System Configuration for Universal Wireless Systems

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Abstract

System Configuration for Universal Wireless Systems

When a mobile station is powered on or handed off in future cellular or wireless LAN environment where multi types of cellular and LAN access techniques (CDMA. GSM. 3G. IEEE802.11 etc.) exist. the universal cellular Base Station will select the best combination of the techniques for the mobile station based on the given mobile station size. power. distance and hardware available. The universal cellular Base Station communicates with the mobile station in many access modes. different modulation modes (PSK. QAM. GMSK etc.) and different FEC coding (Reed-Solomon. convolutional etc.). The base station will run a complex budget calculation to find the best modulation type. FEC type and multiple access technique and inform the mobile station about the best possible modes of operation in its cell. This thesis introduces such complex algorithm and gives few results.

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To my Dad, Mom and my Three Sisters

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List of Acronyms and Abbreviations

ACK	Acknowledgment
ADC	Analog to digital converter
AGC	Automatic Gain Control
AID	Area Identification Numbers
AMPS	Advance Mobile Phone Service
AP	Access Point
APIs	Application Programming Interfaces
ARQ	Automatic Repeat Request
ASICs	Application-Specific Integrated Circuits
AWGN	Additive White Gaussian Noise
A/D	Analog to digital
BER	Bit Error Rate
BSC	Base Station Controller
BSS	Base Station Subsystem
BTS	Base Transceiver Stations
CAI	Common Air Transfer
CDMA	Code Division Multiple Access
CPFSK	Continuous Phase Frequency Shift Keying
CPU	Central Processing Unit
CRC	Cyclic Redundancy Check
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear-To-Send

DDC	Decimating Down Converter
DPSK	Differential Phase Shift Keying
DSP	Digital Signal Processing
DSSSS	Direct Sequence Spread Spectrum
D/A	Digital to Analog
EIRP	Equivalent Isotropically Radiated Power
EMI	Electromagnetic Interference
EP	Extension Point
ESN	Electronic Serial Number
ETACS	European Total Access Communication System
FCC	Forward Control Channels
FEC	Forward Error Control
FFT	Fast Fourier Transforms
FHSS	Frequency Hopping Spread Spectrum
FM	Frequency Modulation
FPGA	Field Programmable Gate Arrays
FSK	Frequency Shift Keying
FVC	Forward Voice Channels
GMSK	Guassian Minimum Shift Keying
GSM	Global System for Mobile
HF	High Frequency
HLR	Home Location Register
IF	Intermediate Frequency

IR	Infra Red
I/O	Input – Output
JTRS	Joint Tactical Radio System
LAN	Local Area Network
LNA	Low-Noise Amplifier
MAC	Medium Access Control
MAHO	Mobile Assisted Handoff
MC-CDMA	Multi-Carrier Code Division Multiple Access
MEMS	Micro Electro-Mechanical Systems
MIMD	Multiple Instruction Multiple Data-Stream
MIN	Mobile Identification Number
MIPS	Million Instructions Per Second
MS	Mobile Station
MSC	Mobile Switching Center
MSK	Minimum Shift Keying
MTSO	Mobile Telephone Switching Office
NOS	Network Operating System
NSS	Network and Switching Subsystem
OSS	Operation Support Subsystem
PAM	Pulse Amplitude Modulation
PM	Phase Modulation
PN	Pseudo Random Noise
PSK	Phase Shift Keying

PSTN	Public Switched Telephone Network
QAM	Quadrature Amplitude Modulation
RCC	Reverse Control Channels
RF	Radio frequency
RSC	Recursive Systematic Convolutional
RTS	Ready-To-Send
RVC	Reverse Voice Channels
SAT	Supervisory Audio Tone
SCM	Station Class Mark
SDMA	Space Division Multiple Access
SFDR	Spurious Free Dynamic Range
SID	System Identification Number
SIM	Subscriber Identity Module
SIR	Signal-to-Interference Ratio
SMS	Short Messaging Service
SNR	Signal to Noise Ratio
SWR	Software Radio
TCM	Trellis-Coded Modulation
TDMA	Time Division Multiple Access
UHF	Ultra High Frequency
VHDL	VHSIC Hardware Description Language
VHF	Very High Frequency
VHSIC	Very High Speed Integrated Circuits

VMAC Voice Mobile Attenuation Code

Chapter 1

Software Radio

1.1 Introduction

Historically, radio systems have been developed to suit a specific application, with the hardware being built to meet one specific set of requirements. Such an approach to radio system design is clearly apparent in the military environment, where historically one type of radio would be designed for one type of scenario. This optimizes the design for one particular set of parameters e.g. range, traffic type, security, probability of interception etc. The use of radio systems, designed exclusively for one service (or one branch of one service) now imposes many problems for users who need to communicate with groups of disparate allies, in very different situations. Thus, in the military environment many see a software radio, which can be reprogrammed to suit any scenario, as being the solution to the communications problems inherited over the last decades. Also, the industrial competition between Asia, Europe and America makes it hard to define unique standards for future mobile systems. Therefore, the use of a technology to simplify operation for the users of telecommunications systems is a clear, and long-standing, objective for manufacturers. The provision of such services may be met by a multi-band, multi-mode, re-programmable system. It is therefore, the software radio is emerging as a solution. An easy way to define the software radio is as a transceiver in which the "frequency band and channel bandwidth, channel coding / modulation, radio resource management and user functions" are all implemented by software.

In fact, the term software radio stands for radio functionalities defined by software, meaning the possibility to define by software the typical functionalities of a radio interface usually implemented by hardware. In software radios, signals on the antenna, or perhaps at an intermediate frequency are digitized with a high performance analog-to-digital converter (ADC) and sent to a terminal (computer, mobile phone, etc.). Once digitized and inside the terminal, code would be used to select an RF channel and demodulate the signal. In the past few decades, radio systems moved from analog to digital in almost every respect from system control to hardware technology. Software radio revolution extends these horizons by liberating radio-based services from chronic dependency on hard-wired characteristics, including frequency band, channel bandwidth, and channel coding. This liberation is accomplished through a combination of techniques that includes multi-band antennas and RF conversion: wideband Analog to Digital (A/D) and Digital to Analog (D/A) conversion (A/D/A conversion); and the implementation of IF, baseband, and bitstream processing functions in general-purpose programmable processors. The resulting software radio extends the evolution of programmable hardware, increasing flexibility via increased programmability [7].

1.2 The Canonical Software Radio Architecture

The components of the canonical software radio consist of a power supply, an antenna, a multi-band RF converter, and a single chip containing A/D/A converters with an on-chip general purpose processor and memory that perform the radio functions and required interfaces [7]. The canonical mobile software radio terminal interfaces directly to the user (e.g. via voice, data, fax, and/or multimedia). The canonical base station interfaces to the public switched telephone network (PSTN). Fully instrumented base stations support operations and maintenance, developers and researchers via services development workstation(s). The placement of the A/D/A converters as close to the antenna as possible and the definition of radio functions in software are the hallmarks of the software radio. Thus, although software radios use digital techniques, software-controlled digital radios are generally not software radios. The key difference is the total programmability of software radios, including programmable RF bands, channel access modes, and channel modulation.

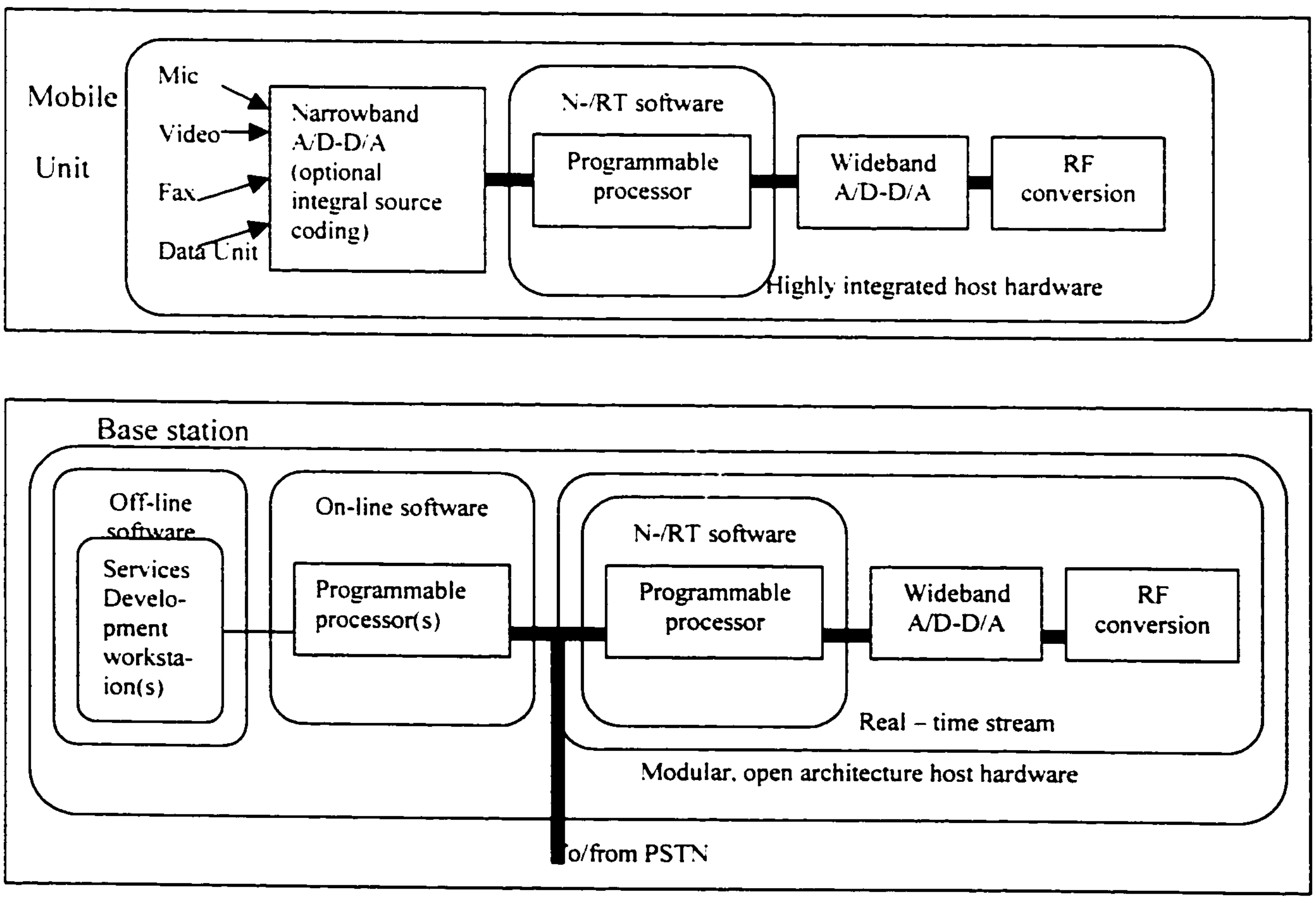


Figure 1.1: Canonical software radio

In an advanced application, a software radio does not just transmit: it characterizes the available transmission channels, probes the propagation path, constructs an appropriate channel modulation, electronically steers its transmit beam in the right direction, selects the appropriate power level and then transmits. Again, in an advanced application, a software radio does not just receive: it characterizes the energy distribution in the channel and in adjacent channels, recognizes the mode of the incoming transmission, adaptively nulls interferers, estimates the dynamic properties of desired-signal multipath, coherently combines desired-signal multipath, adaptively equalizes this ensemble, trellis decodes the channel modulation and then corrects residual errors via forward error control (FEC) decoding to receive the signal with lowest possible BER. Finally, the software radio supports incremental service enhancements through a wide range of software tools. These tools assist in analyzing the radio environment, defining the required enhancements via software and/or hardware. The canonical software radio architecture includes the channel processing stream, the environment management stream and associated software tools [7].

1.2.1 The Real Time Channel Processing Stream

The real-time channel-processing stream incorporates channel coding and radio access protocols. Channel processing is characterized by discrete time point-operations such as the translation of a baseband signal to an intermediate frequency (IF) by multiplying a discrete time-domain baseband waveform by a discrete reference carrier to yield a sampled IF signal. The time between samples is on the order of tens of microseconds to hundreds of nanoseconds. Such point-operations require hundreds of MIPS and/or MFLOPS to Giga-FLOPS with strictly isochronous performance. That is, sampled data values must be computationally produced and consumed within timing windows on the order of the time between samples in order to maintain the integrity of the signals represented therein. Input/output (I/O) data rates of this stream approach a gigabit per second per A/D converter. Although these data rates are decimated through processing, it is challenging to sustain isochronism through I/O interfaces and hard real-time embedded software in this stream. Multiprocessing is therefore best organized as a pipeline with sequential functions of the stream assigned to serially interconnected processors (i.e. a multiple instruction multiple data-stream (MIMD) multi-processing architecture) [3].

The classical canonical model of communications concatenates source encoder, channel encoder, channel (which adds noise, interference, and distortion), channel decoder, and source decoder. The channel encoder/decoder and related radio access functions constitute the real-time stream. The canonical software radio architecture partitions classical channel coding and decoding into the channel access segments. These segments are: antennas, RF conversion, IF processing, base-band processing and bitstream processing. This canonical partitioning is useful because of the significant differences in functionality between segments, the strong cohesion among functions within a segment, the large changes in bandwidth due to decimation within a segment and the ease with which these particular segments are mapped to affordable open-architecture hardware. This partitioning also structures the estimation of first-order resource requirements so that they may be combined in ways that accurately predict system performance.

1.2.2 The Antenna Segment

The antenna(s) of the software radio span multiple bands, up to multiple octaves per band with uniform shape and low losses to provide access to available service bands. In military applications for example, a mobile terminal may need to employ VHF/UHF line of sight frequencies, UHF satellite communications and HF as a backup mode. Switched access to such multiple bands requires octave bandwidth antennas and/or multiple antennas per band and an agile frequency reference in the RF Segment. In addition, multiple antenna elements may be part of a beam forming network for interference reduction or space division multiple access (SDMA). The relationship between interference cancellation capacity and the number of antenna elements varies. A single auxiliary element, for example, can reduce interference of a large number of interferers. Algorithms that reduce interference through non-spatial techniques (e.g., cyclostationary algorithms) can also reduce a large number of interferers with one or with no auxiliary antenna elements. Beam forming of N antenna elements can place N- 1 adaptive nulls on interferers sufficiently separated in azimuth, but coherent multipath may require a distinct null for each distinct multipath direction, reducing the number of interferers accordingly. Polarization scrambling from nearby reflecting surfaces may require 2N + 1 elements for N paths. The structure of the antenna array(s) determines the number of distinct physical and logical signal processing paths in the RF conversion and IF processing segments. As a result, the competing demands for directional selectivity, multipath compensation and interference suppression versus Wideband low-loss antennas versus affordability define the tradeoffs of the antenna segment [10].

1.2.3 The RF Conversion Segment

RF conversion includes output power generation, preamplification, and conversion of RF signals to and from standard intermediate frequencies (IFs) suitable for wideband A/D/A conversion. In most radio bands, RF conversion will be analog. Certain critical RF problems are exacerbated in the software radio. These include the need for amplifier linearity and efficiency across the access band. RF shielding of processors may also be necessary to avoid the introduction of processor clock harmonics into the analog RF/IF circuits. Cositing of multiple transmitters also creates electromagnetic interference (EMI) problems, but these are about the same for software radios as for cosite collections of multiple discrete hardware radios.

1.2.4 Placement of the A/D/A Converters

W_a, the bandwidth of the IF to be digitized, determines what kinds of A/D techniques are feasible. According to the Nyquist criterion for band limited signals f_s, the sampling rate of the A/D converter, must be at least twice W_a. Practical systems ([7]) typically require modest oversampling:

$$f_s > 2.5\ W_a$$

Wideband A/D/A converters access broad instantaneous segments of spectrum, typically 10 to 50 MHz. Such wide access may also be achieved in parallel subbands of more modest 1 to 10 MHz bandwidths each. The dynamic range of each parallel subband depends on the dynamic range of the A/D/A converters. Since the product of dynamic range times sampling rate is approximately constant for a given A/D/A technology, narrower subbands generally increase the useful dynamic range, albeit at the cost of increased system complexity [9]. The placement of wideband A/D/A conversion before the final IF and channel isolation filters achieves three key architectural objectives:

- It enables digital signal processing before detection and demodulation.
- It reduces the cost of mixed channel access modes by consolidating IF and baseband processing into programmable hardware.
- It focuses the component tradeoffs to a single central issue: providing the computational resources (I/O bandwidth, memory, and processing capacity) critical to each architecture segment, subject to the size, weight, power, and cost constraints of the application.

1.2.5 The IF Processing Segment

The IF processing segment maps the transmitted and received signals between modulated baseband and IF. The IF receiver processing segment includes wideband digital filtering to select a service band from among those available. Furthermore, IF filtering recovers medium band channels (e.g. a 200 kHz TDMA channel in GSM) and/or wideband subscriber channels (e.g. a 2 MHz CDMA channel) and converts the signal to baseband.

The complexity of frequency conversion and filtering is the first order determinant of the processing demand of the IF segment. In a typical application, a 12.5 MHz mobile cellular band is sampled at 30.72 MHz (M samples per second). Frequency translation, filtering and decimation requiring 100 operations per sample equates to more than 3000 MIPS of processing demand. Although such microprocessors are on the horizon, contemporary implementations offload this computationally intensive demand to dedicated chips such as the Harris Decimating Down Converter (DDC) or Gray digital receiver chip. Spreading and de-spreading of CDMA, also an IF processing function, creates demand that is proportional to the bandwidth of the spreading waveform (typically the chip rate) times the baseband signal bandwidth. This is so computationally intensive that with current technology limitations, it is typically assigned to dedicated chips as well [1], [7].

1.2.6 The Baseband Processing Segment

The baseband segment imparts the first level of channel modulation onto the signal (and conversely demodulates the signal in the receiver). Predistortion for nonlinear channels would be included in baseband processing. Trellis coding and soft decision parameter estimation also occur in the baseband processing segment. The complexity of this segment therefore depends on the bandwidth at baseband W_b, the complexity of the channel waveform and the complexity of related processing (e.g. soft decision support). For typical digitally encoded baseband waveforms such as binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), Gaussian minimal shift keying (GMSK), and 8-PSK with channel symbol (baud) rates of:

$$R_b: R_b/3 < W_b < 2*R_b$$

In the transmission side of the baseband segment, such waveforms are generated one sample at a time. If three samples are generated for the highest frequency component, demand falls between R_b and $6*R_b$. Greater oversampling decreases the transmitted power of spectral artifacts, but also increases transmit power and processing demand. In the receiver, digital baseband modulations require timing recovery, which typically includes the integration of baud intervals over time. If baud interval is measured in transitions of a high-speed clock, some timing-sensitive signal structures (e.g. TDMA) and some synchronization algorithms require up to 96 b precision integer arithmetic in the clock recovery loop(s), and such extended precision arithmetic may not be readily available, particularly on newer chips. Analog baseband modulation, such as FM voice, may also be encoded and demodulated in software in the baseband segment, with a processing demand of less than 1 MIPS per subscriber. Such software simulation of analog modulations helps achieve backwards compatibility with analog standards [10].

1.2.7 The Bitstream Segment

The bitstream segment digitally multiplexes source-coded bitstreams from multiple users (and conversely frames and demultiplexes them). The bitstream segment imparts forward error control (FEC) onto the bitstream, including bit interleaving and block and/or convolutional coding and/or automatic repeat request (ARQ) detection and response. Frame alignment, bit-stuffing, and radio link encryption occur in the bitstream segment. Encryption requires the isolation of encrypted bits from clear bits, resulting in the requirement to partition and isolate bitstream hardware accordingly. Final trellis-coded modulation (TCM) decisions occur in the bitstream segment. TCM converts soft/delayed decision parameters from the baseband segment to final bit decisions. The complexity of this segment depends on multiplexing, framing, FEC, encryption, and related bit manipulation operations. Signaling, control and operations, administration and maintenance functions are also provided in the bitstream segment. The demand associated with these functions depends on the signaling, control and operations systems. Demand increases linearly with the number of simultaneously active subscribers. These functions are event-driven and typically impart an order of magnitude less computational demand than baseband processing. These functions, may, however, require access to distributed databases, not all of which will be local to the base station. Thus, although the processing demand is relatively small, the timing requirements may be severe [7].

1.2.8 The Source Segment

The source segment differs between the mobile terminal and the base station. In the mobile terminal, the source segment consists of the user and the source encoders and decoders. Here, the relatively narrowband voice and fax A/D/A converters are typically located in the handset, palmtop, or workstation. In the base station, on the other hand, the source segment consists of the interface to the PSTN for access to remote source coding. Conversion of protocols required for interoperability with the PSTN creates processing demand in the base station's source segment. Conversion of DSO 64 kb/s PCM to RPE-LTP (GSM), for example, would create 1 to 2 MIPS of demand per subscriber [9].

1.2.9 The Environment Management Stream

The near-real-time environment management stream continuously characterizes radio environment usage in frequency, time and space. This characterization includes channel identification and the estimation of other parameters such as channel interference levels (depending on the specific signaling and multiple access scheme) and subscriber locations. The environment management stream employs block operations such as fast Fourier transforms (FFTs), wavelet transforms, and matrix multiplies for beam forming. Channel identification results are needed in times on the order of hundreds of microseconds to hundreds of milliseconds, while power levels may be updated in milliseconds and subscriber locations may be updated less frequently. The block structure of such operations is readily accommodated by a MIMD parallel processor. The interface between this highly parallel environment management stream and the pipelined channel processing streams must synchronize the environment management parameters to the channel processing streams [7].

1.2.10 On-Line and Off-Line Software Tools

On-line and off-line systems analysis, signal processing, and rehosting tools allow one to define incremental service enhancements. For example, an enhanced beam former, equalizer and trellis decoder may be needed to increase subscriber density. These enhancements may be prototyped and linked into the channel processing stream, allowing one to debug the algorithm(s), to experiment with parameter settings and to determine the service value (e.g. in improved subscriber density) and resources impact (e.g. on processing resources, I/O bandwidth and time delays). Software-based enhancements may be organized around managed objects, collections of data and associated executable procedures that work with object resource brokers and conform to related open architecture software interface standards such as the Common Object Resource Broker (CORBA). Enhancements may then be delivered over the air to other software radio nodes, as contemplated in the future software-defined telecommunications architectures being considered by ITU-T and embraced by NTT and others. A well integrated set of analysis and rehosting tools leads to the creation of incremental software enhancements relatively quickly, with service upgrades provided over-the-air as software-defined networks proliferate. Technology limitations that require hardware-based delivery are overcome by mapping critical elements of the service enhancement to hardware via VHDL [1].

1.3 DSP Requirements for Contemporary Applications

In narrowband digital radios, baseband signals are typically digitized and processed with a channel bandwidth of tens or hundreds of kHz (30kHz for AMPS or IS54/IS136, 200kHz for GSM, 1.25 MHz for CDMA, etc.). The radio stages are analog, tuning into a particular frequency slot and using conventional filters to exclude other signals. The software radio requirement is to digitize the entire band (perhaps 25MHz) and to perform IF processing, baseband, bitstream and other functions in software. In the United States, operators have a 12.5MHz band, suggesting a 30MSPS rate minimum (2.5x to allow for real filters, etc). However, over-sampling this signal is useful to shift aliases out of band and simplify filtering, so faster sampling rates, or narrower bandwidths, are used. For example the AirNet system operates on a 5MHz band, requiring a sampling rate of at least 12.5MSPS, which increases to more than 25 MSPS with oversampling. Several currently commercially available U.S. systems employ 30.72MSPS x 12 bits per sample, corresponding to a convenient map of one FFT slot to a frequency bin in an FFT which the system uses to manage the environment. The DSP must be fast enough to perform isochronous operations on this rapid flow of data. This results in IF processing requirements on the order of 500 MIPS/MFLOPS to upwards of 10 GFLOPS, baseband processing on the order of 10 to 100 MIPS/MFLOPS per channel, and additional processing burdens for bitstream, overhead, and control that put extreme pressure on the DSP architecture [11].

1.3.1 RF/IF Functions

A modern programmable DSP typically offers up to 200 MIPS or 50 MFLOPS. As even the most rudimentary demodulation or tuning requires 10 operations per sample, this would limit it to filtering signals with a carrier of a few hundred kHz. (All modem DSPs will do a single cycle multiply-accumulate with simultaneous internal transfers, so a FIR filter requires just one cycle per tap.) Obviously, more complex modulation, analysis, estimation, and processing require more DSP power, so any practical system will be more seriously limited. In addition, in reality, data fetches and architectural constraints will also play a significant role in determining the effectiveness of those MIPS, but it is clear that they are limited to operations on fairly low band- widths. A good FIR/IIR channel selection filter could require about 100 operations per sample at 30 Msa/s, or 3000 MIPS. Using a naive brute-force approach, we would require 15 to 60 DSPs cooperating for this section alone, repeated for every channel [11]. As a result, even with faster devices, software on DSPs still cannot be used for the down conversion itself, but must still essentially operate at baseband (albeit a much wider baseband up to a few MHz). Does this mean we are forced to abandon our aim? Not at all: we merely abandon general purpose hardware at IF. Instead, dedicated but highly programmable filtering hardware is used at the earliest stages, doing much of the filtering and processing in fast digital logic, reducing the processing load that must be done to a level that can be handled in software. As long as this specialized hardware is versatile and is controllable from software, this hybrid architecture still meets our requirements. One of the most common implementations of such a hybrid architecture is a time-domain approach, using a digital down-converter, such as the Harris HSP50016 as in figure 1.2. This chip contains a synthesizer, a quadrature pair of digital multipliers (which act as mixers in the digital domain), and some clever filters that implement both low-pass and decimation (Haugenauer filters). The device extracts a narrow band baseband signal from a wideband digital input, and decimates it to a reduced data rate, proportional to the bandwidth of interest, that a DSP can cope with. First the signal is sampled at the wideband sampling rate f_s, which shifts it in frequency by f_c (since it is a real signal, the spectrum is two sided); then it is quadrature filtered to extract the band of interest; and finally, the programmable decimator changes the data rate to f_n giving a slower (more manageable) data stream containing only the desired information. The DDC has a maximum input rate of 52 MSPS, and can operate with 16 b words to give spurious free dynamic range (SFDR) of more than 100 dB. Depending on the clock rates and control parameters, the DDC can be configured in a variety of ways (i.e., real or quadrature outputs) and for a variety of frequency/bandwidth combinations. Given a programmable clock of some description, it is essentially under software control.

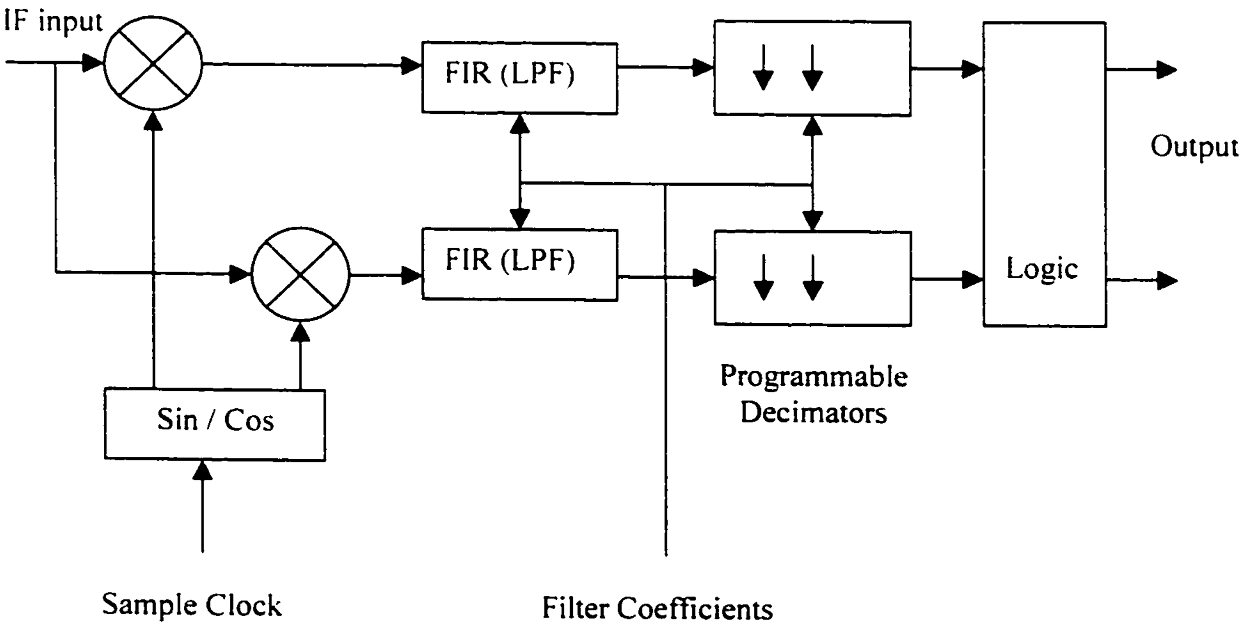


Figure 1.2: Block diagram of the Harris HSP50016

1.3.2 Spectrum Monitoring Using DSPs Alone

Purely software-based spectrum monitoring has been implemented using the fast Fourier transform (FFT). The FFT extracts frequency domain information from a series of time domain samples, to resolve the signal into a set of frequency bins. With no over sampling, each frequency bin corresponds to a channel. The FFT can then be used to compute a power spectrum that reveals the signal level of that channel during the period of data acquisition. A series of such FFTs then creates a sliding window filter bank in the time domain. In practical systems, the power per channel yields key information for well managed channel assignments. Such an FFT is generated in newer PCS base stations in dense urban areas, for dynamic spectrum allocation. The base station selects which channels to use so as to optimize efficiency and minimize noise. In military and emerging PCS applications, such spectrum monitoring may be used to help the base station determine which protocols are being used, and how best to configure its channels and operations among the different systems. A completely non structured system is not required; for most commercial applications the receiver will know which type of signal it wants to receive. A given digital standard will have predictable channel bandwidth, modulation scheme, spectral density and so on, and most include training sequences and preambles to provide even more help in the equalization and recovery. However, a base station will need to perform an overview to decide which signals it is receiving, and which protocols they are using, checking bandwidth and spectral properties so that it can select the appropriate software to tune and recover that signal from all the others. The time domain trace of a single frequency bin in the power spectrum yields a series of levels that is a sampled history of that channel. This can be described as a filter bank or transmultiplexer. With one frequency bin for each channel, the successive power spectrum results yield signal amplitude information, and this is sometimes used as a straightforward parallel AM radio receiver, operating on N channels at once. The rate of sampling each channel is the rate of performing power spectra, so each FFT must be executed quickly enough to sample the AM bandwidth at the Nyquist rate. A 4kHz modulating bandwidth would require at least 8kHz sampling or a FFT /power spectrum at 1.25ms intervals. The SHARC performs a 1024 point complex FFT in just 0.46 ms, so that the power spectrum is computed in less than the required 1.25 ms. Rather than using a series of filters or downconverters, one per channel, the FFT performs the required operations in parallel. The parameters of the FFT can be easily changed, reconfiguring the receiver. Other modulation schemes can be recovered in a similar way. For example, an elementary FSK (frequency shift keying) receiver can be implemented directly with two frequency bins per channel, one for the low tone and one for the higher. This is a highly simplified example. In practical implementations, bit synchronization, Costas loops, integrate and dump filters, etc., increase the performance requirements of the DSP. Sophisticated algorithms to transform the signal to a more usable form often increase the DSP requirements to multiple processors. As the versatility increases, the amount of processing power required is not insignificant. And this leads us inevitably to consider multiprocessing [11], [12].

1.3.3 Multiprocessing Then and Now

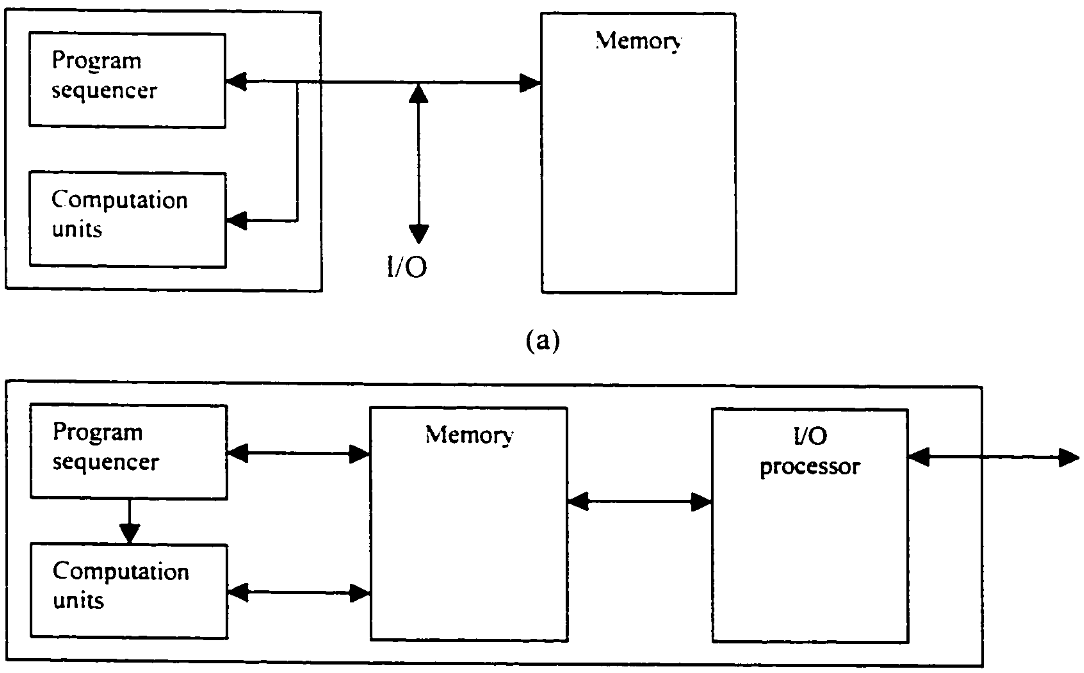
Software radios invariably require the use of parallel and sequential partitioning of algorithms to get required processing power. DSPs are getting ever faster, but it will be a while before we can use a single chip to do everything. Instead, the idea of using multiprocessing to share the effort seems attractive. Traditionally, real time multiprocessing with DSPs has been tricky. Fortunately, recent products have addressed the issue, and it is becoming much simpler. One approach is to integrate a general purpose CPU and a dedicated DSP core on the same die. Motorola, for example, has released a "Communications Processor," the 68356, which includes a general purpose micro-controller with a 56000 series DSP. For those applications that required both general purpose operations and a DSP, this is an attractive approach. For IF and baseband processing, however, which require significant DSP with minimal supervisory functions, it is less relevant. A different approach has been taken by AT &T, who integrated a dedicated Viterbi decoder as co-processor on some of their 16xx series DSPs. This drastically eases the processing load for systems requiring an equalizer (e.g., GSM handsets). It is very likely that more DSPs will support such features in the future. If the system is to operate in real time (which is usually the requirement), then the data must be able to get in and out of the DSP, which can pose I/O problems. For fast data access, fast memory is required, but this is expensive. If several processors are to be used, there must be efficient methods of linking them and coordinating their actions. Traditional DSP architectures were not well suited to multiprocessing. It is a characteristic of a DSP that it must operate on a continuous flow of data. A typical system might require the equivalent of four bus operation each cycle, with an instruction read, two operand fetches (e.g., latest sample of data from the ADC, and filter coefficient), and an I/O transfer (e.g., output of result). Unfortunately, most DSP implementations do not support this many data buses. As a result, the effective processing rate decreases, as operands must be passed through a keyhole -the bus bottleneck [11], [12].

