frac{M-1}{W} \qquad (4\text{-}3)$$

where P is the (power-controlled) power of each mobile, as received at the base station. Assuming that the combiner output are independent and Gaussian, in the absence of thermal noise and Rayleigh fading, Henry was able to show that the bit error probability as a function of a single-to-noise parameter p is given by

$$p_b \cong \frac{N-1}{2} Q(N\bar{p})$$

where

$$p = \frac{N}{2} \frac{p_f}{1 + /2p_f} \tag{4-4}$$

and p_f=N/(M-1), whee N is the number of chips/code symbol. Henry was also able to derive a similar result for the bit error probability for the Rayleigh-fading channel. In Figure 4.3, the probability of bit error is shown plotted for both the nonfaded and faded cases as a function of ρ_f.

Assuming that the required bit probability of error for acceptable communiction is 10^{-3}, then from Figure 4.3 and the definition of efficiency $\eta = \frac{U}{F_r} \cdot \frac{30\text{KHz}}{W}$. The relatie spectral effieiency of the DPSK-FHMA system may be calculated. For the faded case, a bit error probability of 10^{-3} is achievable for ρ_f = 2.5 dB. For N = 32 this corresponds to M = 19 users yielding a relative spectral efficiency for the one-cell case of

$$\eta = 19 \times \frac{30\text{kHz}}{20\text{MHz}} = 0.029 \tag{4-5}$$

4.4 Bell Labs Multilevel-FSK Frequency-Hop System

The small relative spectral efficiency of the Cooper-Nettleton DPSK-FHMA digital cellular system prompted a number of researchers at Bell Labs during the period 1979-1982 to investigate other forms of spread-spectrum multiple-access methods suitable for digital cellular systems. In particular, a team of researchers designed (on paper), a frequency-hopped spread-spectrum multiple-access system that employed multilevel (M-ary) frequency-shift keying as the modulation method. The capacity of this system was shown to be roughly three times the capacity of the Cooper-Nettleton proposal.

The specifications of the Bell Labs proposal are shown in Table 4-4. Fig. 4.4.

Table 4.4

Parameters of th FH-FSK System

Frequency band	825-84 MHz mobile transmit 870-890 MHz base transmit
Access method	Fast-frequency-hop spread-spectrum multiple access
Modulation method	M-ray FSK
Cell design	Single cell reuse
Occupied bandwidth	20 MHz
Source data rate	32.895 kbps
Forward error correlation	Repetition coding, rate K/L

Fig. 4.4 shows a conceptual block diagram of the trasmitter and the receiver for this sytem.

4.4.1 Transmitter and Receiver Operation

As shown in Figure 4.4, the transmitter consists of a buffer, a frequency-hop sequence generator ("address" generator), and a frequency-hop synthesiser (or "tone" generator). The buffer groups K information bits/symbol and forms a code symbol or chip based on the binary representation of the K bits (which ranges from 0 to 2^K - 1). The code symbol is then repeated (L-1) times to form a codeword consisting of L chips.

The address generator generates a frequency-hop sequence or address that is unique to a given user, generating a value in th erange [0, 2^K - 1] every chip time and repeating after every L chips. At each chip time, the output of the codeword buffer and the address buffer are added together modulo 2^k. The resulting M-ary FSK/frequency hop address is then sent to the frequency-hop synthesizer, which generates a hop frequency every chip time according to the equation.

$$f_h = f_0 + (\text{composite address}) + f_{step} \tag{4-6}$$

whee f_0 is the nominal carrier frequency, f_{step} the minimum frequency step size of the synthesizer, and the composite addres take on values in the range [0,2^K -1].

The receiver, which is assumed to be chip and codeword synchronous to the trasnmitter, performs a spectrum analysis of the received signal and outputs a detected frequency index (or indices) in the rane [0,2^K - 1] every chip time. The address of the frequency hopping sequence is then subtracted from the detected index modulo 2^k every chip time. In the absencce of noise and multiple-access interference, the resulting value following the modulo 2^K subtraction would be a value in the range [0,2^K] repeated L times, corresponding to the repetition coding in the transmitter. The decoder would then output the K-bit sequence corresponding to the received codeword.

In the presence of noise and/or multiple-access interference, the spectrum analyzer will output multiple values in the range $[0,2^K -1]$ every chip time. Following subtraction of the desried user's frequency-hop address modulo-2^k, the received value sequence will now consist of multiple values every chip time. A majority logic decision rule is used in this situation which picks the codeword asociated with the row of the detection matrix that contains the greatest number of entries. Error will occur when entries due to a noise and/or multiple-access interference cause a row to be formed with more entries than that corresponding to the correct codeword. The frequency hopping sequences must therefore be selected such that correlation between users is minimized and sufficient frequency diversity is achieved to overcome the effects of Rayleigh fading.

4.4.2 __Performance__ : This yields about ten times the relative spectral efficiency of the DPSK FHMA system as per the performance analysis by Goodman et al. Number of enhancements have ebeen offered to the proposed multilevel FH-FSK system.

4.5 SFH 900 System (Slow Frequency HOP 900 System)

Prior to the development of the GSM system in Europe, described in the next section, several proposals were put forth as trial systems to be used in selecting the access and channelization approaches for GSM.One of these systems, the SFH 900 system, was developed by Laboratoire Central de Telecommunications (LCT) in France. This system is interesting because it combined slow frequency hopping, concatenated coding, and channel equalization to combat the effects of both time and frequency-selective fading. An experimental prototype of this sytem was constructed and was demonstrated in field tests in Paris during late 1986, which were used to test various component parts of the GSM system. The important parameters of the SFH900 sytem are shown in Table 4-5.

Table 4-5

System Parameters of the SFH-900

Frequency band	900 MHZ GSM band
Modualtion	GMSK, $B_bT = 0.3$
Access method	Interacell-TDMA Intercell-SFH CDMA
TDMA structure	3 slots/frame
SFH dwell period	4 ms
Cell reuse pattern	1 cell/3 sectors
Channel coding	Interhop: Reed-Solomon Intrahop : cyclotmically shortened Reed-Solomon
Information data rate	16 kbps
Channel equalization	MLSE equalizer
Gross channel bit rate	200 kbps

4.5.1 System Description

The SFH900 system employs TDMA within a cell and SFH CDMA between cells as the access methods. The TDMA frame format consists of a transmit slot, a receive slot, and a frequency switching slot, denoted by T, R and S slots, respectively. All slots and frames are synchronized within the system to a commonclock. The use of T-R-S slot structure within a cell permits easy implementation of a SFH system without requiring a fast-switching synthesizer. Between cells. SFH is employed as the multiple-access method.

A concatenated coding scheme is employed in the system to provide both frequency and interferer diversity and to combact random errors that would occur on the mobile channel. The concatenated coding scheme employs a Reed-Solomon code as an interhop,or outer code. The coding/hopping is designed to transmit is different frequency collisions among the various users. This is the classical approach to channel coding for frequency hopping communications using Reed-Solomon codes. In addition to the interhop code, within code dwell periods, the information content of each slot is coded further using cyclotomicaly shortened Reed-Solomon codes (CSRS), shortened Reed-Solomon codes in which all computations (error syndrome evaluation, errror locator polynomial computation,and error value determination) are done over the binary field GF(2) rather than the extension field GF(2"’), as is the case for Reed-Solomon codes. The intrahop code is used to correct random errors that occur during the dwell period.

The modulation method employed in the system is Gaussian minimum shift keying with a low--pass filter parameter of B_b T = 0.3. A 16-state maximum-likelihood sequence estimator equalizer is used to combat the effects of intersymbol interference due to frequency-selective fading. Frequency hopping occurs at the TDMA frame rae of 250 hops/s. Within a cell, all hopping is coordinated such that two users never occupy the same frequency at the same time ("orthogonal" hopping). Between cells, a different frequency-hopping code is employed for all nearby cells, resulting in uncorrelated interference from hop to hop. The channel coding is matched to the frequecny hopping pattern so that frequency collisions are corrected. Within the SFH900 system, frequency hopping is therefore used to obtain both frequency diversity and interferer diversity, the latter being a benefit of the CDMA aspects of SFH.

4.5.2 Performance

As per.analysis of the SFH900 the system is able to achieve a symbol erasure rate of the order of 4 x 10^{-2} (which corresponds to a decoded bit error rate of 5 x 10^{-3}) for a channel capacity of 3.5 users per sector per megahertz.

4.6 GSH-SFH Digital Cellular System

The GSM-SFH digital cellular system represents another slow-frequency-hopping approach to digital cellular systems. The GSM sysem has now been deployed commercially throughout western Europe and will be deployed in other countries as well. Its commercial success throughout the world led to European Telecommunications Standards Institute (ETSI), the standard body in charge of the GSM system, to change the meaning of the GSM initials from the original "Groupe Special Mobile,' the designated name for the Pan European digital cellular system, to "Global System for Mobile Communciation" in 1992. The GSM system is described in a formal set of documents consisting of some 5200 pages that is available directly from TSI. In addition, there have been a number of journal articles, trade press articles, commercial journals, trade/technical conferences, and even a complete book or portions of a book directed toward the GSM system. Because of the availability of information on the GSM system, coverage of GSM has been kept concise.

The GSM system has been deployed at 800/900 MHz in many western European nations, including the United Kingdom, France, Germany, Denmark,and Sweden, among others, In additon an extension of the GSM standard defined by ETSI and DCS 1800 for the 1800 MHz band, is currently being deployed in several European countries. A modification of the latter system has been proposed for PCS frequency bands in the United States. Manufacturers of GSM/DCS 1800 equipment include Motorola. Alcatel, Siemens, Ericsson,and others.

