Examensarbete

Design of Ultra Low Power Transmitter for Wireless Medical Application

Master thesis performed in ISY Department, Electronic devices

by

Amit Srivastava

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by
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In this thesis work, system level design of FSK and QPSK transmitter is presented. The proposed transmitter is based on direct conversion to RF architecture, which is known for low power application. Both the transmitters are designed and compared in terms of their performance and efficiency. The simulation results show the BER and constellation plots for both FSK and QPSK transmitter.

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In this thesis work, system level design of FSK and QPSK transmitter is presented. The proposed transmitter is based on direct conversion to RF architecture, which is known for low power application. Both the transmitters are designed and compared in terms of their performance and efficiency. The simulation results show the BER and constellation plots for both FSK and QPSK transmitter.
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Abbreviations:

MICS=Medical Implant Communication System
FCC= Federal Communication Commission
FSK= Frequency Shift Key
QPSK= Quadrature Phase Shift Key
GFSK =Gaussian Frequency Shift key
ASK =Amplitude Shift Key
OOK= On Off Key
BER= Bit Error Rate
MAC=Media Access Controller
SNR= Signal to Noise Ratio
Erfc= Complementary Error Function
ECC= Error Correcting Code
EVM= Error Vector Magnitude
ISI= Inter Symbol Interference
CPM =Continuous Phase Modulation
PSK= Phase Shift Key
MSK= Minimum Shift Key
ACPR= Adjacent Channel Power Ratio
AWGN= Additive White Gaussian Noise
VT-LFSR= Voltage Transient Linear Frequency Shift Register
Modem= Modulator Demodulator
DAMPS = Digital Advanced Mobile Phone System
DECT =Digital Enhanced Cordless Telecommunications
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Chapter 1: Introduction

Implanted medical devices are electronics devices that monitors and diagnose patient body. It has the ability to send current to various parts of a patient body. It consists of a radio which communicates by sending data to and fro to the outside world. In general, implantable devices are self-operating devices which adjust its operation depending upon the patient condition. However, these devices do not rely on external source of power. So, low power consumption and high data rate is one of the main requirements for medical implant devices.

In order to minimize cost, patient trauma and risk associated with the repeated surgeries, it is necessary to increase the lifetime of implanted battery by conserving every joule of energy at every stage of a device, various methods to conserve power is discussed in this thesis work.

A lot of research work in the field of wireless communication is directed towards low power electronics. This report attempts to show an optimum level of system design for low power transmitter for both FSK and QPSK modulation. The performance and efficiency levels are compared for both modulation schemes by evaluating their BER and constellation plot.

1.1: Goal

The goal of this thesis work is to design and analyze an FSK transmitter for medical application. To realize this, transmitter architecture must be small and simple in size and must consume very low power. The analysis of the design is made by calculating performance and efficiency of transmitter. Transmitter is designed using direct conversion to RF architecture in MICS band, with high data rate. Results are evaluated using BER and constellation plot for FSK transmitter, which shows the amount of noise, interference and distortion present in the system. Finally, QPSK transmitter is designed for same data rate and compared with the FSK transmitter in terms of efficiency and performance.

1.2: Organization of Report:

This report is divided into 9 chapters, and a short overview of the chapters is given below:

Chapter 1 & 2: This chapter is about the introduction, goal and system level parameters.

Chapter 3: It is all about the theory on digital modulation, transmitter architecture and its components.

Chapter 4: This chapter presents theory on FSK modulation scheme

Chapter 5: This chapter deals with the theory on QPSK modulation scheme.

Chapter 6: It is about design process, system overview and implementation of the transmitter modules in ADS.

Chapter 7: This chapter presents the results obtained from both ADS and Matlab simulation.

Chapter 8: Conclusion made during this thesis work.

Chapter 9: Last chapter is allocated for references.
Chapter 2: System level design of a transmitter

2.1: Introduction:

Design at the system level is to improve the chances of a successful implementation of guidelines, constraints and standards into specification. It helps to set down the requirement at the circuit’s level. The main objective of a system level design is to identify the best topologies for a wireless system in a cost effective manner. Design at system level is often focused on low power, low cost, high data rate, small size and the environment in which device is expected to work. In this report, standard specification set by Zarlink semiconductor for low power transceiver is taken as reference.

2.2 Implant Devices:

Implanted medical device is an IC device, which is being implanted into the patient body for treatment and diagnostic of diseases, it also stores information like personal identification, medical history and contact information. By implanting such an IC chip, doctors and healthcare professional can access the patients any time, regardless of distance and location. Even though there are number of products available in market like pace makers, implantable drug pumps, blood glucose monitoring and implantable defibrillator.