Function / Radio class	RF receiver	IF stage, tuning	Processing 1, baseband	Processing 2, source	Example
Classical	Analog-LNA, first	Analog, IF mixers, PLLs, mixers, etc	Analog hardware filters	Analog hardware (depends on modulation)	Analog cellular
Digital	"	"	Baseband digitization, Digital equalization and channel decoding	Speech decoding, Error correction done in DSP	Current and future digital cellular, PCS handsets, Current digital cellular base station.
Hybrid	"	IF sampling or wideband ADC	Digital Hardware downconverters, Haugenauer filters	"	Next generation commercial basestation
Software	"	"	Software based. Filterbank, costas loop, integrate & dump, etc. Move to non structure design	"	Research, Military, Emerging commercial

Table 1.1: Comparison of different radio architecture

1.3.4 On and Off Board Memory

The situation gets much worse if reasonable quantities of memory are required. Commodity memories (SRAMS) are designed for the Von-Neuman processor architectures, where only one access per cycle is required. Using such a memory leaves the DSP designer with substantial bus bottleneck problems, and the need to perform heroic data-flow analysis to try to determine system feasibility. Furthermore, the need for speed means that very fast (i.e., very expensive) memories are required to reduce the impact of this bottleneck. However, the on-chip memory aspect deserves a little bit of explanation. As in figure 1.3(b), the ideal DSP system integrates memory on-chip, which allows the program sequencer, the external I/O, and all parts of the computational unit to have simultaneous single-cycle access. In fact, two accesses per cycle are possible under some circumstances. Additionally, the system designer doesn't have to provide board space for memory ICs, or include cost and power budgets for fast external SRAM. Buses within the chip are faster and less power demanding than the long and capacitatively loaded burden of IC to IC connection. Similarly, the I/O peripherals, which were on-chip all along, no longer require interrupts to go off-chip, through the keyhole of a single bus, to the memory and back to the chip. Instead, a dedicated bus can be used within the IC for direct access whenever desired. Finally, there are commercial implications: the designer no longer needs to do a complex data-flow analysis to assess true performance, and time-to-market is reduced. Some estimate that the performance penalty for using off-chip memory in a real system is that single-cycle operations take an average of 2.31 cycles, equivalent to operating at 43 percent of rated speed [11].



(b)

Figure 1.3: (a) Traditional DSP architecture

(b) Multiple buses and internal memory improve DSP architecture

1.3.5 I/O Issues in Multiprocessing

As discussed earlier, the amount of I/O data flow in such a system can be staggering. The ADC could easily produce 60 Msa/s, each 12 or more bits in resolution, requiring the processor system to be reading data at rates of at least 120 Mbytes/s.

While there will be redundancy, filtering, and removal of unwanted channels, it is likely that the output data-flow will be roughly comparable, giving an upper bound of some 240 Mbytes/s, just for the data I/O. In addition, in a real system it is likely that intermediate results, program information, and the like will need to be shared between multiprocessors, necessitating dedicated high-speed inter processor links. This emphasizes the essential importance of the processor communications architecture. Conventional designs have relatively few data paths, often funneling through bottlenecks. Instead, software radio applications require several parallel routes for information: bulk data I/O, processor to processor links, and access to both global and local memory structures. Ideally, these would be all simultaneous with dedicated DMA or I/O processors. But most DSPs were not designed to be used as multiprocessing systems. They did not support arbitration or prioritization, forcing the programmer to spend both development time and precious processing bandwidth in software solutions. There were no hardware systems for global memory addressing/sharing, nor for sempahores or signaling. This is somewhat surprising, given the prevalence of multiprocessor DSP systems and the fact that these techniques, and their implementation in silicon, had been seen with Inmos' Transputer (well engineered if not a staggering commercial success). This changed with the release of Texas Instrument's deservedly popular TMS320C40, which corrected several of these gaps with a DSP that was suited to multiprocessing.

Indeed, it is fair to describe the C40 as the seminal DSP multiprocessor. Figure 1.4(a) shows a typical implementation of a C40 multiprocessor. The second off-chip bus makes it easier to access local memory and helps solve the bus bottleneck, while the dedicated processor-processor links allow for dedicated data-flow paths. In other words, the processor's electrical layout and the algorithms logical layout are mapped, drastically improving the transfer efficiency between processors (and, not incidentally, simplifying the design analysis). A more recent processor from TI goes even further: the C80, or MVP, includes four DSP cores with a RISC supervisor. However, while the MVP is undeniably powerful, it is also undeniably expensive, and does not seem to have been used widely, in contrast to the C40. Just as innovation in the ADC realm has suddenly made wideband receivers and IF sampling with excellent SFDR feasible, the processor market has advanced. Second generation DSP multiprocessing is now a reality, learning from the experience of the C40. While that had some of the features required, it has limits in how deep the multiprocessing ran. In particular, while there were the processor-processor links, there were few other hardware tools provided, e.g., for arbitration, semaphores, etc. (The text box on "Second-Generation DSP Multiprocessing" summarizes some of these features.) The SHARC is the first processor to meet the requirements of true multiprocessor DSP. Of course there will be subsequent devices that also implement these features, and no doubt will add new ones. Figure 1.4(b) shows a cluster/dataflow multiprocessor architecture. In contrast to the earlier case, this system has much greater effective I/O bandwidth and dramatically simplified coordination. The need for fast I/O and a dedicated parallel processor to manage it is hardly surprising: if a single computation core is too slow, one can add more DSPs. But if they cannot read and write fast enough, radio applications are not easy and may not be possible [12].

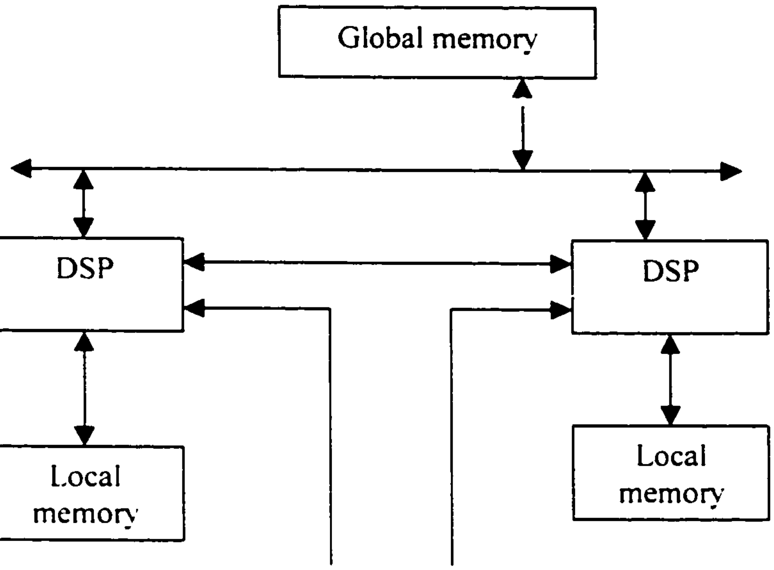
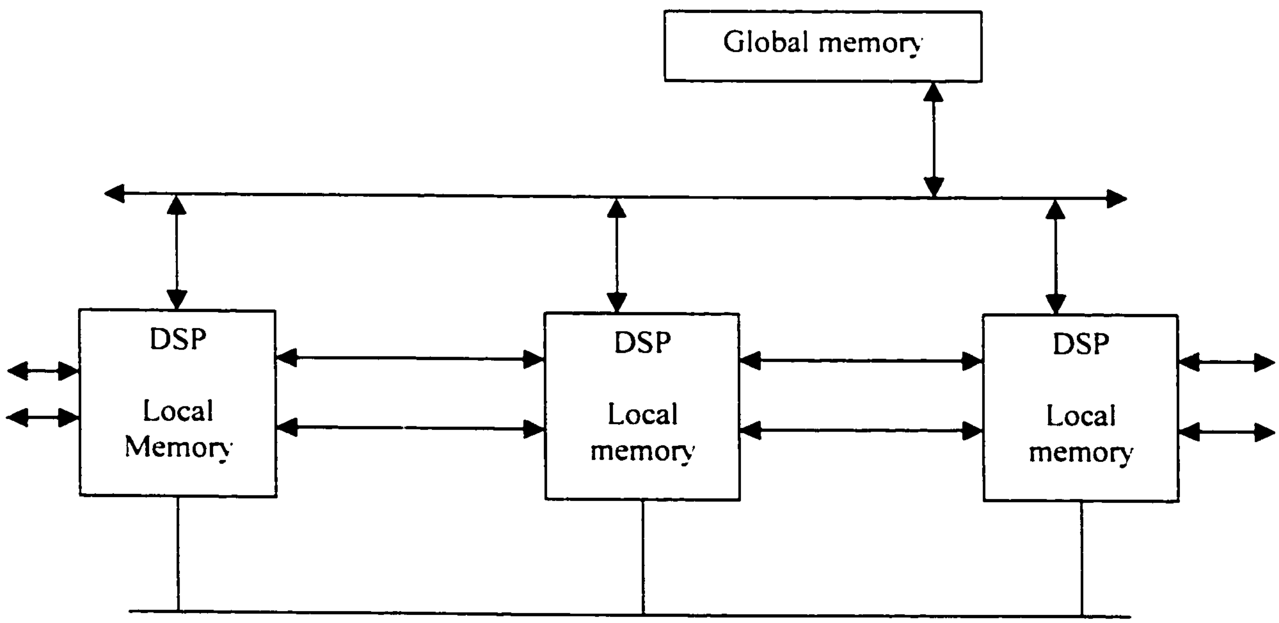


Figure 1.4(a): First generation DSP multiprocessing



(b)

Figure 1.4(b): Second generation DSP multiprocessing

1.4 Portable Unit Challenges

Portable units include handsets, PC cards for laptop computers, and other battery-powered wireless appliances. The related designs demand size, weight, and power that are compatible with a sleek, handheld unit that slips into the shirt pocket and runs for a week on a single charge [13], [2].

1.4.1 Power Management

Power-managed DSP chips now form the basis of power-managed ASICs with the DSP ISA as the ASIC core. Sleep modes make power available for computationally intensive software-radio tasks by exploiting the low duty cycle of voice and data communications. Sleep modes save power but introduce a probability that the radio will be asleep during a paging message. Structured timing of paging messages reduces the miss probability, further conserving battery life.

1.4.2 Clock Generation And Distribution

Clock generation and distribution consumes a large fraction of handset power. Multimode SWR handsets in particular must generate several different clock rates for each supported standard. One reference oscillator per standard increases parts count, complexity, and therefore cost. A single master clock may use the least common multiple (LCM) of the required clocks. The LCM of GSM and IS-136, for example, is 6.31800 GHz. An integer down counter N0 derives the clock for the invoked standard from such a master clock. N0 equals 486 for GSM and 325 for IS-136. Integer decimators derive the channel spacing (N_1) and channel symbol clock (N_2) from these clocks . A W-CDMA clock of 2.56 GHz yields the integer channel spacing, but a W-CDMA and GSM LCM integer clock runs at 33.28 GHz. The total dissipated power is roughly proportional to the square of the clock rate. The impracticality of such high-speed master clocks illustrates the difficulty of such a conventional approach to the handset. Alternatively, the clocks may be generated using a $\Delta\ \Sigma$ approach where clocks are exact on the average, but in error instantaneously. As the timing error variance exceeds a few percent of the channel symbol interval, the bit error rate (BER) begins to degrade. Nearest-fraction clock generation requires high-Q filters that enable the reduction of the master clock rate at the expense of increased circuit complexity. To synthesize the required clocks in software, the spectral purity of the sinusoids from the DAC must be within the tolerance set by the regulatory bodies. A 100 MHz reference clock yields sufficient DAC purity for first-generation standards, and the clock consumes less power than the LCM clock, but the signal is not as spectrally pure. The use of so-called slow clocking is common in commercial handsets, but this approach does not scale readily to the high clock rates required in a handset that supports W-CDMA, IS-136, and GSM. A new technology SWR handset clock with low power dissipation seems to be needed so that the spectrally pure signals may be generated in software in multistandard handsets. Thus, in the near term, multi mode handsets will be software defined to the degree that standards are normalized to avoid clock rates with large LCMs. The LCM of the European Telecommunications Standards Institute's (ETSI's) normalized W-CDMA chip rate of 4.096 Mb/s and IS-95's 1.2288 Mb/s is 1.257472 GHz, an order of magnitude too high for power efficiency. Clock choices could make or break 3G, either reducing the cost of multimode handsets to the levels mass markets will accept, or relegating 3G to a small high-end market niche [8], [10].

1.4.3 Receiver Architecture

Receiver complexity is typically four or more times transmitter complexity. Thus, the receiver architecture has a first order impact on handset cost. Direct conversion receivers mix a reference waveform with the RF signal to extract baseband signals without multiple superheterodyne conversion stages. These ASICs efficiently transform RF to baseband, but each different air interface standard requires additional ASIC area. An Ideal SWR receiver uses a wideband ADC to access the IF, with channel selection and conversion to baseband implemented in programmable filter ASICs or FPGA code. The peak computational demand of such a wideband reconfigurable SWR for a 4.096 MHz W-CDMA mode is about 400MIPS per finger or 1600 MIPS. An FPGA multichip module (MCM) or DSP-core-based ASIC could deliver the required computational capacity. Such an SWR could be reprogrammed for GSM. IS-136. and analog standards. but today's DSP and ADC would consume the battery quickly. Alternatively. a software-reconfigurable direct conversion hybrid could digitally demodulate W-CDMA at essentially RF clock rates of 400 MHz to 2.3 GHz. These MCMs would also have high power dissipation compared to hybrid analog. receivers. Panasonic has described its handset evolution plan as a three-step process that begins with baseband DSP. the present generation. Soon to be introduced is the extension of software to the channel modem at an IF compatible with today's clock rates. Ultimately. the software would include the IF signal processing. an unspecified number of years hence. Since 400 MHz clocks are practical on-chip. several companies are developing ASIC and/or FPGA-based digital IF despreaders and demodulators. With such high clock rates. a demodulator algorithm may count zero-crossings to decode channel symbols. High power dissipation. low immunity to adjacent channel interference, and sensitivity to timing errors must be overcome for this highly software defined RF modem technology to become competitive. Panasonic's timing seems to reflect the industry as a whole. Thus, the 3G handset receiver seems constrained to a few modes of direct conversion and despreader hybrids in the near term. The limited programmability of such a near-term approach does not preclude SDR baseband signal processing such as software-defined vocoders.

1.4.4 Handset Production

The cost of handsets in volume production is a nearly linear function of parts count. Emerging micro electro-mechanical systems (MEMS) technology uses three-dimensional bulk micromachining to integrate components into semiconductor substrates. MEMS devices include 400 micron RF switches with 1/10,000 the size and less than 1/100th the average power of conventional PIN-diode RF switches. Cantilever beam filters have quality factors (Q) as high as 80,000. In addition, nickel MEMS devices may be fabricated onto existing complementary metal oxide semiconductor (CMOS) chips without melting them. The mechanical structures that set the tuned frequency of the MEMS devices themselves may be variable, set to specific values by microactuators. In addition to trimming parameters of production components, such micro-actuators may have sufficient dynamic range and mechanical life for programmable features of future SDR.

1.4.5 Handset Software Computational Efficiency

Finally, handset software has to be extraordinarily efficient in use of computational resources. The W-CDMA despreader is the critical modem component for 3G. Since on the order of 100 operations may be required on the average to process a

CDMA chip, a simple despreader would require on the order of 400 MIPS of processing capacity. Although the new DSP chips can deliver from 400 to 1000 MFLOPS, the trade-off of flexibility versus power dissipation generally favors an ASIC despreader. Software-defined despreaders, however, could encapsulate ASIC personalities as downloadable objects for FPGAs. In addition, the interfaces among software components have to be streamlined. The layered virtual machine allows one to associate implementation levels with each module of the handset. The handset software architecture makes lower-level interfaces more explicit. Drivers, real-time kernels, and mode controllers have simpler application programming interfaces (APIs) than the layered virtual machine might suggest. In addition, fewer layers mean greater computational efficiency in invoking specific handset resources. Some developers have put many years into the reduction of the few lines of code necessary to reduce parts count by one memory chip [10].

The handset economics are such that this cost is recovered within months on lines that produced about 70 million GSM handsets in 1996.

Challenge area	Challenges	Approaches
Power management	Sleep vs. paging delay	Power-managed DSP devices
Clocking	Multiple standards	Normalization, low power
Receiver architecture	Efficiency vs. multiple standards	Direct conversion or wideband SWR
Parts count	Off-chip passive devices	MEMS
Software	Computational efficiency	FPGAs, Java engines

Table 1.2: SWR handset implementation challenges

1.5 Mobile Node Challenges

Mobile nodes share many of the challenges of handsets, but with less of a premium on power efficiency. The vehicular radio exemplifies the mobile node. Law enforcement, aviation and the military all envision mobile nodes with a capability of from four to six simultaneous channels operating generally in high frequency (HF) through ultra high frequency (UHF) (nominally 2 MHz to 3 GHz). In some applications, such as flight safety, there is fixed infrastructure with which the mobile nodes communicate.

However, the military applications are the most demanding in some ways due to the mobility of the network itself as the military unit moves. Coalition partners who engage in joint humanitarian aid, for example, are generally confronted with an amazingly wide array of bands and modes in just the terrestrial bands. The U.S. Joint Tactical Radio System (JTRS) Program's requirements document identifies over 30 different air interfaces with which JTRS should be compatible. Referring to the layered virtual machine reference model, one would like to procure standard hardware engines and infrastructure software as commodity parts. Value-added contributions in the upper layers of the reference model, in principle, should cost less because of the amortization of hardware, distributed processing infrastructure, and radio mode software costs. The military also has to contend with more complex modes than the civilian sector. With its emphasis on information security, some military waveforms hop the signal over hundreds of hegahertz and spread it using CDMA techniques to avoid detection. JTIDS, for example, hops thousands of times per second over about 250 MHz. The ideal software radio would have to convert the signal at 500 MSPS to preserve the JTIDS frequency hop bandwidth. Although such ADCs exist, they lack dynamic range and consume too much power. Instead, the typical JTIDS radio dehops the signal to its 3 MHz instantaneous direct sequence spread spectrum bandwidth. Dehopping uses a fast-settling tunable local oscillator (LO) to track the received signal in accordance with a prearranged plan. For the foreseeable future, JTIDS will employ the fast tuning LO instead of the wideband ADC, limiting the migration of these radios to the software-defined ideal. Military users do not have the luxury of siting antennas at ideal locations. Instead, less than ideal whip antennas on vehicles must operate wherever the driver decides to stop. Military units employ software tools and other mechanisms to avoid interference, but often it is unavoidable. A high power troposcatter system, for example, may be sited near a mobile command post. The troposcatter signal may nonlinearly intermodulate in a metal structure, creating harmonics with high power very high frequency (VHF) or UHF components. Future MEMS narrowband filters may be programmed to suppress such interference. Sometimes, a radio interferes with itself, particularly in the time-domain duplex (TDD) bands (called the "push-to-talk" bands by the military). A four-channel JTRS radio, for example, might need to both listen and transmit in the same ADC band at the same time. Only a few frequency hop modes like SINCGARS, invoked at the same time, can render a node essentially inoperable. In these cases, one may inject a scaled replica of the transmitted signal into the receiver, 180° out of RF phase with the transmitted signal. This technique both reduces the peak interference power and allows the receiver to accept incoming RF in the same ADC band at the same time. Narrowband filters reject the interference and the intended incoming signal, so are inappropriate for suppressing this kind of cosite interference. In the future, such military-driven applications may lag behind handset and base station technology since the compelling economics of 3G do not apply to the military.

Challenge area	Challenges	Illustrative approach
Protocols	Network mobility	Dynamic networks
Multimode personalities	20 – 40 different modes	Open architecture API standards
Wideband modes	> 200 MHz agility	Hybrid SDRs with fast LOs
Cosite interference	Noise, high power artefacts	MEMS roofing filters
Self-generated interference	Time domain duplexing	Active cancellation

Table 1.3: Mobile node challenges

1.6 Base Station Challenges

The Flexible Integrated Radio System and Technology (FIRST) and FRAMES projects of the ACTS program investigated next generation air interfaces using prototype SWRs. The lack of ADC performance is the economic showstopper for base station SWRs. The number of parallel digital channels required for a base station application depends on the effective dynamic range (resolution accuracy) of the ADC at a given bandwidth. The total allocated spectrum (W) is processed in N_c " parallel RF-ADC wideband channels to yield baseband channels of bandwidth W_c. Some IF oversampling (Nyq) yields a required real sampling rate (R_s). The near-far ratio (R) plus the minimum detectable signal (S_{min}) yields the net dynamic range (R_{max}). In a conservative design, two pad bits are allocated to the automatic gain control ceiling bit and to the least significant bit, yielding B bits required: but the wideband oversampling of $R_{oversamp}$ provides $G_{oversamp}$ gain, which is recoverable in the channel isolation filters. This yields RES_{req} bits actually required of the ADC. The maximum sampling rates of the available (WADC Best) and affordable (WADC COTS) ADCs are divided into the required sampling rates (R_s) to establish the number of channels required. The cost of the base station is strongly linear with the number of RF-ADC channels. Thus, the GSM base station with 32 channels seems to require too much parallelism to be affordable. The IS-95 and AMPS base stations require only two RF-ADC channels. These may be competitive for a single standard, but the architecture does not address ETSI's basic W-CDMA requirement. Hence, the ADC technology as yet falls short of SWR products with truly global capabilities. Continued investments and innovation, however, may yield viable base station products within a year or two [13].

1.7 Benefits of Software Radio

Software radio offers many advantages to any one involved in telecommunication market. Reducing the hardware platform will allow manufacturers to lower the costs. Another relevant advantage would be the possibility to improve the software in successive steps, and the correction of software errors and bugs discovered during operation. Operators will be able to offer services that suit users and differentiated from other operators. With the same terminal it will be possible to provide all services even if supported by different communication standards. The advantages for users are the possibility to roam their communications to other cellular systems and take advantage of worldwide mobility and coverage. Also, SW radio technology increases hardware lifetime, reducing the obsolescence risk. System reprogrammability allows hardware reuse until a new generation of hardware platform is available [1].

Chapter 2
The Cellular Concept - System Design Fundamentals

2.1 Introduction

The cellular concept was a major breakthrough in solving the problem of spectral congestion and user capacity. It offered very high capacity in a limited spectrum allocation without any major technological changes. The cellular concept is a system level idea which calls for replacing a single, high power transmitter with many low power transmitters, each providing coverage to only a small portion of the service area. Each base station is allocated a portion of the total number of channels available to the entire system, and nearby base stations are assigned different groups of channels so that all the available channels are assigned to a relatively small number of neighbouring base stations. Neighbouring base stations are assigned different groups of channels so that the interference between base stations (and the mobile users under their control) is minimized. By systematically spacing base stations and their channel groups throughout a market, the available channels are distributed throughout the geographic region and maybe reused as many times as necessary, so long as the interference between co-channel stations is kept below acceptable levels. As the demand for service increases (i.e., as more channels are needed within a particular market), the number of base stations may be increased, thereby providing additional radio capacity with no additional increase in radio spectrum. This fundamental principle is the foundation for all modern wireless communication systems, since it enables a fixed number of channels to serve an arbitrarily large number of subscribers by reusing the channels throughout the coverage region. Furthermore, the cellular concept allows every piece of subscriber equipment within a country or continent to be manufactured with the same set of channels, so that any mobile may be used anywhere within the region [16].

2.2 Wireless Communications System Definitions

Base Station: A fixed station in a mobile radio system used for radio communication with mobile stations. Base stations are located at the centre or on the edge of a coverage region and consist of radio channels and transmitter and receiver antennas mounted on a tower.

Control Channel: Radio channels used for transmission of call setup, call request, call initiation, and other beacon or control purposes.

Forward Channel: Radio channel used for transmission of information from the base station to the mobile.

Full Duplex Systems: Communication systems, which allow simultaneous two-way communication. Transmission and reception is typically on two different channels (FDD) although new cordless PCS systems are using TDD.

Half Duplex Systems: Communication systems, which allow two-way communication by using the same radio channel for both transmission and reception. At any given time, the user can only either transmit or receive information.

Handoff: The process of transferring a mobile station from one channel or base station to another.

Mobile Station: A station in the cellular radio service intended for use while in motion at unspecified locations. Mobile stations may be hand-held personal units (portables) or installed in vehicles (mobiles).

Mobile Switching Centre: Switching centre, which coordinates the routing of calls in a large service area. In a cellular radio system, the MSC connects the cellular base stations and the mobiles to the PSTN. An MSC is also called a mobile telephone switching office (MTSO).

Page: A brief message which is broadcast over the entire service area, usually in a simulcast fashion by many base stations at the same time.

Reverse Channel: Radio channel used for transmission of information from the mobile to base station.

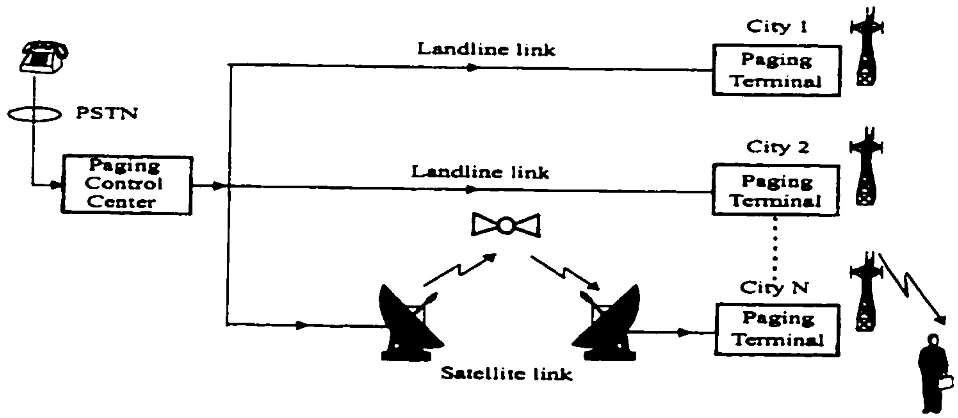


Figure 2.1: Wide area paging system

Roamer: A mobile station which operates in a service area (market) other than that from which service has been subscribed.

Simplex Systems: Communication systems, which provide only one-way communication.

Subscriber: A user who pays subscription charges for using a mobile communications system.

Transceiver: A device capable of simultaneously transmitting and receiving radio signals.

2.3 Frequency Reuse

Each cellular base station is allocated a group of radio channels to be used within a small geographic area called a cell. Base stations in adjacent cells are assigned channel groups, which contain completely different channels than neighbouring cells. The base station antennas are designed to achieve the desired coverage within the particular cell. By limiting the coverage area to within the boundaries of a cell, the same group of channels may be used to cover different cells that are separated from one another by distances large enough to keep interference levels within tolerable limits. The design process of selecting and allocating channel groups for all of the cellular base stations within a system is called frequency reuse or frequency planning. Figure 2.2 illustrates the concept of cellular frequency reuse, where cells labeled with the same letter use the same group of channels. Cells with the same letter use the same set of frequencies. The frequency reuse plan is overlaid upon a map to indicate where different frequency channels are used. The hexagonal cell shape is conceptual and is a simplistic model of the radio coverage for each base station, but it has been universally adopted since the hexagon permits easy and manageable analysis of a cellular system. While it might seem natural to choose a circle to represent the coverage area of a base station, adjacent circles cannot be overlaid upon a map without leaving gaps or creating overlapping regions. Thus, when considering geometric shapes, which cover an entire region without overlap and with equal area, there are three sensible choices: a square; an equilateral triangle; and a hexagon. A cell must be designed to serve the weakest mobiles within the cell, and these are typically located at the edge of the cell. For a given distance between the centre of a polygon and its farthest perimeter points, the hexagon has the largest area of the three. Thus, by using the hexagon geometry, the fewest number of cells can cover a geographic region, and the hexagon closely approximates a circular radiation pattern, which would occur for an omni directional base station antenna and free space propagation. The factor N is called the cluster size and is typically equal to 4, 7, or 12. If the cluster size N is reduced while the cell size is kept constant, more clusters are required to cover a given area and hence more capacity is achieved. A large cluster size indicates that the ratio between the cell radius and the distance between co-channel cells is large. Conversely, a small cluster size indicates that co-channel cells are located much closer together. The value for N is a function of how much interference a mobile or base station can tolerate while maintaining a sufficient quality of communications [18].

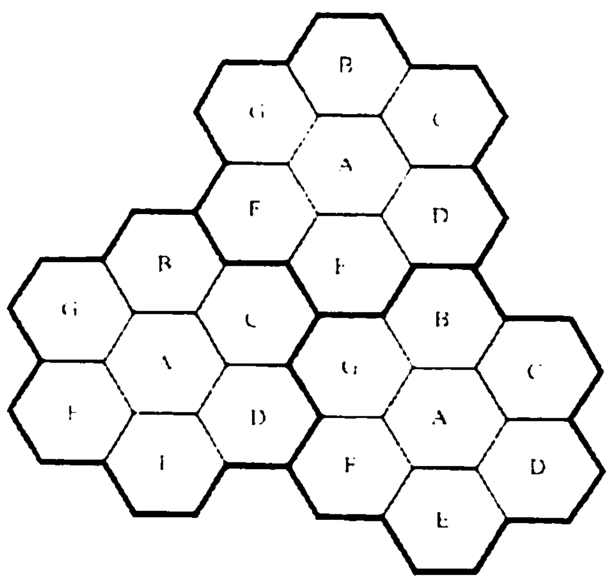


Figure 2.2: Cellular frequency reuse concept

2.4 Channel Assignment Strategies

For efficient utilization of the radio spectrum, a frequency reuse scheme that is consistent with the objectives of increasing capacity and minimizing interference is required. A variety of channel assignment strategies have been developed to achieve these objectives. Channel assignment strategies can be classified as either fixed or dynamic. The choice of channel assignment strategy impacts the performance of the system, particularly as to how calls are managed when a mobile user is handed off from one cell to another.

In a fixed channel assignment strategy, each cell is allocated a predetermined set of voice channels. Any call attempt within the cell can only be served by the unused channels in that particular cell. If all the channels in that cell are occupied, the call is blocked and the subscriber does not receive service. Several variations of the fixed assignment strategy exist. In one approach, called the borrowing strategy, a cell is allowed to borrow channels from a neighbouring cell if all of its own channels are already occupied. The mobile switching centre (MSC) supervises such borrowing procedures and ensures that the borrowing of a channel does not disrupt or interfere with any of the calls in progress in the donor cell. In a dynamic channel assignment strategy, voice channels are not allocated to different cells permanently. Instead, each time a call request is made, the serving base station requests a channel from the MSC. The switch then allocates a channel to the requested cell following an algorithm that takes into account the likelihood of future blocking within the cell, the frequency of use of the candidate channel, the reuse distance of the channel, and other cost functions. Accordingly, the MSC only allocates a given frequency if that frequency is not presently in use in the cell or ant other cell which falls within the minimum restricted distance of frequency reuse to avoid co-channel interference. Dynamic channel assignment reduce the likelihood of blocking, which increases the trunking capacity of the system, since all the available channels in a market are accessible to all of the cells. Dynamic channel assignment strategies require the MSC to collect real-time data on channel occupancy, traffic distribution and radio signal strength indications (RSSI) of all channels on a continuous basis. This increases the storage and computational load on the system but provides the advantage of increased channel utilization and decreased probability of a blocked call [18].