The GSM system was designed to supplant the wide variety of analog cellular sysems within Europe with a common digital cellular system. It was designed at the outset to support a wide range of digital services. The system is an 8 slot/frame TDMA system operating at a data rate of 27.8333 kbps over the air. The duration of the basic TDMA frame is 4.615 ms and the modulation format employed is B_bT = 0.3 GMSK. Speech information is convolutionally coded using a rate ½ constraint length 4 convolutional code. At the channel data rates employed, the transmitted signal is expected to undergo moderate to severe frequency selective fading of up to four symbol times ($\approx 15\mu s$). Hence the GSM specifications implicitly require that some form of equalizer be incorporated into both the mobile and base receivers. To combat slow time-selective fading and to provide interference diversity, slow frequency hopping at the frame rate of 217 hops/s is specified in the GSM specifications. Table 4-6 summarizes many of the parameters of the GSM/DCS 1800 specifications. Figure 4.5 shows a conceptual block diagram of a GSM transceiver that is based on an experimental system. In the following. A brief description of the signal processing aspects of one specific implementation of a GSM transceiver is given below.

4.6.1 Signal Processing Description

In the transmitter, the speech is transformed into a digital representation at 13 kbps using a residual pulse-excited, linear prediction coder with long-term prediction (RPE-LPC/LTP). The speech coder, which also implements a voice activity detector (VAD), is then used to turn off the transmitter during low-speech-activity periods . The most significant bits of the speech coder output are then rate coded, and the resulting (coded plus uncoded bits) are block diagonal interleaved. The interleaved symbols are then formatted with training symbols inserted and applied to a GMSK modulator where the carrier is modulated with the coded, interleaved information stream and transmitted. Every frame time, the carrier is frequency hopped, using S-F-H Algorithm.

In the receiver, the signal is dehopped and demodulated to baseband using a quadrature demodulator. The demodulated signal is then phase and frequency corrected, equalized, deinterleaved,convolutionaly decoded, and applied to a speech decoder.The speech decoder then converts the signal back to analog speech.

Significant amount of control structure is required to support the GSM system There exists a framing hierarchy whereby 8 slots form a TDMA frame, 26 frames form a multiframe, 51 x 26 multiframes form a superframe, and 2048 superframes (2,715,648 TDMA frames) form a hyperframe. The framing hierarchy is used for synchronization, moitoring of other carriers, frequency-hopping control and encryption of the TDMA slots. In addition to the information bearing slots, other synchronisation information and both common and dedicated control channel information are transmitted periodically between the base site and the subscriber unit.

4.6.2 Slow-Frequency-Hopping Algorithm

Early in the design of the GSM system, the system architects realized the benefits of including slow frequency hopping in the system. At the present time, two algorithm .

Table 4.6

GSM/DCS 1800 SYstem Specifications

	GSM System	DCS1800 System
Frequency bands Mobile transmit	890-915 MHz	1710-1785 MHz
Base transmit	935-960 MHz	1805-1880 MHz
Channels per carrier	8	
Channel bit rate	270.83 kbps	
Channel spacing	200 kHz	
Modulation .	$B_bT = 0.3$ GMSK	
Symbol alphabet size	Binary, differentially coded	
Co-channel interference Protection	≤ 12 dB	
Time slot duration	0.58 ms	
Frame duration	4.6 ms	
Frequency hopping rate	216.8 hops	
Channel coding		
Type	Convolution	
Rate		
Speech channel	½.	
Signaling channels	½	

Interleaving depth	Eight-block diagonal interleaving for speech channel	
Maximum channel delay to be equalized	16μs	
Speech coder		
Type	RPE/TP-LPC	
Rate	13.0 kbps	
Frame length	20ms	
Block length	260 bits	
Classes	Class I:182 bits Class II:78 bits	
Gross speech rate with FEC coding	22.8 kbps	
Frequency accuracy	Base station 0.05 ppm Mobile station 0.1 ppm	

for hopping the channels are available to the system operators. The first, designed for systems for employing a small number of RF carrier, is simply a cycle permutation of the frequencies available to within a cell. This approach will not result in interference diversity but will improve the performance of the system at low vehicle speeds via randomization of time selective fading. The second approach employes pseudo-random sequence generator to generate pseudo-random sets of carrier frequencies to be used throughout a cellular system. With this approach, all users within a cell are orthogonal in frequency and users in immediately adjacent cell will interfere at most once per n frames, where n is the number of available frequencies.

4.6.3 Performance

The GSM system is currently commercially deployed. As a result , except for information contained in the literature that describes pre-commercial systems, information on the performance of the GSM system is difficult to obtain, as such information has been tightly controlled by the equipment manufacturers and the system operators, for competitive reasons. An early version of the GSM specification indicated that for the typical urban channel model and an equivalent 50-km/h vehicle speed,with a signal power input to the receiver of -104 dBm, the word error rate was to be less than 3% without frequency hopping and 6% with frequency hopping.

4.7 Other Digital Cellular System

Hybrid SFH TDMA/CDMA system for PCS Applications has been developed by Motorola which incorporates a hybrid form of multiple access in particular SFH CDMA combined with TDMA.

CHAPTER - 5

MILITARY APPLICATIONS

AND

CONCLUSION

5.1 Military Applications

The CDMA Digital Cellular communication systems can play a major role in military operations. The cellular network is being spread to the lengths and breadth of the country.

During defensive operations the commander will remain accessible. CDMA Digital Communication can be used to pass both voice and data in defensive operations though application is limited in offensive mobile operations.

The reasons for military application are the following characteristics of the CDMA cellular systems.

(a) Secrecy

(b) Anti-jamming

(c) Easy accessibility to the user

5.2 Conclusion

In this thesis an introduction to mobile cellular systems, has been given. The relevance of spread spectrum signals to CDMA has been brought out. Cellular system designs are functions of both the topology of the cell and the modulation/coding/diversity methods employed. Different CDMA Digital Cellular systems including DS-CDMA system, frequency-hopped CDMA systems with their important aspects were described.

The CDMA Digital Mobile Cellular Systems are expected to be implemented in a big way as they offer, improvements over analog cellular systems, increased system capacity, speech quality and system reliability. Their military applications because of features of secrecy and immunity to jamming cannot be overlooked in the future. The CDMA Digital Mobile Cellular Systems therefore hold a promise for the future in a world which is increasingly becoming wireless.

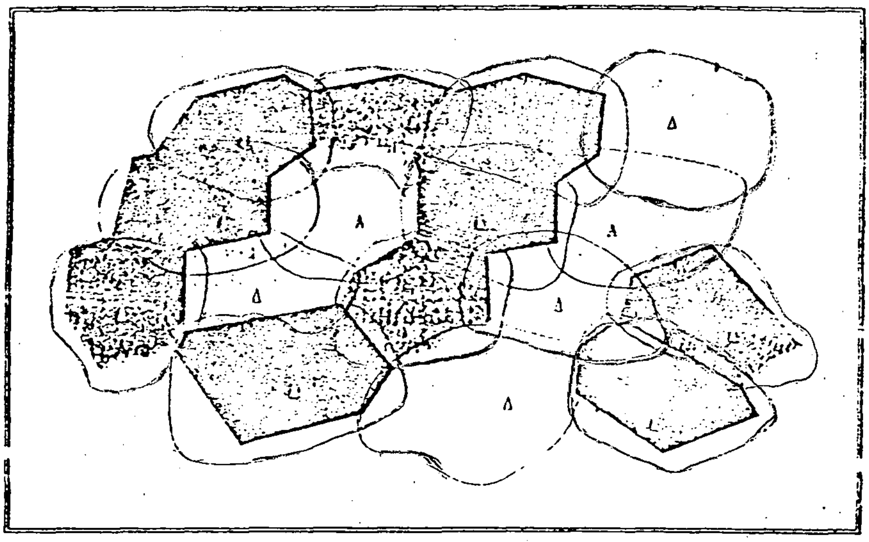


Figure 1.1 – The concept of cellular coverage

Numerous omnidirectional or sectorised antenna sites allow wide coverage, by splitting the geographical area into overlapping coverage areas. The lines show the limits of the overlapping coverage of the cells, whereas the polygons represent the more usual non-overlapping representation.