There are still a lot of challenges remains like:

- Biocompatibility of device with human body
- Ultra low power consumption
- Small size combines with high data rate.

But, In future we can see the use of present day technologies like Zig bee, Wi-Fi and GPS in medical application. Wireless communication is far more advantageous than wired technology in implanted medical devices due to its:

- Simple usage
- Reduced risk of failure
- High mobility
- Low cost of treatment
- Low risk of infection

There are some factors that needed to be considered for implanted device, before it is adopted widely, few important ones are:

- High and accurate data rate
- Regulatory constraints
- Security
- Resilience to interference.

Enormous benefits associated with medical device combined with wireless technology have reduced cost of treatment, which results in fewer traumas, low risk, continuous diagnose and no need for surgery. The implanted device from Zarlink semiconductor, which is taken as a reference
here, consists of 3 main sub systems:

- A RF transceiver, which works in 403 MHz band.
- Media access controller (MAC) layer and
- 2.45 GHz wake up receiver.

However, in this project we have concentrated on transmitter at 403 MHz band. Here, we have used a direct conversion transmitter architecture, which is known for low power application and FSK modulation scheme, which reduces transmitter amplifiers linearity requirement.

![Schematic of the complete RF communication system for implanted medical device](image)

**Figure 1: Schematic of the complete RF communications system for implanted medical device.**

### 2.3: System Level Parameters:

The main challenge for implant medical devices is to have high data rate transmission with lowest power consumption. Data integrity is very important in implant device, so transmission of data from source to destination requires being high performance efficient with minimum noise. In this report we have concentrated on the performance and efficiency of the system level transmitter design. To reduce power consumption and to increase the lifetime of the battery, parameters like power consumption, frequency band, modulation scheme and data rate plays a crucial role. So, we will see each and every parameter and their effect in the following topics.
2.3.1: Power Consumption:

The goal of ultra low power consumption in implant medical device allows us to reduce the size of the device considerably. In order to achieve such a low power device, engineer are focused on the sleep mode time, this is the time where device will spend most of its time.

Ultra low power is one of the most vital requirements for medical implanted device. In order to minimize the cost of treatment and patient trauma, it is important to save energy and maximize the battery life of implanted device. One way of doing this is by keeping the transmitter circuitry off when it is not in use.

There are few more techniques, which help reduces power consumption:

- High data rate transmission
- Quick wake up and return to sleep
- Optimizing system and host interaction
- High level of integration
- High level of reliability
- Device should sleep most of the time, while having periodic sniff for signal at appropriate time. Thus standby current and wake up time can be minimized.

2.3.2: Frequency Band:

Federal communication commission (FCC) has allocated 402-405MHz frequency band to MICS (medical implant communication service) for medical use. MICS band offer wide opportunities like

- MICS band offers optimal far field radiation characteristics.
- Low specific absorption rate that makes it suitable for low power medical devices.
- No interference risk involved, as no other radio operates in this band.
- No licensing required.

2.3.3: Symbol Rate:

The limited use of power in today wireless systems does not permit data to be transmitted continuously. As the data rate increases, noise increases with increase in power consumption, so data rate is very critical to design of a transmitter. But low data rate transmission means that transmitter has to be on for a long time, which ultimately leads to increase in power consumption. So, there is a tradeoff involved between date rate, power and system efficiency of the system design.

Symbol rate is the bit rate in bps (bit per second) divided by total number of bits transmitted with each symbol. Symbol rate is often called as baud rate, bandwidth of a communication channel depends upon the symbol rate not on bit rate. Symbol rate is very important as it sets the bandwidth requirement for the signal transmission.\(^9\)

In the case of BPSK, where only 1 bit is transmitted, symbol rate =bit rate. \( (2.1)^9 \)

While in QPSK, 2 bit are transmitted per symbol, \( Symbol \ rate = \frac{bitrate}{2} \) \( (2.2)^9 \)

Thus if more bits are sent with each symbol, then same data can be sent in narrow spectrum.\(^9\)

Implantable transceiver should use the highest possible data rate, while satisfying receiver
sensitivity. Sending data in the form of packet in the short burst not only conserve power, but also help reduce interference risk associated within the system.

According to Zarlink semiconductor, different ranges of data rate (800/400/200) kbps are possible in the transceiver with varying receiver’s sensitivity, to reduce the complexity, system uses either 2FSK or 4FSK modulation format.

The following table taken from Zarlink semiconductor shows clearly the modulation format and actual data rate used.