2.5 Handoff Strategies

When a mobile moves into a different cell while a conversation is in progress, the MSC automatically transfers the call to a new channel belonging to the new base station. This handoff operation not only involves identifying a new base station, but also requires that the voice and control signals be allocated to channels associated with the new base station. Processing handoffs is an important task in any cellular radio system. Many handoff strategies prioritize handoff requests over call initiation requests when allocating unused channels in a cell site. Handoffs must be performed successfully and as infrequently as possible, and be imperceptible to the users. In order to meet these requirements, system designers must specify an optimum signal level at which to initiate a handoff. Once a particular signal level is specified as the minimum usable signal for acceptable voice quality at the base station receiver, a slightly stronger signal level is used as a threshold at which a handoff is made. This margin, given by

$$\Delta = P_{r\ handoff} - P_{r\ minimum\ usable},$$

can not be too large or too small. If Δ is too large, unnecessary handoffs which burden the MSC may occur, and if Δ is too small, there may be insufficient time to complete a handoff before a call is lost due to weak signal conditions. Therefore, Δ is chosen carefully to meet these conflicting requirements. This dropped call event can happen when there is an excessive delay by the MSC in assigning a handoff, or when the threshold is set too small for the handoff time in the system. Excessive delays may occur during high traffic conditions due to computational loading at the MSC or due to the fact that no channels are available on any of the nearby base stations (thus forcing the MSC to wait until a channel in a nearby cell becomes free). In deciding when to handoff, it is important to ensure that the drop in the measured signal level is not due to momentary fading and that the mobile is actually moving away from the serving base station. In order to ensure this, the base station monitors the signal level for a certain period of time before a hand-off is initiated. This running average measurement of signal strength should be optimized so that unnecessary handoffs are avoided, while ensuring that necessary handoffs are completed before a call is terminated due to poor signal level. The length of time needed to decide if a handoff is necessary depends on the speed at which the vehicle is moving. If the slope of the short-term average received signal level in a given time interval is steep, the handoff should be made quickly. Information about the vehicle speed, which can be useful in handoff decisions, can also be computed from the statistics of the received short-term fading signal at the base station. The time over which a call may be maintained within a cell, without hand-off, is called the dwell time. The dwell time of a particular user is governed by a number of factors, which include propagation, interference, distance between the subscriber and the base station, and other time varying effects. Analysis indicates that the statistics of dwell time vary greatly, depending on the speed of the user and the type of radio coverage. For example, in mature cells which provide coverage for vehicular highway users, most users tend to have a relatively constant speed and travel along fixed and well-defined paths with good radio coverage. In such instances, the dwell time for an arbitrary user is a random variable with a distribution that is highly concentrated about the mean dwell time. On the other hand, for users in dense, cluttered microcell environments, there is typically a large variation of dwell time about the mean, and the dwell times are typically shorter than the cell geometry would otherwise suggest. In first generation analog cellular systems, signal strength measurements are made by the base stations and supervised by the MSC. Each base station constantly monitors the signal strengths of all of its reverse voice channels to determine the relative location of each mobile user with respect to the base station tower. In addition to measuring the RSSI of calls in progress within the cell, a spare receiver in each base station, called the locator receiver, is used to determine signal strengths of mobile users which are in neighbouring cells. The locator receiver is controlled by the MSC and is used to monitor the signal strength of users in neighbouring cells which appear to be in need of handoff and reports all RSSI values to the MSC. Based on the locator receiver signal strength information from each base station, the MSC decides if a handoff is necessary or not. In second generation systems that use digital TDMA technology, handoff decisions are mobile assisted. In mobile assisted handoff (MAHO), every mobile station measures the received power from surrounding base stations and continually reports the results of these measurements to the serving base station. A handoff is initiated when the power received from the base station of a neighbouring cell begins to exceed the power received from the current base station by a certain level or for a certain period of time. The MAHO method enables the call to be handed over between base stations at a much faster rate than in first generation analog systems since the handoff measurements are made by each mobile, and the MSC no longer constantly monitors signal strengths. MAHO is particularly suited for microcellular environments where handoffs are more frequent. During the course of a call, if a mobile moves from one cellular system to a different cellular system controlled by a different MSC, an intersystem handoff becomes necessary. An MSC engages in an intersystem handoff when a mobile signal becomes weak in a given cell and the MSC cannot find another cell within its system to which it can transfer the call in progress. There are many issues that must be addressed when implementing an intersystem handoff. For instance, a local call may become a long-distance call as the mobile moves out of its home system and becomes a roamer in a neighbouring system. Also, compatibility between the two MSCs must be determined before implementing an intersystem handoff. Different systems have different policies and methods for managing handoff requests. Some systems handle handoff requests in the same way they handle originating calls. In such systems, the probability that a handoff request will not be served by a new base station is equal to the blocking probability of incoming calls. However, from the user's point of view, having a call abruptly terminated while in the middle of a conversation is more annoying than being blocked occasionally on a new call attempt. To improve the quality of service as perceived by the users, various methods have been devised to prioritize handoff requests over call initiation requests when allocating voice channels [18].

2.6 Interference and System Capacity

Interference is the major limiting factor in the performance of cellular radio systems. Sources of interference include another mobile in the same cell, a call in progress in a neighbouring cell, other base stations operating in the same frequency band, or any noncellular system which inadvertently leaks energy into the cellular frequency band. Interference on voice channels causes cross talk, where the subscriber hears interference in the background due to an undesired transmission. On control channels, interference leads to missed and blocked calls due to errors in the digital signaling. Interference is more severe in urban areas, due to the greater RF noise floor and the large number of base stations and mobiles. Interference has been recognized as a major bottleneck in increasing capacity and is often responsible for dropped calls. The two major types of system generated cellular interference are co-channel interference and adjacent channel interference. Even though interfering signals are often generated within the cellular system, they are difficult to control in practice (due to random propagation effects). Even more difficult to control is interference due to out-of-band users, which arises without warning due to front-end overload of subscriber equipment or intermittent intermodulation products. In practice, the transmitters from competing cellular carriers are often a significant source of out-of-band interference, since competitors often locate their base stations in close proximity to one another in order to provide comparable coverage to customers [18],[22], [23].

2.7 Trunking and Grade of Service

Cellular radio systems rely on trunking to accommodate a large number of users in a limited radio spectrum. The concept of trunking allows a large number of users to share the relatively small number of channels in a cell by providing access to each user, on demand, from a pool of available channels. In a trunked radio system, each user is allocated a channel on a per call basis, and upon termination of the call, the previously occupied channel is immediately returned to the pool of available channels. Trunking exploits the statistical behaviour of users so that a fixed number of channels or circuits may accommodate a large, random user community. The telephone company uses trunking theory to determine the number of telephone circuits that need to be allocated for office buildings with hundreds of telephones, and this same principle is used in designing cellular radio systems. There is a trade-off between the number of available telephone circuits and the likelihood of a particular user finding that no circuits are available during the peak calling time. As the number of phone lines decreases, it becomes more likely that all circuits will be busy for a particular user. In a trunked mobile radio system, when a particular user requests service and all of the radio channels are already in use, the user is blocked, or denied access to the system. In some systems, a queue may be used to hold the requesting users until a channel becomes available [18].

2.8 Improving Capacity in Cellular Systems

As the demand for wireless service increases, the number of channels assigned to a cell eventually becomes insufficient to support the required number of users. At this point, cellular design techniques are needed to provide more channels per unit coverage area. Techniques such as cell splitting, sectoring, and coverage zone approaches are used in practice to expand the capacity of cellular systems. Cell splitting allows an orderly growth of the cellular system. Sectoring uses directional antennas to further control the interference and frequency reuse of channels. The zone microcell concept distributes the coverage of a cell and extends the cell boundary to hard-to-reach places. While cell splitting increases the number of base stations in order to increase capacity, sectoring and zone microcells rely on base station antenna placements to improve capacity by reducing co-channel interference. Cell splitting and zone microcell techniques do not suffer the trunking inefficiencies experienced by sectored cells, and enable the base station to oversee all handoff chores related to the microcells, thus reducing the computational load at the MSC. These three popular capacity improvement techniques will be explained in detail [19].

2.8.1 Cell Splitting

Cell splitting is the process of subdividing a congested cell into smaller cells, each with its own base station and a corresponding reduction in antenna height and transmitter power. Cell splitting increases the capacity of a cellular system since it increases the number of times that channels are reused. By defining new cells which have a smaller radius than the original cells and by installing these smaller cells (called microcells) between the existing cells, capacity increases due to the additional number of channels per unit area. Imagine if every cell in figure 3 were reduced in such a way that the radius of every cell was cut in half. In order to cover the entire service area with smaller cells, approximately four times as many cells would be required. This can be easily shown by considering a circle with radius R. The area covered by such a circle is four times as large as the area covered by a circle with radius R/2. The increased number of cells would increase the number of clusters over the coverage region, which in turn would increase the number of channels, and thus capacity, in the coverage area. Cell splitting allows a system to grow by replacing large cells with smaller cells, while not upsetting the channel allocation scheme required to maintain the minimum co-channel reuse ratio between co-channel cells. Figure 2.3 is an example for cell splitting. The base stations are placed at corners of the cells, and the area served by base station A is assumed to be saturated with traffic. New base stations are needed in the region to increase the number of channels in the area and to reduce the area served by the single base station.

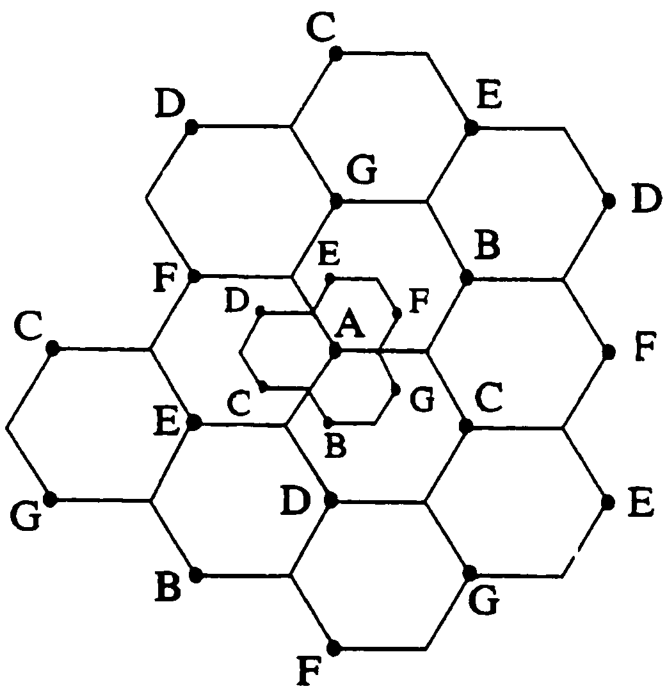


Figure 2.3: Cell splitting

Note in the figure that the original base station A has been surrounded by six new microcell base stations. The smaller cells were added in such a way as to preserve the frequency reuse plan of the system. For the new cells to be smaller in size, the transmit power of these cells must be reduced. The transmit power of the new cells with radius half that of the original cells can be found by examining the received power p_r at the new and old cell boundaries and setting them equal to each other. This is necessary to ensure that the frequency reuse plan for the new microcells behaves exactly as for the original cells [18].

2.8.2 Sectoring

Cell splitting achieves capacity improvement by essentially rescaling the system. By decreasing the cell radius R and keeping the co-channel reuse ratio D/R unchanged, cell splitting increases the number of channels per unit area. However, another way to increase capacity is to keep the cell unchanged and seek methods to decrease the D/R ratio. In this approach, capacity improvement is achieved by reducing the number of cells in a cluster thus increasing the frequency reuse. However, in order to do this, it is necessary to reduce the relative interference without decreasing the transmit power [18].

The co-channel interference in a cellular system may be decreased by replacing a single omni-directional antenna at the base station by several directional antennas, each radiating within a specific sector. By using directional antennas, a given cell will receive interference and transmit with only a fraction of the available co-channel cells. The technique for decreasing co-channel interference and thus increasing system capacity by using directional antennas is called sectoring. The factor by which the co-channel interference is reduced depends on the amount of sectoring used. A cell is normally partitioned into three 120° sectors or six 60° sectors as shown in figure 2.4.

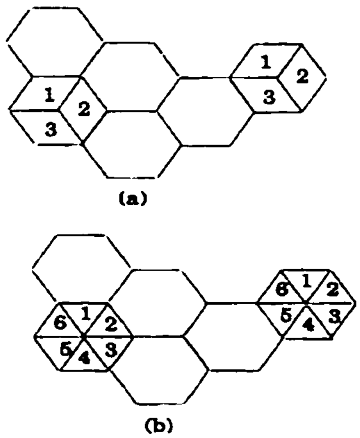


Figure 2.4: (a) 120° sectoring (b) 60° sectoring

2.9 Cellular Telephone Systems

A cellular telephone system provides a wireless connection to the PSTN for any user location within the radio range of the system. Cellular systems accommodate a large number of users over a large geographic area, within a limited frequency spectrum. Cellular radio systems provide high quality service that is often comparable to that of the landline telephone systems. High capacity is achieved by limiting the coverage of each base station transmitter to a small geographic area called a cell so that the same radio channels may be reused by another base station located some distance away. A sophisticated switching technique called a handoff enables a call to proceed uninterrupted when the user moves from one cell to another. Communication between the base station and the mobiles is defined by a standard common air transfer (CAI) that specifies four different channels. The channels used for voice transmission from the base station to mobiles are called forward voice channels (FVC) and the channels used for voice transmission from mobiles to the base station are called reverse voice channels (RVC).

The two channels responsible for initiating mobile calls are the forward control channels (FCC) and reverse control channels (RCC). Control channels are often called setup channels because they are only involved in setting up a call and moving it to an unused voice channel. Control channels transmit and receive data messages that carry call initiation and service requests. and are monitored by mobiles when they do not have a call in progress. Forward control channels also serve as beacons. which continually broadcast all of the traffic requests for all mobiles in the system [17]. [18].

2.9.1 How a Cellular Telephone Call is Made

When a cellular phone is turned on. but is not yet engaged in a call. it first scans the group of forward control channels to determine the one with the strongest signal. and then monitors that control channel until the signal drops below an usable level. At this point it again scans the control channels in search of the strongest base station signal. Since the control channels are standardized and are identical throughout different markets within the country or continent. every phone scans the same channels while idle. When a telephone call is placed to a mobile user. the MSC dispatches the request to all base stations in the cellular system. The mobile identification number (MIN). which is the subscriber's telephone number. is then broadcast as a paging message over all of the forward control channels throughout the cellular system. The mobile receives the paging message sent by the base station which it monitors. and responds by identifying itself over the reverse control channel. The base station relays the acknowledgment sent by the mobile and informs the MSC of the handshake. Then. the MSC instructs the base station to move the call to an unused voice channel within the cell. At this point the base station signals the mobile to change frequencies to an unused forward and reverse voice channel pair, at which point another data message (called an alert) is transmitted over the forward voice channel to instruct the mobile telephone to ring, thereby instructing the mobile user to answer the phone. All of these events occur within a few seconds and are not noticeable by the user. Once a call is in progress, the MSC adjusts the transmitted power of the mobile and changes the channel of the mobile unit and base stations in order to maintain call quality as the subscriber moves in and out of range of each base station. This is called a handoff. Special control signaling is applied to the voice channels so that the mobile unit may be controlled by the base station and the MSC while a call is in progress. When a mobile originates a call, a call initiation request is sent on the reverse control channel. With this request the mobile unit transmits its telephone number (MIN), electronic serial number (ESN), and the telephone number of the called party. The mobile also transmits a station class mark (SCM) which indicates what the maximum transmitter power level is for the particular user. The cell base station receives this data and sends it to the MSC. The MSC validates the request, makes connection to the called party through the PSTN, and instructs the base station and mobile user to move to an unused forward and reverse voice channel pair to allow the conversation to begin. All cellular systems provide a service called roaming. This allows subscribers to operate in service areas other than the one from which service is subscribed. When a mobile enters a city or geographic area that is different from its home service area, it is registered as a roamer in the new service area. This is accomplished over the FCC, since each roamer is camped on to a FCC at all times. Every several minutes, the MSC issues a global command over each FCC in the system, asking for all mobiles which are previously unregistered to report their MIN and ESN over the RCC. New unregistered mobiles in the system periodically report back their subscriber information upon receiving the registration request, and the MSC then uses the MIN/ESN data to request billing status from the home location register (HLR) for each roaming mobile. If a particular roamer has roaming authorization for billing purposes, the MSC registers the subscriber as a valid roamer. Once registered, roaming mobiles are allowed to receive and place calls from that area, and billing is routed automatically to the subscriber's home service provider [18].

2.10 AMPS and ETACs

In the late 1970s, AT&T Bell Laboratories developed the first U.S. cellular telephone system called the Advance Mobile Phone Service (AMPS). AMPS was first deployed in late 1983 in the urban and suburban areas of Chicago by Ameritech. In 1983, a total of 40 MHz of spectrum in the 800 MHz band was allocated by the Federal Communications Commission for the Advanced Mobile Phone Service. In 1989, as the demand for cellular telephone services increased, the Federal Communications Commission allocated an additional 10 MHz (called the extended spectrum) for cellular telecommunications. The first AMPS cellular system used large cells and omni-directional base station antennas to minimize initial equipment needs, and the system was deployed in Chicago to cover approximately 2100 square miles. The AMPS system uses a 7-cell reuse pattern with provisions for sectoring and cell splitting to increase capacity when needed. After extensive subjective tests, it was found that the AMPS 30 kHz channel requires a signal-to-interference ratio (SIR) of 18 dB for satisfactory system performance. The smallest reuse factor which satisfies this requirement using 120 degree directional antennas is $N = 7$, and hence a 7-cell reuse pattern has been adopted. AMPS is used throughout the world and is particularly popular in the U.S., South America, Australia, and China. While the U.S. system has been designed for a duopoly market (e.g., two competing carriers per market), many countries have just a single provider. Thus, while U.S. AMPS restricts the A and B side carriers to a subset of 416 channels each, other implementations of AMPS allow all possible channels to be used. Furthermore, the exact frequency allocations for AMPS differ from country to country. Nevertheless, the air interface standard remains identical throughout the world. The European Total Access Communication System (ETACS) was developed in the mid 1980s, and is virtually identical to AMPS, except it is scaled to fit in 25 kHz (as opposed to 30 kHz) channels used throughout Europe. Another difference between ETACS and AMPS is how the telephone number of each subscriber (called the mobile identification number or MIN) is formatted, due to the need to accommodate different country codes throughout Europe and area codes in the U.S. [18].

2.10.1 AMPS and ETACS System Overview

Like all other first generation, analog, cellular systems, AMPS and ETACS use frequency modulation (FM) for radio transmission. In the United States, transmissions from mobiles to base stations (reverse link) use frequencies between 824 MHz and 849 MHz, while base stations transmit to mobiles (forward link) using frequencies between 869 MHz and 894 MHz. ETACS uses 890 MHz to 915 MHz for the reverse link and 935 MHz to 960 MHz for the forward link. Every radio channel actually consists of a pair of simplex channels separated by 45 MHz. A separation of 45 MHz between the forward and reverse channels was chosen to make use of inexpensive but highly selective duplexers in the subscriber units. AMPS and ETACS cellular radio systems generally have tall towers which support several receiving antennas and have transmitting antennas which typically radiate a few hundred watts of effective radiated power. Each base station typically has one control channel transmitter (that broadcasts on the forward control channel), one control channel receiver (that listens on the reverse control channel for any cellular phone switching to set-up a call), and eight or more FM duplex voice channels. Commercial base stations support as many as fifty-seven voice channels. Forward voice channels (FVC) carry the portion of the telephone conversation originating from the landline telephone network caller and going to the cellular subscriber. Reverse voice channels (RVC) carry the portion of the telephone conversation originating from the cellular subscriber and going to the landline telephone network caller. The actual number of control and voice channels used at a particular base station varies widely in different system installations depending on traffic, maturity of the system, and locations of other base stations. The number of base stations in a service area varies widely, as well, from as few as one cellular tower in a rural area to several hundred or more base stations in a large city. Each base station in the AMPS or ETACS system continuously transmits digital FSK data on the forward control channel (FCC) at all times so that idle cellular subscriber units can lock onto the strongest FCC wherever they are. All subscribers must be locked, or "camped" onto a FCC in order to originate or receive calls. The base station reverse control channel (RCC) receiver constantly monitors transmissions from cellular subscribers that are locked onto the matching FCC. In the U .S. AMPS system, there are twenty-one control channels for each of the two service providers in each market, and these control channels are standardized throughout the country. ETACS supports fortytwo control channels for a single provider. Thus any cellular telephone in the system only needs to scan a limited number of control channels to find the best serving base station.

It is up to the service provider to ensure that neighbouring base stations within a system are assigned forward control channels that do not cause adjacent channel interference to subscribers which monitor different control channels in nearby base stations. In each U.S. cellular market, the nonwireline service provider (the "A" provider") is assigned an odd system identification number (SID) and the wireline service provider (the "B" provider) is assigned an even SID. The SID is transmitted once every 0.8 seconds on each FCC, along with other overhead data which reports the status of the cellular system. Transmitted data might include information such as whether roamers are automatically registered, how power control is handled, and whether other standards, such as USDC or narrowband AMPS, can be handled by the cellular system. In the U.S., subscriber units generally access channels exclusively on the A or B side, although cellular phones are capable of allowing the user to access channels on both sides. For ETACS, area identification numbers (AID) are used instead of SID, and ETACS subscriber units are able to access any control or voice channel in the standard [18].

2.10.2 Call Handling in AMPS and ETACs

When a call to a cellular subscriber originates from a conventional telephone in the public-switched telephone network (PSTN) and arrives at the mobile switching centre (MSC), a paging message is sent out with the subscriber's mobile identification number (MIN) simultaneously on every base station forward control channel in the system. If the intended subscriber unit successfully receives its page on a forward control channel, it will respond with an acknowledgment transmission on the reverse control channel. Upon receiving the subscriber's acknowledgment, the MSC directs the base station to assign a forward voice channel (FVC) and reverse voice channel (RVC) pair to the subscriber unit so that the new call can take place on a dedicated voice channel. The base station also assigns the subscriber unit a supervisory audio tonc (SAT tone) and a voice mobile attenuation code (VMAC) as it moves the call to the voice channel. The subscriber unit automatically changes its frequency to the assigned voice channel pair. The SAT, as described subsequently, has one of three different frequencies which allows the base and mobile to distinguish each other from co-channel users located in different cells. The SAT is transmitted continuously on both the forward and reverse voice channels during a call at frequencies above the audio band. The VMAC instructs the subscriber unit to transmit at a specific power level. Once on the voice channel, wideband FSK data is used by the base station and subscriber unit in a blank-and-burst mode to initiate handoffs, change the subscriber transmit power as needed, and provide other system data. Blank-and-burst signaling allows the MSC to send bursty data on the voice channel by temporarily omitting the speech and SAT, and replacing them with data. This is barely noticed by the voice users. When a mobile user places a call, the subscriber unit transmits an origination message on the reverse control channel (RCC). The subscriber unit transmits its MIN, electronic serial number (ESN), station class mark (SCM), and the destination telephone number. If received correctly by the base station, this infonnation is sent to the MSC which checks to see if the subscriber is properly registered, connects the subscriber to the PSTN, assigns the call to a forward and reverse voice channel pair with a specific SAT and VMAC, and commences the conversation. During a typical call, the MSC issues numerous blank-and-burst commands which switch subscribers between different voice channels on different base stations, depending on where the subscriber is travelling in the service area. In AMPS and ETACS, handoff decisions are made by the MSC when the signal strength on the reverse voice channel (RVC) of the serving base station drops below a preset threshold, or when the SAT tone experiences a certain level of interference. Thresholds are adjusted at the MSC by the service provider, are subject to continuous measurement, and must be changed periodically to accommodate customer growth, system expansion, and changing traffic patterns. The MSC uses scanning receivers called "locate receivers" in nearby base stations to determine the signal level of a particular subscriber which appears to be in need of a handoff. In doing so, the MSC is able to find the best neighbouring base station which can accept the handoff. When a new call request arrives from the PSTN or a subscriber, and all of the voice channels in a particular base station are occupied, the MSC will hold the PSTN line open while instructing the current base station to issue a directed retry to the subscriber on the FCC. A directed retry forces the subscriber unit to switch to a different control channel (i.e., different base station) for voice channel assignment. Depending on radio propagation effects, the specific location of the subscriber, and the current traffic on the base station to which the subscriber is directed, a directed retry mayor may not result in a successful call. Several factors may contribute to degraded cellular service or dropped or blocked calls. Factors such as the performance of the MSC, the current traffic demand in a geographic area, the specific channel reuse plan, the number of base stations relative to the subscriber population density, the specific propagation conditions between users of the system, and the signal threshold settings for handoffs play major roles in system performance.

Parameter	AMPS Specification	ETACS Specification
Multiple Access	FDMA	FDMA
Duplexing	FDD	FDD
Channel Bandwidth	30 kHz	25 kHz
Traffic channel per RF channel	1	1
Reverse channel frequency	824 – 849 MHz	890 – 915 MHz
Forward channel frequency	869 – 894 MHz	935 – 960 MHz
Voice modulation	FM	FM
Peak deviation: Voice Channels control/Wideband data	± 12 kHz ± 8 kHz	± 10 kHz ± 6.4 kHz
Channel coding for data transmission	BCH (40,28) on FC BCH (48,36) on RC	BCH (40,28) on FC BCH (48,36) on RC
Data rate on control/wideband channel	10 kbps	8 kbps
Spectral efficiency	0.33 bps/Hz	0.33 bps/Hz
Number of channels	832	1000

Table 2.1: AMPS and ETACS radio interface specifications

Maintaining perfect service and call quality in a heavily populated cellular system is practically impossible due to the tremendous system complexity and lack of control in determining radio coverage and customer usage patterns. System operators strive to forecast system growth and do their best to provide suitable coverage and sufficient capacity to avoid co-channel interference within a market, but inevitably some calls will be dropped or blocked. In a large metropolitan market, it is not unusual to have 3-5 percent dropped calls and in excess of 10 percent blocking during extremely heavy traffic conditions [18].

2.11 Global System for Mobile (GSM)

Global System for Mobile (GSM) is a second generation cellular system standard that was developed to solve the fragmentation problems of the first cellular systems in

Europe. GSM is the world's first cellular system to specify digital modulation and network level architectures and services. Before GSM, European countries used different cellular standards throughout the continent, and it was not possible for a customer to use a single subscriber unit throughout Europe. GSM was originally developed to serve as the pan-European cellular service and promised a wide range of network services through the use of ISDN. GSM's success has exceeded the expectations of virtually everyone, and it is now the world's most popular standard for new cellular radio and personal communications equipment throughout the world. The task of specifying a common mobile communication system for Europe the 900 MHz band was taken up by the GSM (Groupe special mobile) committee which was a working group of the Conference Europeene Postes des et Telecommunication (CEPT). Recently. GSM has changed its name to the Global system for Mobile Communications for marketing reasons. The setting standards for GSM is currently under the aegis of the European Technical standards Institute (ETSI). GSM was first introduced into the European market in 1991. By the end of 1993. several non European countries in South America. Asia. and Australia had adopted GSM and the technically equivalent offshoot. DCS 1800. which supports personal Communication Services (PCS) in the 1.8 GHz to 2.0 GHz radio bands recently created by governments throughout the world [18]. [19].

2.11.1 GSM Services and Features

GSM services follow ISDN guidelines and are classified as either teleservices or data services. Teleservices include standard mobile telephony and mobile-originated or base-originated traffic. Data services include computer-to-computer communication and packet-switched traffic. User services may be divided into three major categories:

- Telephone services, including emergency calling and facsimile. GSM also supports Videotex and Teletex, though they are not integral parts of the GSM standard.
- Bearer services or data services which are limited to layers 1, 2, and 3 of the open system interconnection (OSI) reference model. Supported services include packet switched protocols and data rates from 300 bps to 9.6 kbps. Data may be transmitted using either a transparent mode (where GSM provides standard channel coding for the user data) or non transparent mode (where GSM offers special coding efficiencies based on the particular data interface).
- Supplementary ISDN services, are digital in nature, and include call diversion, closed user groups, and caller identification, and are not available in analog mobile networks. Supplementary services also include the short messaging service (SMS) which allows GSM subscribers and base stations to transmit alphanumeric pages of limited length (160 7 bit ASCII characters) while simultaneously carrying normal voice traffic. SMS also provides cell broadcast, which allows GSM base stations to repetitively transmit ASCII messages with as many as fifteen 93-character strings in concatenated fashion. SMS may be used for safety and advisory applications, such as the broadcast of highway or weather information to all GSM subscribers within reception range.

From the user's point of view, one of the most remarkable features of GSM is the Subscriber Identity Module (SIM), which is a memory device that stores information such as the subscriber's identification number, the networks and countries where the subscriber is entitled to service, privacy keys, and other user-specific information. A subscriber uses the SIM with a 4-digit personal ID number to activate service from any GSM phone. SIM's are available as smart cards (credit card sized cards that may be inserted into any GSM phone) or plug in modules, which are less convenient than the SIM cards but are nonetheless removable and portable. Without a SIM installed, all GSM mobiles are identical and non operational. It is the SIM that gives GSM subscriber units their identity. Subscribers may plug their SIM into any suitable terminal -such as a hotel phone, public phone, or any portable or mobile phone and are then able to have all incoming GSM calls routed to that terminal and have all outgoing calls billed to their home phone, no matter where they are in the world. A second remarkable feature of GSM is the on-the-air privacy which is provided by the system. Unlike analog FM cellular phone systems which can be readily monitored, it is virtually impossible to eavesdrop on a GSM radio transmission. The privacy is made possible by encrypting the digital bit stream sent by a GSM transmitter, according to a specific secret cryptographic key that is known only to the cellular carrier. This key changes with time for each user. Every carrier and GSM equipment manufacturer must sign the Memorandum of Understanding before developing GSM equipment or deploying a GSM system. The Memorandum of Understanding is an international agreement which allows the sharing of cryptographic algorithms and other proprietary information between countries and carriers [18].

2.11.2 GSM System Architecture

The GSM system architecture consists of three major interconnected subsystems that interact between themselves and with the users through certain network interfaces. The subsystems are the Base Station Subsystem (BSS), Network and Switching Subsystem (NSS), and the Operation Support Subsystem (OSS). The Mobile Station

(MS) is also a subsystem, but is usually considered to be part of the BSS for architecture purposes. Equipment and services are designed within GSM to support one or more of these specific subsystems. The BSS, also known as the radio subsystem, provides and manages radio transmission paths between the mobile stations and the Mobile Switching Center (MSC). The BSS also manages the radio interface between the mobile stations and all other subsystems of GSM. Each BSS consists of many Base Station Controllers (BSCs) which connect the MS to the NSS via the MSCs. The NSS manages the switching functions of the system and allows the MSCs to communicate with other networks such as the PSTN and ISDN.

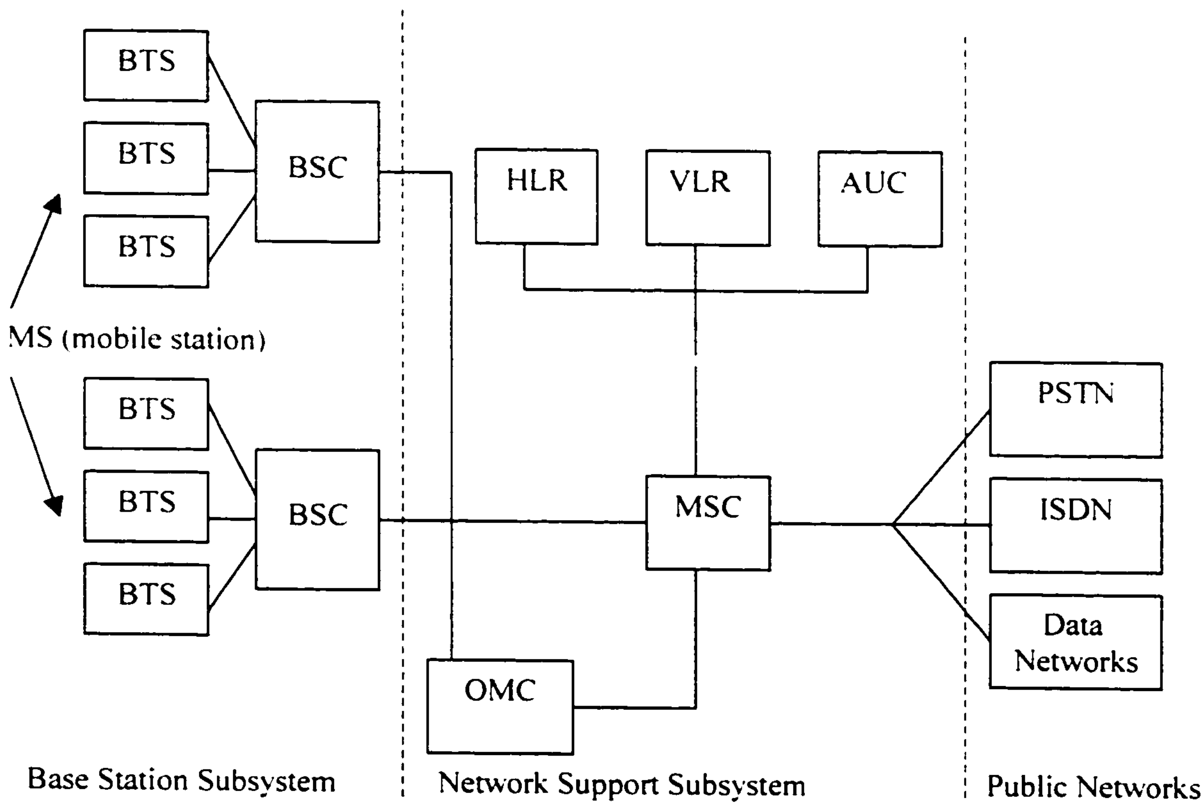


Figure 2.5: GSM system architecture

The OSS supports the operation and maintenance of GSM and allows system engineers to monitor, diagnose, and troubleshoot all aspects of the GSM system. This subsystem interacts with the other GSM subsystems, and is provided solely for the staff of the GSM operating company which provides service facilities for the network [18].

Figure 2.5 shows the block diagram of the GSM system architecture. The Mobile Stations (MS) communicate with the Base Station Subsystem (BSS) over the radio air interface. The BSS consists of many BSCs which connect to a single MSC, and each BSC typically controls up to several hundred Base Transceiver Stations (BTSs). Some of the BTSs may be co-located at the BSC, and others may be remotely distributed and physically connected to the BSC by microwave link or dedicated leased lines. Mobile handoffs (called handovers, or HO, in the GSM specification) between two BTSs under the control of the same BSC are handled by the BSC, and not the MSC. This greatly reduces the switching burden of the MSC [18], [19].

2.12 CDMA Digital Cellular Standard (1S-95)

Code Division Multiple Access (CDMA) offers some advantages over TDMA and FDMA. A U .S. digital cellular system based on CDMA which promises increased capacity has been standardized as Interim Standard 95 (IS-95) by the U.S. Telecommunications Industry Association (TIA). The IS-95 system is designed to be compatible with the existing U.S. analog cellular system (AMPS) frequency band, hence mobiles and base stations can be economically produced for dual mode operation. Pilot production, CDMA/AMPS, dual mode phones were made available by Qualcomm in 1994. IS-95 allows each user within a cell to use the same radio channel, and users in adjacent cells also use the same radio channel, since this is a direct sequence spread spectrum CDMA system. CDMA completely eliminates the need for frequency planning within a market. To facilitate graceful transition from AMPS to CDMA, each IS-95 channel occupies 1.25 MHz of spectrum on each one-way link, or 10% of the available cellular spectrum for a U.S. cellular provider. In practice, AMPS carriers must provide a 270 kHz guard band (typically 9 AMPS channels) on each side of the spectrum dedicated for IS-95. Unlike other cellular standards, the user data rate (but not the channel chip rate) changes in real-time, depending on the voice activity and requirements in the network. Also, IS-95 uses a different modulation and spreading technique for the forward and reverse links. On the forward link, the base station simultaneously transmits the user data for all mobiles in the cell by using a different spreading sequence for each mobile. A pilot code is also transmitted simultaneously and at a higher power level, thereby allowing all mobiles to use coherent carrier detection while estimating the channel conditions. On the reverse link, all mobiles respond in an asynchronous fashion and have ideally a constant signal level due to power control applied by the base station [18], [23].