HEXAGONAL CELLS

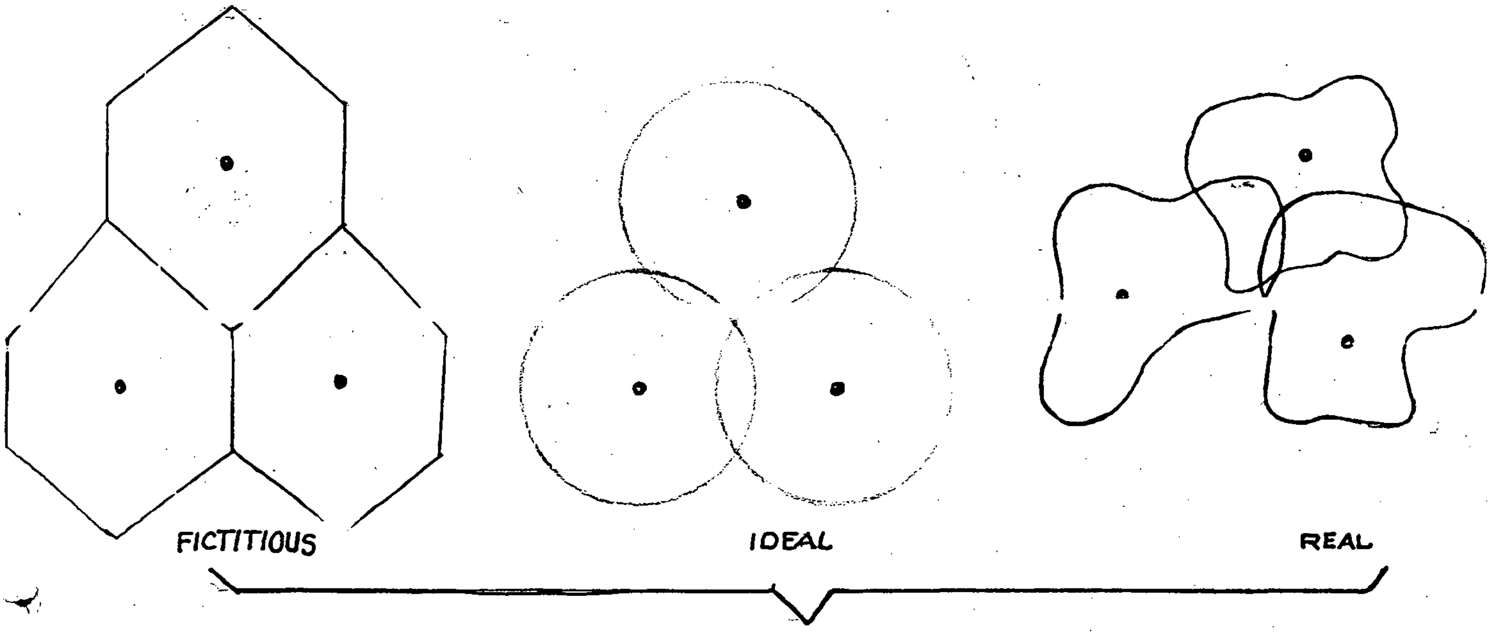


Fig 1.2 HEXAGONAL CELLS AND THE REAL SHAPES OF THEIR COVERAGES

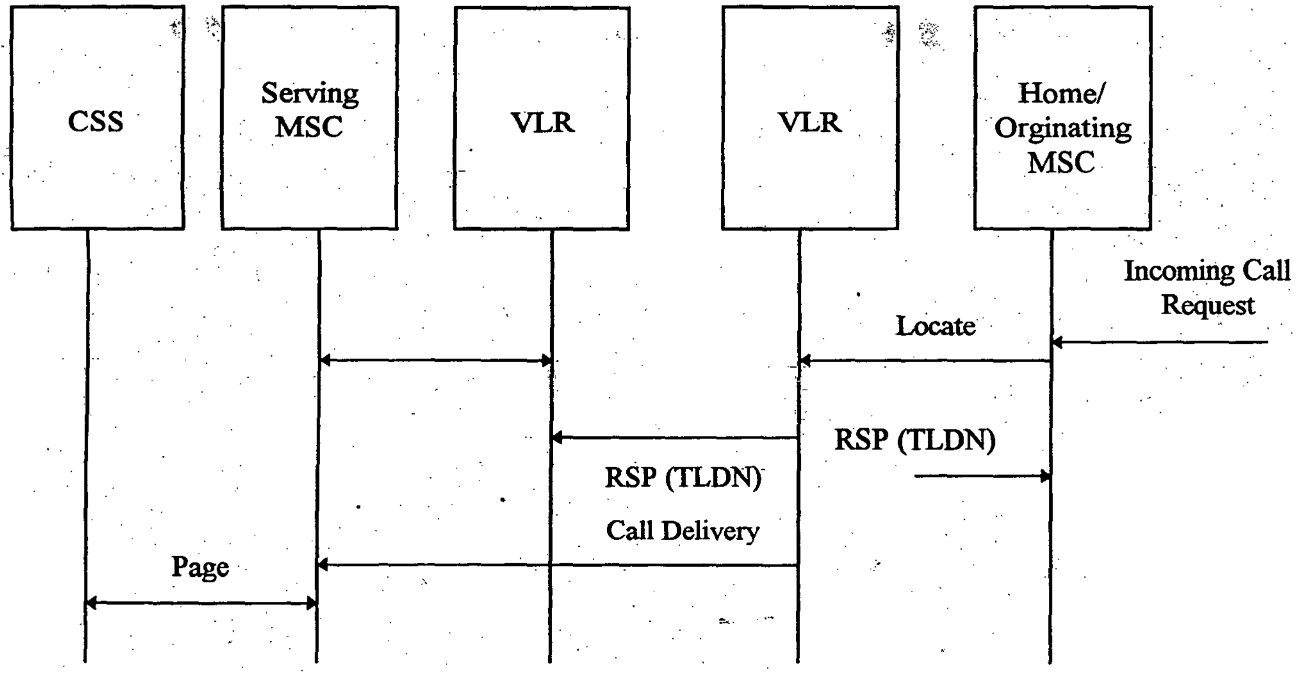


Figure 1.3 Call Delivery

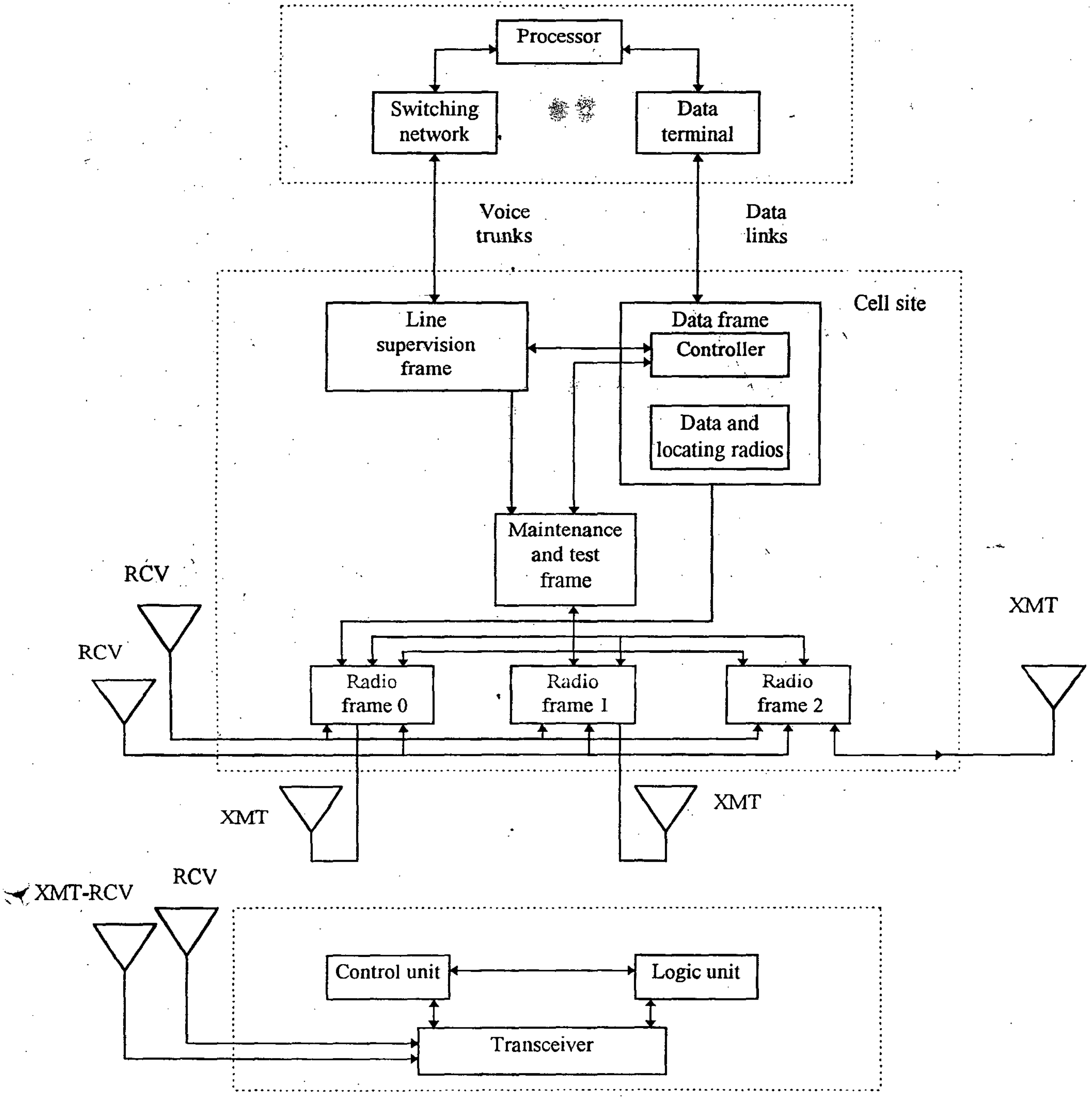


Figure 1.4 Cellular mobile major systems