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Data rate (Kbps)</th>
<th>Receiver sensitivity(µV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4FSK, high data rate</td>
<td>800</td>
<td>&lt;90</td>
</tr>
<tr>
<td>2FSK, high data rate</td>
<td>400</td>
<td>&lt;35</td>
</tr>
<tr>
<td>2FSK, high deviation</td>
<td>200</td>
<td>&lt;20</td>
</tr>
</tbody>
</table>

Table 1: Data rate vs. modulation level

2.3.4: BER (Bit Error Rate):

Bit error rate is the degree of error in the transmission of data. It can be due to many reasons like bad hardware and noise links. Higher the bit error rate, noisier the data be. In order to examine the performance and reliability of a radio system, we simulate the system and calculate BER. In digital communication, transmitter transmit a series of data (0 or 1), while the receiver will receive the data and convert it into original form. In ideal case, receiver will receive the exact data transmitted by transmitter. However, due to the presence of noise and distortion in the communication system, the received data is not the same as the transmitted data. The difference between the transmitted and received data is commonly known as probability of error.

The average probability of error for coherent BFSK modulation scheme:

\[ P_e = \frac{1}{2} \text{erfc}(\sqrt{\frac{E_b}{2N_0}}) \]  

BER is defined in terms of probability of error.

\[ \text{BER} = \frac{p_e}{\log_2 M} \quad M \geq 2 \], In BFSK M=2, BER= P_e \quad (2.4)

Where erfc = Complementary error function.

\[ P_e = \text{Probability of error} \]
\[ M = \text{Number of symbols} \]
\[ \frac{E_b}{N_0} = \text{Bit energy to noise power spectral density} \]

The dimension of \( E_b \) is W-sec, while dimension for \( N_0 \) is W/Hz. Thus, it is a dimensionless quantity.

If \( \frac{E_b}{N_0} \) is increased, BER can be reduced. If BER is high, \( \frac{E_b}{N_0} \) is low, then it would be more difficult for the receiver to reconstruct the original information. Carrier power, bit rate and power spectral density of noise power often concludes the probability of error.

In QPSK, information is contained in the phase of the signal, so average probability of error:
For QPSK modulation Scheme:

\[
Pe = \text{erfc} \left( \sqrt{\frac{E_b}{N_0}} \right)
\]

(2.5)

In QPSK, BER is related to probability of error as

\[
\text{BER} = \frac{Pe}{\log_2 M} \quad \text{M} \geq 2
\]

(2.6)

In MPSK = QPSK = 4(PSK), M = 4, BER = \( \frac{Pe}{2} \)

(2.7)

For example: if a system transmit ‘1’ bit of information during each period, bandwidth efficiency is 1bps/Hz. when number of states gets increased, the separation between two neighboring states gets decreased this will cause BER to increase. Error correction coding (ECC) scheme allows ‘N’ bit error to be corrected in a block of bits.

Higher the \( \frac{E_b}{N_0} \) ratio for the transmitter, lower the probability of error. \( \frac{E_b}{N_0} \) defines the spectral purity and quality of modulated signal.

2.3.5: Constellation plot:

Constellation is a plot of symbols on states diagram. Constellation plot indicates the phase of the symbols and their relationship with each other. The X-axis projection for each symbol is called ‘I’ channel amplitude, while y-axis projection is known as ‘Q’ channel amplitude. Each symbol represents the packet of data that has transmitted, this set of symbol points is called as constellation. Constellation point provides compact characteristics of signal set with definite information about the performance of the system. Constellation is the graphical representation of complex envelope of each symbol state. It is always performed at baseband signal.

As shown in figure 5 and figure 8, modulated signal in digital communication is often expressed in terms of ‘I’ and ‘Q’ plot. I-axis lies on 0º phase reference, while Q-axis is rotated by 90º phase. Thus signal vector projection on I and Q axis is called I component and Q component respectively.

EVM (Error vector magnitude) is the measure of difference between ideal and distorted constellation. Error vector magnitude define the signal quality, it has the ability to identify the type of degradation present in the signal. Signal which is send from the source to destination with all constellation points at ideal location, noises such as phase noise, leakage, and ISI will change the actual constellation point from ideal location, to a point nearby and this deviation shows the amount of imperfection present in the signal. Thus EVM is a measure of how far the signal (points) has been deviated from the ideal location in the I-Q plane.

Relation between bits per symbol and constellation point is given as

\[
M = 2^N \quad \text{where } M = \text{Number of constellation points or symbol vector.}
\]

N= bits per symbol

(2.8)
Chapter 3: Digital Modulation:

Digital modulation is the technique in which digital signal is impressed onto a carrier signal for transmission. A sequence of digital data are used to alter the parameter of a high frequency signal called carrier signal. Thus by modulating different parameters like amplitude, phase and frequency of the signal, transmission of signal takes place.

Digital modulation techniques provide:
- High data rate transmission
- Data security
- High quality signal
- Simple architecture
- Low power consumption
- Good performance over a fading communication channel.