2.12.1 Frequency and Channel Specifications

IS-95 is specified for reverse link operation in the 824 -849 MHz band and 869 - 894 MHz for the forward link. A forward and reverse channel pair is separated by 45 MHz. Many users share a common channel for transmission. The maximum user data rate is 9.6 kb/s. User data in IS-95 is spread to a channel chip rate of 1.2288 Mchip/s (a total spreading factor of 128) using a combination of techniques. The spreading process is different for the forward and reverse links. On the forward link, the user data stream is encoded using a rate 1/2 convolutional code, interleaved, and spread by one of sixty-four orthogonal spreading sequences (Walsh functions). Each mobile in a given cell is assigned a different spreading sequence, providing perfect separation among the signals from different users, at least for the case where multipath does not exist. To reduce interference between mobiles that use the same spreading sequence in different cells, and to provide the desired wideband spectral characteristics (not all of the Walsh functions yield a wideband power spectrum), all signals in a particular cell are scrambled using a pseudorandom sequence of length 2^{15} chips. Orthogonality among all forward channel users within a cell is preserved because their signals are scrambled synchronously. A pilot channel (code) is provided on the forward link so that each subscriber within the cell can determine and react to the channel characteristics while employing coherent detection. The pilot channel is transmitted at higher power than the user channels [18].

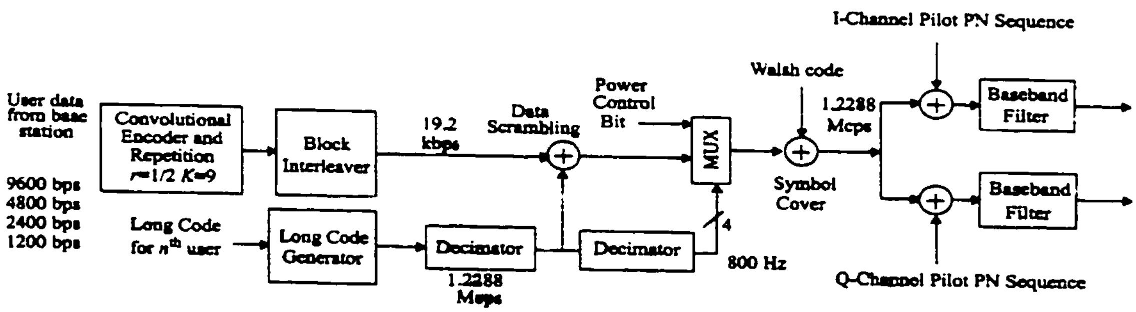


Figure 2.6: Forward CDMA channel modulation process

On the reverse link, a different spreading strategy is used since each received signal arrives at the base station via a different propagation path. The reverse channel user data stream is first convolutionally encoded with a rate 1/3 code. After interleaving, each block of six encoded symbols is mapped to one of the 64 orthogonal Walsh functions, providing sixty-four-ary orthogonal signaling. A final fourfold spreading, giving a rate of 1.2288 Mchip/s, is achieved by spreading the resulting 307.2 kchip/s stream by user-specific and base-station specific codes having periods of 2^{42} -1 chips and 2^{15} chips, respectively. The rate 1/3 coding and the mapping onto Walsh functions result in a greater tolerance for interference than would be realized from traditional repetition spreading codes. This added robustness is important on the reverse link, due to the noncoherent detection and the in-cell interference received at the base station.

Another essential element of the reverse link is tight control of each subscriber's transmitter power, to avoid the "near-far" problem that arises from varying received powers of the users. A combination of open loop and fast, closed-loop power control is used to adjust the transmit power of each in-cell subscriber so that the base station receives each user with the same received power. The commands for the closed-loop power control are sent at a rate of 800 b/s, and these bits are stolen from the speech frames. Without fast power control, the rapid power changes due to fading would degrade the performance of all users in the system. At both the base station and the subscriber, RAKE receivers are used to resolve and combine multipath components, thereby reducing the degree of fading. A RAKE receiver exploits the multipath time delays in a channel and combines the delayed replicas of the transmitted signal in order to improve link quality. In IS-95, a three finger RAKE is used at the base station. The IS-95 architecture also provides base station diversity during "soft" handoffs, whereby a mobile making the transition between cells maintains links with both base stations during the transition. The mobile receiver combines the signals from the two base stations in the same manner as it would combine signals associated with different multipath components [18], [19], [25].

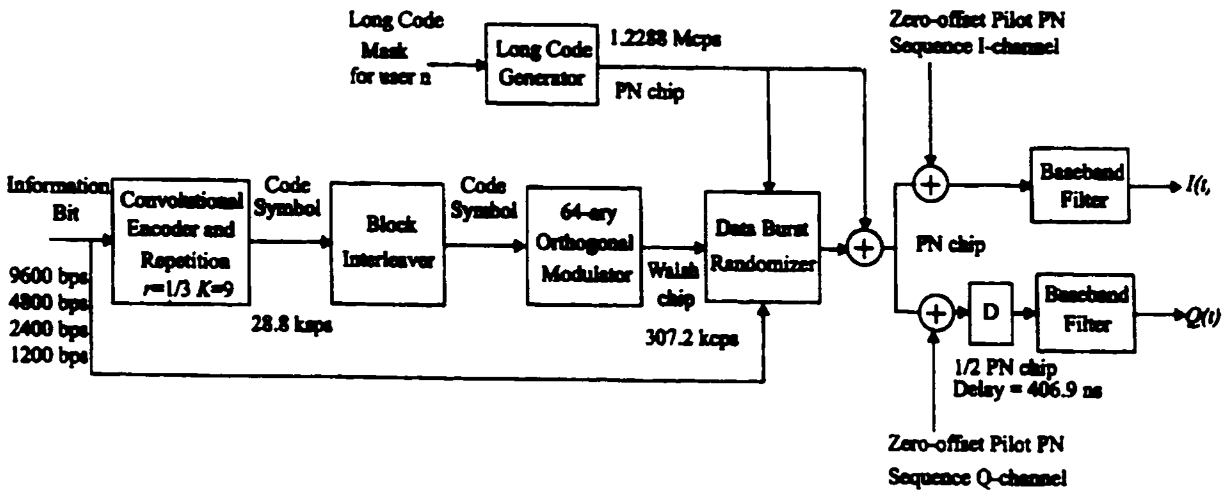


Figure 2.7: Reverse IS-95 channel modulation process for a single user

Chapter 3

Wireless LANs

3.1 Introduction

In a wireless LAN the connection between the client and user is accomplished by the use of a wireless medium such as Radio Frequency (RF) or Infra Red (IR) communications instead of a cable. This allows the remote user to stay connected to the network while mobile or not physically attached to the network. The wireless connection is most usually accomplished by the user having a handheld terminal or laptop that has an RF interface card installed inside the terminal or through the PC Card slot of the laptop. The client connection from the wired LAN to the user is made through an Access Point (AP) that can support multiple users simultaneously. The AP can reside at any node on the wired network and acts as a gateway for wireless users' data to be routed onto the wired network. The range of these systems is very dependent on the actual usage and environment of the system but varies from one hundred feet inside a solid walled building to several thousand feet outdoors, in direct line of sight. This is a similar order of magnitude as the distance that can be covered by the wired LAN in a building. However, much like a cellular phone system the wireless LAN is capable of roaming from the AP and reconnecting to the network through other AP's residing at other points on the wired network. This can allow the wired LAN to be extended to cover a much larger area than the existing coverage by the use of multiple AP's such as in a campus environment. An important feature of the wireless LAN is that it can be used independently of a wired network. it may be used as a stand alone network anywhere to link multiple computers together without having to build or extend a wired network. A useful example that is in use today is an outside auditing group inside a client company. If each of the auditors has a laptop equipped with a wireless client adapter, then a peer to peer workgroup can immediately be established for transfer or access of data. A member of the workgroup may be established as the server or the network can act in a peer to peer mode [27].

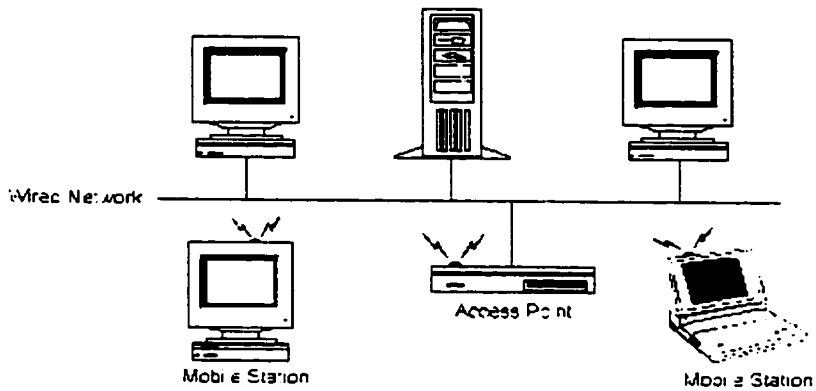


Figure 3.1: Wireless LAN application

A wireless LAN is capable of operating at speeds in the range of 1-2 Mbps depending on the actual system, both of these speeds are supported by the standard for Wireless LAN networks defined by the international body, IEEE. At first approach this suggests that the wireless network will have throughput that is 5 to 10 times less than the wired network. In practice however, the real user of wireless networks will see a reduction in throughput compared to a wired network but not as great as the raw numbers suggest. The actual usage of the network is a much better indication of the throughput that can be expected. This is not dissimilar to the model of highway traffic when a surface street is compared to a highway to get from point A to B. While travel is significantly faster on the highway at the optimum time, off peak hours when maximum speeds are possible. during peak usage the highway can often be slower than the surface streets due to the load of traffic that the highway has to deal with. Wireless LAN's are billed on the basis of installed equipment cost. once in place there are no charges for use of the network. The network communications take place in a part of the radio spectrum that is designated as "license free". In this band. 2.4-2.5 GHz. users can operate without a license so long as they use equipment that has been type approved for use in the license free bands. The 2.4 GHz band has been designated as license free by the International Telecommunications Union (ITU) and is available for use. license free in most countries in the world. Unfortunately. the rules of operation are different in almost every country but they are similar enough that the products can be programmed for use in every country without changing the hardware component.

3.2 Wireless LAN Technology

Manufacturers of wireless LANs have a range of technologies to choose from when designing a wireless LAN solution. Each technology comes with its own set of advantages and limitations [30].

3.2.1 Radio Frequency Systems

RF is very capable of being used for applications where communications are not "line of sight" and over longer distances. The RF signals will travel through walls and communicate where there is no direct path between the terminals. In order to operate in the license free portion of the spectrum called the ISM band (industrial. Scientific and Medical). the radio system must use a modulation technique called Spread Spectrum (SS). In this mode a radio is required to distribute the signal across the entire spectrum and cannot remain stable on a single frequency. This is done so that no single user can dominate the band and collectively that all users look like noise. Spread Spectrum communications were developed during World War II by the military for secure communications links. The fact that such signals appear to be noise in the band means that they are difficult to find and to jam. This technique lends itself well to the expected conditions of operation of a real Wireless LAN application in this band and is by its very nature difficult to intercept, thus increasing security against unauthorized listeners. The use of Spread Spectrum is especially important as it allows many more users to occupy the band at any given time and place than if they were all static on separate frequencies. With any radio system one of the greatest limitations is available bandwidth and so the ability to have many users operate simultaneously in a given environment is critical for the successful deployment of Wireless LAN. There are several bands available for use by license free transmitters. the most commonly used are at 902-928 MHz. 2.4-2.5 GHz and 5.7 to 5.8 GHz. Of these the most useful is probably the 2.4 GHz band as it is available for use throughout most of the world. In recent years nearly all of the commercial development and the basis for the new IEEE standard has been in the 2.4 GHz band. While the 900 MHz band is widely used for other systems it is only available in the US and has greatly limited bandwidth available. In the license free bands there is a strict limit on the broadcast power of any transmitter so that the spectrum can be reused at a short distance away without interference from a distant transmitter. This is much the same as the operation of a cellular telephone system.

3.2.2 Infra Red Systems

The second technology that is used for Wireless LAN systems is Infra Red, where the communication is carried by light in the invisible part of the spectrum. This system has much to recommend it in some circumstances. It is primarily of use for very short distance communications, less than 3 feet where there is a line of sight connection. It is not possible for the Infra Red light to penetrate any solid material, it is even attenuated greatly by window glass, so it is really not a useful technology in comparison to Radio Frequency for use in a Wireless LAN system. The application where Infra Red comes into its element is as a docking function and in applications where the power available is extremely limited, such as a pager or PDA. There is a standard for such products called IrDA that has been championed by Hewlett Packard, IBM and many others. This now to be found in many notebook and laptop PC's and allows a connectionless docking facility at up to 1 Mbps to a desktop machine at up to 2 feet, line of sight. Such products are point-to-point communications and not networks, this makes them very difficult to operate as a network but does offer increased security as only the user to whom the beam is directed can pick it up. Attempts to provide wider network capability by using a diffused IR system where the light is distributed in all directions have been developed and marketed, but they are limited to 30 -50 feet and cannot go through any solid material. There are now very few companies pursuing this implementation. The main advantage of the point to point IR system, increased security, is undermined by the distributing of the light source as it can now be received by any body within range, not just the intended recipient.

3.3 Spread Spectrum Implementation

There are two methods of Spread Spectrum modulation used to comply with the regulations for use in the ISM band, Frequency Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS) [29], [32].

3.3.1 Direct Sequence Spread Spectrum

Historically many of the original systems available used DSSS as the required spread spectrum modulation because components and systems were available from the Direct Broadcast Satellite industry, in which DSSS is the modulation scheme used. However, the majority of commercial investment in wireless LAN systems is now in FHSS and the user base of FHSS products will exceed that of DSSS next year. By 1998 it is likely that almost all new wireless LAN applications will be FHSS. The term "Direct Sequence Spread Spectrum" is a complicated way of describing a system that takes a signal at a given frequency and spreads it across a band of frequencies where the center frequency is the original signal. The spreading algorithm, which is the key to the relationship of the spread range of frequencies, changes with time in a pseudo random sequence that appears to make the spread signal a random noise source. The strength of this system is that when the ratio between the original signal bandwidth and the spread signal bandwidth is very large, the system offers great immunity to interference. For instance if a 1 Kbps signal is spread across 1 GHz of spectrum, the spreading ratio is one million times or 60 dB. This is the type of system developed for strategic military communications systems as it is very difficult to find and even more difficult to jam. However, in an environment such as Wireless LAN in the license free, ISM band, where the available bandwidth critically limits the ratio of spreading, the advantages that the

DSSS method provides against interference become greatly limited. A realistic example in use today is a 2 Mbps data signal that is spread across 20 MHz of spectrum and offering a spreading ratio of 10 times. This is only just enough to meet the lower limit of "Processing Gain", a measure of this spreading ratio, as set by the Federal Communications Corporation (FCC), the US government body that determines the rule of operation of radio transmitters. This limitation significantly undermines the value of DSSS as a method to resist interference in real wireless LAN applications.

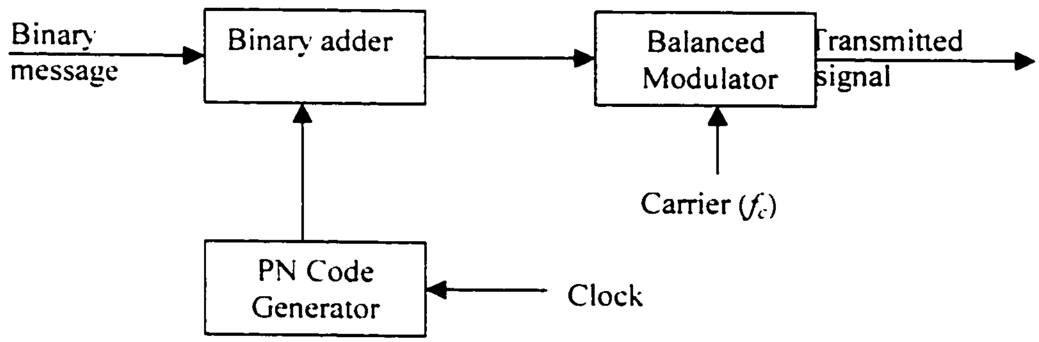


Figure 3.2: Direct Sequence Transmitter

3.3.2 Frequency Hopping Spread Spectrum

In simple terms a FHSS system is not dissimilar to the radio in a car where the preset buttons are pushed one after another in an apparent random sequence. The time on each channel is very short, but at a data rate of 1 Mbps or higher, even a fraction of a second provides significant overall throughput for the communications system. Frequency Hopping Spread Spectrum is an altogether much simpler system to understand than DSSS. It is based on the use of a signal at a given frequency that is constant for a small amount of time and then moves to a new frequency. The sequence of different channels determined for the hopping pattern, i.e. "where will the next frequency be to engage with this signal source", is pseudo random. Pseudo means that a very long sequence code is used before it is repeated, over 65,000 hops, making it appear to be random. This makes it very difficult to predict the next frequency at which such a system will stop and transmit or receive data as the system appears to be a random noise source to an unauthorized listener. This makes the FHSS system very secure against interference and interception. This system is a very robust method of communicating as it is statistically close to impossible to block all of the frequencies that can be used and as there is no "spreading ratio" requirement that is so critical for DSSS systems. The resistance to interference is actually determined by the capability of the hardware filters that are used to reject signals other than the frequency of interest, not by a mathematical spreading algorithms.

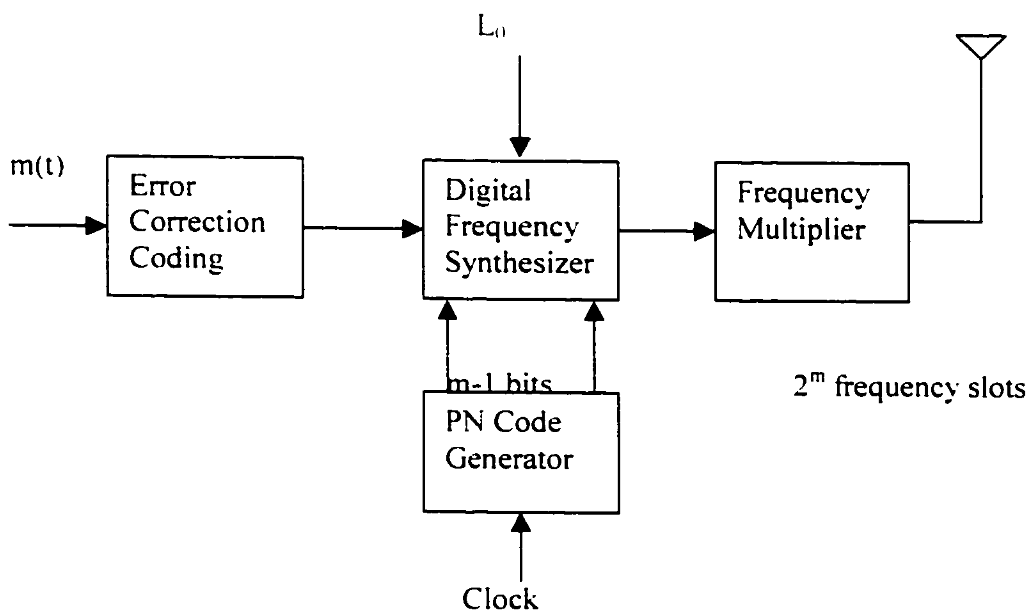


Figure 3.3: Frequency Hopping Transmitter

3.4 Specifications

There are a number of other key specifications that should be reviewed.

3.4.1 Data rate

The most significant variation in data rate can usually be attributed to the how well the underlying data transfer protocol is designed and implemented by the specific manufacturer and the quality of the overall systems architecture they have developed not the spread spectrum implementation used. Because of the spreading ratio it is possible for existing DSSS implementations to marginally exceed the performance of FHSS systems. but they will both nominally be rated at 1-2 Mbps over the air data rate. In effective throughput the DSSS system has an advantage because the data packets are transmitted continuously. whereas in FHSS a percentage of the operational time is spent hopping between frequencies and resynchronising. This time is minimized by design and should not reduce throughput by more than 20% if properly designed. Some systems are now including data compression that allows a 50-100% increase in effective data rate under some conditions. However. compression is algorithmic in nature and is very dependent on what sort of data is being transmitted. The algorithm for text compression is capable of around 2-3 times reduction and is very different from the algorithm used for. say. video compression where an optimized algorithm can provide 50-100 times reduction. Therefore compression is most useful when it can be tailored to a known type of data source [29].

3.4.2 Range

In the analysis of range. there is marginal theoretical difference in the range capabilities of FHSS and DSSS systems. The largest range difference will be caused by two sources; the type and placement of the antenna system not the spread spectrum modulation used and the environment that the system is operating in. Antenna Diversity is one of the most significant influences on the range and performance of systems, especially near the edge of the range profile, the marginal area. Antenna diversity is the use of multiple antennas that are physically separated. This is done because the radio waves will reflect off all objects, walls, buildings, bridges, cars, etc and cause nulls and peaks randomly distributed in the air. This is much the same as the peaks and troughs that are seen on the surface of water when separate waves encounter each other and is called "Multipath" in the radio environment. With two antennas separated by a quarter of a wavelength, a few inches for 2.4 GHz systems, it is statistically very unlikely that both antennas will be in a null or wave trough at the same time, whereas a single antenna will be reasonably likely to be in a null in a highly reflective environment, such as an office building.

Large antennas placed high above the ground will always provide better range than small antennas that extend marginally from a PC card and are low down on the side of a notebook computer. The range of the different system components is therefore different. Single piece PC Cards have the shortest range, 100-500 feet depending on the environment. Access Points with elevated, efficient antennas will achieve 500-3,000 feet. Luckily in most systems the client card will communicate with an Access Point and the overall link will benefit from the better antenna on the Access Point, though it will still have a shorter range than two Access Points communicating with each other. The environment that the system is used in is a very significant influence on the range and performance. This should be of little surprise to anybody that has used a cordless phone.

as they suffer from similar range and performance problems as wireless LAN's (except that voice quality can be substituted for data rate). When the environment is outside, in line of sight, with little to reflect off and cause multipath, the range is at its best. When the environment is in a solid walled building, such as an old stone house, the range is greatly reduced. This is the same for wireless LAN, however the multipath problem can significantly degrade megabit communications where it will not significantly affect voice quality.

3.4.3 Cost, Size and Power

Although these are 3 different and critical specifications, they are very closely linked in the wireless LAN environment. They also align with each other closely in a comparative review of DSSS and FHSS technology. The reason for this is because these specifications are all driven by implementation which is limited by the required components to implement the spread spectrum and the level of integration of those components. DSSS is driven by DSP multiplication therefore it has a heavy requirement for large, expensive and power hungry digital circuitry in its implementation. The spreading can be achieved by multiplying the data signal by the spreading code, which is very DSP intensive. This is in addition to the baseband processing requirements for the communications protocol being used. While further integration and increases in the capability of DSP processors will reduce the vulnerability of DSSS technology in these specifications, it will probably always lag the simplicity of FHSS systems. All practical DSSS systems use phase modulation (PM) as the basic data modulation prior to spreading, whereas all practical FHSS systems use frequency modulation (FM) as the basic data modulation prior to spreading. This is important for several reasons. FM is a method of modulation in which the frequency represents the value of a digital 1 or 0 as an offset above or below the nominal channel frequency. In this technique the only information that needs to be recovered from the received signal is the frequency. This requires no linearity of the receive path, it is very cheap and low in power consumption to implement. PM is essentially a version of AM, amplitude modulation, in which the amplitude or size of a signal at a given frequency is measured. The size of this signal represents a digital 1 or 0. In this technique it is not only necessary to know which frequency the signal is at but it is also necessary to know the amplitude of the signal, two pieces of information instead of just one for FM. The limitation of such a system is that a change in range from the receiver has a similar effect on amplitude as a change in amplitude that represents a 1 or a 0. So the system needs to resolve whether an amplitude change is caused by a change in the range of the transmitted signal or a different bit. This requires a linear system so that the measurement of amplitude is accurate and automatic gain control circuitry (AGC). The requirement to have a linear system costs money and more importantly uses power to implement. FHSS implementation is effectively the same system that is found in a consumer radio with the addition of a system to hop the frequency through the band. This is a simple and very well understood technique that is simple and cheap to implement. There is no requirement for any DSP to implement FHSS, so the power requirements are significantly reduced from that needed for DSSS with no additional cost for components or extra size for the product. It is notable that there are now several one piece Type II PC card designs for FHSS while there are no one piece designs for DSSS in a Type II PC Card. It would be extremely difficult to put a complete DSSS product in such a package, even with extremely dense (and expensive) silicon integration. It is also unlikely that the heat from such an implementation could be dissipated in a PC card slot without effecting reliability and performance greatly [28].

3.5 How Wireless LANs Work

Wireless LANs use electromagnetic airwaves (radio or infrared) to communicate information from one point to another without relying on any physical connection. Radio waves are often referred to as radio carriers because they simply perform the function of delivering energy to a remote receiver. The data being transmitted is superimposed on the radio carrier so that it can be accurately extracted at the receiving end. This is generally referred to as modulation of the carrier by the information being transmitted. Once data is superimposed (modulated) onto the radio carrier, the radio signal occupies more than a single frequency, since the frequency or bit rate of the modulating information adds to the carrier. Multiple radio carriers can exist in the same space at the same time without interfering with each other if the radio waves are transmitted on different radio frequencies. To extract data, a radio receiver tunes in one radio frequency while rejecting all other frequencies. In a typical wireless LAN configuration, a transmitter/receiver (transceiver) device, called an access point, connects to the wired network from a fixed location using standard cabling. At a minimum, the access point receives, buffers, and transmits data between the wireless LAN and the wired network infrastructure. A single access point can support a small group of users and can function within a range of less than one hundred to several hundred feet. The access point (or the antenna attached to the access point) is usually mounted high but may be mounted essentially anywhere that is practical as long as the desired radio coverage is obtained. End users access the wireless

LAN through wireless-LAN adapters, which are implemented as PC cards in notebook or palmtop computers, as cards in desktop computers, or integrated within hand-held computers. Wireless LAN adapters provide an interface between the client network operating system (NOS) and the airwaves via an antenna. The nature of the wireless connection is transparent to the NOS [28].

3.6 Wireless LAN Configurations

Wireless LANs can be simple or complex. At its most basic, two PCs equipped with wireless adapter cards can set up an independent network whenever they are within range of one another. This is called a peer-to-peer network. On-demand networks such as in this example require no administration or preconfiguration. In this case each client would only have access to the resources of the other client and not to a central server. Installing an access point can extend the range of an ad hoc network, effectively doubling the range at which the devices can communicate. Since the access point is connected to the wired network each client would have access to server resources as well as to other clients. Each access point can accommodate many clients; the specific number depends on the number and nature of the transmissions involved. Many real-world applications exist where a single access point services from 15-50 client devices. Access points have a finite range, on the order of 500 feet indoor and 1000 feet outdoors. In a very large facility such as a warehouse, or on a college campus it will probably be necessary to install more than one access point. Access point positioning is accomplished by means of a site survey. The goal is to blanket the coverage area with overlapping coverage cells so that clients might range throughout the area without ever losing network contact. The ability of clients to move seamlessly among a cluster of access points is called roaming. Access points hand the client off from one to another in a way that is invisible to the client, ensuring unbroken connectivity. To solve particular problems of topology, the network designer might choose to use Extension Points to augment the network of access points. Extension Points look and function like access points, but they are not tethered to the wired network as are APs. EPs function just as their name implies: they extend the range of the network by relaying signals from a client to an AP or another EP. EPs may be strung together in order to pass along messaging from an AP to far-flung clients, just as humans in a bucket brigade pass pails of water hand-to-hand from a water source to a fire. One last item of wireless LAN equipment to consider is the directional antenna. Let's suppose you had a wireless LAN in your building A and wanted to extend it to a leased building B, one mile away. One solution might be to install a directional antenna on each building, each antenna targeting the other. The antenna on A is connected to your wired network via an access point. The antenna on B is similarly connected to an access point in that building, which enables wireless LAN connectivity in that facility [29], [30].

3.7 Integration With Existing Networks

While you can operate a wireless LAN as a standalone network, chances are you will want to connect it to your wired infrastructure. This is easily accomplished by using a wireless access point, a small device that bridges wireless traffic to your network. The wireless LAN then appears as one network segment in your overall network. Today you usually need to purchase the access point from the same vendor as the wireless NIC, though with standards such as IEEE 802.11 and industry interoperability initiatives such as the Wireless LAN Interoperability Forum, you will have increasing options to combine equipment from different vendors. Most access point bridge wireless LANs into Ethernet networks, but Token-Ring options are often available as well.

3.8 Roaming

In many wireless LAN applications, you would like users to maintain a continuous connection as they roam from one physical area to another. In doing so, they may well move from the coverage of one access point to another. Nearly all wireless LAN vendors support this kind of roaming through a process by which the mobile nodes automatically register with the new access point. What you will need to consider in your network planning is how your infrastructure network is divided into subnets. If one access point is on one subnet and another access point is on another subnet, traffic will have to cross a router, something that most wireless LAN vendors currently do not support [30].

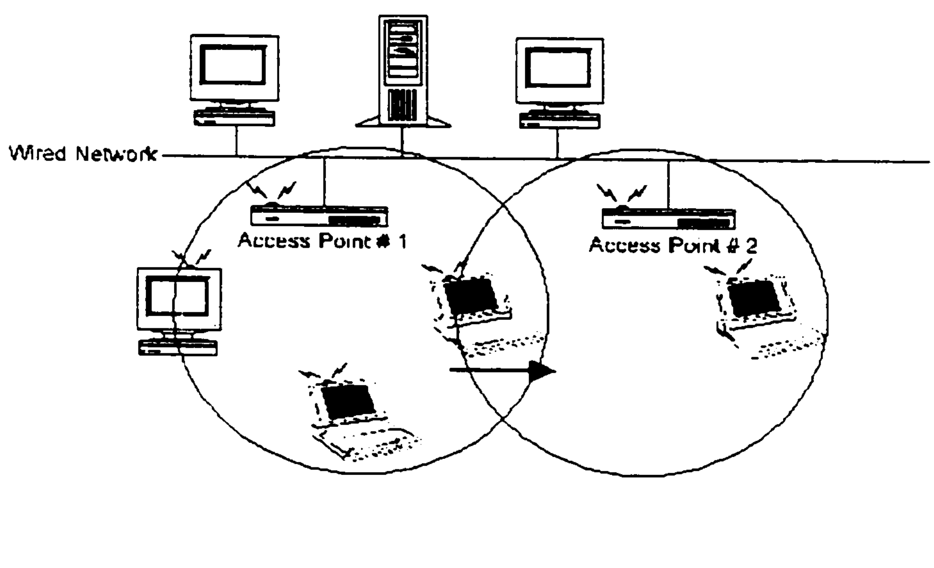


Figure 3.4: Roaming between access points

The two possible solutions are:

• Connect all access points back to one subnet, which might require extra cabling.

• Use Mobile IP if your network protocol is IP.

Sine the IEEE 802.11 standard does not address roaming, you may need to purchase equipment from one vendor if your users need to roam from one access point to another.

3.9 Security

The thought of radio waves propagating in all directions from your network may concern you. Fortunately most wireless LANs provide a number of effective security measures. First of all, spread spectrum radio signals are inherently difficult to decipher without knowing the exact hopping sequences or direct sequence codes used. This at least keeps honest people honest. To protect you against truly determined intruders, most wireless LAN products also offer optional encryption mechanisms. Also, the IEEE 802.11 standard specifies optional security called "Wired Equivalent Privacy," whose goal is that a wireless LAN offer privacy equivalent to that offered by a wired LAN. The standard also specifies optional authentication measures [30].

3.10 Interoperability

Before the IEEE 802.11 specification, the only interoperability between wireless NICs and access points occurred when vendors worked cooperatively. One such effort is the Wireless LAN Interoperability Forum (WLIF), which was formed by a number of wireless LAN vendors to address interoperability issues. WLIF has published protocol specifications based on Proxim's airlink and also performs certification testing. A number of vendors are also working together to create what is called the Inter-Access Point Protocol (IAPP), which defines how access points communicate with each other.

3.11 IEEE 802.11 Architectures

In IEEE's proposed standard for wireless LANs (IEEE 802.11), there are two different ways to configure a network: ad-hoc and infrastructure. In the ad-hoc network, computers are brought together to form a network. Tnere is no structure to the network; there are no fixed points; and usually every node is able to communicate with every other node. A good example of this is the aforementioned meeting where employees bring laptop computers together to communicate and share design or financial information. Although it seems that order would be difficult to maintain in this type of network, algorithms such as the spokesman election algorithm have been designed to "elect" one machine as the base station (master) of the network with the others being slaves. Another algorithm in ad-hoc network architectures uses a broadcast and flooding method to all other nodes to establish who's who. The second type of network structure used in wireless LANs is the infrastructure. This architecture uses fixed network access points with which mobile nodes can communicate. These network access points are sometime connected to landlines to widen the LAN's capability by bridging wireless nodes to other wired nodes. If service areas overlap, handoffs can occur. This structure is very similar to the present day cellular networks around the world [29].

3.12 IEEE 802.11 Layers

The IEEE 802.11 standard places specifications on the parameters of both the physical (PHY) and medium access control (MAC) layers of the network. The PHY layer, which actually handles the transmission of data between nodes, can use either direct sequence spread spectrum, frequency hopping spread spectrum, or infrared (IR) pulse position modulation. IEEE 802.11 makes provisions for data rates of either 1 Mbps or 2 Mbps, and calls for operation in the 2.4 - 2.4835 GHz frequency band (in the case of spread-spectrum transmission), which is an unlicensed band for industrial, scientific, and medical (ISM) applications, and 300 - 428,000 GHz for IR transmission. Infrared is generally considered to be more secure to eavesdropping, because IR transmissions require absolute line-of-sight links (no transmission is possible outside any simply connected space or around corners), as opposed to radio frequency transmissions, which can penetrate walls and be intercepted by third parties unknowingly. However, infrared transmissions can be adversely affected by sunlight, and the spread-spectrum protocol of 802.11 does provide some rudimentary security for typical data transfers. The MAC layer is a set of protocols which is responsible for maintaining order in the use of a shared medium. The 802.11 standard specifies a carrier sense multiple access with collision avoidance (CSMA/CA) protocol. In this protocol, when a node receives a packet to be transmitted, it first listens to ensure no other node is transmitting. If the channel is clear, it then transmits the packet. Otherwise, it chooses a random "backoff factor" which determines the amount of time the node must wait until it is allowed to transmit its packet. During periods in which the channel is clear, the transmitting node decrements its backoff counter. (When the channel is busy it does not decrement its backoff counter.)