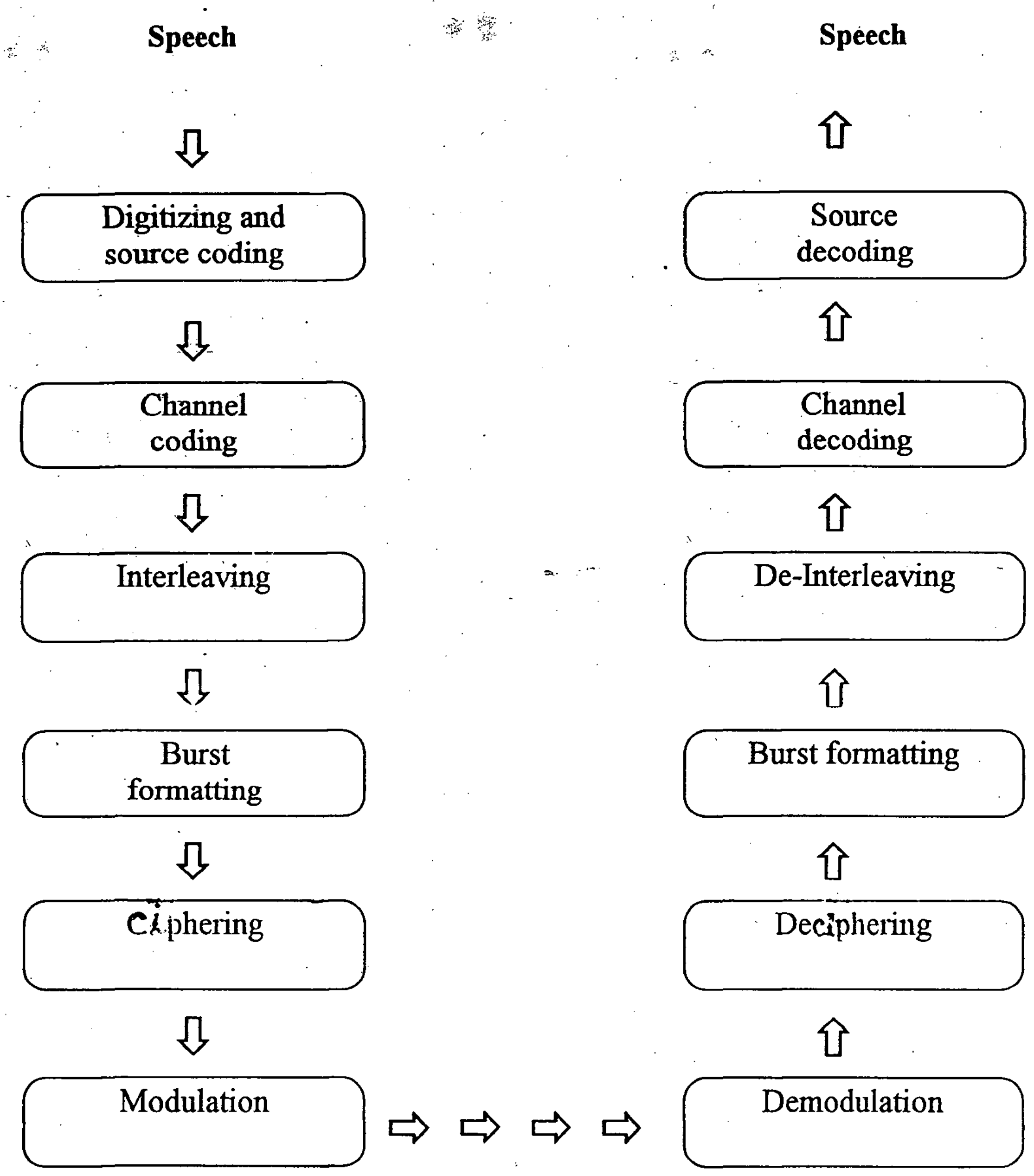


Figure 1.5 - Sequence of operations from speech to radio waves and back to speech

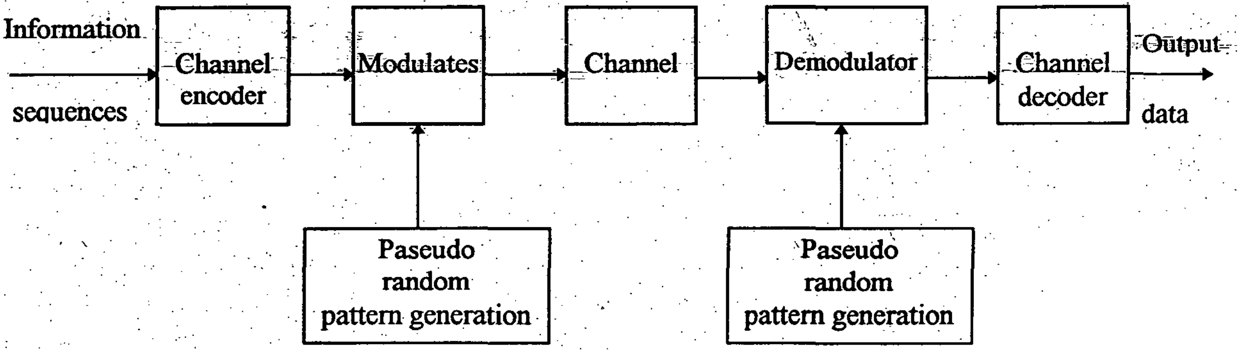
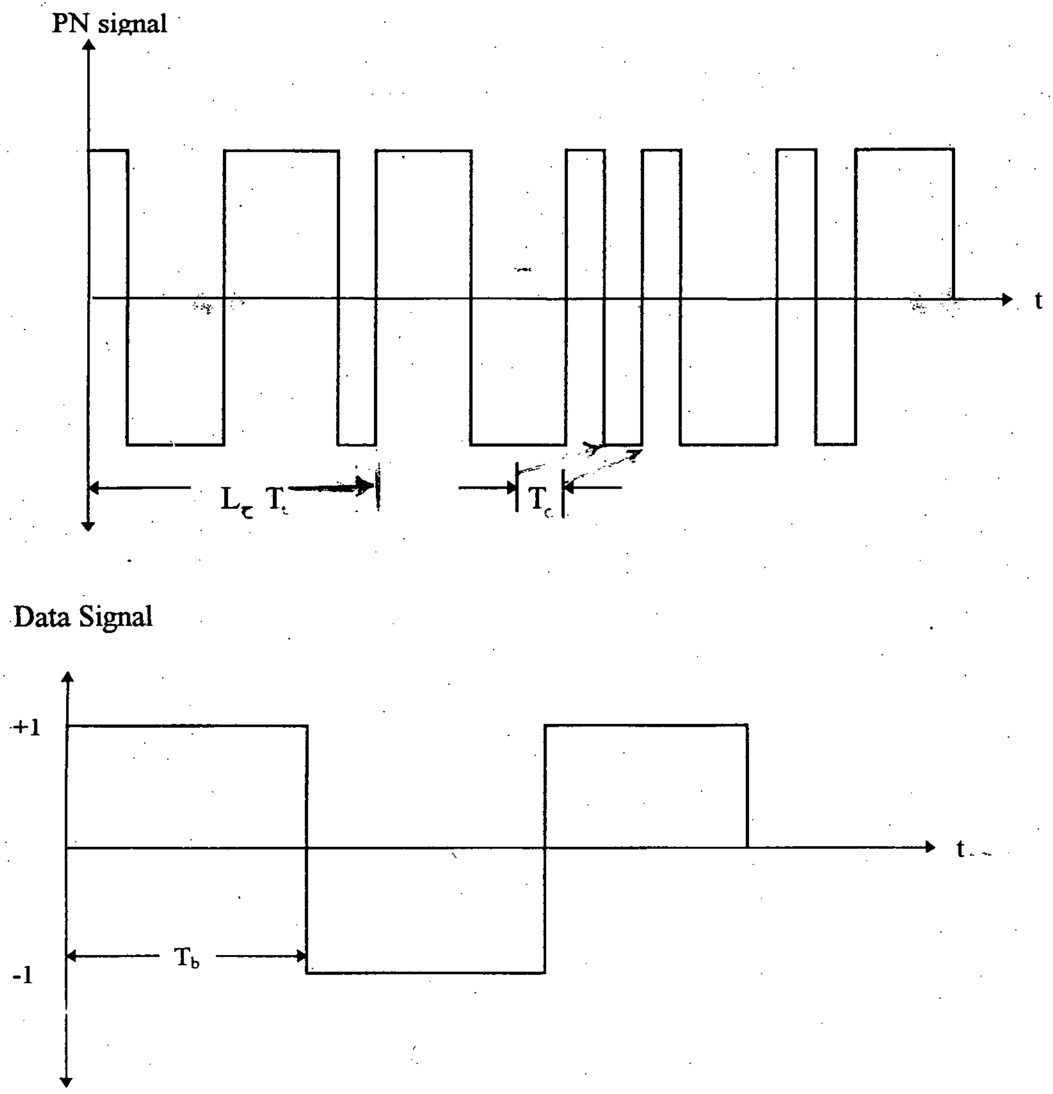
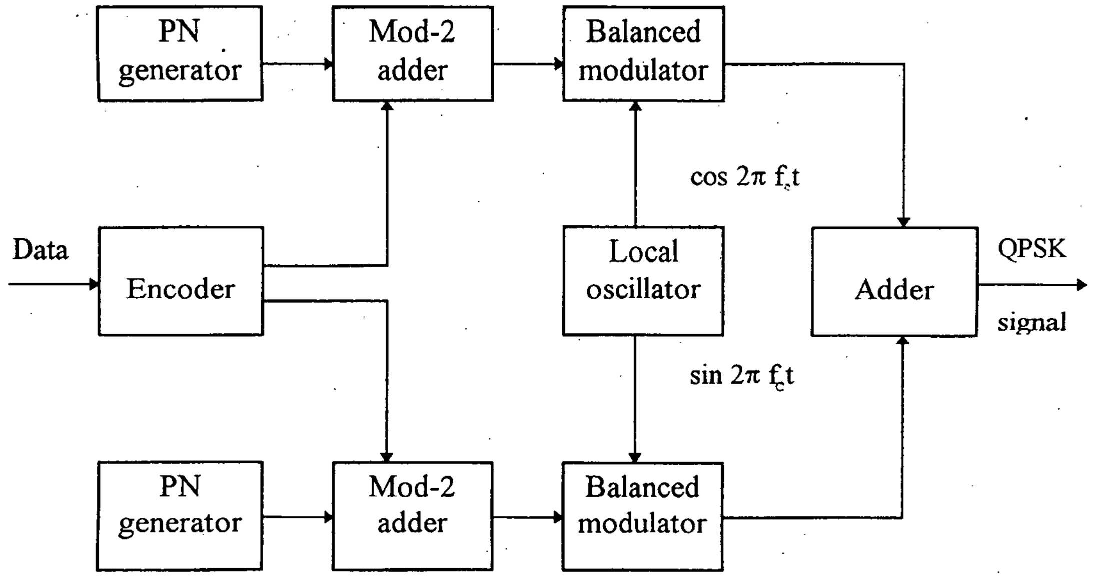


Figure 2.1 Model of spread spectrum digital communication system.