Still, there are some tradeoffs exist in a digital communication like, simple hardware structure that is used to communicate data signal uses a lot of spectrum, which limit the number of users. So, if complex hardware is used to communicate the same data, it requires less bandwidth but that complex structure are hard to design and build.

Digital modulation techniques are far more advantageous than their analog counterpart. It offers benefits like
- Increased channel capability and
- Greater accuracy in the presence of noise and distortion.

3.1 Choice of Modulation:

The main function of modem design is to efficiently and effectively transmit data without being getting corrupted from noise. Modulation is a process in which lower frequency signal (analog or digital) is superimposed onto a higher frequency signal. Need of modulation process is to change the baseband signal frequency into RF signal frequency. Modulation allows transmitting a number of channels simultaneously at different carrier frequency.

There are 3 primary criteria for choosing the kind of modulation scheme.

- Power efficiency
- Bandwidth efficiency
- System efficiency

3.1.1 Power Efficiency:

Power efficiency is defined as the required SNR for a certain probability of error over an additive white gaussian noise channel. It is defined as a measure of signal quality at low power level. Hence, this kind of system uses large bandwidth in order to get required power and cost efficiency.

Example: battery runs devices.

3.1.2 Bandwidth Efficiency:

This is the rate of transmission of number of bits per second in one hertz of a system bandwidth.
is the ability of a modulation scheme to accommodate data within a given bandwidth. As data rate increases, bandwidth of the signal increases, if ‘R’ is the data rate and ‘B’ is the bandwidth of the signal. Then bandwidth efficiency is defined as

\[ \eta = \frac{R}{B} \text{ Bit/s/Hz.} \]  

Spectral width of main lobe of spectrum provides easy way to measure bandwidth of M-ary PSK signal. It is often called as null-to-null bandwidth. M-ary PSK signals are more spectral efficient than M-ary FSK signals.

The theoretical bandwidth efficiency for digital modulation system is equal to X bps/Hz. Where X=1 for Binary modulation scheme and X=2 for Quadrature modulation scheme.

### 3.1.3 System Efficiency:

This represents the simplicity of circuit. This is defined by the cost, circuit complexity and amount of circuitry involved.

Hence, the compromise is between one or more parameter, if power efficiency is increased, ultimately bandwidth efficiency decrease. Thus a designer looks for a radio which works fairly well in all the three parameter, for low power battery operated device bandwidth efficiency is quite poor.

Finally, choice of modulation depends upon the following factors:

- High data rate transmission.
- Minimum bit error rate.
- Low transmitted power.
- Minimum bandwidth requirement.
- Minimum circuitry involved.
- Maximum resistance to interfering noise.

However, not all these factors can be considered, there will always be conflict between one and the other, depending upon the device requirement, whether a power efficient device or bandwidth efficient device is required. Thus, best modulation scheme is one that has lowest bit error rate with use of minimum bandwidth in a cost effective manner.

### 3.2 Transmitter Architecture:

**Direct conversion to RF architecture:**

There are two types of transmitter architecture, which are normally used in communication, depending on the final requirement and application.

1) 2-step conversion transmitter
2) Direct conversion transmitter.

Both the transmitter architecture is suitable for constant and non-constant envelope modulation schemes and both this architecture can be realized by making use of quadrature modulator technique. 2-step conversion transmitter is used, when the requirement is high performance at the expense of
increased power consumption while, direct conversion transmitter is appropriate for system with low power consumption and low cost.

![Direct conversion transmitter block diagram.](image)

**Figure 2: Direct conversion transmitter block diagram.**

### 3.2.1 Advantages:

The advantage of direct digital modulation technique is enormous, when compared with their counterpart heterodyne structure.

- No need of IF oscillator, IF band pass filter and up converter
- High efficiency
- Higher data rate transmission possible.
- Reduced hardware complexity

Thus, by reducing the number of component, significant amount of power could be conserved.

But it also brings some drawbacks with it:

- Corruption of carrier signal by power amplifier, which is widely known as “injection pulling”, noisy signal from power amplifier leaks into LO carrier, thereby corrupting oscillator spectrum, this degrades the performance of the transmitter and causes transmitter spectrum to widen.
  
  However, many shielding and filtering techniques are available, which isolate carrier signal.

### 3.3 Transmitter Components:

A simple transmitter consists of modulator, power amplifier and filters. Here, we will discuss about the most important parameter which affect the performance of the system, namely power amplifier and filters.

#### 3.3.1 Power amplifier:

Once the signal is being modulated, it is necessary to improve the strength of signal, which is otherwise very weak. Power amplifier will strengthen the signal, while at the same time increasing the overall efficiency of the signal.