When the backoff counter reaches zero, the node transmits the packet. Since the probability that two nodes will choose the same backoff factor is small, collisions between packets are minimized. Collision detection, as is employed in Ethernet, cannot be used for the radio frequency transmissions of IEEE 802.11. The reason for this is that when a node is transmitting it cannot hear any other node in the system which may be transmitting, since its own signal will drown out any others arriving at the node. Whenever a packet is to be transmitted, the transmitting node first sends out a short ready-to-send (RTS) packet containing information on the length of the packet. If the receiving node hears the RTS, it responds with a short clear-to-send (CTS) packet. After this exchange, the transmitting node sends its packet. When the packet is received successfully, as determined by a cyclic redundancy check (CRC), the receiving node transmits an acknowledgment (ACK) packet. This back-and-forth exchange is necessary to avoid the "hidden node" problem [29].

3.13 Benefits of Wireless LANs

The widespread reliance on networking in business and the meteoric growth of the Internet and online services are strong testimonies to the benefits of shared data and shared resources [27]. With wireless LANs, users can access shared information without looking for a place to plug in, and network managers can set up or augment networks without installing or moving wires. Wireless LANs offer the following productivity, convenience, and cost advantages over traditional wired networks:

• **Mobility**: Wireless LAN systems can provide LAN users with access to real-time information anywhere in their organization. This mobility supports productivity and service opportunities not possible with wired networks.

• **Installation Speed and Simplicity**: Installing a wireless LAN system can be fast and easy and can eliminate the need to pull cable through walls and ceilings.

• **Installation Flexibility**: Wireless technology allows the network to go where wire cannot go.

• **Reduced Cost-of-Ownership**: While the initial investment required for wireless LAN hardware can be higher than the cost of wired LAN hardware. overall installation expenses and life-cycle costs can be significantly lower. Long-term cost benefits are greatest in dynamic environments requiring frequent moves and changes.

• **Scalability**: Wireless LAN systems can be configured in a variety of topologies to meet the needs of specific applications and installations. Configurations are easily changed and range from peer-to-peer networks suitable for a small number of users to full infrastructure networks of thousands of users that enable roaming over a broad area.

Chapter 4

Links Budget for Universal Wireless Systems

4.1 Introduction

The base station will calculate the mobile's probability of bit error. The base station then will run an algorithm using different types of digital modulation, spread spectrum techniques and forward error correcting codes. The purpose of the algorithm is to choose the best environment for the mobile to operate at. Specifically speaking, the base station will choose the best type of modulation, spread spectrum technique and coding under which the mobile can operate best (considering some constraints, i.e. power, distance). To calculate the probability of bit error, we have to calculate the signal to noise ratio (SNR) first. This step is discussed in details in the section below.

4.2 Link design

The main purpose of a mobile communication system is to deliver a message of the desired quality to the destination. A link design endeavours to achieve this objective by the judicious choice of various link parameters. The figure of merit to measure the signal quality is the carrier-to-noise ratio measured at the input of the destination base station demodulator. The carrier-to-noise ratio is related to the baseband signal quality, the message, through a modulation-dependent factor. The parameters affecting the link design may be categorized according to the system element to which they relate, i.e. earth station, satellite or propagation channel, as follows.

4.2.1 Base station related

- Geographical location provides an estimate of rain fades, mobile station.
- Mobile station EIRP in the direction of the base station and base station-mobile path loss.
- Transmit antenna gain and transmitted power provide the base station EIRP.
- Receive antenna gain is related to the *G/T* of the base station.
- System noise temperature gives the sensitivity of the base station and is related to the *G/T*.
- Inter-modulation noise affects the total carrier-to-noise ratio.
- Equipment characteristics (e.g. demodulator implementation margin, crosspolar discrimination, filter characteristics) dictate the additional link margins.

4.2.2 Mobile station related

- Transmit antenna gain and radiation pattern provide the EIRP and coverage area
- Receive antenna gain and radiation pattern are related to the *G/T* and coverage area.
- Transmitted power is related to the mobile EIRP.
- Transponder gain and noise characteristics are related to EIRP and *G/T*.
- Inter-modulation noise affects the total carrier-to-noise power at the base station receiver.

4.2.3 Channel related

- Operating frequency is related to path loss and link margin.
- Modulation/coding characteristics govern the required carrier-to-noise ratio.
- Propagation characteristics govern the link margin and the choice of modulation and coding.

• Inter-system noise.

4.3 Concepts in a link budget

Many parameters that are involved in calculating a link budget should be understood. Understanding these parameters will help in having an accurate link budget. Here are some of them that we will need in calculating the link budget [33].

4.3.1 Transmitter Power p

The start of the RF transmission through space, and the first number in a link budget, is the transmitter power. The transmitter power is often adjusted to obtain the desired performance. The transmitter power P is usually specified in W, and not in dBW. In decibel equations the term for the transmitter is then displayed as

$$P_{dBW} = 10 \log P \text{ (dBW)} \quad (4.1)$$

where P is the absolute value in watts and P_{dBW} is in dBW. dBW is just a notation to point that the power was measured in watts. There may be some losses between the output of the transmitter and the antenna feed. If losses are significant, the transmitter power is measured at the input flange to the antenna. This is a practical point to make measurements. Losses before this point can be deducted from the original transmitter power.

4.3.2 Antenna Gain G

The purpose of a transmit antenna is to focus the RF power on the receive antenna. Its effectiveness is measured as the antenna gain, and is

G^* = power transmitted with antenna toward receiver / power transmitted without antenna (isotropic) (4.2)

This is a ratio that is referred to an ideal isotropic antenna. The antenna gain G of a parabolic reflector is

$$G^* = 4\pi \eta A / \lambda^2 \qquad (4.3)$$

where A is the physical area of the reflector, η is the antenna efficiency (a fraction less than 1), and λ is the wavelength. The typical range of antenna efficiency is 0.4 to 0.8 and a common approximation is 0.55. For circular antennas with a diameter D, the area A equals $\pi D^2/4$. The wavelength λ is equal to the velocity of light c divided by the frequency f. So the antenna gain can be written as

$$G^* = \eta(\pi D f / c)^2 \text{ (ratio)} \qquad (4.4)$$

For calculations, the antenna gain G is usually expressed in decibels. Taking the logarithm of both sides, and multiplying by 10, the antenna gain can be written as

$$G = 20 \log D + 20 \log f + 10 \log \eta + 20.4 \text{ (dBi)} \qquad (4.5)$$

where D is the diameter in m, and f is the frequency in GHz. The antenna efficiency η is expressed as a decimal, such as 0.55. The constant 20.4 dB/m^2 GHZ^2 is equal to 20 log (π/c). The velocity of light c is 0.299792458 m/ns. The i in dBi indicates that the ratio refers to an isotropic radiator. The dimensions of c are unusual, but appropriate if f is in GHz and D is in m. The antenna gain increases linearly with antenna area. It also increases for higher frequencies (smaller wavelengths). For a given area, an antenna will have a higher gain at K-band (14/11 GHz) than at C-band (6/4 GHz). The antenna gain is defined for the peak of the antenna beam.

4.3.3 Equivalent Isotropically Radiated Power EIRP

The transmit antenna focuses the RF power toward the receiver. The product of the transmitter power P and the antenna gain G_t is

$$\text{EIRP}^* = PG_t^* \text{ (W)} \tag{4.6}$$

where G_t is the transmit antenna gain ratio. The widely used term EIRP stands for equivalent isotropically radiated power. The antenna has increased the power received by a certain ratio, and the receiver "sees" it as a more powerful transmitter. The above equation is usually written in decibels as

$$\text{EIRP} = 10 \log P + G_t \quad \text{(dBW)} \tag{4.7}$$

The power P is in W, the gain G_t is in dB, and the product EIRP is in dBW.

4.3.4 Illumination Level W

The illumination level W is the power received per unit area, or the power received by an ideal antenna (efficiency = with 1 square-meter-area (A = 1 m^2). If the transmitter were isotropic, that is, radiating equally in all directions, then the illumination at a slant range of S would be $P/4\pi S^2$. With an antenna gain of G_t, the illumination level W at the receiver is increased by this ratio, and is

$$W^* = PG_t^* / 4\pi d^2 \quad \text{(W/m}^2\text{)} \tag{4.8}$$

where d is the distance from the transmitter to the receiver. If the distance is in m, then the illumination W is in W/m^2. The product $P\,.G_t^*$ is equal to the EIRP, as discussed above. The equation can be written in decibel form by taking the logarithm of both sides, and multiplying by 10. Then the illumination level W is

$$W = \text{EIRP} - 20 \log\ d - 71.0 \text{ (dBW/m}^2\text{)} \tag{4.9}$$

where the EIRP is in dBW, the distance S between transmitter and receiver is in km, and the illumination level W is in dBW /m^2. The constant 71.0 dBm^2/ km^2 is equal to 10 log[4π(1000 m/km)^2].

4.3.5 Free Space Path Loss L_F

The path loss in free space is an important concept in link budgets. It is a function of distance, but by using the wavelength it is expressed as a ratio (in dB). The free space path loss is not the only loss of received power attributable to the distance between the transmitter and receiver. Another path loss is due to atmospheric losses. The received carrier power is equal to the illumination W times the effective area of the receive antenna. Multiplying W^* by the effective area ηA yields the received carrier power C

$$C^* = \text{EIRP}^*\ \eta A \,/\, 4\pi d^2 \text{ (W)} \qquad (4.10)$$

where EIRP is the equivalent isotropically radiated power (P x G_t^*), η is the antenna efficiency, A the antenna cross-sectional area, and d the distance between transmitter and receiver. In the above equation A and d^2 must be in the same units. The performance of the transmit antenna is measured by an antenna gain G_t. The performance of the receive antenna is proportional to its effective area ηA. However, antennas are passive reciprocal devices. An antenna can be used for either transmission or reception. It is better to use the same performance criteria for reception as for transmission. In link budgets the performance of either antenna is measured by its gain. The antenna gain G is given by

$$G^* = 4\pi\eta A \,/\, \lambda^2 \qquad (4.11)$$

where A is the wavelength in meters. Solving this equation for the effective area ηA, and substituting into the above Equation yields

$$C^* = \text{EIRP}^*\ \lambda^2\, G_r^* \,/\, (4\pi d)^2 \qquad (4.12)$$

The received carrier power C is a product of three factors:

- The EIRP determined by the power and antenna gain of the transmitter
- The receive antenna gain determined by the receive end of the link

- The middle factor consisting of the rest of the link, which is a function of the wavelength λ and the distance d.

The free space path loss L_F:

$$L_F^* = (4\pi d)^2 / \lambda^2 \tag{4.13}$$

where the distance d and the wavelength λ must be in compatible units. The path loss L_F is a large ratio, with no dimensions. The received carrier power C can be written as EIRP* G_r^* / L_F^*. Taking the logarithm of both sides, and multiplying by 10 gives, in decibel notation:

$$C = \text{EIRP} - L_F + G_r \ (\text{dBW}) \tag{4.14}$$

The receiver power C and EIRP are in dBW, while the path loss L_F and receive antenna gain G_r are ratios in dB and dBi, respectively. The communications engineer speaks of a path loss of 196 dB as a positive quantity. It is convenient to express the path loss as a function of distance d and frequency f, rather than wavelength. The wavelength λ is equal to the velocity of light c divided by the frequency f in GHz (λ=c/f). Therefore, using decibel units, the free space path loss can be written as

$$L_F = 20 \log d + 20 \log f - 147.56 \ (\text{dB}) \tag{4.15}$$

where the range d is in m and the frequency in Hz. The constant is

$10 \log (4\pi/c)^2 = -147.56$ dB/m^2 HZ^2, where c is 3×10^8 m/s.

4.3.6 Okumura Model

Okumura's model is one of the most widely used models for signal prediction in urban areas. This model is applicable for frequencies in the range 150 MHz to 1920 MHz (although it is typically extrapolated up to 3000 MHz) and distances of 1 km to 100 km. It can be used for base station antenna heights ranging from 30 m to 1000 m.

Okumura developed a set of curves giving the median attenuation relative to free space (A_{mu}) in an urban area over a quasi-smooth terrain with a base station effective antenna height (h_{te}) of 200 m and a mobile antenna height (h_{re}) of 3 m. These curves were developed from extensive measurements using vertical omni-directional antennas at both the base and mobile, and are plotted as a function of frequency in the range 100 MHz to 1920 MHz and as a function of distance from the base station in the range 1 km to 100 km. To determine path loss using Okumura's model, the free space path loss between the points of interest is first determined, and then the value of $A_{mu}(f,d)$ (as read from the curves) is added to it along with correction factors to account for the type of terrain. The model can be expressed as

$$L_{50}(\text{dB}) = L_F + A_{mu}(f,d) - G(h_{te}) - G(h_{re}) - G_{AREA} \tag{4.16}$$

where L_{50} is the 50th percentile (i.e., median) value of propagation path loss, L_F is the free space propagation loss, A_{mu} is the median attenuation relative to free space, $G(h_{te})$ is the base station antenna height gain factor, $G(h_{re})$ is the mobile antenna height gain factor, and G_{AREA} is the gain due to the type of environment. Note that the antenna height gains are strictly a function of height and have nothing to do with antenna patterns. Okumura found that $G(h_{te})$ varies at a rate of 20 dB/decade and $G(h_{re})$ varies at a rate of 10 dB/decade for heights less than 3 m.

$$G(h_{te}) = 20 \log (h_{te}/200) \qquad 1000\text{ m} > h_{te} > 30\text{ m} \tag{4.17}$$

$$G(h_{re}) = 10 \log (h_{re}/3) \qquad h_{re} \leq 3\text{ m} \tag{4.18a}$$

$$G(h_{re}) = 20 \log (h_{re}/3) \qquad 10\text{ m} > h_{re} > 3\text{ m} \tag{4.18b}$$

Other corrections may also be applied to Okumura's model. Some of the important terrain related parameters are the terrain undulation height (Δh), isolated ridge height, average slope of the terrain and the mixed land-sea parameter. Once the terrain related parameters are calculated, the necessary correction factors can be added or subtracted as required. All these correction factors are also available as Okumura curves. Okumura's model is wholly based on measured data and does not provide any analytical explanation. For many situations, extrapolations of the derived curves can be made to obtain values outside the measurement range, although the validity of such extrapolations depends on the circumstances and the smoothness of the curve in question. Okumura's model is considered to be among the simplest and best in terms of accuracy in path loss prediction for mature cellular and land mobile radio systems in cluttered environments. It is very practical and has become a standard for system planning in modern land mobile radio systems in Japan. The major disadvantage with the model is its slow response to rapid changes in terrain, therefore the model is fairly good in urban and suburban areas, but not as good in rural areas. Common standard deviations between predicted and measured path loss values are around 10 dB to 14 dB [18].

4.3.7 Noise Temperature T

The absolute received carrier power C is important only when compared to the noise present in the system. Each of the several links involved in a satellite service adds noise. The overall end-to-end, or system carrier-to-noise ratio (C/N) is the composite of each of these links. Noise may be expressed in various ways. It is often expressed as an equivalent noise temperature T_S. The system noise temperature is composed of several factors, such as antenna noise temperature and receiver noise temperature. There are many other noise sources. Some may not be related to an actual temperature, but the noise power can still be expressed as a noise temperature.

The antenna noise is often related to the temperature of the background at which the antenna is pointed. The noise temperature of an earth station antenna may range from 30 Kelvin, for a good antenna looking at space to 10000 Kelvin or higher for an antenna pointed at the sun. The ratio G/Ts of the receive antenna gain to the noise temperature is used as a figure of merit for the receiving system. The ratio of received carrier power C to noise is commonly expressed in three ways: C/T, C/kT, C/kTB.

4.3.8 Figure of Merit G/Ts for Receiving System

The two important parameters for the receiving system are the receive antenna gain G_r and the receiving system noise temperature T_s. The latter is the sum of the low-noise amplifier (LNA), and the noise from any loss elements between the antenna and the LNA. The ratio of G_r to T_s is called the figure of merit, written as G/T_s. Receiving stations can be improved with a larger antenna gain G_r (larger diameter antenna), or a lower noise temperature T_s (better low-noise amplifier).

The antenna gain is usually given in dBi (i for isotropic), and the system noise temperature T_s in K, so the figure of merit G/T_s is in dBi/K. The numerical values of the gain in dBi and the temperature in K cannot be divided. One is in decibels, and the other is not. The noise temperature can be converted to decibels, and then combined with the antenna gain. Then the quotient is found by subtracting the gain in dBi and the temperature in dBK. This calculation can be expressed in the equation

$$G/T_s = G_r - 10 \log T_s \text{ (dBi/K)} \quad (4.19)$$

where G_r is in dBi, T_s in Kelvin, and G/T_s in dBi/K. The figure of merit of an antenna system (G/T_s) is nearly always given in dBi/K and is part of the vocabulary of a communication.

4.3.9 Carrier-to- Thermal-Noise Ratio C/T

One criterion of link performance is the ratio of the carrier power C to the noise temperature T. To calculate this, start with the equation

$$C = \text{EIRP} - L + G_r \text{ (dBW)} \qquad (4.20)$$

To calculate C/T, the term 10 log T is subtracted from each side of the equation. The result can be written

$$C/T = \text{EIRP} - L + G/T_s \text{ (dBW/K)} \qquad (4.21)$$

The C/T ratio is equal to the EIRP in dBW, minus the path loss L in dB, plus the receiving system figure of merit G/T_s in dBi/K. The ratio is then in dBW/K.

The reason for writing the equation in this form is that the terms C/T and G/T_s, expressed in decibel notation, have specific meanings for a communications engineer. It is common practice to group terms in equations that are part of the engineer's vocabulary. Note that the EIRP is a function of the transmitter power and antenna, L is a function of the distance (and the frequency), and G/T_s is a figure of merit for the receiver.

4.3.10 Carrier-to-Noise-Density Ratio C/N$_0$

All objects at a physical temperature T generate electromagnetic radiation. Part of this radiation will be at microwave frequencies, and will be present in a receiving system. The noise power N of radiation within a bandwidth B is

$$N = kTB \quad \text{(W)} \qquad (4.22)$$

where k is Boltzmann's constant:

k = 1.3806 x 10-23 W s/K = -228.60 dBW/Hz.K

where Hz.K is equal to Hertz times Kelvin.

The noise density N_o is the noise power in a bandwidth of 1 Hz, and is uniform at microwave frequencies. It is

$$N_o = N/B = kT \text{ (dBW/Hz)} \tag{4.23}$$

and is equal to Boltzmann's constant times the noise temperature. If the signal has not been demodulated, or the bandwidth is unknown, a measure of system performance is the ratio of the carrier power C to the noise density $N_o = kT$. Then this carrier-to-noise-density ratio is

$$C/N_o = C/kT = C/T + 228.6 \text{ (dBHz)} \tag{4.24}$$

This ratio is written as C/N_o or as C/kT. It is the carrier-to-thermal-noise ratio referred to a standard 1-Hz bandwidth. The absolute value of Boltzmann's constant is a very small number, so in decibels it is a large negative number. In link budgets k is usually in the denominator, so a negative number is subtracted. This is the same as adding +228.6, which is equivalent to multiplying by $1/k$, the reciprocal of Boltzmann's constant.

4.3.11 Carrier-to-Noise Ratio C/N

A filter in the receiver usually blocks most of the noise, and only the frequency bandwidth needed for communications is allowed to pass. The carrier-to-noise ratio is then

$$C/N = C/kTB = C/kT - 10 \log B \text{ (dB)} \tag{4.25}$$

where the carrier-to-noise-density ratio C/kT or C/N_o is in dBHz, and the bandwidth B is in Hz.

4.3.12 Total carrier-to-noise ratio

As noted above, the main objective in the link design is to establish the desired carrier-to-noise ratio at the input of a base station demodulator, within all practical constraints. The carrier-to-noise ratio at the demodulator input is a function of the uplink and downlink EIRP; the noise introduced in the base station receiver and the mobile; and the amount of interference. The received message quality is related to the carrier-to-noise ratio at the demodulator input as follows:

S/N (or bit error rate) = C/N_T

The relationship for obtaining the total carrier-to-noise ratio is developed as follows.

The total noise N_T at the receiver is the summation of noise from all sources:

$$N_T = N_U + N_D + N_I + N_i \qquad (4.26)$$

Where N_U = uplink noise, measured at the satellite

N_D = downlink noise, measured at the receiving earth station

N_I = inter-modulation noise in the satellite link

N_i = Interference noise.

The total carrier-to-noise ratio is then

$$C/N_T = C / (N_U + N_D + N_I + N_i) \qquad (4.27)$$

For digital systems it is usual to measure the system performance as bit energy-to-noise power density E_b/N_o. Then E_b/N_o directly replaces C/N_T in the above equations and noise power is expressed in terms of power density.

4.3.13 Received carrier power

The transmission equation

$$C = P_s\,(\text{dB}) + G_s\,(\text{dB}) + G_d\,(\text{dB}) - 20\log(4\pi D/\lambda) \qquad (4.28)$$

is the basis for the derivation of the received carrier level in terms of the effective isotropic radiated power (EIRP}, path loss and the receiver antenna gain. The transmission equation assumes an ideal condition with path loss as the only loss factor.

However, in practice additional losses and link degradations must be considered. Such degradations are compensated by transmitting additional power, termed link margin. Thereby it is ensured that the desired quality objective is met under the worst possible conditions. It should be noted that degradations are usually present for only a small fraction of the time and therefore the link quality is in effect better than or most of the time. It is worth mentioning here that the overall system cost increases as the link reliability is improved because the transmitter or receiver sensitivity or both must be increased, tending to increase the system cost. Hence a compromise is struck between the link and system cost.

The main components considered in obtaining the downlink margin are:

- Antenna tracking loss.
- Atmospheric absorption.
- A statistical loss parameter due to hydrometers (mainly rain).
- A statistical loss parameter due to shadowing and multipath when a mobile system is considered.
- A statistical loss parameter associated with scintillation.
- Intra and inter-system interference.
- Miscellaneous losses, e.g. wet radome, equipment ageing, demodulator inefficiencies.

A simple arithmetic addition of the statistical loss parameters gives a pessimistic fading scenario. Hence a root sum square of the standard deviations of various losses is often used in practice. The link margin depends on the frequency of operation and service (e.g. mobile, fixed, direct-to-home broadcasts). Therefore the transmission equation can be modified to

$$C = P_e - L_p - L_m + G_d \text{ dB} \quad (4.29)$$

where P_e = EIRP (dBW) [earth station or satellite]

L_p = uplink path loss (dB)

L_m = link margin (dB)

G_d = destination antenna gain (dB) in the direction of the transmitter.

4.3.14 Uplink carrier-to-noise ratio

Considering the uplink only (base station-mobile), the main source of noise power at the destination is the thermal noise power at the mobile receiver. We know that

$$N = kT_sB$$

where k is the Boltzman constant

T_s the noise temperature of the receiver

B the pre-detection bandwidth.

The carrier-to-noise ratio (C_u/N_u) in dB at the mobile is then

$$C_u/N_u = (P_e - L_{pu} - L_{mu} + G_s) - 10 \log (kT_sB) \quad (4.30a)$$

or

$$C_u/N_u = P_e - L_{pu} - L_{mu} + G_s - 10 \log (T_s) - 10 \log (kB) \quad (4.30b)$$

The above equation can be rearranged as

$$C_u/N_u = P_e - L_{pu} - L_{mu} + G_s/T_s - 10 \log (k) - 10 \log (B) \quad (4.30c)$$

where P_e = base station EIRP

L_{pu} = uplink path loss

L_{mu} = uplink margin

$G_s/T_s = G/T$

$10 \log (k) = -228.6$ dBW/K.

The carrier-to-noise ratio, when expressed in per Hertz of bandwidth, is known as the carrier-to-noise power spectral density and obtained from above equation by setting B to unity. The term G_s/T_s is the figure of merit for measuring the receiver sensitivity. The sensitivity increases with an increase in G_s/T_s.

4.3.15 Downlink carrier-to-noise ratio

Similarly the downlink carrier-to-noise ratio C_d/N_d is

$$C_d/N_d = P_s - L_{pd} - L_{md} + G_e/T_e - 10 \log (k) - 10 \log (B) \quad (4.31)$$

Where P_s = EIRP from satellite in the direction of the earth station

L_{pd} = downlink path loss

L_{md} = downlink margin

G_e/T_e = G/T of destination base station.

4.4 Example for the uplink budget calculation

Assume the following:

R_b = 10k bits/sec = 40 dBHz. R_b is the bit data rate

BW = 1.28 MHz = 61.1 dBHz

T = 27 dB.K

f_c = 920 MHz. f_c is the carrier frequency

U = 60. U is the number of users

P_t = 200 mW. P_t is the power transmitted

d = 1 km

k = -228.6 dBW/K.Hz. (Boltzmann constant)

From (4.15)

$$L_F = 20 \log d + 20 \log f - 147.56 \text{ (dB)} \quad (4.15)$$

We get Path loss $L_F = 60 + 179.27 - 147.56 = 91.72$ dB

Using Okumura Model:

From the graphs, A_{mu}(920Mhz,1000m) ≈ 18 dB

$G_{AREA} \approx 9$ dB (for suberban areas)

From (4.17a,b)

$G(h_{te}) = 20 \log (30/200) = -16.48$ dB

$G(h_{re}) = 10 \log (3/3) = 0$

Using (4.16)

$$L_{50}(\text{dB}) = L_F + A_{mu}(f,d) - G(h_{te}) - G(h_{re}) - G_{AREA} \quad (4.16)$$

$L_{50}(\text{dB}) = 91.72 + 18 - (-16.48) - 0 - 9 = 117.2$ dB

Assume that the gain of the transmit antenna is $G_t = 20$ dB, and the gain of the receive antenna is $G_r = 0$.

Also Assume Receiver Margin = 3 dB

Multipath margin = 5 dB

Fade margin = 10 dB

From (4.7)

$$\text{EIRP} = 10 \log P + G_t \quad (\text{dBW}) \quad (4.7)$$

EIRP = 10 log (200mW) + 20 = 13 dBW

Using (4.14) to find the received carrier power

$$C = \text{EIRP} - L_F + G_r \quad (\text{dBW}) \quad (4.14)$$

And taking in account the effect of the Receiver Margin, the Multipath margin and the Fade margin.

Equation (4.14) becomes:

C = EIRP - $L_F + G_r$ - Receiver Margin - Multipath Margin - Fade Margin (dBW)

$C = 13 - 117.2 + 0 - 3 - 5 - 10 = -122.2$ dB

From (4.23)

$N_o = kT = -201.6$ dB

From (4.22)

$$N = kTB \quad \text{(W)} \tag{4.22}$$

$N = N_o$ (dB) + BW (dB) = -201.6 + 61.07 = -140.53 dB = 8.85×10^{-15} W

N_I (interference power) = C dB + 10 log U = -104.41 dB

N_T (total noise power) = N (W) + N_I(W) = 3.61×10^{-11} W = -104.41 dB

$(Nu)_{IF}$ (uplink noise power at IF) = N_T (dB) – BW(dB) = -104.41 – 61.07 = - 165.48 dB

$(C/N_u)_{IF} = -122.2 + 165.48 = 43.28$ dB

$Eb/Nu = C/W_dN_u$

For PSK modulation. $W_d = R_b = 40$ dB

$Eb/Nu = 3.28$ dB

4.5 Example for the downlink budget calculation

Assume $f_c = 1.9$ GHz

$d = 1000$ m

$P_t = 0.1$ W

U(# of users) = 20

From (4.15)

$$L_F = 20 \log d + 20 \log f - 147.56 \quad \text{(dB)} \tag{4.15}$$

We get Path loss $L_F = 60 + 185.58 - 147.56 = 98.02$ dB

Using Okumura Model:

From the graphs, $A_{mu}(1.9 \text{ GHz}, 1000\text{m}) \approx 20$ dB

$G_{AREA} \approx 12$ dB (for suberban areas)

From (4.17a,b)

$G(h_{te}) = 20 \log (30/200) = -16.48$ dB

$G(h_{re}) = 10 \log (3/3) = 0$

Using (4.16)

$$L_{50}(\text{dB}) = L_F + A_{mu}(f,d) - G(h_{te}) - G(h_{re}) - G_{AREA} \qquad (4.16)$$

$L_{50}(\text{dB}) = 98.02 + 20 - (-16.48) - 0 - 12 = 122.49$ dB

Assume that the gain of the transmit antenna is $G_t = 0$ dB, and the gain of the receive antenna is $G_r = 0$.

Also Assume Receiver Margin = 3 dB

Multipath margin = 5 dB

Fade margin = 10 dB

From (4.7)

$$\text{EIRP} = 10 \log P + G_t \quad (\text{dBW}) \qquad (4.7)$$

EIRP = 10 log (0.1 W) + 0 = -10 dBW

Using (4.14) to find the received carrier power

$$C = \text{EIRP} - L_F + G_r \ (\text{dBW}) \qquad (4.14)$$

And taking in account the effect of the Receiver Margin, the Multipath margin and the Fade margin.

Equation (4.14) becomes:

C = EIRP - L_F + G_r - Receiver Margin - Multipath Margin - Fade Margin (dBW)

$C = -10 - 122.49 + 0 - 3 - 5 - 10 = -150.49$ dB $= 3.23 \times 10^{-16}$ W

From (4.23)

$N_o = kT = -201.6$ dB

From (4.22)

$$N = kTB \quad \text{(W)} \tag{4.22}$$

$N = N_o$ (dB) + BW (dB) $= -201.6 + 61.07 = -140.53$ dB $= 8.85 \times 10^{-15}$ W

N_I (interference power) $= C$ dB + 10 log $U = -150.49 + 13.01 = -137.48$ dB

$= 1.79 \times 10^{-14}$W

N_T (total noise power) $= N$ (W) + N_I(W) $= 2.68 \times 10^{-14}$ W $= -135.72$ dB

$(Nu)_{IF}$ (uplink noise power at IF) $= N_T$(dB) – BW(dB) $= -135.72 - 61.07 = -196.79$ dB

$(C/N_u)_{IF} = -150.49 + 196.79 = 46.3$ dB

$Eb/Nu = C/W_d N_u$

For PSK modulation. $W_d = R_b = 40$ dB

$Eb/Nu = 6.3$ dB

4.6 The AWGN Channel Considered in the Wireless Universal Power Budget Algorithm

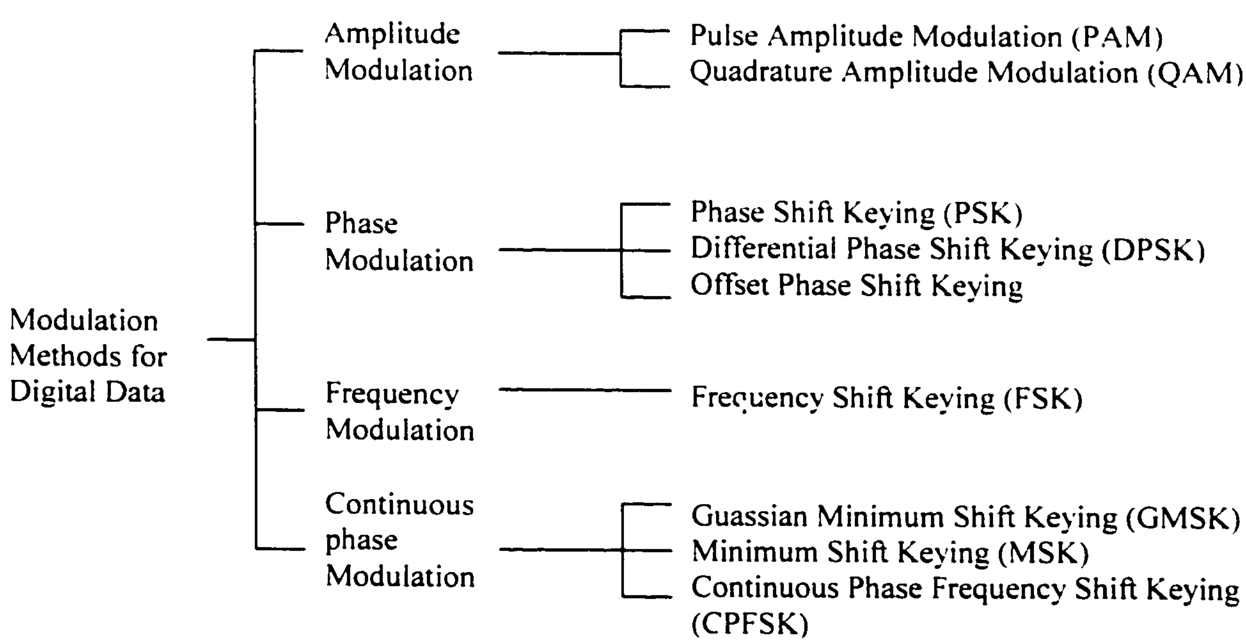
The study will assume the noise in the channel to be Additive White Gaussian Noise (AGWN). The white gaussian noise is a model for the thermal noise generated by random electron movement in the receiver. This model can be thought of as a wireline channel model. since there is effectively perfect transmission from transmitter to receiver. The equation for the received signal in an AWGN channel is

R(t) = S(t) + N(t)

Where S(t) is the transmitted signal, R(t) is the received signal, and N(t) is a zero-mean wide-sense stationary random process with power spectral density S(jw) = No/2. We can use the performance of the AWGN channel to compare systems using different methods of modulation. These probability of error plots, because of their shape, are called "waterfall curves." These waterfall curves can be used to compare the performance of different digital communication systems.

4.7 Potential Digital Modulation Techniques for the Wireless Universal Power Budget Algorithm

There are different methods to modulate digital data. It can be briefed as follows:



The study uses 23 different modulation types.

These types are as follows:

1- Phase shift keying (PSK).

2- 8-phase shift keying (8-PSK).

3- 16-phase shift keying (16-PSK).

4- 32-phase shift keying (32-PSK).

5- Quadrature phase shift keying (QPSK).

6- Offset quadrature phase shift keying (OQPSK).

7- π/4 quadrature phase shift keying (π/4 QPSK).

8- Minimum shift keying (MSK).

9- Binary differential phase shift keying (BDPSK).

10- 16-quadrature amplitude modulation (16-QAM).

11- 64-quadrature amplitude modulation (64-QAM).

12- Coherent binary frequency shift keying (Coherent BFSK).