(a) PN and data signals



(b) DS-QPSK modulator

Fig.2.2 The PN and data signals (a) and the QPSK modulator (b) for a DS spread spectrum system

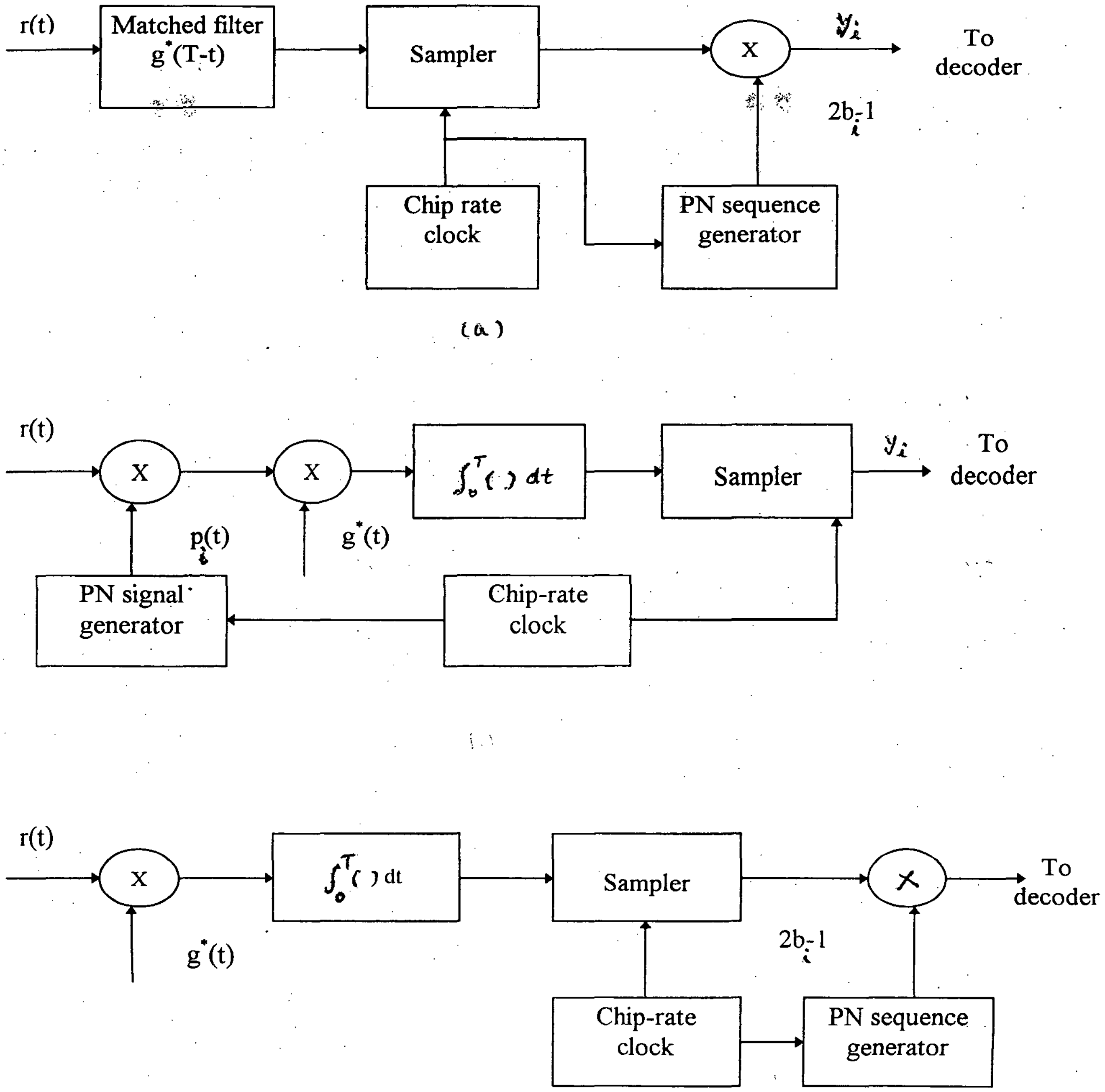


Figure 2.3 Possible demodulator structures to PN spread spectrum signals

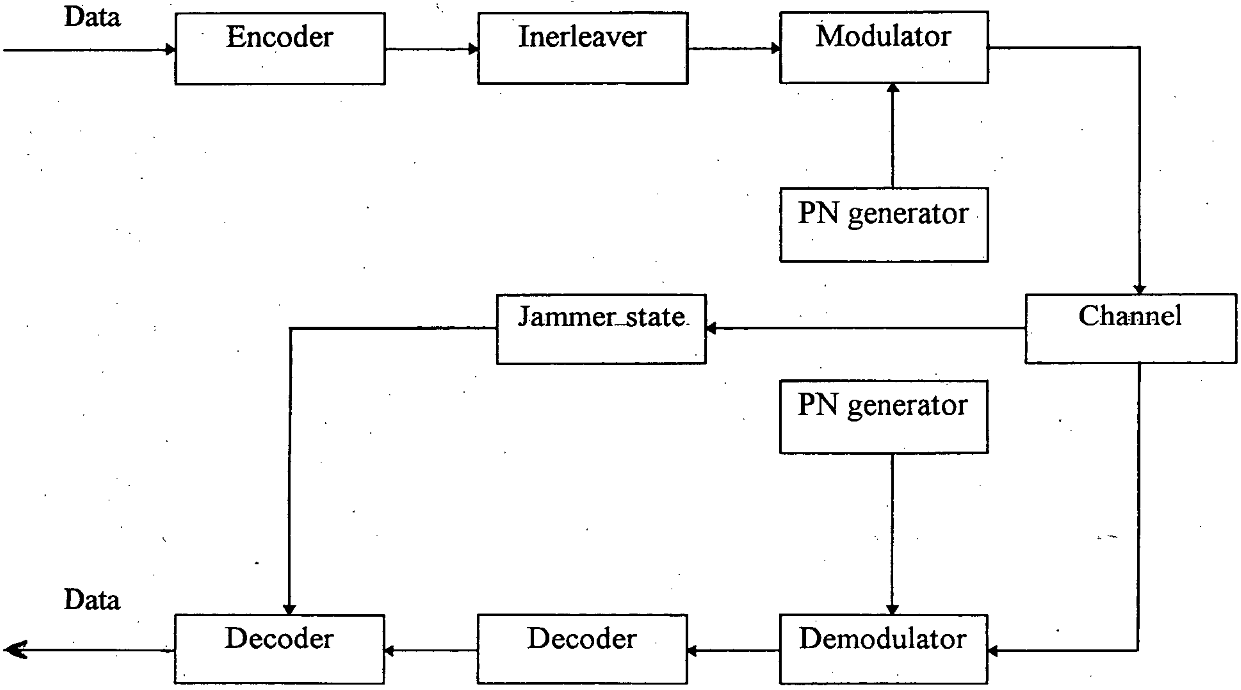


Figure 2.4 Block diagram of AJ communication system.