By increasing the efficiency of amplifier, cost of electricity could also be brought down. Efficiency,
output power and linearity of power amplifier are very crucial.\textsuperscript{12}

- Low power or battery operated devices needs high power efficiency.
- Linearity is crucial for data transmission and it also helps to contain RF signal within an allocated band. Thus limiting the interference to adjacent channels.
- High output power determine the geographical distance.

Efficiency = \frac{\text{Power dissipated into the load}}{\text{Power absorbed from the supply}} \quad (3.2)\textsuperscript{12}

However, not all these requirement can be meet, if an amplifier has good linearity, then it consume large DC power, thus it is not a power efficient and could not be used for low power application. Amplifiers which operate in linear mode are less efficient when compared with the amplifier which operates in non linear mode. By increasing efficiency of amplifier at the cost of linearity, low power, low cost device can be realized.\textsuperscript{4}

Nonlinearity in power amplifier results in distortion and interference in the adjacent channels. This effect of distortion can be seen on symbols in the constellation plot, where symbols are so badly distorted that symbol are hard to recognized.\textsuperscript{12} Nonlinearity in power amplifier makes bandwidth spread out, which is sometimes called as spectral regrowth.

\textbf{3.3.2 Filters:}

Filtering technique reduces bandwidth requirement, removes unwanted signal and minimize inter symbol interference. But unfortunately it is not possible to remove all the noises; there will always be some form of noise or distortion present in the signal.\textsuperscript{33} However it is important to make sure that these noise levels are reduced to certain minimum level, where they are not in the position to damage the signal.

Filtering reduces transmitted bandwidth without having any effect on the content of the signal. This improves the spectral efficiency of signal, and also helps to smooth the transition levels in ‘I’ and ‘Q’ component.

However, there are some tradeoffs that must be considered.\textsuperscript{9}

- Filtering causes trajectory of signal to overshoot.
- It makes the radio more complex.
- Sometime it makes the radio large.
- When signal is filter enough, it can also create ISI, which can be determined by time domain response of a filter.

Mainly, there are 3 different kinds of filter, which help to smooth the transition, minimize bandwidth and reduce ISI.

1) Raised cosine or Nyquist
2) Square root raised cosine.
3) Gaussian filter.

Most commonly used filter is Nyquist filter, which reduce both bandwidth and ISI interference.
Chapter 4. FSK Modulation

4.1 Introduction:

Modulation scheme employed is a compromise between data rate, power consumption, spectral efficiency and circuit complexity. Modulation scheme generally are categorized into two categories:

- Constant envelope modulation schemes: MFSK, MPSK and CPM
- Non constant envelope modulation schemes: ASK, QAM and Q^2PSK.

However FSK, ASK and PSK are the basis modulation scheme which are normally used in digital communication, while QPSK, MSK and Q^2PSK are the advanced scheme, which offer reasonable power and bandwidth efficiency, but at the expense of complex hardware. In low power application, constant envelope modulation scheme are employed, where power amplifier must operate in the nonlinear region, in order to achieve maximum efficiency for battery operated devices.

However, if spectral efficiency and coexistence are important, then non constant envelope modulation techniques like QAM can be used. But for narrowband MICS channel application, FSK and ASK are the most popular used scheme.

4.1.1 Theory:

FSK is the one of the most commonly used modulation techniques in the communication system. Here, information is stored in the form of frequency shifts, frequency shift keying involves switching a sinusoidal carrier wave between two frequencies. It employs a tunable oscillator to switch between two frequencies. For binary FSK a ‘+1’ is represented by positive shift, while a ‘-1’ is represented by negative shift. In FSK, the amplitude of the modulated signal is kept constant, while change in frequency that carries information, which allows use of nonlinear amplifiers with little or no distortion. In FSK, transmitted signal is represented in the form of a symbol, which is either 1 or 2 bits depending upon whether it is 2 or 4 level modulation scheme.

Frequency of the carrier is changed as a function of transmitted modulated data signal while amplitude remains constant.

FSK signal produces constant envelopes carrier with no variation in amplitude. This is desirable property for improving power efficiency of transmitter. Variation in amplitude can lead to spectral regrowth and ACPR (adjacent channel power ratio). Hence for low power consumption, more efficient amplifier with less linearity could be used.
Figure 3: (a) Block diagram of FSK modulation scheme.

Figure 4: (a) Binary input sequence, (b) BFSK modulated signal
4.1.2 MFSK signal: M-ary frequency shift signal can be represented by

\[ S_i(t) = A \cos(2\pi f_i t + \theta), \quad 0 \leq t \leq T_b \]

\[ 0, \quad \text{elsewhere} \]  

(4.1)

Where \( i = 0, 1, \ldots, M-1 \) and

\[ A = \sqrt{\frac{2E_b}{T_b}}, \]

\( E_b \) = Transmitted signal energy per bit

\( f_i \) = Transmitted frequency signal

\( \theta \) is the initial phase angle and

\( T_b \) is the symbol duration.