13- Coherent 4-frequency shift keying (Coherent 4-FSK).

14- Coherent 8-frequency shift keying (Coherent 8-FSK).

15- Coherent 16-frequency shift keying (Coherent 16-FSK).

16- Coherent 32-frequency shift keying (Coherent 32-FSK).

17- Non-Coherent binary frequency shift keying (Non-Coherent BFSK).

18- Non-Coherent 4-frequency shift keying (Non-Coherent 4-FSK).

19- Non-Coherent 8-frequency shift keying (Non-Coherent 8-FSK).

20- Non-Coherent 16-frequency shift keying (Non-Coherent 16-FSK).

21- Non-Coherent 32-frequency shift keying (Non-Coherent 32-FSK).

22- Guassian Minimum Shift Keying (GMSK, BT= 0.25).

23- Guassian Minimum Shift Keying (GMSK, BT= ∞).

Tables of the values of Probability of bit error (P_b) vs. Signal to noise ratio (SNR) for each type of modulation is included in the appendix. The program will calculate the signal to noise ratio (SNR) based on the given data (i.e. data rate, power, distance etc.). The program will search the tables looking for the probability of bit error (P_b) that corresponds to the calculated SNR.

4.8 Potential Spread Spectrum Techniques for the Wireless Universal Power Budget Algorithm

In Code Division Multiple Access (CDMA) systems all users transmit in the same bandwidth simultaneously. Communication systems following this concept are spread spectrum systems. In this transmission technique, the frequency spectrum of a data-signal is spread using a code uncorrelated with that signal. As a result the bandwidth occupancy is much higher than required for modulation. The codes used for spreading have low cross-correlation values and are unique to every user. This is the reason that a receiver which has knowledge about the code of the intended transmitter, is capable of selecting the desired signal. The main parameter in spread spectrum systems is the processing gain:the ratio of transmission and information bandwidth which is basically the spreading factor. The processing gain determines the number of users that can be allowed in a system, the amount of multi-path effect reduction, the difficulty to jam or detect a signal etc. For spread spectrum systems it is advantageous to have a processing gain as high as possible. There exist different techniques to spread a signal: Direct-Sequence (DS), Frequency-Hopping (FH). Time-Hopping (TH) and Multi-Carrier CDMA (MC-CDMA). It is also possible to make use of combinations of them. The study will focus only on Direct-Sequence (DS). Frequency-Hopping (FH), 802.11 Direct-Sequence (802.11 DS) and 802.11 Frequency-Hopping (802.11 FH) systems.

4.8.1 Direct Sequence

Direct Sequence is the best known Spread Spectrum Technique. The data signal is multiplied by a Pseudo Random Noise Code (PN code). A PN code is a sequence of chips valued -1 and 1 (polar) or 0 and 1 (non-polar) and has noise-like properties. This results in low cross-correlation values among the codes and the difficulty to jam or detect a data message. In direct-sequence systems the length of the code is the same as the spreading factor. The generation of PN codes is relatively easy, a number of shift-registers is all that is required. For this reason it is easy to introduce a large processing-gain in Direct-Sequence systems. In the receiver, the received signal is multiplied again by the same (synchronized) PN code. Since the code existed of +1s and -1s, this operation completely removes the code from the signal and the original data-signal is left. The main problem with applying Direct Sequence spreading is the so-called Near-Far effect which is illustrated in the figure below. This effect is present when an interfering transmitter is much closer to the receiver than the intended transmitter. Although the cross-correlation between codes A and B is low, the correlation between the received signal from the interfering transmitter and code A can be higher than the correlation between the received signal from the intended transmitter and code A. The result is that proper data detection is not possible.

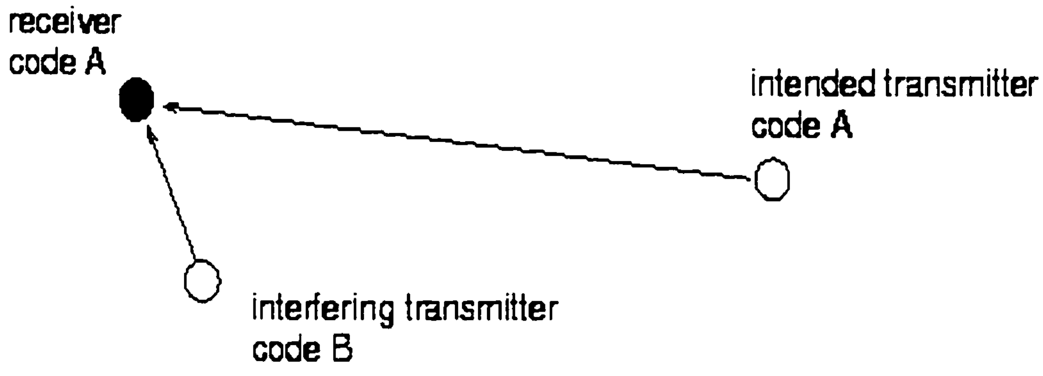


Figure 4.1: Near-far problem in Direct Sequence systems

The program will calculate the signal to noise ratio (SNR) for Direct Sequence systems The same way as before except for replacing No (thermal noise) by $No + (U.P/W_s)$, where U is the number of users, P is the power of the received carrier and W_s is the spread spectrum bandwidth. The program will search the tables looking for the probability of bit error (P_b) that corresponds to the calculated SNR.

4.8.2 IEEE 802.11 DSSS PHY characteristics

• 2.4 GHz ISM band (FCC 15.247)

• 1 and 2 Mb/s data rate (DBPSK and DQPSK modulation)

• Symbol rate 1MHz

• Chipping rate 11 MHz with 11-chip Barker sequence

• Multiple channels in 2.4 to 2.4835 GHz band

For 802.11 Direct Sequence systems, a 22 MHz spread spectrum bandwidth is used.

4.8.3 Frequency Hopping

When applying Frequency Hopping, the carrier frequency is hopping according to a unique sequence. A disadvantage of Frequency-Hopping as opposed to Direct-Sequence is that obtaining a high processing-gain is hard. There is need for a frequency-synthesizer able to perform fast hopping over the carrier-frequencies. The faster the hopping-rate is, the higher the processing gain. On the other hand, Frequency-Hopping is less affected by the Near-Far effect than Direct-Sequence. Frequency-Hopping sequences have only a limited number of hits with each other. This means that if a near-interferer is present, only a number of frequency-hops will be blocked instead of the whole signal. From the hops that are not blocked it should be possible to recover the original data-message.

The probability of bit error for a Frequency Hopping System is calculated as follows:

$$P_{FH} = P_b (1 - \{(U - 1) / (W_s/W_d) \}) + 0.5 \{ (U - 1) / (W_s/W_d) \}$$

Where U is the number of users

W_s is the spread spectrum bandwidth

W_d is the data bandwidth

P_b is the probability of bit error of the system without spread spectrum

4.8.4 PHY of the 802.11 FHSS Wireless LAN

Frequency Hopping is one of the variants of Spread Spectrum- a technique which enables coexistence of multiple networks (or other devices) in same area. FCC recognizes Frequency Hopping as one of the techniques withstanding "fairness" requirements for unlicensed operation in the ISM bands. 802.11 Frequency Hopping PHY uses 79 nonoverlapping frequency channels with 1 MHz channel spacing. FH enables operation of up to 26 collocated networks, enabling therefore high aggregate throughput. Frequency Hopping is resistant to multipath fading through the inherent frequency diversity mechanism.

For 802.11 Frequency hopping system, a 79 MHz spread spectrum bandwidth is used.

4.8.5 Regulatory requirements for FH

For North America:

- Frequency band: 2400-2483.5 MHz
- At most 1 MHz bandwidth (at -20 dB re peak)
- 79 hopping channels, pseudorandom hopping pattern
- At most 1 W transmit power and 4 W EIRP (including antenna)

4.8.6 802.11 FHSS Frame Format

- PHY header indicates payload rate and length: CRC16 protected
- Data is whitened by a synchronous scrambler and formatted to limit DC offset variations
- Preamble and Header always at 1 M bit/sec: Data at 1 or 2 M bit/sec

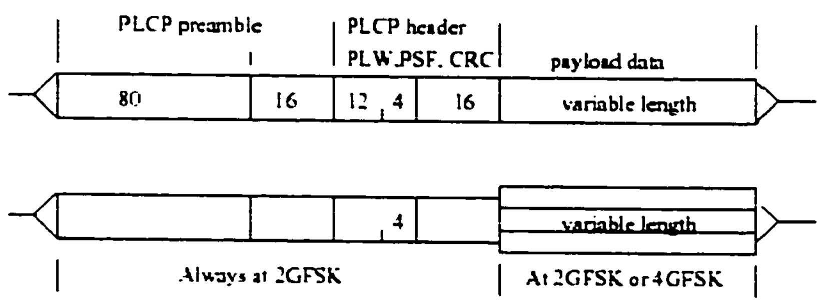


Figure 4.2: Frame format for 802.11 FHSS

4.9 Potential Forward Error Correcting Codes for the Wireless Universal Power Budget Algorithm

The purpose of forward error correction (FEC) is to improve the capacity of a channel by adding some carefully designed redundant information to the data being transmitted through the channel. The process of adding this redundant information is known as channel coding. In our search for useful and efficient codes there are several objectives to keep in mind.

1. Detection and correction of errors introduced in the channel.
2. Efficient transmission of data.
3. Easy encoding and decoding schemes.

The first item in the list above is the most important. Ideally we'd like a code that is capable of correcting all errors due to noise. The second objective is an efficiency issue. We don't want to waste time sending extraneous data. Easy encoding and decoding is also desirable for efficiency reasons as well as the ease of implementation in hardware. In general, the more errors that a code needs to correct per message digit, the less efficient the transmission and also probably the more complicated the encoding and decoding schemes. A good code balances these objectives.

4.9.1 Turbo Codes

The turbo code is composed of two or more identical recursive systematic convolutional (RSC) encoders, separated by an interleaver. The interleaver randomizes the information sequence of the second encoder to uncorrelate the inputs of the two encoders. Since there are two encoded sequences, in the decoder, decoding operation begins by decoding one of them to get the first estimate of the information sequence. This requires that the decoder has to use a soft decision input and to produce some kind of soft-output.

4.9.2 Convolutional Codes

Convolutional codes operate on serial data, one or a few bits at a time. There are a variety of useful convolutional codes, and a variety of algorithms for decoding the received coded information sequences to recover the original data. Convolutional codes are usually described using two parameters: the code rate and the constraint length. The code rate, k/n, is expressed as a ratio of the number of bits into the convolutional encoder (k) to the number of channel symbols output by the convolutional encoder (n) in a given encoder cycle. The constraint length parameter, K, denotes the "length" of the convolutional encoder, i.e. how many k-bit stages are available to feed the combinatorial logic that produces the output symbols. Closely related to K is the parameter m, which indicates how many encoder cycles an input bit is retained and used for encoding after it first appears at the input to the convolutional encoder. The m parameter can be thought of as the memory length of the encoder.

4.9.3 Reed-Solomon Codes

Reed-Solomon codes are block-based error correcting codes with a wide range of applications in digital communications and storage. The Reed-Solomon encoder takes a block of digital data and adds extra redundant bits. Errors occur during transmission or storage for a number of reasons (for example noise or interference, scratches on a CD, etc). The Reed-Solomon decoder processes each block and attempts to correct errors and recover the original data. The number and type of errors that can be corrected depends on the characteristics of the Reed-Solomon code. Reed-Solomon code is specified as RS(n,k)

with s-bit symbols. This means that the encoder takes k data symbols of s bits each and adds parity symbols to make an n symbol codeword. There are n-k parity symbols of s bits each. A Reed-Solomon decoder can correct up to t symbols that contain errors in a codeword, where $2t = n\text{-}k$.

4.9.4 Concatenated coding

Concatenated codes have been introduced to exploit the best from both block-coding and convolutional coding. Good performance has been achieved with an outer block-code and an inner convolution code. Optimization is necessary to obtain high performance together with low transmission delay and overhead.

4.9.5 Codes used in this thesis

10 different codes were used in the study to see the effect of coding in performance.

- Reed-Solomon (256,192).
- Concatenated (Reed-Solomon & Convolutional) RS (255,233) & Convolutional R=½, K = 7.
- Convolutional (68,32), K=3 (constraint length), k = 32 bits.
- Turbo (68,32), K=3 (constraint length), k = 32 bits.
- Convolutional (68,30), K=5 (constraint length), k = 30 bits.
- Turbo (68,30), K=5 (constraint length), k = 30 bits.
- Convolutional (96,44), K=5 (constraint length), k = 44 bits.
- Turbo (96,44), K=5 (constraint length), k = 44 bits.
- Convolutional, K=5 (constraint length), R = ½, Soft Decision.
- Convolutional, K=5 (constraint length), R = ½, Hard Decision.

4.10 A New Universal Power Budget Algorithm and System Selection

As mentioned in the introduction, after calculating the signal to noise ratio (SNR) and then the probability of bit error, a universal power budget algorithm is followed to choose the environment under which the mobile performs best. Environment means the type of digital modulation, spread spectrum technique and forward error correcting code that is used. A C++ program was written to run the algorithm for 24 different modulation types, 4 different spread spectrum techniques and 10 types of forward error correcting codes. The program will choose the best 10 performances. The steps of the program will be discussed in details below.

In simple words, the program will ask the user to enter the following information: Data Rate (R_b), Spread Spectrum Bandwidth (W's), Mobile Transmission Power, Maximum Distance, Number of Users, Carrier Frequency (Fc), Base Station effective antenna height, Mobile effective antenna height, Receiver Margin, Multipath Margin, Fade Margin, Temperature and Maximum Cost. All these variables were defined in the sections above except for the cost. We mean by the cost: the complexity of the hardware and the software of the system. Our reference is the DPSK system. The performance of a mobile system under low cost conditions doesn't support many different modulation types or spread spectrum techniques or coding types. For example, if the maximum cost is set to 15, that means the mobile can use any modulation type but can't use any spread spectrum technique or coding. The cost of different systems is showed in the tables below.

Modulation Type	Relative Cost to DPSK
DPSK	1
FSK (non-coherent)	3
FSK (coherent)	4
PSK	4
QPSK,OQPSK, π/4 QPSK	6
MSK	6
QAM 16	10
QAM 64	12

Multiple Access Technique	Relative Cost to DPSK
Direct Sequence	20
Frequency Hopping	15
802.11	20

Coding Type	Relative Cost to DPSK
Convolutional (K=3,5)	20
Reed-Solomon (256-k)	30
Concatenated	40
Turbo	50

Table 4.1: Relative Cost of the Systems to DPSK

Using the information which the user specified, the total carrier to noise ratio (SNR) is calculated. Probability of bit error can be found from the tables of P_b vs. SNR provided in the appendix. The algorithm is run in real time for 24 potential modulation types as explained in section 4.7. Once P_b for the first modulation is found, we check the cost of the system. If the cost is more than the maximum cost specified, we ignore the system and go to check the second modulation type. If the cost is less than the maximum cost, we go to the next level, which is using spread spectrum techniques. As explained in section 4.8, there are 4 potential techniques. P_b is calculated for the new system (which uses modulation and spread spectrum techniques). If the cost is more than the maximum cost specified, we ignore the system and go to check the second spread spectrum technique. If the cost is less than the maximum cost, we go to the next level, which is forward error correcting codes. As mentioned in section 4.9, the study included 10 potential different codes. P_b is then calculated for the new system (which uses modulation, spread spectrum and coding). If the cost is more than the maximum cost specified, we ignore the system and go to check the second coding type. If the cost is less than the maximum cost, P_b is saved and the system will be a candidate for the best 10 systems that give the best performance (the lowest P_b). Then, the loop starts again. The Pb of the second modulation will be found. The cost of the system will be checked and so on.

As mentioned above, the P_b of the modulated system will be calculated from the graphs and tables of P_b vs. SNR given that SNR is known. The P_b of the system changes when you add spread spectrum techniques. The new SNR for a direct sequence system is calculated by replacing the thermal noise (N_0) by $N_0 + U.P/W_s$ where U is the number of users, P is the carrier power and Ws is the spread spectrum bandwidth as shown in sections 4.4 and 4.5. P_b is figured as before from P_b vs. SNR graphs and tables using the new SNR. The P_b is calculated in the same fashion for direct sequence 802.11. For a frequency hopping system, P_{bfh} is calculated differently. We use the following equation:

$$P_{bfh} = P_b \, . \, (1 - \; (U - 1)/(W_s \, / \, W_d) \;) + 0.5 \, (\, (U - 1)/(W_s \, / \, W_d))$$

Where P_b is the probability of bit error of the system using only modulation.

When coding is used, the P_b of system changes as well. Using the new SNR and using the tables provided in the appendix, P_b can be found easily.

4.10.6 Important note

The performance (P_b vs. SNR) of the 10 types of coding were available only for Binary Phase Shift Keying (BPSK). To find the performance for the other types of modulation, (i.e. the P_b for QPSK modulation using Reed-Solomon codes Vs. SNR) the following method is used. The difference in SNR between uncoded BPSK and uncoded other types of modulation at the same P_b, will yield the same difference in the case of coding. For example, in the uncoded case: we have a P_b of 0.05 at 1 dB for BPSK, however, we get a P_b of 0.05 at 3 dB for 8-PSK. So the difference in SNR is 2 dB. In the coded case: (taking (256,192) Reed-Solomon code as an example) we have a P_b of 0.1 at 4 dB for BPSK, so we should get a P_b of 0.1 at 6 dB for 8-PSK.

Table 4.2 in the next page clarifies the SNR difference between uncoded BPSK and uncoded other types of modulation is below. Another example, it can be seen from the table that there is a difference of 3 dB between BPSK and 8-PSK at P_b of 10^{-3}. Meaning that 8-PSK needs 3dB more than BPSK to achieve the P_b of 10^{-3}. This was the case of uncoded BPSK. The same thing approximately applies using coding. Using this method we construct tables of P_b vs. SNR for other coded modulations.

Modulation \ P_b	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
BPSK	0	0	0	0	0	0
8-PSK	2	3	3	3	3	3
16-PSK	4	6	7	7	7	7
32-PSK	6	11	12	12	12	12
QPSK	0	0	0	0	0	0
OQPSK	0	0	0	0	0	0
π/4 QPSK	0	0	0	0	0	0
MSK	0	0	0	0	0	0
BDPSK	4	3	1.5	1	1	1
16-QAM	2	3.5	3.5	3	3.5	4.5
64-QAM	6	7	7	8	8.5	8.5
Coherent BFSK	4	3	3	3	3	3
Coherent 4-FSK	2.5	0.5	0	0	0	0.5
Coherent 8-FSK	2	-0.5	-1	0	-0.5	-1
Coherent 16-FSK	1	-1	-2	-0.5	-2	-2
Coherent 32-FSK	1	-1.5	-2.5	-1.5	-3	-2.5
Non-Coherent BFSK	7	4.5	4	4	4	4
Non-Coherent 4-FSK	5	2	1.5	1	-1	1
Non-Coherent 8-FSK	4	0.5	0	0	-0.5	0
Non-Coherent 16-FSK	3.5	0	-0.5	-1	-1	-1
Non-Coherent 32-FSK	3	-0.5	-2	-2	-2.5	-2.5
GMSK (BT = 0.25)	3	1.5	0.5	1.5	0.5	1
GMSK (BT = ∞)	2	0.5	0	0.5	0	0

Table 4.2: The dB needed in SNR to achieve the same P_b level

The flow chart in the following pages will give a general idea about the steps of the algorithm.

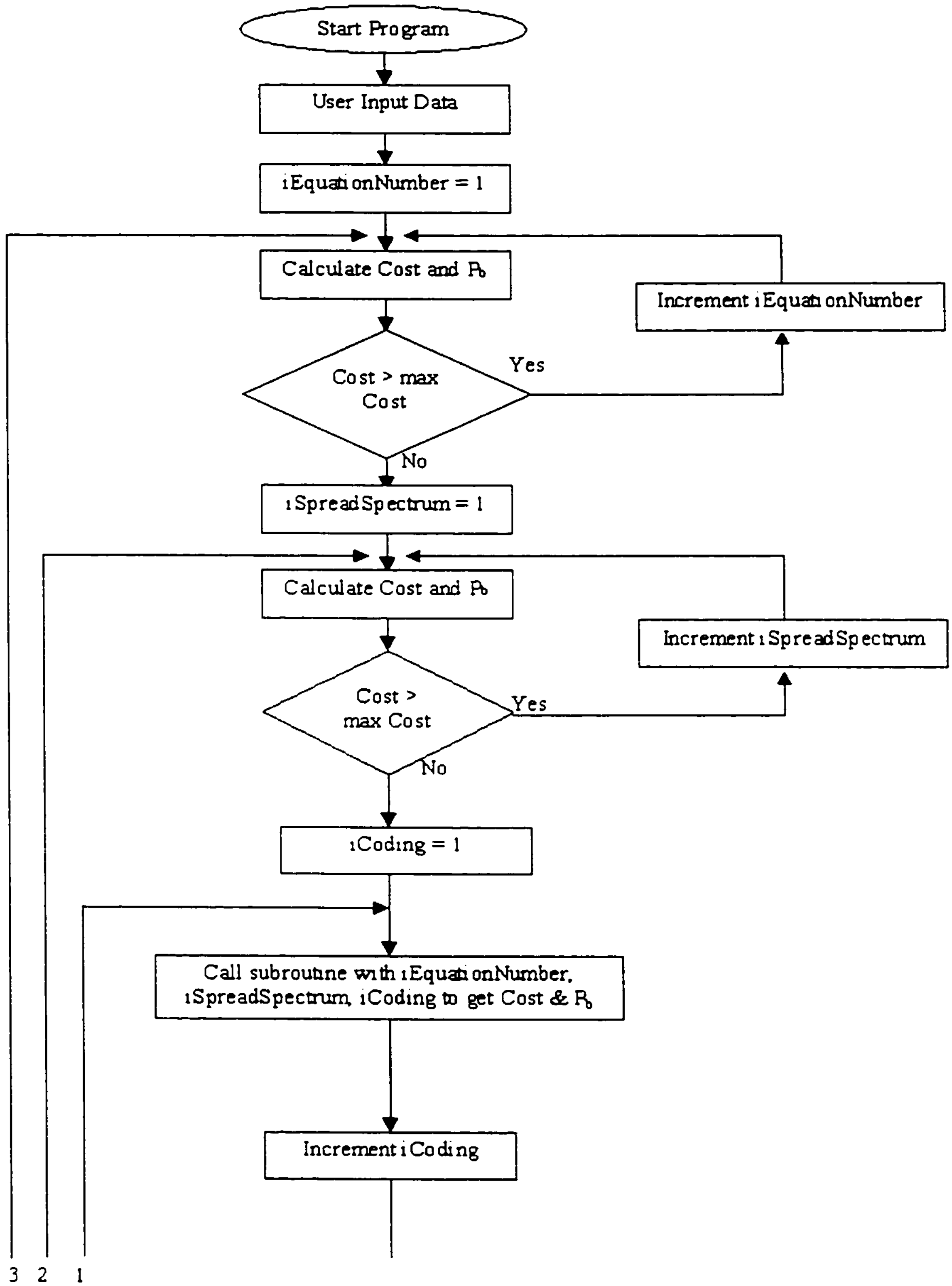


Figure 4.3: (page1) Flow Chart for the Universal Wireless Systems Algorithm

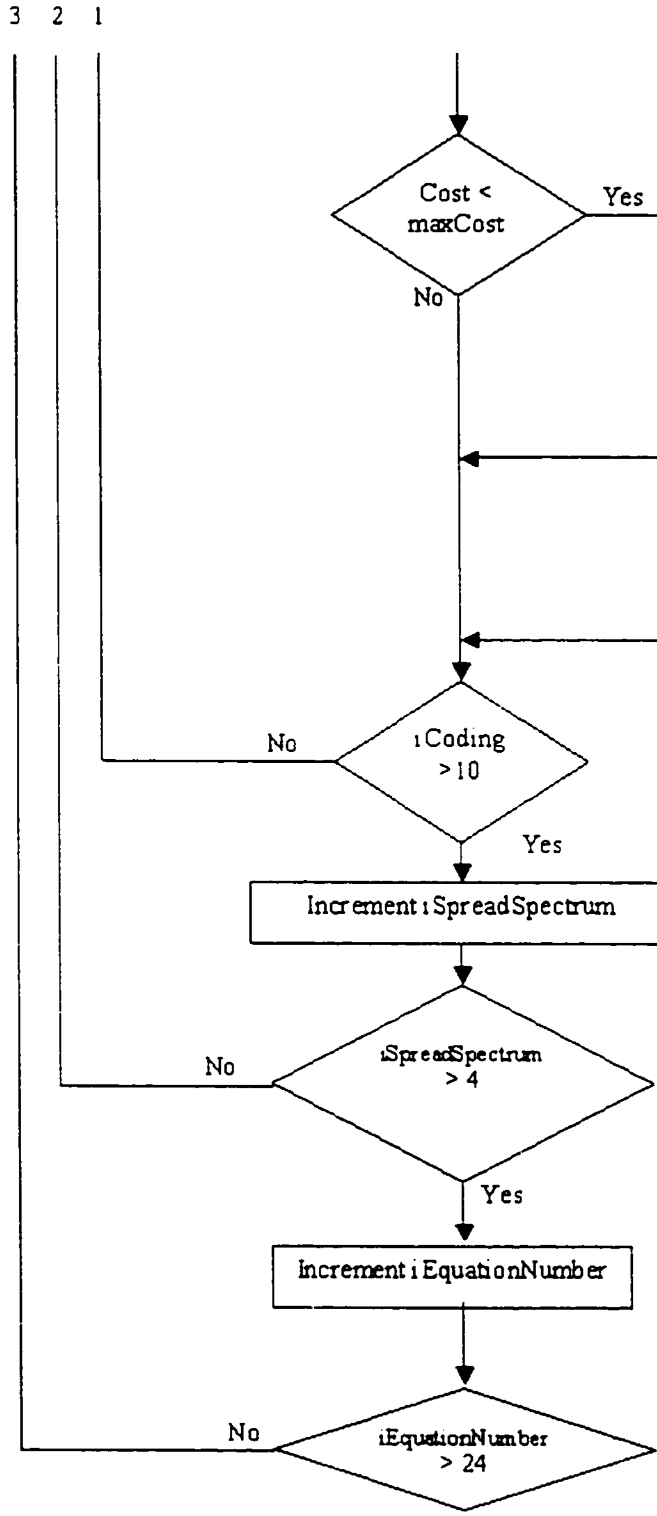


Figure 4.3: (Page 2) Flow Chart for the Universal Wireless Systems Algorithm

4.11 Results

The program will ask the user (Base station operator) to enter some information like Data Rate (R_b), Spread Spectrum Bandwidth (Ws), Mobile Transmission Power, Maximum Distance, Number of Users, Carrier Frequency (Fc), Base Station effective antenna height, Mobile effective antenna height, Receiver Margin, Multipath Margin, Fade Margin, Temperature and Maximum Cost.

These information are either available at the base station, or the mobile will provide for the base station. Then the base station will process this information and tell the mobile his best options under which it can operate. Meaning the modulation type, spread spectrum technique and coding type.

The program was run for different values for the various parameters and the results follow in tables, where we use the following notation:

M: Modulation type, and it is numbered from 1 to 24 as mentioned earlier.

SS: Spread Spectrum technique, and it is numbered from 1 to 4 as mentioned earlier.

C: Coding type, and it is numbered from 1 to 10 as mentioned earlier.

Run # 1

For Data Rate (R_b) = 10 kHz, Spread Spectrum Bandwidth (Ws) = 1.28 MHz, Mobile Transmission Power = 0.1 W, Maximum Distance = 500 m, Number of Users = 20, Carrier Frequency (Fc) = 1.9 GHz, Base Station effective antenna height = 30 m, Mobile effective antenna height = 3 m, Receiver Margin = 3 dB, Multipath Margin = 5 dB, Fade Margin = 10 dB, Temperature = 27 and Maximum Cost = 100.

The results of running the program for this case are in table 4.3. We see that at required $P_b = 10^{-11}$ for example, the possible mobile station configuration is:

Modulation type: Binary differential phase shift keying (BDPSK)

Spread Spectrum Technique: Direct Sequence

Coding type: Convolutional (68,30), K=5 (constraint length), k = 30 bits

However, at required $P_b = 10^{-13}$ for example, one of the many possible mobile station configuration is: Modulation type: Coherent 8-frequency shift keying (Coherent 8-FSK), Spread Spectrum Technique: Direct Sequence, Coding type: Reed-Solomon (256,192).

In this run, we allowed a high price (i.e. 100) and close distance (i.e. 500 m).

P_b	Possible Systems
1×10^{-13}	M:15,SS:1,C:1 ; M:19,SS:1,C:1 ; M:20,SS:1,C:1 ; M:16,SS:1,C:1 M:2,SS:1,C:1 ; M:24,SS:1,C:1 ; M:10,SS:1,C:1 ; M:17,SS:1,C:1 M:9,SS:1,C:1 ; M:11,SS:1,C:1 ; M:18,SS:1,C:1 ; M:17,SS:1,C:1 M:9,SS:1,C:1
3.23682×10^{-13}	M:10,SS:1,C:9 ; M:10,SS:1,C:8
4.44019×10^{-13}	M:8,SS:1,C:1
5.32382×10^{-13}	M:10,SS:1,C:6
6.48402×10^{-13}	M:11,SS:1,C:9 ; M:11,SS:1,C:8
1.0685×10^{-12}	M:11,SS:1,C:6
1.17508×10^{-12}	M:16,SS:1,C:8 ; M:16,SS:1,C:9
1.63202×10^{-12}	M:1,SS:1,C:1 ; M:1,SS:3,C:1
1.93805×10^{-12}	M:16,SS:1,C:6
4.12682×10^{-12}	M:14,SS:1,C:1
7.16431×10^{-12}	M:10,SS:1,C:7
8.80619×10^{-12}	M:9,SS:1,C:9
1.03852×10^{-11}	M:10,SS:1,C:5
1.44935×10^{-11}	M:11,SS:1,C:7
2.11583×10^{-11}	M:11,SS:1,C:5
2.6381×10^{-11}	M:16,SS:1,C:7

Table 4.3: results of Run 1

Run # 2

For Data Rate (R_b) = 100 kHz, Spread Spectrum Bandwidth (Ws) = 1.28 MHz, Mobile Transmission Power = 0.1 W, Maximum Distance = 500 m, Number of Users = 20, Carrier Frequency (Fc) = 1.9 GHz, Base Station effective antenna height = 30 m, Mobile effective antenna height = 3 m, Receiver Margin = 3 dB, Multipath Margin = 5 dB, Fade Margin = 10 dB, Temperature = 27 and Maximum Cost = 100.

The results of running the program for this case are in table 4.4. We see that at required $P_b = 10^{-10}$ for example, one of the many possible mobile station configurations is: Modulation type: Coherent 16-frequency shift keying (Coherent 16-FSK), Spread Spectrum Technique: Frequency Hoping, Coding type: Concatenated (Reed-Solomon & Convolutional) RS (255,233) & Convolutional R=½, K = 7.

However, at required P_b = 0.0004 for example, the possible mobile station configuration is: Modulation type: Offset quadrature phase shift keying (OQPSK), Spread Spectrum Technique: Direct Sequence, Coding type: Turbo (96,44), K=5 (constraint length), k = 44 bits. In this run, only the data rate was changed to 100KHz compared to the previous run.

P_b	Possible Systems
1×10^{-10}	M:16,SS:2,C:02 ; M:21,SS:2,C:02 ; M:22,SS:2,C:02
1.8×10^{-5}	M:16,SS:2,C:08 ; M:21,SS:2,C:08 ; M:22,SS:2,C:08
5×10^{-5}	M:22,SS:2,C:09
6.6×10^{-5}	M:16,SS:2,C:06 ; M:21,SS:2,C:06 ; M:22,SS:2,C:06
0.0001	M:14,SS:2,C:08 ; M:15,SS:2,C:08 ; M:10,SS:2,C:08
0.0002	M:16,SS:2,C:07 ; M:21,SS:2,C:07 ; M:22,SS:2,C:07
0.0003	M:14,SS:2,C:06 ; M:15,SS:2,C:06 ; M:16,SS:2,C:05 M:10,SS:2,C:06 ; M:21,SS:2,C:05 ; M:11,SS:2,C:06 M:22,SS:2,C:05
0.0004	M:7,SS:1,C:08 ; M:13,SS:2,C:08 ; M:14,SS:1,C:08 M:1,SS:3,C:08 ; M:7,SS:2,C:08 ; M:2,SS:2,C:08

Table 4.4: results of Run 2

Run # 3

For Data Rate (R_b) = 1 MHz, Spread Spectrum Bandwidth (Ws) = 1.28 MHz, Mobile Transmission Power = 0.1 W, Maximum Distance = 500 m, Number of Users = 20, Carrier Frequency (Fc) = 1.9 GHz, Base Station effective antenna height = 30 m, Mobile effective antenna height = 3 m, Receiver Margin = 3 dB, Multipath Margin = 5 dB, Fade Margin = 10 dB, Temperature = 27 and Maximum Cost = 100.

The results of running the program for this case are in table 4.5. We see that at required $P_b = 5\times10^{-5}$ for example, the possible mobile station configuration is: Modulation type: Non-Coherent 32-FSK. Spread Spectrum Technique: Frequency Hoping, Coding type: Convolutional. K=5 (constraint length). R = ½. Soft Decision.

However, at required P_b = 0.0001 for example, the possible mobile station configuration is: Modulation type: Coherent 4-FSK. Spread Spectrum Technique: Frequency Hoping. Coding type: Turbo (96,44). K=5 (constraint length). k = 44 bits. In this run, data rate is changed to 1 MHz.