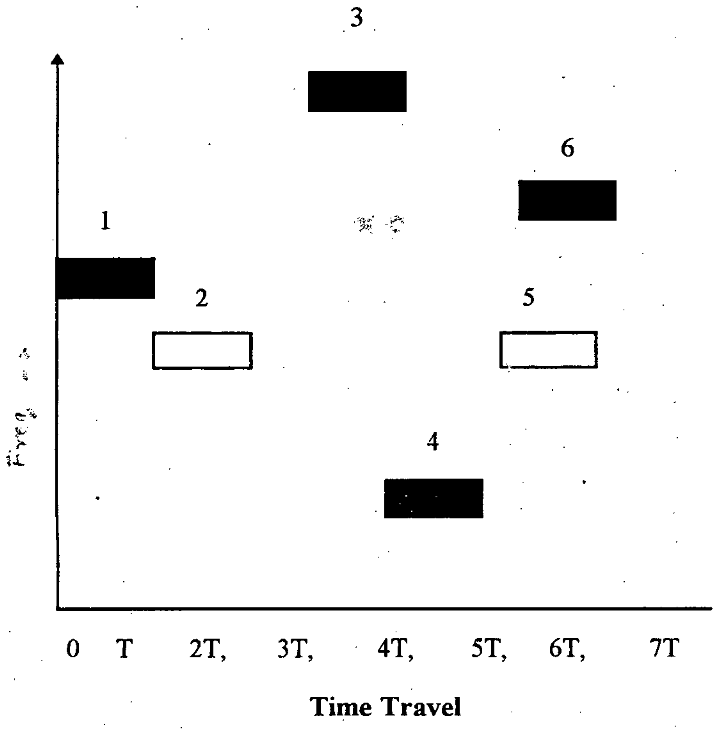


Figure 2.5 An Example of a frequency-hopped (FH) pattern

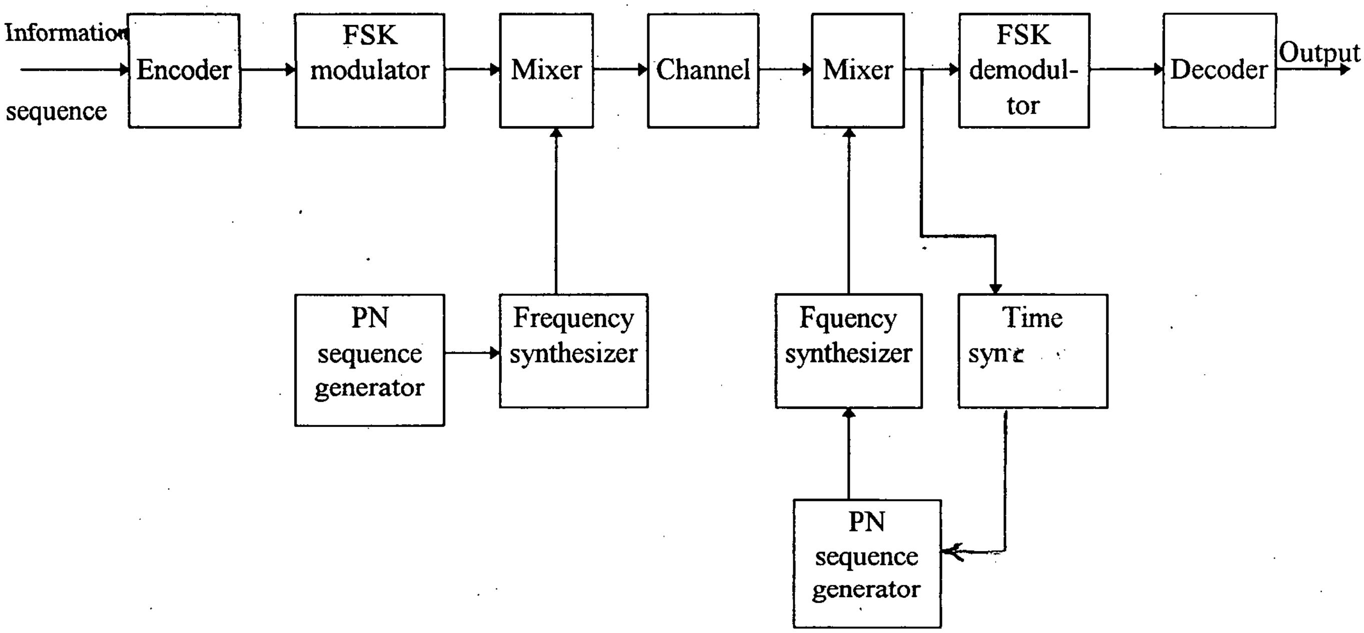


Figure 2.6 Block Diagram of FH spread spectrum system

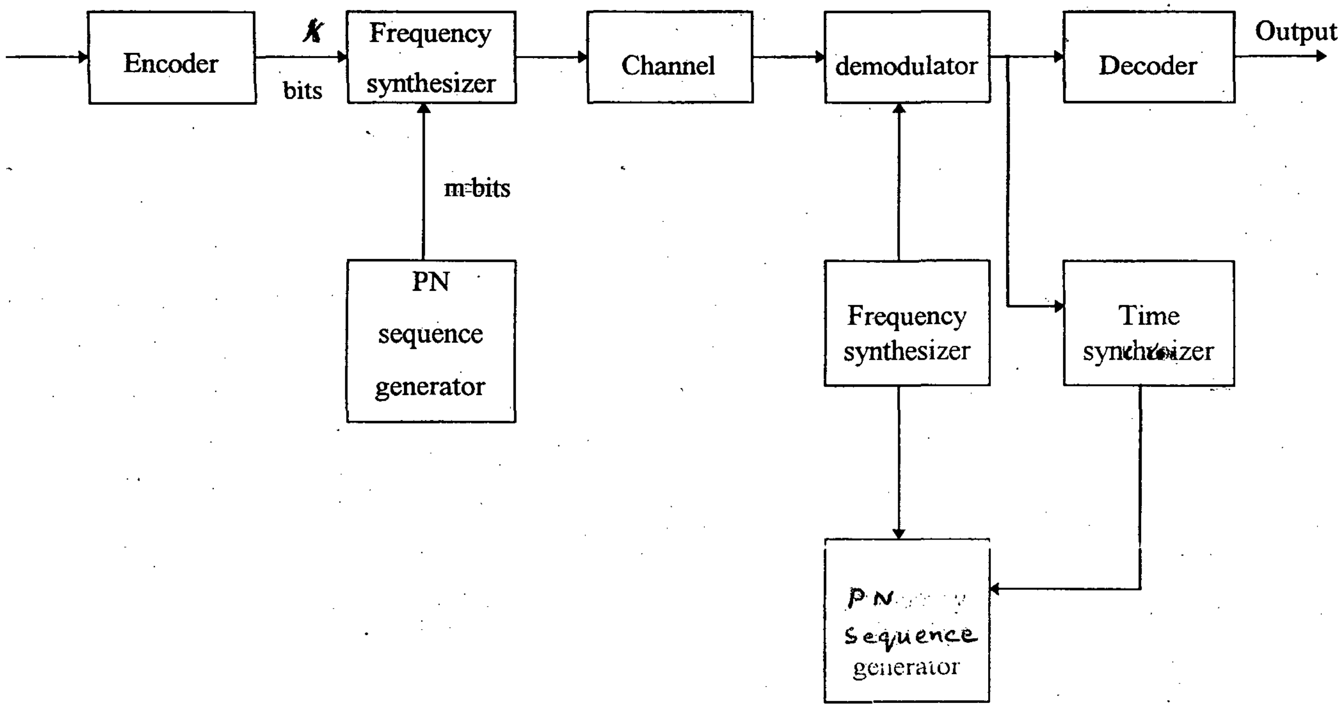


Figure 2.7 Block diagram of an independent tone FH spread spectrum system

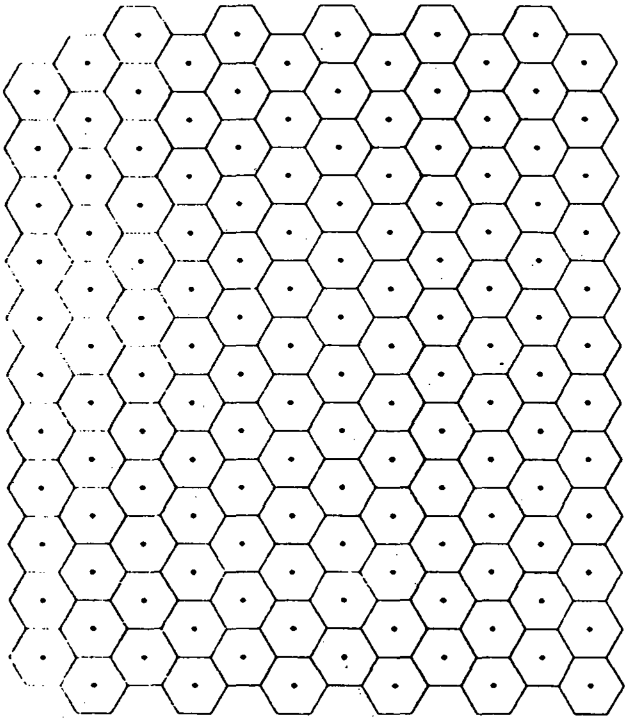


FIGURE 3.1. Hexagonal cell pattern for cellular radio systems. Center dot denotes base site antenna.

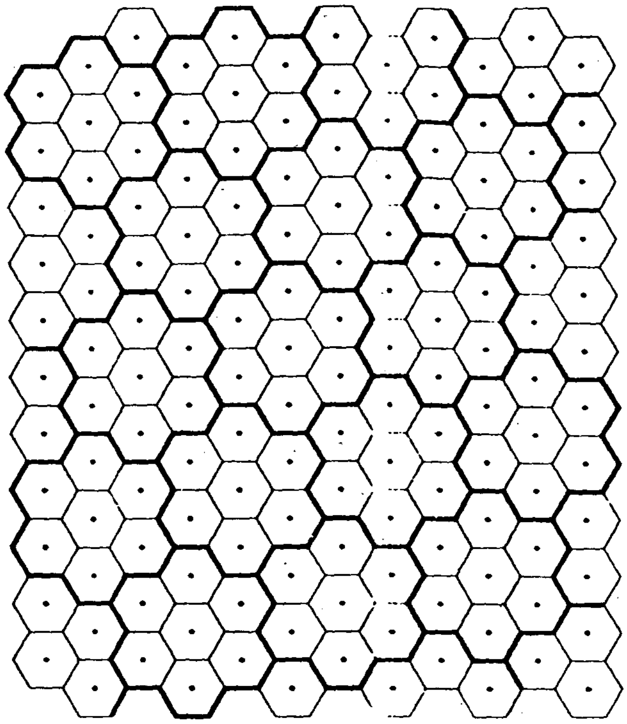


FIGURE 3-2. Seven-cell reuse pattern.

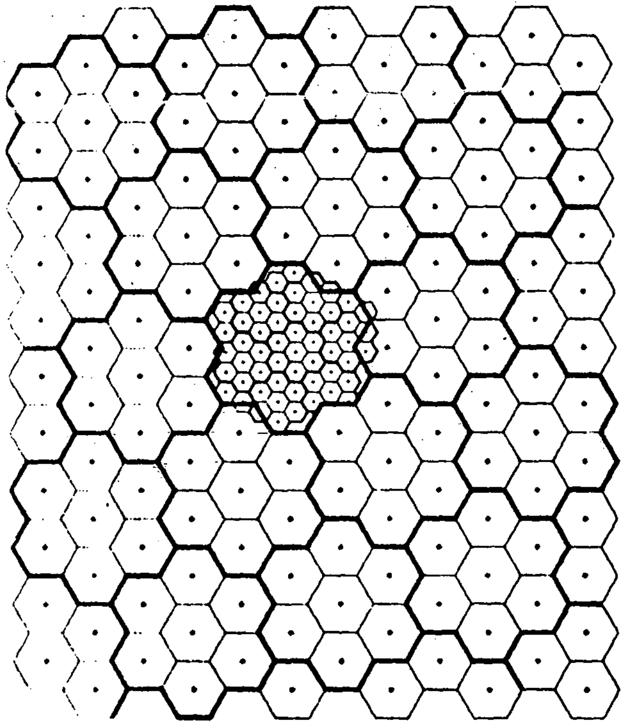


FIGURE 3-3. Cell splitting in seven-cell pattern.

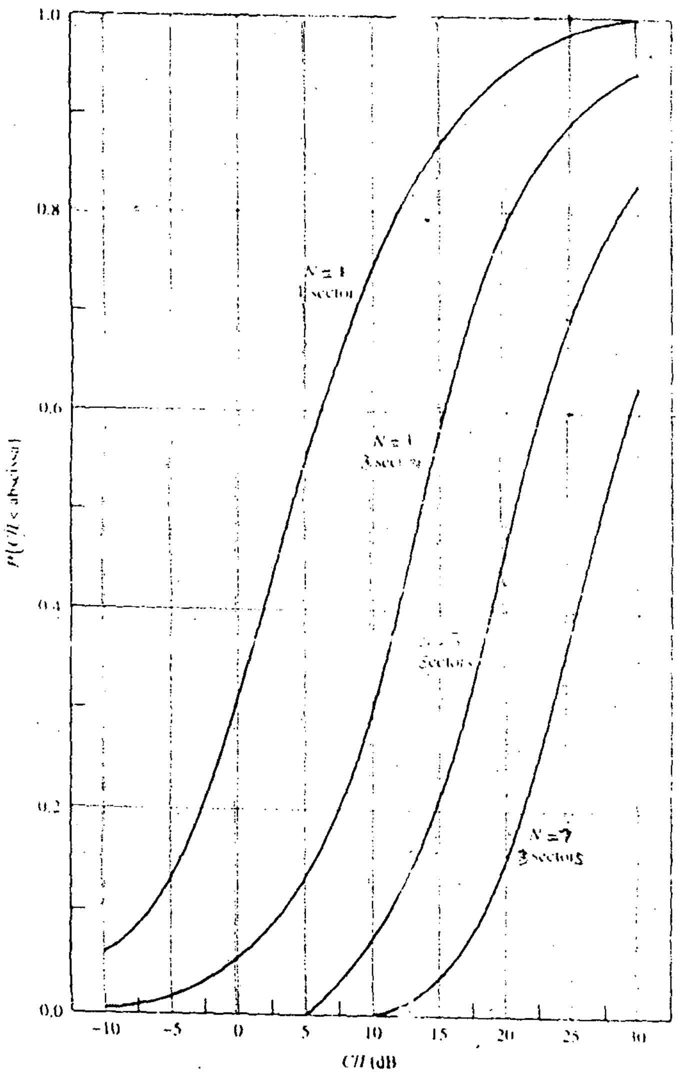


FIGURE 3.4. C/I location reliability for several cellular system topologies.