\( S_1(t) \) represents symbol 1 and \( S_2(t) \) represents symbol 0. Both the signal \( S_1(t) \) and \( S_2(t) \) are orthogonal, let \( \phi_i(t) \) represent the phase of the signal.

\[ \phi_i(t) = \sqrt{\frac{2}{T_b}} \cos(2\pi f_i t), \quad 0 \leq t \leq T_b \]

\[ 0, \quad \text{elsewhere} \]  

(4.2)

Coherent FSK controls both frequency and phase of the signal, so resultant output signal is represented as:

\[ S_{ij} = \int_0^{T_b} S_i(t) \phi_j(t) \, dt \]

\[ = \int_0^{T_b} \frac{2E_b}{T_b} \cos(2\pi f_i t) \sqrt{2E_b} \cos(2\pi f_j t) \, dt \]

\[ = \sqrt{E_b}, \quad i = j \]

\[ 0, \quad i \neq j \]  

(4.4)

Where \( i = 1, 2 \)

\( j = 1, 2 \)

BFSK signal can also be represented by \( f_1 = f_c - \Delta f \) and \( f_2 = f_c + \Delta f \).

Where \( f_c = \) carrier frequency, \( f_1 \) and \( f_2 \) are two transmitted frequency.

For orthogonality, \( f_1 = \frac{m}{T} \) and \( f_2 = \frac{n}{T} \)

(4.5)

\( n > m \), where \( n, m \) are integers.

\( \Delta f \approx 2\Delta f \),

\( \Delta f = \) Frequency deviation,

\( R = \) data rate,

\( B = 1/T \) represents bandwidth of the modulating signal.

\( \Delta f \gg 1/T \), the resultant signal is a wideband signal with bandwidth approximately equal to \( 2\Delta f \).

\( \Delta f \ll 1/T \), the resultant signal is a narrow band signal with resultant bandwidth equals to \( 2B \).
4.1.3 Frequency deviation: \( \Delta f = \beta B \), \(^{(4.8)^1}\)

\( \beta \) = Modulation index and
\( B \) represents bandwidth of the signal

The bandwidth of a FSK signal is derived from Carson’s rule which is given as
\( BT = 2\Delta f + 2R \) \(^{(4.9)^1}\)

Bandwidth of a signal depends upon Modulation index ‘m’ of the signal

Where \( m = \Delta f/fm \) \((4.10)\)
\( fm \) = modulating frequency.
\( \Delta f \) = frequency deviation.

4.1.4 Bandwidth efficiency: For \( M \)-ary FSK signal,

Bandwidth of a signal is \( B = Rb \times \frac{M}{2\log_2 M} \) \((4.11)^1\)

Bandwidth efficiency of \( M \)-ary FSK is

\[ \rho = \frac{2 \log_2 M}{M} = \frac{Rb}{B} \] \((4.12)^1\)

Where \( R_b \) = Bit rate

So, In the case of \( M \)-FSK signal, as the value of ‘\( M \)’ increases, Bandwidth efficiency decreases.
By using Gaussian filter right after the data generator, help smoothen the pulses, and also limit the bandwidth of the signal.

4.1.5 FSK constellation:

Phasor diagram describes a phasor that is fixed in frequency. FSK modulation cannot be represented on the phasor diagram, because in FSK modulation, information is contained in the frequency transition not in a phase. To represent FSK on pseudo–phasor diagram, frequency is approximated as being fixed, while maximum real frequency shift is taken as 180° shift of the phasor.\(^{20}\)

Constellation is a graphical representation of discrete states and their transition, constellation diagram indicates that the amplitude of a phasor is constant.\(^{20}\) Power efficiency is connected to minimum distance between the points in the constellation. In case of MFSK, as value of ‘\( M \)’ increases, distance between any two symbol vector in constellation plot increases. Power efficiency increases as shown in figure below:
4.1.6 Advantages:

- FSK modulation has good power efficiency
- Low sensitivity to interference
- Simple hardware.
- Less affected by multipath propagation and interferences.
- Easy to demodulate.

It has advantage over ASK in terms of reliability, higher power efficiency and better noise performance.

For frequency below 1 GHz, we often use FSK/GFSK scheme, because of the relaxed requirement on linearity of system. Hence FSK modulation scheme is a good compromise between data requirement on linearity and complexity.\(^5\) Constant envelope modulation scheme is not well suited for bandwidth efficiency system. Instead, it is used for power efficient system.