P_b	Possible Systems
1×10^{-10}	M:16,SS:2,C:02 ; M:21,SS:2,C:02 ; M:22,SS:2,C:02
1.8×10^{-5}	M:16,SS:2,C:08 ; M:21,SS:2,C:08 ; M:22,SS:2,C:08
5×10^{-5}	M:22,SS:2,C:09
6.6×10^{-5}	M:16,SS:2,C:06 ; M:21,SS:2,C:06 ; M:22,SS:2,C:06
0.0001	M:14,SS:2,C:08 ; M:15,SS:2,C:08 ; M:10,SS:2,C:08
0.0002	M:16,SS:2,C:07 ; M:21,SS:2,C:07 ; M:22,SS:2,C:07
0.0003	M:14,SS:2,C:06 ; M:15,SS:2,C:06 ; M:16,SS:2,C:05 M:10,SS:2,C:06 ; M:21,SS:2,C:05 ; M:11,SS:2,C:06 M:22,SS:2,C:05
0.0004	M:7,SS:1,C:08 ; M:13,SS:2,C:08 ; M:14,SS:1,C:08 M:1,SS:3,C:08 ; M:7,SS:2,C:08 ; M:2,SS:2,C:08

Table 4.5: results of Run 3

Run # 4

For Data Rate (R_b) = 10 kHz, Spread Spectrum Bandwidth (Ws) = 1.28 MHz, Mobile Transmission Power = 0.1 W, Maximum Distance = 5000 m, Number of Users = 20, Carrier Frequency (Fc) = 1.9 GHz, Base Station effective antenna height = 30 m, Mobile effective antenna height = 3 m, Receiver Margin = 3 dB, Multipath Margin = 5 dB, Fade Margin = 10 dB, Temperature = 27 and Maximum Cost = 100.

The results of running the program for this case are in table 4.6. We see that at required $P_b = 10^{-10}$ for example, one of the many possible mobile station configuration is: Modulation type: Coherent 16-FSK, Spread Spectrum Technique: Frequency Hoping, Coding type: Concatenated (Reed-Solomon & Convolutional) RS (255,233) & Convolutional R=½, K = 7.

However, at required P_b = 0.0004 for example, the possible mobile station configuration is: Modulation type: Offset quadrature phase shift keying (OQPSK), Spread Spectrum Technique: Direct Sequence, Coding type: Turbo (96,44), K=5 (constraint length), k = 44 bits. In this run, the distance is set to 5000 m, and data rate is set to 10 KHz.

P_b	Possible Systems
1×10^{-10}	M:16,SS:2,C:02 ; M:21,SS:2,C:02 ; M:22,SS:2,C:02
1.8×10^{-5}	M:16,SS:2,C:08 ; M:21,SS:2,C:08 ; M:22,SS:2,C:08
5×10^{-5}	M:22,SS:2,C:09
6.6×10^{-5}	M:16,SS:2,C:06 ; M:21,SS:2,C:06 ; M:22,SS:2,C:06
0.0001	M:14,SS:2,C:08 ; M:15,SS:2,C:08 ; M:10,SS:2,C:08
0.0002	M:16,SS:2,C:07 ; M:21,SS:2,C:07 ; M:22,SS:2,C:07
0.0003	M:14,SS:2,C:06 ; M:15,SS:2,C:06 ; M:16,SS:2,C:05 M:10,SS:2,C:06 ; M:21,SS:2,C:05 ; M:11,SS:2,C:06 M:22,SS:2,C:05
0.0004	M:7,SS:1,C:08 ; M:13,SS:2,C:08 ; M:14,SS:1,C:08 M:1,SS:3,C:08 ; M:7,SS:2,C:08 ; M:2,SS:2,C:08

Table 4.6: results of Run 4

Run # 5

For Data Rate (R_b) = 100 kHz, Spread Spectrum Bandwidth (Ws) = 1.28 MHz, Mobile Transmission Power = 0.1 W, Maximum Distance = 5000 m, Number of Users = 20, Carrier Frequency (Fc) = 1.9 GHz, Base Station effective antenna height = 30 m, Mobile effective antenna height = 3 m, Receiver Margin = 3 dB, Multipath Margin = 5 dB, Fade Margin = 10 dB, Temperature = 27 and Maximum Cost = 100.

The results of running the program for this case are in table 4.7. We see that at required $P_b = 5\times10^{-5}$ for example, the possible mobile station configuration is: Modulation type: Non-Coherent 32-FSK, Spread Spectrum Technique: Frequency Hoping, Coding type: Convolutional, K=5 (constraint length), R = ½, Soft Decision.

However, at required P_b = 0.0001 for example, the possible mobile station configuration is: Modulation type: Coherent 4-FSK, Spread Spectrum Technique: Frequency Hoping, Coding type: Turbo (96,44), K=5 (constraint length), k = 44 bits. In this run, the distance stays at 5000 m, but the data rate changes to 100 KHz.

P_b	Possible Systems
1×10^{-10}	M:16,SS:2,C:02 ; M:21,SS:2,C:02 ; M:22,SS:2,C:02
1.8×10^{-5}	M:16,SS:2,C:08 ; M:21,SS:2,C:08 ; M:22,SS:2,C:08
5×10^{-5}	M:22,SS:2,C:09
6.6×10^{-5}	M:16,SS:2,C:06 ; M:21,SS:2,C:06 ; M:22,SS:2,C:06
0.0001	M:14,SS:2,C:08 ; M:15,SS:2,C:08 ; M:10,SS:2,C:08
0.0002	M:16,SS:2,C:07 ; M:21,SS:2,C:07 ; M:22,SS:2,C:07
0.0003	M:14,SS:2,C:06 ; M:15,SS:2,C:06 ; M:16,SS:2,C:05 M:10,SS:2,C:06 ; M:21,SS:2,C:05 ; M:11,SS:2,C:06 M:22,SS:2,C:05
0.0004	M:7,SS:1,C:08 ; M:13,SS:2,C:08 ; M:14,SS:1,C:08 M:1,SS:3,C:08 ; M:7,SS:2,C:08 ; M:2,SS:2,C:08

Table 4.7: results of Run 5

Run # 6

For Data Rate (R_b) = 1 MHz, Spread Spectrum Bandwidth (Ws) = 1.28 MHz, Mobile Transmission Power = 0.1 W, Maximum Distance = 5000 m, Number of Users = 20, Carrier Frequency (Fc) = 1.9 GHz, Base Station effective antenna height = 30 m, Mobile effective antenna height = 3 m, Receiver Margin = 3 dB, Multipath Margin = 5 dB, Fade Margin = 10 dB, Temperature = 27 and Maximum Cost = 100.

The results of running the program for this case are in table 4.8. We see that at required $P_b = 5\times10^{-5}$ for example, the possible mobile station configuration is: Modulation type: Non-Coherent 32-FSK, Spread Spectrum Technique: Frequency Hoping, Coding type: Convolutional, K=5 (constraint length), R = ½, Soft Decision.

However, at required P_b = 0.0001 for example, the possible mobile station configuration is: Modulation type: Coherent 4-FSK, Spread Spectrum Technique: Frequency Hoping, Coding type: Turbo (96,44), K=5 (constraint length), k = 44 bits. In this run, the distance stays at 5000 m, but the data rate changes to 1 MHz.

P_b	Possible Systems
1×10^{-10}	M:16,SS:2,C:02 ; M:21,SS:2,C:02 ; M:22,SS:2,C:02
1.8×10^{-5}	M:16,SS:2,C:08 ; M:21,SS:2,C:08 ; M:22,SS:2,C:08
5×10^{-5}	M:22,SS:2,C:09
6.6×10^{-5}	M:16,SS:2,C:06 ; M:21,SS:2,C:06 ; M:22,SS:2,C:06
0.0001	M:14,SS:2,C:08 ; M:15,SS:2,C:08 ; M:10,SS:2,C:08
0.0002	M:16,SS:2,C:07 ; M:21,SS:2,C:07 ; M:22,SS:2,C:07
0.0003	M:14,SS:2,C:06 ; M:15,SS:2,C:06 ; M:16,SS:2,C:05 M:10,SS:2,C:06 ; M:21,SS:2,C:05 ; M:11,SS:2,C:06 M:22,SS:2,C:05
0.0004	M:7,SS:1,C:08 ; M:13,SS:2,C:08 ; M:14,SS:1,C:08 M:1,SS:3,C:08 ; M:7,SS:2,C:08 ; M:2,SS:2,C:08

Table 4.8: results of Run 6

Run # 7

For Data Rate (R_b) = 10 kHz, Spread Spectrum Bandwidth (Ws) = 1.28 MHz, Mobile Transmission Power = 0.1 W, Maximum Distance = 1000 m, Number of Users = 20, Carrier Frequency (Fc) = 1.9 GHz, Base Station effective antenna height = 30 m, Mobile effective antenna height = 3 m, Receiver Margin = 3 dB, Multipath Margin = 5 dB, Fade Margin = 10 dB, Temperature = 27 and Maximum Cost = 100.

The results of running the program for this case are in table 4.9. We see that at required $P_b = 10^{-13}$ for example, the possible mobile station configuration is: Modulation type: Binary differential phase shift keying (BDPSK), Spread Spectrum Technique: Direct Sequence, Coding type: Reed-Solomon (256,192). However, at required $P_b = 10^{-10}$ for example, the possible mobile station configuration is: Modulation type: Phase shift keying (PSK), Spread Spectrum Technique: Direct Sequence, Coding type: Concatenated (Reed-Solomon & Convolutional) RS (255,233) & Convolutional R=½, K = 7.

In this run, the distance is set to 1000 m, and the data rate is set to 10 KHz.

P_b	Systems
1×10^{-13}	M:10,SS:1,C:01
1.55498×10^{-12}	M:11,SS:1,C:01
6.09429×10^{-12}	M:16,SS:1,C:01
1×10^{-10}	M:1,SS:1,C:02 ; M:22,SS:2,C:02 ; M:17,SS:1,C:02 M:16,SS:1,C:02 ; M:24,SS:1,C:02 ; M:18,SS:1,C:02 M:14,SS:1,C:02 ; M:23,SS:1,C:02 ; M:19,SS:1,C:02 M:10,SS:1,C:02 ; M:6,SS:1,C:02 ; M:9,SS:1,C:02 M:20,SS:1,C:02 ; M:2,SS:1,C:02 ; M:15,SS:1,C:02 M:11,SS:1,C:02 ; M:16,SS:2,C:02 ; M:21,SS:2,C:02 M:13,SS:1,C:02 ; M:8,SS:1,C:02
1.74803×10^{-10}	M:10,SS:1,C:09 ; M:10,SS:1,C:08
5.27003×10^{-10}	M:11,SS:1,C:08
2.88047×10^{-9}	M:10,SS:1,C:06 ; M:10,SS:1,C:05
2.8944×10^{-9}	M:16,SS:1,C:08
2.97305×10^{-9}	M:10,SS:1,C:07

Table 4.9: results of Run 7

Run # 8

For Data Rate (R_b) = 100 kHz, Spread Spectrum Bandwidth (Ws) = 1.28 MHz, Mobile Transmission Power = 0.1 W, Maximum Distance = 1000 m, Number of Users = 20, Carrier Frequency (Fc) = 1.9 GHz, Base Station effective antenna height = 30 m, Mobile effective antenna height = 3 m, Receiver Margin = 3 dB, Multipath Margin = 5 dB, Fade Margin = 10 dB, Temperature = 27 and Maximum Cost = 100.

The results of running the program for this case are in table 4.10. We see that at required $P_b = 5\times10^{-5}$ for example, the possible mobile station configuration is: Modulation type: Non-Coherent 32-FSK, Spread Spectrum Technique: Frequency Hoping, Coding type: Convolutional, K=5 (constraint length), R = ½, Soft Decision.

However, at required P_b = 0.0001 for example, the possible mobile station configuration is: Modulation type: Coherent 4-FSK, Spread Spectrum Technique: Frequency Hoping, Coding type: Turbo (96,44), K=5 (constraint length), k = 44 bits. In this run, the distance stays at 1000 m, but the data rate changes to 100 KHz.

P_b	Possible Systems
1×10^{-10}	M:16,SS:2,C:02 ; M:21,SS:2,C:02 ; M:22,SS:2,C:02
1.8×10^{-5}	M:16,SS:2,C:08 ; M:21,SS:2,C:08 ; M:22,SS:2,C:08
5×10^{-5}	M:22,SS:2,C:09
6.6×10^{-5}	M:16,SS:2,C:06 ; M:21,SS:2,C:06 ; M:22,SS:2,C:06
0.0001	M:14,SS:2,C:08 ; M:15,SS:2,C:08 ; M:10,SS:2,C:08
0.0002	M:16,SS:2,C:07 ; M:21,SS:2,C:07 ; M:22,SS:2,C:07
0.0003	M:14,SS:2,C:06 ; M:15,SS:2,C:06 ; M:16,SS:2,C:05 M:10,SS:2,C:06 ; M:21,SS:2,C:05 ; M:11,SS:2,C:06 M:22,SS:2,C:05
0.0004	M:7,SS:1,C:08 ; M:13,SS:2,C:08 ; M:14,SS:1,C:08 M:1,SS:3,C:08 ; M:7,SS:2,C:08 ; M:2,SS:2,C:08

Table 4.10: results of Run 8

Run # 9

For Data Rate (R_b) = 1 MHz, Spread Spectrum Bandwidth (Ws) = 1.28 MHz, Mobile Transmission Power = 0.1 W, Maximum Distance = 1000 m, Number of Users = 20, Carrier Frequency (Fc) = 1.9 GHz, Base Station effective antenna height = 30 m, Mobile effective antenna height = 3 m, Receiver Margin = 3 dB, Multipath Margin = 5 dB, Fade Margin = 10 dB, Temperature = 27 and Maximum Cost = 100.

The results of running the program for this case are in table 4.11. We see that at required $P_b = 5\times10^{-5}$ for example, the possible mobile station configuration is: Modulation type: Non-Coherent 32-FSK. Spread Spectrum Technique: Frequency Hoping. Coding type: Convolutional. K=5 (constraint length). R = ½. Soft Decision.

However, at required P_b = 0.0001 for example, the possible mobile station configuration is: Modulation type: Coherent 4-FSK. Spread Spectrum Technique: Frequency Hoping. Coding type: Turbo (96,44). K=5 (constraint length). k = 44 bits. In this run, the distance stays at 1000 m, but the data rate changes to 1 MHz.

P_b	Possible Systems
1×10^{-10}	M:16.SS:2.C:02 ; M:21.SS:2.C:02 ; M:22.SS:2.C:02
1.8×10^{-5}	M:16.SS:2.C:08 ; M:21.SS:2.C:08 ; M:22.SS:2.C:08
5×10^{-5}	M:22.SS:2.C:09
6.6×10^{-5}	M:16.SS:2.C:06 ; M:21.SS:2.C:06 ; M:22.SS:2.C:06
0.0001	M:14.SS:2.C:08 ; M:15.SS:2.C:08 ; M:10,SS:2.C:08
0.0002	M:16.SS:2.C:07 ; M:21.SS:2.C:07 ; M:22.SS:2.C:07
0.0003	M:14.SS:2.C:06 ; M:15.SS:2.C:06 ; M:16.SS:2.C:05 M:10.SS:2.C:06 ; M:21.SS:2.C:05 ; M:11,SS:2.C:06 M:22.SS:2.C:05
0.0004	M:7.SS:1.C:08 ; M:13.SS:2.C:08 ; M:14.SS:1.C:08 M:1.SS:3.C:08 ; M:7.SS:2.C:08 ; M:2.SS:2.C:08

Table 4.11: results of Run 9

Run # 10

For Data Rate (R_b) = 10 kHz, Spread Spectrum Bandwidth (Ws) = 1.28 MHz, Mobile Transmission Power = 0.1 W, Maximum Distance = 500 m, Number of Users = 20, Carrier Frequency (Fc) = 1.9 GHz, Base Station effective antenna height = 30 m, Mobile effective antenna height = 3 m, Receiver Margin = 3 dB, Multipath Margin = 5 dB, Fade Margin = 10 dB, Temperature = 27 and Maximum Cost = 50.

The results of running the program for this case are in table 4.12. We see that at required $P_b = 10^{-13}$ for example, the possible mobile station configuration is: Modulation type: Non-Coherent BFSK, Spread Spectrum Technique: Direct Sequence, Coding type: Reed-Solomon (256,192). However, at required $P_b = 10^{-10}$ for example, the possible mobile station configuration is: Modulation type: 16-quadrature amplitude modulation, Spread Spectrum Technique: Direct Sequence, Coding type: Concatenated (Reed-Solomon & Convolutional) RS (255,233) & Convolutional R=½, K = 7. In this run, the cost used is 50. Also, the distance is set to 500 m and data rate is set to 10 KHz.

P_b	Possible Systems
1×10^{-13}	M:18,SS:1,C:01 ; M:10,SS:1,C:01 ; M:19,SS:1,C:01 M:20,SS:1,C:01 ; M:24,SS:1,C:01 ; M:9,SS:1,C:01 M:15,SS:1,C:01 ; M:2,SS:1,C:01 ; M:11,SS:1,C:01 M:17,SS:1,C:01 ; M:16,SS:1,C:01
4.44019×10^{-13}	M:8,SS:1,C:01
1.63202×10^{-12}	M:1,SS:1,C:01 ; M:1,SS:3,C:01
4.12682×10^{-12}	M:14,SS:1,C:01
1.03852×10^{-11}	M:10,SS:1,C:05
2.11583×10^{-11}	M:11,SS:1,C:05
3.86319×10^{-11}	M:16,SS:1,C:05
1×10^{-10}	M:11,SS:1,C:02 ; M:7,SS:1,C:02 ; M:1,SS:3,C:02 M:10,SS:1,C:02 ; M:16,SS:2,C:02 ; M:2,SS:1,C:02 M:16,SS:1,C:02 ; M:6,SS:1,C:02 ; M:8,SS:1,C:02 M:9,SS:1,C:02 ; M:13,SS:1,C:02 ; M:3,SS:1,C:02

Table 4.12: results of Run 10

Run # 11

For Data Rate (R_b) = 100 kHz, Spread Spectrum Bandwidth (Ws) = 1.28 MHz, Mobile Transmission Power = 0.1 W, Maximum Distance = 500 m, Number of Users = 20, Carrier Frequency (Fc) = 1.9 GHz, Base Station effective antenna height = 30 m, Mobile effective antenna height = 3 m, Receiver Margin = 3 dB, Multipath Margin = 5 dB, Fade Margin = 10 dB, Temperature = 27 and Maximum Cost = 50.

The results of running the program for this case are in table 4.13. We see that at required $P_b = 10^{-10}$ for example, the possible mobile station configuration is: Modulation type: Non-Coherent 16-FSK, Spread Spectrum Technique: Frequency Hopping, Coding type: Concatenated (Reed-Solomon & Convolutional) RS (255,233) & Convolutional R=½, K = 7. However, at required P_b = 0.001 for example, the possible mobile station configuration is: Modulation type: 16-phase shift keying (16-PSK), Spread Spectrum Technique: Frequency Hopping, Coding type: Turbo (68,30), K=5 (constraint length), k = 30 bits. In this run, both cost and distance stay the same, and data rate is set to 100 KHz.

P_b	Systems
1×10^{-10}	M:21,SS:2,C:02 ; M:22,SS:2,C:02 ; M:16,SS:2,C:02
6.6×10^{-5}	M:16,SS:2,C:06
0.0003	M:10,SS:2,C:06 ; M:11,SS:2,C:06 ; M:14,SS:2,C:06 M:21,SS:2,C:05 ; M:15,SS:2,C:06 ; M:16,SS:2,C:05
0.0006	M:22,SS:2,C:03
0.001	M:4,SS:2,C:06 ; M:6,SS:2,C:06 ; M:12,SS:2,C:06 M:7,SS:2,C:06 ; M:13,SS:2,C:06 ; M:1,SS:2,C:06 M:21,SS:2,C:04 ; M:3,SS:2,C:06 ; M:22,SS:2,C:04 M:9,SS:2,C:06 ; M:16,SS:2,C:04 ; M:2,SS:2,C:06 M: 8,SS:2,C:06 ; M:5,SS:2,C:06
0.002	M:10,SS:2,C:05 ; M:11,SS:2,C:05 ; M:14,SS:2,C:05 M:15,SS:2,C:05
0.003	M:21,SS:2,C:03

Table 4.13: results of Run 11

Run # 12

For Data Rate (R_b) = 1 MHz, Spread Spectrum Bandwidth (Ws) = 1.28 MHz, Mobile Transmission Power = 0.1 W, Maximum Distance = 500 m, Number of Users = 20, Carrier Frequency (Fc) = 1.9 GHz, Base Station effective antenna height = 30 m, Mobile effective antenna height = 3 m, Receiver Margin = 3 dB, Multipath Margin = 5 dB, Fade Margin = 10 dB, Temperature = 27 and Maximum Cost = 50.

The results of running the program for this case are in table 4.14. We see that at required $P_b = 10^{-10}$ for example, the possible mobile station configuration is: Modulation type: Non-Coherent 16-FSK, Spread Spectrum Technique: Frequency Hopping, Coding type: Concatenated (Reed-Solomon & Convolutional) RS (255,233) & Convolutional R=½, K = 7. However, at required P_b = 0.001 for example, the possible mobile station configuration is: Modulation type: 16-phase shift keying (16-PSK), Spread Spectrum Technique: Frequency Hopping, Coding type: Turbo (68,30), K=5 (constraint length), k = 30 bits. In this run, both cost and distance stay the same, and data rate is set to 1 MHz.

P_b	Systems
1×10^{-10}	M:21,SS:2,C:02 ; M:22,SS:2,C:02 ; M:16,SS:2,C:02
6.6×10^{-5}	M:16,SS:2,C:06
0.0003	M:10,SS:2,C:06 ; M:11,SS:2,C:06 ; M:14,SS:2,C:06 M:21,SS:2,C:05 ; M:15,SS:2,C:06 ; M:16,SS:2,C:05
0.0006	M:22,SS:2,C:03
0.001	M:4,SS:2,C:06 ; M:6,SS:2,C:06 ; M:12,SS:2,C:06 M:7,SS:2,C:06 ; M:13,SS:2,C:06 ; M:1,SS:2,C:06 M:21,SS:2,C:04 ; M:3,SS:2,C:06 ; M:22,SS:2,C:04 M:9,SS:2,C:06 ; M:16,SS:2,C:04 ; M:2,SS:2,C:06 M: 8,SS:2,C:06 ; M:5,SS:2,C:06
0.002	M:10,SS:2,C:05 ; M:11,SS:2,C:05 ; M:14,SS:2,C:05 M:15,SS:2,C:05
0.003	M:21,SS:2,C:03

Table 4.14: results of Run 12

Run # 13

For Data Rate (R_b) = 10 kHz, Spread Spectrum Bandwidth (Ws) = 1.28 MHz, Mobile Transmission Power = 0.1 W, Maximum Distance = 1000 m, Number of Users = 20, Carrier Frequency (Fc) = 1.9 GHz, Base Station effective antenna height = 30 m, Mobile effective antenna height = 3 m, Receiver Margin = 3 dB, Multipath Margin = 5 dB, Fade Margin = 10 dB, Temperature = 27 and Maximum Cost = 50. The results of running the program for this case are in table 4.15. We see that at required $P_b = 10^{-13}$ for example, the possible mobile station configuration is: Modulation type: Binary differential phase shift keying (BDPSK), Spread Spectrum Technique: Spread Spectrum, Coding type: Reed-Solomon (256,192). However, at required $P_b = 4\times10^{-7}$ for example, the possible mobile station configuration is: Modulation type: Coherent 16-FSK, Spread Spectrum Technique: Spread Spectrum, Coding type: Turbo (68,32), K=3 (constraint length), k = 32 bits. The distance is set to 1000 and the data rate is set to 10 KHz.

P_b	Systems
1×10^{-13}	M:10,SS:1,C:01
1.55498×10^{-12}	M:11,SS:1,C:01
1×10^{-10}	M:9,SS:1,C:02 ; M:1,SS:1,C:02 ; M:23,SS:1,C:02 M:20,SS:1,C:02 ; M:18,SS:1,C:02 ; M:6,SS:1,C:02 M:22,SS:2,C:02 ; M:17,SS:1,C:02 ; M:2,SS:1,C:02 M:13,SS:1,C:02 ; M:21,SS:2,C:02 ; M:10,SS:1,C:02 M:11,SS:1,C:02 ; M:16,SS:2,C:02 ; M:14,SS:1,C:02 M:19,SS:1,C:02 ; M:24,SS:1,C:02 ; M:8,SS:1,C:02, M:16,SS:1,C:02 ; M:15,SS:1,C:02
2.88845×10^{-9}	M:10,SS:1,C:05
1.16294×10^{-8}	M:11,SS:1,C:05
7.19316×10^{-8}	M:16,SS:1,C:05
3.93545×10^{-7}	M:21,SS:1,C:02
4.00042×10^{-7}	M:16,SS:1,C:04
4.85372×10^{-7}	M:10,SS:1,C:04
5.26998×10^{-7}	M:15,SS:1,C:05
6.09429×10^{-2}	M:16,SS:1,C:01

Table 4.15: results of Run 13

Run # 14

For Data Rate (R_b) = 100 kHz, Spread Spectrum Bandwidth(Ws) = 1.28 MHz, Mobile Transmission Power = 0.1 W, Maximum Distance = 1000 m, Number of Users = 20, Carrier Frequency (Fc) = 1.9 GHz, Base Station effective antenna height = 30 m, Mobile effective antenna height = 3 m, Receiver Margin = 3 dB, Multipath Margin = 5 dB, Fade Margin = 10 dB, Temperature = 27 and Maximum Cost = 50.

The results of running the program for this case are in table 4.16. We see that at required $P_b = 10^{-10}$ for example, the possible mobile station configuration is: Modulation type: Non-Coherent 16-FSK, Spread Spectrum Technique: Frequency Hopping, Coding type: Concatenated (Reed-Solomon & Convolutional) RS (255,233) & Convolutional R=½, K = 7. However, at required P_b = 0.001 for example, the possible mobile station configuration is: Modulation type: 16-phase shift keying (16-PSK), Spread Spectrum Technique: Frequency Hopping, Coding type: Turbo (68,30), K=5 (constraint length), k = 30 bits. In this run, both cost and distance stay the same, and data rate is set to 100 KHz.

P_b	Systems
1×10^{-10}	M:21,SS:2,C:02 ; M:22,SS:2,C:02 ; M:16,SS:2,C:02
6.6×10^{-5}	M:16,SS:2,C:06
0.0003	M:10,SS:2,C:06 ; M:11,SS:2,C:06 ; M:14,SS:2,C:06 M:21,SS:2,C:05 ; M:15,SS:2,C:06 ; M:16,SS:2,C:05
0.0006	M:22,SS:2,C:03
0.001	M:4,SS:2,C:06 ; M:6,SS:2,C:06 ; M:12,SS:2,C:06 M:7,SS:2,C:06 ; M:13,SS:2,C:06 ; M:1,SS:2,C:06 M:21,SS:2,C:04 ; M:3,SS:2,C:06 ; M:22,SS:2,C:04 M:9,SS:2,C:06 ; M:16,SS:2,C:04 ; M:2,SS:2,C:06 M: 8,SS:2,C:06 ; M:5,SS:2,C:06
0.002	M:10,SS:2,C:05 ; M:11,SS:2,C:05 ; M:14,SS:2,C:05 M:15,SS:2,C:05
0.003	M:21,SS:2,C:03

Table 4.16: results of Run 14

Run # 15

For Data Rate (R_b) = 1 MHz, Spread Spectrum Bandwidth (Ws) = 1.28 MHz, Mobile Transmission Power = 0.1 W, Maximum Distance = 1000 m, Number of Users = 20, Carrier Frequency (Fc) = 1.9 GHz, Base Station effective antenna height = 30 m, Mobile effective antenna height = 3 m, Receiver Margin = 3 dB, Multipath Margin = 5 dB, Fade Margin = 10 dB, Temperature = 27 and Maximum Cost = 50.

The results of running the program for this case are in table 4.17. We see that at required $P_b = 10^{-10}$ for example, the possible mobile station configuration is: Modulation type: Non-Coherent 16-FSK, Spread Spectrum Technique: Frequency Hopping, Coding type: Concatenated (Reed-Solomon & Convolutional) RS (255,233) & Convolutional R=½, K = 7. However, at required P_b = 0.001 for example, the possible mobile station configuration is: Modulation type: 16-phase shift keying (16-PSK), Spread Spectrum Technique: Frequency Hopping, Coding type: Turbo (68,30), K=5 (constraint length), k = 30 bits. In this run, both cost and distance stay the same, and data rate is set to 1 MHz.

P_b	Systems
1×10^{-10}	M:21,SS:2,C:02 ; M:22,SS:2,C:02 ; M:16,SS:2,C:02
6.6×10^{-5}	M:16,SS:2,C:06
0.0003	M:10,SS:2,C:06 ; M:11,SS:2,C:06 ; M:14,SS:2,C:06 M:21,SS:2,C:05 ; M:15,SS:2,C:06 ; M:16,SS:2,C:05
0.0006	M:22,SS:2,C:03
0.001	M:4,SS:2,C:06 ; M:6,SS:2,C:06 ; M:12,SS:2,C:06 M:7,SS:2,C:06 ; M:13,SS:2,C:06 ; M:1,SS:2,C:06 M:21,SS:2,C:04 ; M:3,SS:2,C:06 ; M:22,SS:2,C:04 M:9,SS:2,C:06 ; M:16,SS:2,C:04 ; M:2,SS:2,C:06 M: 8,SS:2,C:06 ; M:5,SS:2,C:06
0.002	M:10,SS:2,C:05 ; M:11,SS:2,C:05 ; M:14,SS:2,C:05 M:15,SS:2,C:05
0.003	M:21,SS:2,C:03

Table 4.17: results of Run 15

Run # 16

For Data Rate (R_b) = 10 kHz, Spread Spectrum Bandwidth (Ws) = 1.28 MHz, Mobile Transmission Power = 0.1 W, Maximum Distance = 5000 m, Number of Users = 20, Carrier Frequency (Fc) = 1.9 GHz, Base Station effective antenna height = 30 m, Mobile effective antenna height = 3 m, Receiver Margin = 3 dB, Multipath Margin = 5 dB, Fade Margin = 10 dB, Temperature = 27 and Maximum Cost = 50.

The results of running the program for this case are in table 4.18. We see that at required $P_b = 10^{-10}$ for example, the possible mobile station configuration is: Modulation type: Non-Coherent 16-FSK, Spread Spectrum Technique: Frequency Hopping, Coding type: Concatenated (Reed-Solomon & Convolutional) RS (255,233) & Convolutional R=½, K = 7. However, at required P_b = 0.001 for example, the possible mobile station configuration is: Modulation type: 16-phase shift keying (16-PSK), Spread Spectrum Technique: Frequency Hopping, Coding type: Turbo (68,30), K=5 (constraint length), k = 30 bits. In this run, the distance is set to 5000 m, and data rate is set to 10 KHz.

P_b	Systems
1×10^{-10}	M:21,SS:2,C:02 ; M:22,SS:2,C:02 ; M:16,SS:2,C:02
6.6×10^{-5}	M:16,SS:2,C:06
0.0003	M:10,SS:2,C:06 ; M:11,SS:2,C:06 ; M:14,SS:2,C:06 M:21,SS:2,C:05 ; M:15,SS:2,C:06 ; M:16,SS:2,C:05
0.0006	M:22,SS:2,C:03
0.001	M:4,SS:2,C:06 ; M:6,SS:2,C:06 ; M:12,SS:2,C:06 M:7,SS:2,C:06 ; M:13,SS:2,C:06 ; M:1,SS:2,C:06 M:21,SS:2,C:04 ; M:3,SS:2,C:06 ; M:22,SS:2,C:04 M:9,SS:2,C:06 ; M:16,SS:2,C:04 ; M:2,SS:2,C:06 M: 8,SS:2,C:06 ; M:5,SS:2,C:06
0.002	M:10,SS:2,C:05 ; M:11,SS:2,C:05 ; M:14,SS:2,C:05 M:15,SS:2,C:05
0.003	M:21,SS:2,C:03

Table 4.18: results of Run 16

Run # 17

For Data Rate (R_b) = 100 kHz, Spread Spectrum Bandwidth (Ws) = 1.28 MHz, Mobile Transmission Power = 0.1 W, Maximum Distance = 5000 m, Number of Users = 20, Carrier Frequency (Fc) = 1.9 GHz, Base Station effective antenna height = 30 m, Mobile effective antenna height = 3 m, Receiver Margin = 3 dB, Multipath Margin = 5 dB, Fade Margin = 10 dB, Temperature = 27 and Maximum Cost = 50.

The results of running the program for this case are in table 4.19. We see that at required $P_b = 10^{-10}$ for example, the possible mobile station configuration is: Modulation type: Non-Coherent 16-FSK, Spread Spectrum Technique: Frequency Hopping, Coding type: Concatenated (Reed-Solomon & Convolutional) RS (255,233) & Convolutional R=½, K = 7. However, at required P_b = 0.001 for example, the possible mobile station configuration is: Modulation type: 16-phase shift keying (16-PSK), Spread Spectrum Technique: Frequency Hopping, Coding type: Turbo (68,30), K=5 (constraint length), k = 30 bits. In this run, both cost and distance stay the same, and data rate is set to 100 KHz.

P_b	Systems
1×10^{-10}	M:21,SS:2,C:02 ; M:22,SS:2,C:02 ; M:16,SS:2,C:02
6.6×10^{-5}	M:16,SS:2,C:06
0.0003	M:10,SS:2,C:06 ; M:11,SS:2,C:06 ; M:14,SS:2,C:06 M:21,SS:2,C:05 ; M:15,SS:2,C:06 ; M:16,SS:2,C:05
0.0006	M:22,SS:2,C:03
0.001	M:4,SS:2,C:06 ; M:6,SS:2,C:06 ; M:12,SS:2,C:06 M:7,SS:2,C:06 ; M:13,SS:2,C:06 ; M:1,SS:2,C:06 M:21,SS:2,C:04 ; M:3,SS:2,C:06 ; M:22,SS:2,C:04 M:9,SS:2,C:06 ; M:16,SS:2,C:04 ; M:2,SS:2,C:06 M: 8,SS:2,C:06 ; M:5,SS:2,C:06
0.002	M:10,SS:2,C:05 ; M:11,SS:2,C:05 ; M:14,SS:2,C:05 M:15,SS:2,C:05
0.003	M:21,SS:2,C:03

Table 4.19: results of Run 17

Run # 18

For Data Rate (R_b) = 1 MHz, Spread Spectrum Bandwidth (Ws) = 1.28 MHz, Mobile Transmission Power = 0.1 W, Maximum Distance = 5000 m, Number of Users = 20, Carrier Frequency (Fc) = 1.9 GHz, Base Station effective antenna height = 30 m, Mobile effective antenna height = 3 m, Receiver Margin = 3 dB, Multipath Margin = 5 dB, Fade Margin = 10 dB, Temperature = 27 and Maximum Cost = 50.