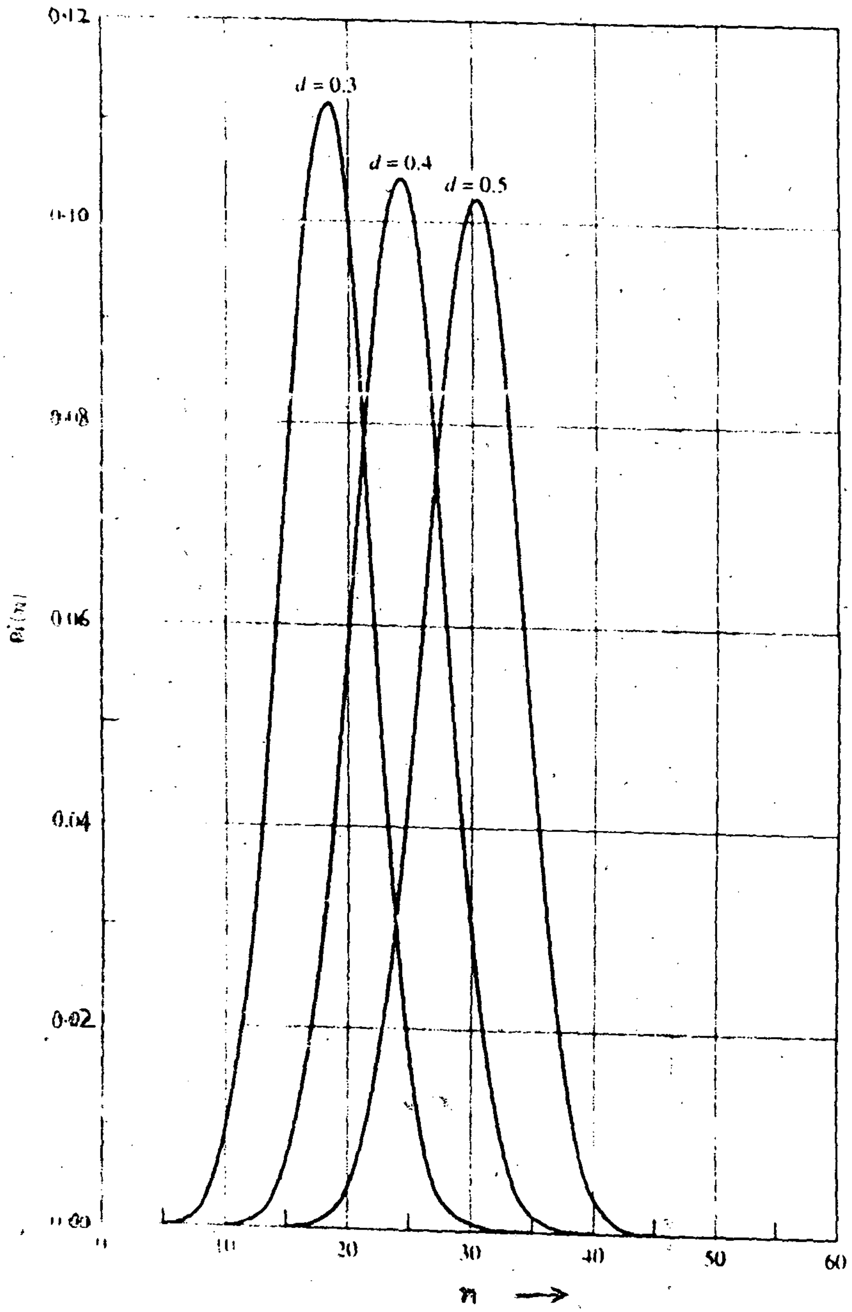
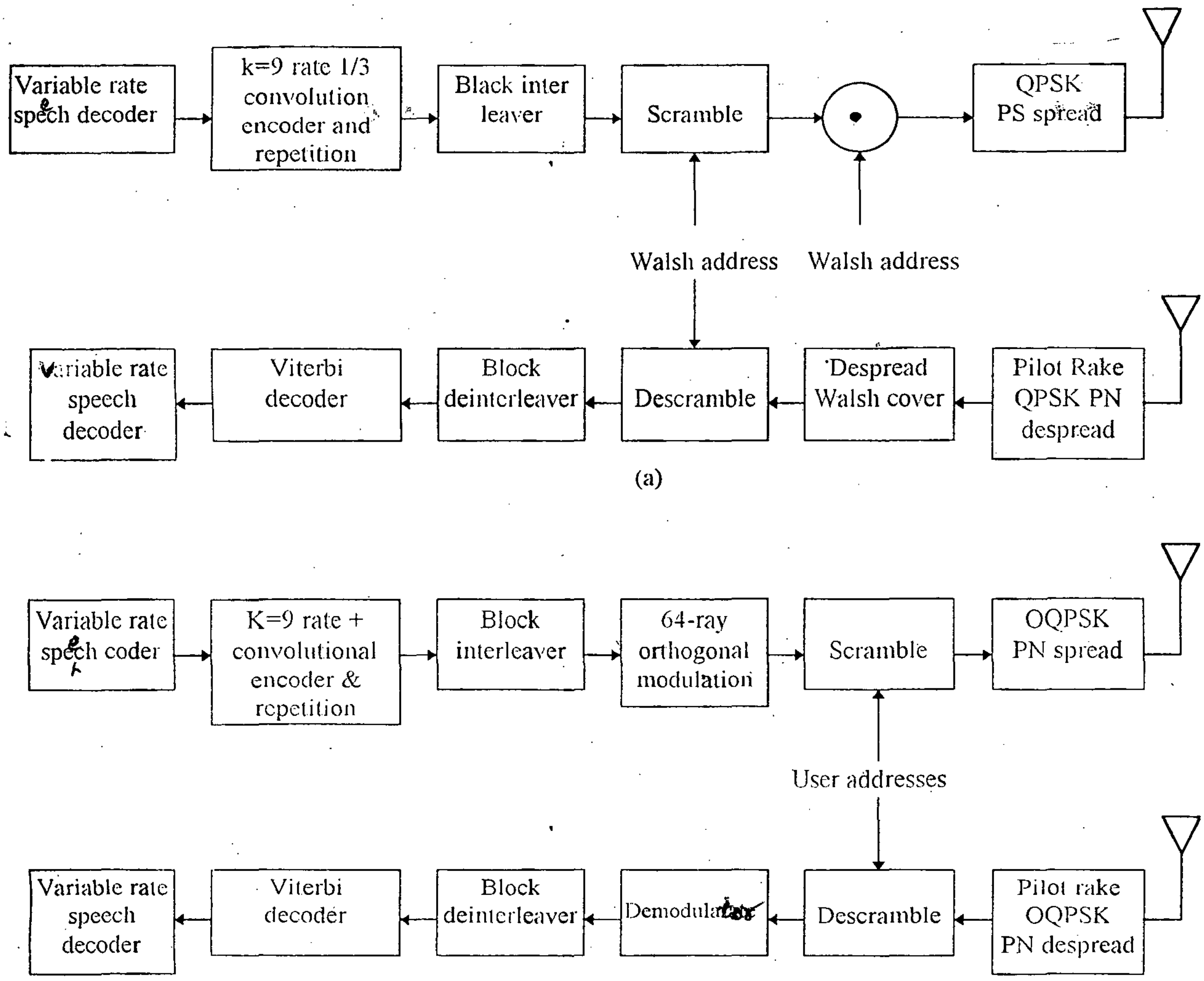