In M-ary FSK, for fixed probability of error, increase in the value of ‘M’ results in reduced power consumption, so power efficiency increases as value of ‘M’ increases. However, reduction in transmitted power is achieved at the cost of channel bandwidth.\(^1\)

**Application:** Low power application, AMPS, land mobile, DECT etc.
Chapter 5: QPSK Modulation:

5.1 Theory:

QPSK transmitter can be realized using Quadrature modulation technique. Figure shown below is Quadrature modulator used for QPSK transmitter in ADS environment. Two independent signals are combined and summed together with 90° phase shift to get resultant modulated output signal. The main advantage of quadrature modulation techniques is its:

- Simple hardware
- Flexible structure.
- Low power consumption.

QPSK consist of a two BPSK modulator with 90° phase shift mode of transmission. In QPSK, information is contained in the phase of the signal. QPSK has the ability to transmit higher data rate, i.e. two bits per symbols simultaneously. QPSK has two independent quadrature carriers, even (or odd) bits are used to modulate in phase component and odd (or even) bits are used to modulate quadrature phase component of carrier. In phase (I) data stream and quadrature phase (Q) data stream transmit data simultaneous.¹

QPSK has 4 phases to transmit data efficiently, thus QPSK modulation has 4 allowable phase states per symbol period. In QPSK, data is divided into pairs of 2 bit, each of 2 bit pair is known as symbol. Each symbol is equispaced at different phases of carrier such as 45°, 135°, 225°, 315°. Symbol values are complex, but they determine the amplitude and phase of a modulated carrier at instant sampling. This symbol set could be represented by constellation plot.¹

The input binary message m(t) with data rate of $R_b$ is split into two bits streams of I (in phase) and Q (Quadrature) component.

Each having a bit rate of $R_s = R_b/2$  

Where $R_s$ = Symbol rate in Hz.

$R_b$ = Bit rate in bps.

\[
I_K \rightarrow \text{SERIAL TO PARALLEL} \rightarrow \text{WAVEFORM SHAPING} \rightarrow \text{I(i)} \rightarrow q(t) + b(t) \rightarrow s(t)
\]

\[
Q_K \rightarrow \text{WAVEFORM SHAPING} \rightarrow q(t) \rightarrow b(t) \rightarrow s(t)
\]

Figure 6: Quadrature modulation technique used for QPSK modulation scheme.²⁰
5.1.1 QPSK signal:

QPSK signal is represented as\(^1\):\(^{26}\):

\[
Si(t) = A \cos(2\pi f c t + \varphi(t)), \; 0 \leq t \leq T
\]

=0, elsewhere

Where:

\[
A = \sqrt{2E/T}
\]

\[
\varphi(t) = (2i + 1)\pi/4
\]

\(i = 0,1,2,3\) represents symbol states

\(Si(t)\)=QPSK signal

\(\varphi(t)\)= phase of the signal.

\(T=\) Symbol duration

\(E=\) Transmitted energy signal per symbol

\(f c=\) Carrier frequency

Let ‘I’ and ‘Q’ channels are represented as

\[
I = \sqrt{\frac{2E}{T}} \cos(2\pi f c t)
\]

\[
Q = \sqrt{\frac{2E}{T}} \sin(2\pi f c t)
\]
The above two equation are orthogonal, if we multiplied the above function with the phase angle \( \cos \varphi(t) \) and \( \sin \varphi(t) \) respectively, for \( i=0, 1, 2, 3 \) (since \( M=4 \) then

\[
I = \sqrt{\frac{2E}{T}} \cos(2\pi fct) \left( \cos \left( \frac{\pi}{4} \right) \cos \left( \frac{3\pi}{4} \right) \right)
\]

\[
Q = \sqrt{\frac{2E}{T}} \sin(2\pi fct) \left( \sin \left( \frac{\pi}{4} \right) \cos \left( \frac{3\pi}{4} \right) \right)
\]

(5.7)

(5.8)

Modulator mixes the ‘I’ component with RF carrier and mixes the ‘Q’ component with same RF carrier but with 90° phase offset. Q signal is subtracted from ‘I’ signal producing a final RF modulated signal.

Modulation signal can be expressed as:

\[
s(t) = \sqrt{\frac{2E}{T}} \cos (\theta(t)) \cos (2\pi fct) - \sqrt{\frac{2E}{T}} \sin (\theta(t)) \sin (2\pi fct)
\]

(5.9)

Radius of circle representing QPSK signal is \( \sqrt{E} \) and amplitude of each I and Q component is 1 and calculated angle would be 360/M.

In case of QPSK, \( M=4 \) which means 360/4=90°, so 4 symbol points, each 90° apart on the circle.