The results of running the program for this case are in table 4.20. We see that at required $P_b = 10^{-10}$ for example, the possible mobile station configuration is: Modulation type: Non-Coherent 16-FSK, Spread Spectrum Technique: Frequency Hopping, Coding type: Concatenated (Reed-Solomon & Convolutional) RS (255,233) & Convolutional R=½, K = 7. However, at required P_b = 0.001 for example, the possible mobile station configuration is: Modulation type: 16-phase shift keying (16-PSK), Spread Spectrum Technique: Frequency Hopping, Coding type: Turbo (68,30), K=5 (constraint length), k = 30 bits. In this run, both cost and distance stay the same, and data rate is set to 1 MHz.

P_b	Systems
1×10^{-10}	M:21,SS:2,C:02 ; M:22,SS:2,C:02 ; M:16,SS:2,C:02
6.6×10^{-5}	M:16,SS:2,C:06
0.0003	M:10,SS:2,C:06 ; M:11,SS:2,C:06 ; M:14,SS:2,C:06 M:21,SS:2,C:05 ; M:15,SS:2,C:06 ; M:16,SS:2,C:05
0.0006	M:22,SS:2,C:03
0.001	M:4,SS:2,C:06 ; M:6,SS:2,C:06 ; M:12,SS:2,C:06 M:7,SS:2,C:06 ; M:13,SS:2,C:06 ; M:1,SS:2,C:06 M:21,SS:2,C:04 ; M:3,SS:2,C:06 ; M:22,SS:2,C:04 M:9,SS:2,C:06 ; M:16,SS:2,C:04 ; M:2,SS:2,C:06 M: 8,SS:2,C:06 ; M:5,SS:2,C:06
0.002	M:10,SS:2,C:05 ; M:11,SS:2,C:05 ; M:14,SS:2,C:05 M:15,SS:2,C:05
0.003	M:21,SS:2,C:03

Table 4.20: results of Run 18

4.12 Conclusion and Future Research

Software radio will bring benefits to many enterprises involved in the telecommunication business: manufacturer, operators and users. Manufacturers can concentrate on research and development to reduce the hardware used which will allow lower costs. Operators will be able to offer services that suit users and differentiated from other operators. With the same terminal it will be possible to provide all services even if supported by different communication standards. The advantages for users are the possibility to roam their communications to other cellular systems and take advantage of worldwide mobility and coverage. Also, SW radio technology increases hardware lifetime, reducing the obsolescence risk. System reprogrammability allows hardware reuse until a new generation of hardware platform is available. The software radio is a powerful architecture framework that helps us deliver such advanced radio services in a way that leverages the economics of contemporary microelectronics and software technologies.

Assuming that we reached a common platform for the base stations, and both base station and mobile station are digitized and reprogrammable, in this thesis, we developed an algorithm that will take advantage of reprogrammability to achieve the best performance for both the base and mobile station. Best performance could means quality in voice and saving power which means money.

In this thesis, we have looked at budget calculations and system selection for a software radio base multi wireless system. Users receiving among different wireless and cellular standards will be able to select one of many available access types, modulation types or coding types. This new algorithm will facilitate receiving among different systems and maximize power efficiency, equipment lifetime, performance and cost. More R&D is needed to further investigate real time aspects and run time evaluation of the new algorithm.

The flexibility of an SW radio system consists in its capability to operate in multiservice environments, without being constrained to a particular standard, but able to offer, in theory, services of any already standardized systems or future ones on any radio frequency band. The compatibility of an SW radio system with any defined radio mobile is guaranteed by its reconfigurability, that is, by digital signal processing (DSP) engine reprogrammability, which, in real time, implements radio interface and upper layer protocols. It is important to note that by DSP is really intended the concept of digital signal processing, and therefore not only DSP chipsets in strict sense, but also field programmable gate arrays (FPGAs) and general-purpose processors such as Intel Pentium/MMX. At present, the development of an SW radio system remains very utopian because of several, problems, overall technological ones, which at the moment do not seem easy and quick to solve.

The development of an SW radio system implies, above all, the achievement of two main goals:

• To move, in transmitting and receiving, the border between the analog and digital worlds as much as possible toward radio frequency (RF), by adopting analog-digital (A/D) and digital-analog (D/A) wideband conversion as near as possible to the antenna.

• To replace application-specific integrated circuits (ASICs) (dedicated hardware) with DSPs for baseband signal processing, in order to define, as many radio functionalities as possible in SW.

The software radio concept is critically dependent on high performance general-purpose processor hardware architectures. The stumbling blocks in development of a commercially usable software radio have been the availability of hardware, in particular the fast DSP required. As high performance ADCs have become available commercially, with the sample rates and SFDRs required, hybrid techniques using specialized digital hardware, operating under software control (e.g., digital down- converters) have become more common. These techniques use digital mixers (multipliers) to select a narrowband channel from the fast, wideband data coming out of the ADC, then filter and decimate it before passing a manageable flow to the general purpose DSPs. Some technology challenges arise due to an inability to normalize air interfaces across regions of the world. Others arise due to the laws of physics that limit technical progress in power dissipation, clock speeds, dynamic range, and linearity. Over time, both should yield to advancing ADC, DSP, ASIC, FPGA, and software technologies. One key to success is to leverage the progress being made on these fronts through open architecture standards.

Bibliography

[1] J. Mitola, "Software Radios: Survey, Critical Evaluation and Future Directions," Proceedings of the national Telesystems Conference, McGraw Hill, New York, 1992.

[2] Kant, Introduction to Computer System Performance Evaluation, McGraw Hill, New York, 1992.

[3] Collins and Tebbs, Real Time Systems. McGraw Hill, UK, 1977.

[4] Kleinrock, Queueing Systems, vol. II, Macmillan, New York, 1982.

[5] Mouly and Pautet, The GSM System for Mobile Communications, Palaiseau, France, 1995.

[6] Ziemer and Peterson, Digital Communications and Spread Spectrum Systems, Macmillan, New York, 1985).

[7] J. Mitola, "The Software Radio Architecture," IEEE Communications Magazine, May 1995.

[8] J. Mitola, "Software Radio Technology Challenges and Opportunities. " SW Radio Wksp., Brussels, Belgium, May 1997.

[9] J. Wepman, "A/D Converters and Their Applications in Radio Receivers," IEEE Communications Magazine, May 1995.

[10] Special Issue on Software Radio, IEEE Communications Magazine, Aug. 1999.

[11] R. Baines, "The DSP Bottleneck," IEEE Communications Magazine, May 1995.

[12] Z. Kostic, "DSPs in Cellular Radio Communications," IEEE Communications Magazine, Dec. 1997.

[13] J. Mitola, "Technical Challenges in the Globalization Of Software Radio," IEEE

Communications Magazine, Feb. 1999.

[14] Lackey and Upmall, "SPEAKeasy: The Military Software Radio," IEEE Communications Magazine, May 1995.

[15] Abidi, "Low power Radio Frequency Ics for Portable Communications," Proc. IEEE, New York: IEE Press, Apr. 1995.

[16] j. Oeting, "Cellular Mobile Radio - An Emerging Technology," Communications Magazine, Nov. 1983.

[17] V. H. MacDonald, "The Cellular Concept," The Bell Systems Technical Journal, Vol. 58, Jan. 1979.

[18] T. S. Rappaport, Wireless Communications – Principles and practice, Prentice Hall, New Jersy, 1996.

[19] R. Steele, Mobile Radio Communications, IEEE Fress, 1994.

[20] T. S. Rappaport and L. Milstein, "Effects of Radio Propagation Path Loss on DS_CDMA Cellular Frequency Reuse Efficiency for the reverse Channel," IEEE Transactions on Vehicular Technology, Vol. 41, No. 3, Aug. 1992.

[21] W. R. Young, "Advanced Mobile Phone Service: Introduction, Background and Objectives," Bell Systems Technical Journal, Vol. 58, Jan. 1979.

[22] K. Raith and J. Uddenfeldt, "Capacity of Digital Cellular TDMA Systems," IEEE Transactions on Vehicular Technology, Vol. 40, No. 2, May 1991.

[23] E. A. Gilhousen, "On the Capacity of Cellular CDMA System," IEEE Transactions on Vehicular Technology, Vol. 40, No. 2, May 1991.

[24] TIA/EIA Interim Standard-95, "Mobile Station – Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System" July 1993.

[25] TIA/EIA Interim Standard-95, "Cellular System Dual Mode Mobile Station – Land Station Compatibility Specifications," IS-54, Electronic Industries Association, May 1990.

[26] R.M. Metcalfe and D.R. Boggs, "Ethernet: Distributed Packet Switching for Local Computer Networks," Communications of the Association for Computing Machinery, Vol. 19, July 1976.

[27] L. Goldberg, "Wireless LANs: Mobile Computing's Second Wave," Electronic Design, 26 June 1995.

[28] C. Perkins, "IP Mobility Support," RFC 2002, October 1996.

[29] K. Chen, "Medium Access Control of Wireless LANs for Mobile Computing," IEEE Network, September / October 1994.

[30] T.S. Rappaport, private communication, June 1997.

[31] B.E. Mullins, N.J. Davis IV, and S.F. Midkiff, "A Wireless Local Area Network Protocol That Improves Throughput Via Adaptive Control," Proceedings of the IEEE International Conference on Communications, pp. 1427-1431, June 1997.

[32] B.E. Mullins, N.J. Davis IV, and S.F. Midkiff, "An Adaptive Wireless Local Area Network Protocol That Improves Throughput Via Adaptive Control of Direct Sequence Spread Spectrum Parameters, to appear in ACM Mobile Computing and Communication Review, Vol. 1, No. 3, 1997.

[33] M. Richharia, Satelite Communication Systems – Design Principles, McGraw Hill, New York, 1995.

Appendix

Probability of Error in AWGN

BPSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.08	0.05	0.04	0.02	0.015	0.0075	0.003	0.00075	0.0002	0.00002

8-PSK

SNR	0	1	2	3	4	5	6	8	10	12
P_b	0.1	0.066	0.06	0.05	0.04	0.0266	0.0166	0.0058	0.0058	0.000066

16-PSK

SNR	0	1	2	4	6	8	10	12	14	16
P_b	0.125	0.1125	0.1	0.087	0.0625	0.0375	0.0187	0.0075	0.00125	0.000125

32-PSK

SNR	0	4	8	10	12	14	16	18	20	22
P_b	0.14	0.1	0.08	0.06	0.04	0.02	0.01	0.003	0.0004	0.00002

DPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.2	0.1	0.075	0.04	0.02	0.009	0.003	0.0009	0.00015	0.00002

COHERENT BFSK

SNR	2	4	5	6	7	8	9	10	11	12
P_b	0.1	0.05	0.035	0.02	0.015	0.0075	0.003	0.0008	0.0001	0.00002

COHERENT 4-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.118	0.0844	0.05625	0.0345	0.01875	0.009	0.0036	0.0012	0.000286	0.00005

COHERENT 8-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.0971	0.0611	0.034	0.017	0.00723	0.00233	0.00064	0.000123	0.0000158	0.00000123

COHERENT 16-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.085	0.0468	0.0225	0.009	0.0029	0.00075	0.000124	0.0000142	0.00000095	0.000000033

COHERENT 32-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.0786	0.0372	0.0155	0.005	0.00124	0.000218	$2.53*10^{-5}$	$1.73*10^{-6}$	$6.02*10^{-8}$	$9.18*10^{-10}$

NON-COHERENT BFSK

SNR	4	5	6	7	8	9	10	11	12	13
P_b	0.1425	0.103	0.08	0.05	0.03	0.007	0.0034	0.0015	0.00018	0.0000232

NON-COHERENT 4-FSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.2127	0.1545	0.1025	0.06	0.0318	0.02	0.007	0.002	0.0003	0.00004

NON-COHERENT 8-FSK

SNR	2	3	4	5	6	7	8	9	10	11
P_b	0.1	0.07	0.04	0.01	0.005	0.001	0.0002	0.00002	0.000002	0.0000002

NON-COHERENT 16-FSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.15	0.08	0.05	0.02	0.004	0.001	0.0002	0.00002	0.000001	$1*10^{-7}$

NON-COHERENT 32-FSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.1	0.05	0.03	0.01	0.002	0.0003	0.00002	0.000001	10^{-7}	10^{-8}

QPSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.08	0.05	0.04	0.02	0.015	0.0075	0.003	0.00075	0.0002	0.00002

OQPSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.08	0.05	0.04	0.02	0.015	0.0075	0.003	0.00075	0.0002	0.00002

PI 4 QPSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.08	0.05	0.04	0.02	0.015	0.0075	0.003	0.00075	0.0002	0.00002

MSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.08	0.05	0.04	0.02	0.015	0.0075	0.003	0.00075	0.0002	0.00002

16-QAM

SNR	6	7	8	9	10	11	12	13	14	15
P_b	0.025	0.02	0.01	0.00437	0.002	0.0005	10^{-4}	$2.5*10^{-5}$	$7.5*10^{-6}$	$7.5*10^{-7}$

64-QAM

SNR	11	12	13	14	15	16	17	18	19	20
P_b	0.0133	0.0066	0.005	0.0022	0.00066	0.00016	$5*10^{-5}$	$1.16*10^{-5}$	$1.5*10^{-6}$	$1.6*10^{-7}$

GMSK BT=0.25

SNR	0	2	3	4	6	7	8	9	10	11
P_b	0.121	0.072	0.05	0.0322	0.0102	0.0045	0.0017	0.0005	0.000113	0.0000175

GMSK BT=INFINITY

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.097	0.072	0.05	0.033	0.0197	0.01	0.0047	0.0018	0.0005	0.00012

Coding (256,192) Reed-Solomon

//BPSK

SNR	4	4.5	4.75	5	5.25	5.5	5.75	6	6.5	7
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

//8-PSK

SNR	7	7.5	7.75	8	8.25	8.5	8.75	9	9.5	10
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

16-PSK

SNR	8	11.5	11.75	12	12.25	12.5	12.75	13	13.5	14
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

32-PSK

SNR	10	15.5	16.75	17	17.25	17.5	17.75	18	18.5	19
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

DPSK

SNR	6	6.5	6.75	7	7.25	7.5	7.75	8	8.5	9
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

COHERENT BFSK

SNR	7	7.5	7.75	8	8.25	8.5	8.75	9	9.5	10
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

COHERENT 4-FSK

SNR	4	4.5	4.75	5	5.25	5.5	5.75	6	6.5	7
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

//COHERENT 8-FSK

SNR	3.5	4	4.25	4.5	4.75	5	5.25	5.5	6	6.5
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

COHERENT 16-FSK

SNR	2.5	3	3.25	3.5	3.75	4	4.25	4.5	4.75	5
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

COHERENT 32-FSK

SNR	2.5	3	3.25	3.5	3.75	4	4.25	4.5	4.75	5
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

//NON-COHERENT BFSK

SNR	8	8.5	8.75	9	9.25	9.5	9.75	10	10.5	11
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

NON-COHERENT 4-FSK

SNR	5	5.5	5.75	6	6.25	6.5	6.75	7	7.5	8
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

NON-COHERENT 8-FSK

SNR	4	4.5	4.75	5	5.25	5.5	5.75	6	6.5	7
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

NON-COHERENT 16-FSK

SNR	3	3.5	3.75	4	4.25	4.5	4.75	5	5.5	6
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

NON-COHERENT 32-FSK

SNR	2	2.5	2.75	3	3.25	3.5	3.75	4	4.5	5
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

QPSK

SNR	4	4.5	4.75	5	5.25	5.5	5.75	6	6.5	7
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

OQPSK

SNR	4	4.5	4.75	5	5.25	5.5	5.75	6	6.5	7
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

PI/4 QPSK

SNR	4	4.5	4.75	5	5.25	5.5	5.75	6	6.5	7
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

MSK

SNR	4	4.5	4.75	5	5.25	5.5	5.75	6	6.5	7
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

16-QAM

SNR	7	7.5	7.75	8	8.25	8.5	8.75	9	9.5	10
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

64-QAM

SNR	11	11.5	11.75	12	12.25	12.5	12.75	13	13.5	14
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

GMSK BT=0.25

SNR	5	5.5	5.75	6	6.25	6.5	6.75	7	7.5	8
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

GMSK BT=INFINITY

SNR	4	4.5	4.75	5	5.25	5.5	5.75	6	6.5	7
P_b	0.1	0.02	0.01	0.005	0.001	0.0001	0.00001	$4*10^{-7}$	10^{-11}	10^{-13}

Concatenated RS & Convolutional Code

BPSK

SNR	1.5	1.6	1.75	1.9	2	2.1	2.25	2.4	2.5	3
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

8-PSK

SNR	4.5	4.6	4.75	4.9	5	5.1	5.25	5.4	5.5	6
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

16-PSK

SNR	6.5	8.6	8.75	8.9	9	9.1	9.25	9.4	9.5	10
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

32-PSK

SNR	7.5	12.6	12.75	12.9	13	13.1	13.25	13.4	13.5	14
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

DPSK

SNR	3.5	3.6	3.75	3.9	4	4.1	4.25	4.4	4.5	5
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

COHERENT BFSK

SNR	4.5	4.6	4.75	4.9	5	5.1	5.25	5.4	5.5	6
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

COHERENT 4-FSK

SNR	1.5	1.6	1.75	1.9	2	2.1	2.25	2.4	2.5	3
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

COHERENT 8-FSK

SNR	1	1.1	1.25	1.4	1.5	1.6	1.75	1.9	2	2.5
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

COHERENT 16-FSK

SNR	0	0.1	0.25	0.4	0.5	0.6	0.75	0.9	1	1.5
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

COHERENT 32-FSK

SNR	0	0.1	0.25	0.4	0.5	0.6	0.75	0.9	1	1.5
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

NON-COHERENT BFSK

SNR	5.5	5.6	5.75	5.9	6	6.1	6.25	6.4	6.5	7
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

NON-COHERENT 4-FSK

SNR	2.5	2.6	2.75	2.9	3	3.1	3.25	3.4	3.5	4
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

NON-COHERENT 8-FSK

SNR	1.5	1.6	1.75	1.9	2	2.1	2.25	2.4	2.5	3
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

NON-COHERENT 16-FSK

SNR	0.5	0.6	0.75	0.9	1	1.1	1.25	1.4	1.5	2
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

NON-COHERENT 32-FSK

SNR	-0.5	-0.4	-0.25	-0.1	0	0.1	0.25	0.4	0.5	1
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

QPSK

SNR	1.5	1.6	1.75	1.9	2	2.1	2.25	2.4	2.5	3
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

OQPSK

SNR	1.5	1.6	1.75	1.9	2	2.1	2.25	2.4	2.5	3
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

PI/4 QPSK

SNR	1.5	1.6	1.75	1.9	2	2.1	2.25	2.4	2.5	3
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

MSK

SNR	1.5	1.6	1.75	1.9	2	2.1	2.25	2.4	2.5	3
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

16-QAM

SNR	4.5	4.6	4.75	4.9	5	5.1	5.25	5.4	5.5	6
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

64-QAM

SNR	8.5	8.6	8.75	8.9	9	9.1	9.25	9.4	9.5	10
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

GMSK BT=0.25

SNR	2.5	2.6	2.75	2.9	3	3.1	3.25	3.4	3.5	4
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

GMSK BT=INFINITY

SNR	1.5	1.6	1.75	1.9	2	2.1	2.25	2.4	2.5	3
P_b	0.1	0.05	0.02	0.01	0.005	0.001	0.0001	0.00001	10^{-6}	10^{-10}

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Coding (68,32) Convolutional, K=3 (constraint length 3),k=32 bits

BPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

8-PSK

SNR	4	5	6	7	8	9	10	11	12	13
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

16-PSK

SNR	5	8	10	11	12	13	14	15	16	17
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

32-PSK

SNR	12	13	15	16	17	18	19	20	21	22
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

DPSK

SNR	2	3	4	5	6	7	8	9	10	11
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

//COHERENT BFSK

SNR	4	5	6	7	8	9	10	11	12	13
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

COHERENT 4-FSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

COHERENT 8-FSK

SNR	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

COHERENT 16-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

COHERENT 32-FSK

SNR	-1	0	1	2	3	4	5	6	7	8
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

NON-COHERENT BFSK

SNR	5	6	7	8	9	10	11	12	13	14
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

NON-COHERENT 4-FSK

SNR	2	3	4	5	6	7	8	9	10	11
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

NON-COHERENT 8-FSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

NON-COHERENT 16-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

NON-COHERENT 32-FSK

SNR	-1	0	1	2	3	4	5	6	7	8
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

QPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

OQPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

PI/4 QPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

MSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

16-QAM

SNR	4	5	6	7	8	9	10	11	12	13
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

64-QAM

SNR	8	9	10	11	12	13	14	15	16	17
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

GMSK BT=0.25

SNR	2	3	4	5	6	7	8	9	10	11
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

//GMSK BT=INFINITY

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.03	0.02	0.003	0.0006	0.0002	0.0001	$6.25*10^{-7}$	$2.8*10^{-8}$	$3.1*10^{-10}$	$3.1*10^{-12}$

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Coding (68,32) Turbo, K=3 (constraint length 3),k=32 bits

BPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

8-PSK

SNR	4	5	6	7	8	9	10	11	12	13
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

16-PSK

SNR	7	9	10	11	12	13	14	15	16	17
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

32-PSK

SNR	12	13	14	15	16	17	18	19	20	21
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

DPSK

SNR	2	3	4	5	6	7	8	9	10	11
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

COHERENT BFSK

SNR	4	5	6	7	8	9	10	11	12	13
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

COHERENT 4-FSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

COHERENT 8-FSK

SNR	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

COHERENT 16-FSK

SNR	-0.5	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

COHERENT 32-FSK

SNR	-0.5	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

NON-COHERENT BFSK

SNR	5	6	7	8	9	10	11	12	13	14
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

NON-COHERENT 4-FSK

SNR	2	3	4	5	6	7	8	9	10	11
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

NON-COHERENT 8-FSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

NON-COHERENT 16-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

NON-COHERENT 32-FSK

SNR	-1	0	1	2	3	4	5	6	7	8
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

QPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

OQPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

PI/4 QPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

MSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

16-QAM

SNR	4	5	6	7	8	9	10	11	12	13
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

64-QAM

SNR	7	10	11	12	13	14	15	16	17	18
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

GMSK BT=0.25

SNR	2	3	4	5	6	7	8	9	10	11
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

GMSK BT=INFINITY

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.01	0.003	0.001	0.0001	0.00002	$1.25*10^{-6}$	$3.1*10^{-8}$	$1.5*10^{-9}$	$2.2*10^{-10}$	$2*10^{-13}$

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Coding (68,30) Convolutional, K=5 (constraint length 5),k=30 bits

//BPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

8-PSK

SNR	4	5	6	7	8	9	10	11	12	13
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

16-PSK

SNR	8	9	10	11	12	13	14	15	16	17
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

32-PSK

SNR	12	13	14	15	16	17	18	19	20	21
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

DPSK

SNR	2	3	4	5	6	7	8	9	10	11
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

COHERENT BFSK

SNR	4	5	6	7	8	9	10	11	12	13
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

COHERENT 4-FSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

COHERENT 8-FSK

SNR	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

COHERENT 16-FSK

SNR	-1	0	1	2	3	4	5	6	7	8
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

COHERENT 32-FSK

SNR	-1	0	1	2	3	4	5	6	7	8
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

NON-COHERENT BFSK

SNR	5	6	7	8	9	10	11	12	13	14
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

NON-COHERENT 4-FSK

SNR	2	3	4	5	6	7	8	9	10	11
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

NON-COHERENT 8-FSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

NON-COHERENT 16-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

NON-COHERENT 32-FSK

SNR	-1	0	1	2	3	4	5	6	7	8
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

QPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

OQPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

PI/4 QPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

MSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

16-QAM

SNR	4	5	6	7	8	9	10	11	12	13
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

64-QAM

SNR	9	10	11	12	13	14	15	16	17	18
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

GMSK BT=0.25

SNR	2	3	4	5	6	7	8	9	10	11
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

GMSK BT=INFINITY

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.007	0.002	0.0003	$3.3*10^{-5}$	$3.3*10^{-6}$	$2.3*10^{-7}$	$3.3*10^{-9}$	$6.6*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

==

Coding (68,30) Turbo, K=5 (constraint length 5),k=30 bits

//BPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

8-PSK

SNR	4	5	6	7	8	9	10	11	12	13
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

16-PSK

SNR	8	9	10	11	12	13	14	15	16	17
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

32-PSK

SNR	13	14	15	16	17	18	19	20	21	22
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

DPSK

SNR	2	3	4	5	6	7	8	9	10	11
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

COHERENT BFSK

SNR	4	5	6	7	8	9	10	11	12	13
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

COHERENT 4-FSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

COHERENT 8-FSK

SNR	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

COHERENT 16-FSK

SNR	-1	0	1	2	3	4	5	6	7	8
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

COHERENT 32-FSK

SNR	-1	0	1	2	3	4	5	6	7	8
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

NON-COHERENT BFSK

SNR	5	6	7	8	9	10	11	12	13	14
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

NON-COHERENT 4-FSK

SNR	2	3	4	5	6	7	8	9	10	11
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

NON-COHERENT 8-FSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

NON-COHERENT 16-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

NON-COHERENT 32-FSK

SNR	-1	0	1	2	3	4	5	6	7	8
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

QPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

OQPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

PI/4 QPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

MSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

16-QAM

SNR	4	5	6	7	8	9	10	11	12	13
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

64-QAM

SNR		10	11	12	13	14	15	16	17	18
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

GMSK BT=0.25

SNR	2	3	4	5	6	7	8	9	10	11
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

GMSK BT=INFINITY

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.001	0.0003	$6.6*10^{-5}$	$6.6*10^{-6}$	$3.3*10^{-7}$	$1.6*10^{-8}$	$3.3*10^{-9}$	$3.3*10^{-12}$	$3.1*10^{-14}$	$3.1*10^{-16}$

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Coding (96,44) Convolutional, K=5 (constraint length 5),k=44 bits

BPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

8-PSK

SNR	4	5	6	7	8	9	10	11	12	13
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

16-PSK

SNR	8	9	10	11	12	13	14	15	16	17
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

32-PSK

SNR	12	13	14	15	16	17	18	19	20	21
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

DPSK

SNR	2	3	4	5	6	7	8	9	10	11
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

COHERENT BFSK

SNR	4	5	6	7	8	9	10	11	12	13
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

COHERENT 4-FSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

COHERENT 8-FSK

SNR	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

COHERENT 16-FSK

SNR	-1	0	1	2	3	4	5	6	7	8
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

COHERENT 32-FSK

SNR	-1	0	1	2	3	4	5	6	7	8
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

NON-COHERENT BFSK

SNR	5	6	7	8	9	10	11	12	13	14
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

NON-COHERENT 4-FSK

SNR	2	3	4	5	6	7	8	9	10	11
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

NON-COHERENT 8-FSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

NON-COHERENT 16-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

NON-COHERENT 32-FSK

SNR	-1	0	1	2	3	4	5	6	7	8
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

QPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

OQPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

PI/4 QPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

MSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

16-QAM

SNR	4	5	6	7	8	9	10	11	12	13
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

64-QAM

SNR	9	10	11	12	13	14	15	16	17	18
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

GMSK BT=0.25

SNR	2	3	4	5	6	7	8	9	10	11
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

GMSK BT=INFINITY

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.007	0.002	0.0002	$4.5*10^{-5}$	$3.4*10^{-6}$	$2*10^{-7}$	$3.4*10^{-9}$	$4.5*10^{-11}$	$3.1*10^{-13}$	$3.1*10^{-15}$

Coding (96,44) Turbo, K=5 (constraint length 5),k=44 bits

//BPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

8-PSK

SNR	4	5	6	7	8	9	10	11	12	13
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

16-PSK

SNR	8	9	10	11	12	13	14	15	16	17
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

32-PSK

SNR	13	14	15	16	17	18	19	20	21	22
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

DPSK

SNR	2	3	4	5	6	7	8	9	10	11
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

COHERENT BFSK

SNR	4	5	6	7	8	9	10	11	12	13
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

COHERENT 4-FSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

COHERENT 8-FSK

SNR	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

COHERENT 16-FSK

SNR	-1	0	1	2	3	4	5	6	7	8
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

COHERENT 32-FSK

SNR	-1	0	1	2	3	4	5	6	7	8
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

NON-COHERENT BFSK

SNR	5	6	7	8	9	10	11	12	13	14
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

NON-COHERENT 4-FSK

SNR	2	3	4	5	6	7	8	9	10	11
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

NON-COHERENT 8-FSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

NON-COHERENT 16-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

NON-COHERENT 32-FSK

SNR	-1	0	1	2	3	4	5	6	7	8
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

QPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

OQPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

PI/4 QPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

MSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

16-QAM

SNR	4	5	6	7	8	9	10	11	12	13
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

64-QAM

SNR	9	10	11	12	13	14	15	16	17	18
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

GMSK BT=0.25

SNR	2	3	4	5	6	7	8	9	10	11
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

GMSK BT=INFINITY

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.0004	0.0001	$1.8*10^{-5}$	$2.3*10^{-6}$	$1.8*10^{-7}$	$9.1*10^{-9}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

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Coding Convolutional R=1/2, K=7, Soft Decision

//BPSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.1	0.05	0.01	0.001	0.00005	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$

8-PSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.5	0.5	0.2	0.2	0.07	0. 01	0.001	0.00005	0.000001	$2*10^{-8}$

16-PSK

SNR	0	7	9	10	11	12	13	14	15	16
P_b	0.1	0.05	0.01	0.001	0.00005	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$

32-PSK

SNR	12	13	14	15	16	17	18	19	20	21
P_b	0.1	0.05	0.01	0.001	0.00005	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$

DPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.4	0.4	0.05	0.001	0.00005	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$

COHERENT BFSK

SNR	3	4	5	6	7	8	9	10	11	12
P_b	0.1	0.05	0.01	0.001	0.00005	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$

COHERENT 4-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.5	0.2	0.01	0.001	0.00005	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$

COHERENT 8-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.4	0.3	0.005	0.00005	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

COHERENT 16-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.4	0.2	0.001	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$	$2*10^{-18}$

COHERENT 32-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.1	0.06	$4*10^{-4}$	$1.5*10^{-7}$	$1.5*10^{-7}$	10^{-10}	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$	$2*10^{-18}$

NON-COHERENT BFSK

SNR	0	1	6	7	8	9	10	11	12	13
P_b	0.5	0.4	0.01	0.001	0.00005	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$

NON-COHERENT 4-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.5	0.4	0.2	0.01	0.001	0.00005	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$

NON-COHERENT 8-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.5	0.05	0.01	0.001	0.00005	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$

NON-COHERENT 16-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.5	0.05	0.001	0.00005	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$

NON-COHERENT 32-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.5	0.05	0.01	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$	$2*10^{-16}$	$2*10^{-18}$

QPSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.1	0.05	0.01	0.001	0.00005	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$

OQPSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.1	0.05	0.01	0.001	0.00005	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$

PI/4 QPSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.1	0.05	0.01	0.001	0.00005	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$

MSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.1	0.05	0.01	0.001	0.00005	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$

16-QAM

SNR	0	1	2	6	7	8	9	10	11	12
P_b	0.5	0.4	0.1	0.001	0.00005	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$

64-QAM

SNR	0	8	9	10	11	12	13	14	15	16
P_b	0.1	0.05	0.01	0.001	0.00005	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$

GMSK BT=0.25

SNR	0	2	3	4	5	6	7	8	9	10
P_b	0.4	0.05	0.01	0.001	0.00005	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$

GMSK BT=INFINITY

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.4	0.1	0.01	0.001	0.00005	0.000001	$2*10^{-8}$	$2*10^{-10}$	$2*10^{-12}$	$2*10^{-14}$

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Coding Convolutional R=1/2, K=7, Hard Decision

BPSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

8-PSK

SNR	3	4	5	6	7	8	9	10	11	12
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

16-PSK

SNR	7	8	9	10	11	12	13	14	15	16
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

32-PSK

SNR	6	12	14	15	16	17	18	19	20	21
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

DPSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

COHERENT BFSK

SNR	3	4	5	6	7	8	9	10	11	12
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

COHERENT 4-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

COHERENT 8-FSK

SNR	-0.5	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

COHERENT 16-FSK

SNR	-2	-1	0	1	2	3	4	5	6	7
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

COHERENT 32-FSK

SNR	-2	-1	0	1	2	3	4	5	6	7
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

NON-COHERENT BFSK

SNR	4	5	6	7	8	9	10	11	12	13
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

NON-COHERENT 4-FSK

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

NON-COHERENT 8-FSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

NON-COHERENT 16-FSK

SNR	-1	0	1	2	3	4	5	6	7	8
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

NON-COHERENT 32-FSK

SNR	-2	-1	0	1	2	3	4	5	6	7
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

QPSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

OQPSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

PI/4 QPSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

MSK

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

16-QAM

SNR	3	4	5	6	7	8	9	10	11	12
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

64-QAM

SNR	8	9	10	11	12	13	14	15	16	17
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

GMSK BT=0.25

SNR	1	2	3	4	5	6	7	8	9	10
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

GMSK BT=INFINITY

SNR	0	1	2	3	4	5	6	7	8	9
P_b	0.1	0.05	0.04	0.02	0.005	0.0006	0.00006	0.000002	10^{-7}	$2*10^{-9}$

Relative Cost to DPSK System

Type of Modulation	**Cost**
BPSK	4
4-PSK	4
8-PSK	4
16-PSK	4
32-PSK	4
DPSK	1
Coherent BFSK	4
Coherent 4-FSK	4
Coherent 8-FSK	4
Coherent 16-FSK	4
Coherent 32-FSK	4
Non-Coherent BFSK	3
Non-Coherent 4-FSK	3
Non-Coherent 8-FSK	3
Non-Coherent 16-FSK	3
Non-Coherent 32-FSK	3
QPSK	6
OQPSK	6
PI/4 QPSK	6
MSK	6
16-QAM	10
64-QAM	12
GMSK BT=0.25	6
GMSK BT=INFINITY	6

Spread spectrum Technique	**Cost**
Direct Sequence	20
Frequency Hop	15
DS 802.11	20
FH 802.11	20

Coding Type	Cost
(256,192) Reed-Solomon	15
Concatenated RS & Convolutional Code	15
(68,32) Convolutional, K=3	20
(68,32) Turbo, K=3	20
(68,30) Convolutional, K=5	25
(68,30) Turbo, K=5	30
(68,30) Turbo, K=5	40
(96,44) Turbo, K=5	50
Convolutional R=1/2, K=7, Soft Decision	50
Convolutional R=1/2, K=7, Hard Decision	50