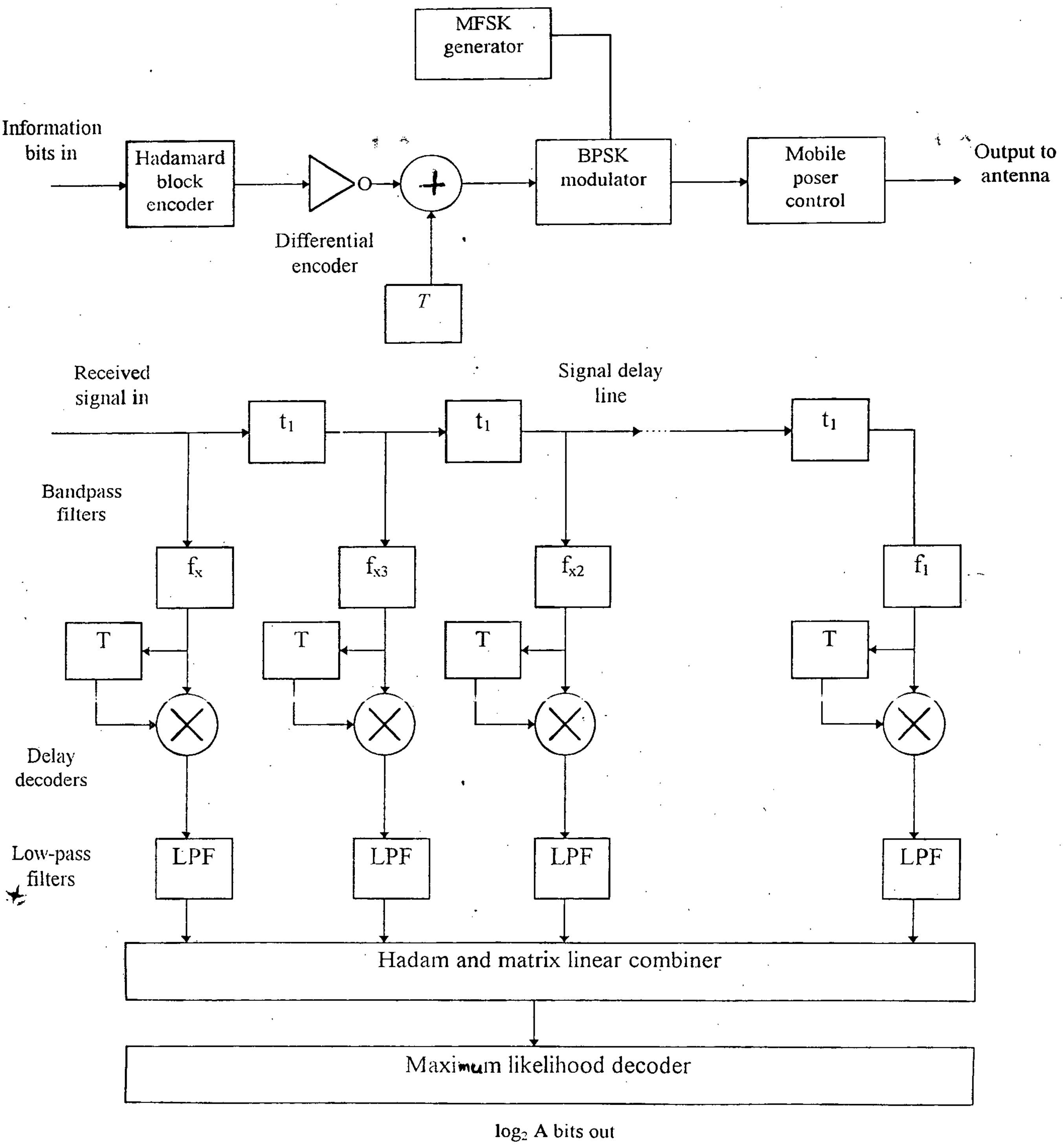
FIGURE 3.5 Envelope of discrete density function for various voice activity factors. $N = 60$.



(a)

(b)

Figure 4.1 Conceptual block diagram of IS-95 (a) forward link and (b) reverse



(b)

Figure 4.2 Block diagram of DPSK-FHMA (a) transmiter and (b) receiver

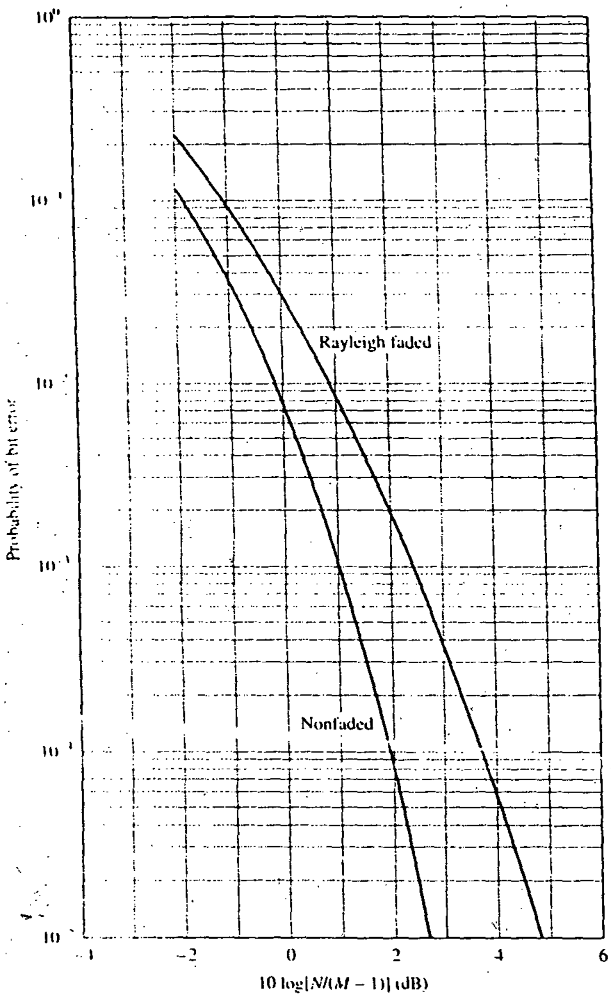


FIGURE 4-13 Probability of bit error for DPSK-FHMA, single-cell case.

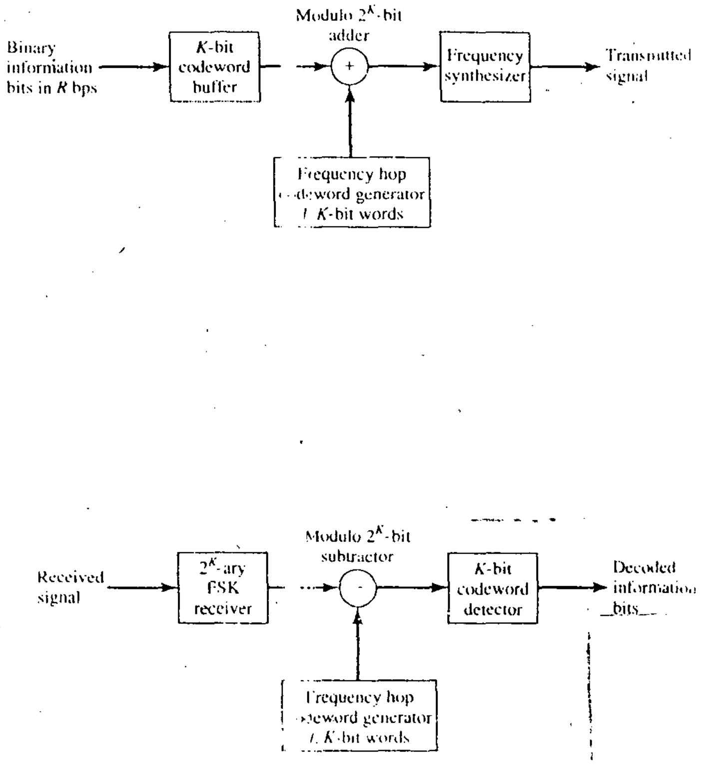


FIGURE 4.4 Multilevel FSK-FH transmitter (a) and receiver (b) block diagrams.

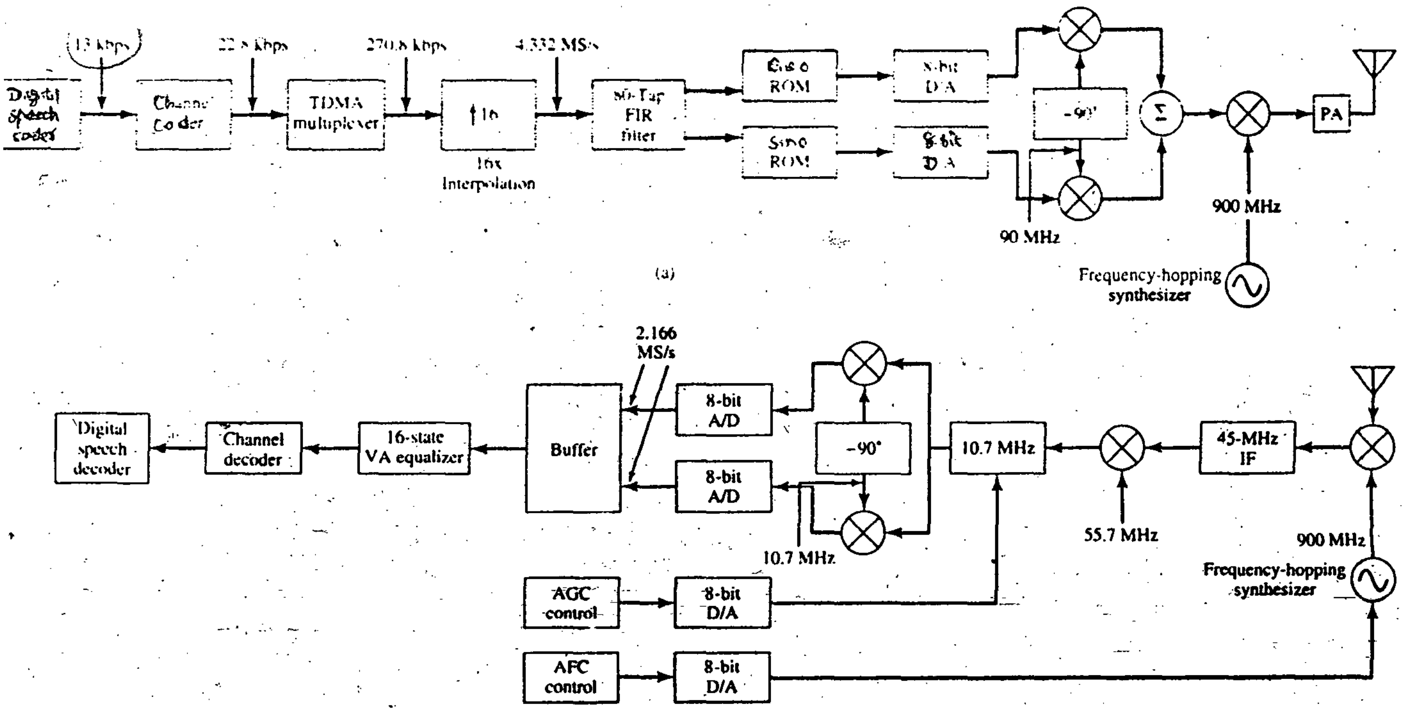


FIGURE 4.5 Block diagram of a GSM transceiver: (a) transmitter; (b) receiver.

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