QPSK have 4 symbols, each start at 45° and then phase change by 90° each time to get next symbol.

QPSK encode dibits per symbol, in order to minimize BER.

### 5.1.2 Bandwidth efficiency:

Channel bandwidth require to pass M-ary PSK signal is given as

\[
B = \frac{2Rb}{\log_2 M}, \text{ while}
\]

(5.10)

Bandwidth efficiency for M-ary PSK signal\(^1\) is

\[
\rho = \frac{\log_2 M}{2} = \frac{Rb}{B}
\]

(5.11)

\( M= \)Number of symbol vector.

The importance of M-ary PSK scheme is due to its bandwidth efficiency. In MPSK, \( n=\log_2 M \) data bits are represented as symbol rate. If the modulation scheme is QPSK, then \( M=4 \), so \( n=2 \) bits represents each symbol, bandwidth efficiency is increased twice to BPSK. Thus, QPSK transmit data twice as fast as BPSK.

In MPSK, as the value of \( M \) increases bandwidth efficiency increases. M-ary PSK signal are more spectral efficient than M-ary FSK signals.

### 5.1.3 QPSK Constellation:

BFSK signal uses 2 point in the constellation plot, equispaced around the circle, BFSK encode 1 bit per symbol, while its counterpart QPSK uses 4 point in the plot, which encode 2 bit per symbol.

By looking at constellation plot(figure 8) for QPSK and comparing it with BPSK, reveals that as the
distance between any two symbols decreases, there is high probability of error which effect system performance. However more detail study shows that symbol energy is twice as large as bit energy in BPSK. Thus both the scheme will have same probability of error at high signal to noise ratio. The performance test of a QPSK signal is done with BER tool. Bit error rate of QPSK is same as BPSK, but at the same time large (twice) data can be sent in the same bandwidth. Thus QPSK is more spectral efficient for same energy when compared to BPSK.

Bandwidth efficiency is related to the number of points in the constellation (in case of MPSK). Noise and distortion will distort received constellation symbol. Noise is mostly generated from the surrounding environment and from RF hardware. The effect of noise and distortion is described in the constellation plot.

Performance of a communication system can be improved by using coding techniques in a system. The most common coding techniques are gray coding and Reed-Solomon coding. In a gray coding scheme, QPSK system takes input binary data, and creates a symbol with 2 bit at a time. Bit pairs that are used to generate symbol are only having one bit different from each adjacent symbol. Thus, it helps to identify error and at the same time improves performance. This coding scheme will reduce the error rate of a system.

5.1.4 Advantages:

- MFSK and MPSK modulation have constant envelopes they are not very sensitive to amplitude nonlinearity in transmitted power amplifier, thus relaxing the power amplifier linearity requirement for higher power efficiency. This is the only reason why above techniques are more widely used when compared to ASK.

- While bandwidth efficiency is increased, QPSK is the only modulation scheme in MPSK, which does not suffer from BER degradation.
• QPSK has advantages like simple implementation and resilience to noise.

**Tradeoff:**

M-ary signaling schemes are preferred when the requirement is to conserve bandwidth of the signal, but at the expense of increased power consumption. QPSK offers best tradeoff between power and bandwidth efficiency requirement that is the only reason why QPSK is most often used scheme.\(^1\) As for M > 4, power requirement becomes too excessive and system requires more complex circuitry. Hence, they are not widely used.\(^1\)

**Application:**

1) Satellite communication, CDMA, cable modem etc
Chapter 6: Design process

The design of FSK and QPSK transmitter is carried out by using Agilent advanced design system. The design process is basically carried out in two phases. In the first step, the architecture suitable for low power transmitter is designed. In the second step, schematic is simulated and required equations are written to evaluate the performance and efficiency limits of both transmitter. In this chapter, we will look at the system overview of both the transmitters independently.

6.1 FSK transmitter:

The architecture shown below is a block diagram of FSK transmitter based on single ended backend direct conversion to RF architecture. The main purpose of transmitter is to transmit a signal by modulating a RF carrier with the baseband signal. Transmitter architecture used in low power application must be simple and small. By making use of advanced development in the monolithic technique, it is possible to realize direct conversion transmitter architecture. In this technique, modulator directly converts data to the RF frequency. The detail description about each and every component used in the design is discussed in the following topic.

![Figure 9: FSK transmitter block diagram](image)

6.1.1 System overview:

Figure 9 shows the block diagram of FSK transmitter. Here, oscillator is used to generate carrier signal which is being modulated by digital data. The modulated output will pass through band pass filter, which removes any out of band signals present in the system. Power amplifier will amplify the strength of the signal, which is otherwise a very weak signal. Band pass filter at the output of power amplifier is used to remove any harmonics or spurious signals generated by power amplifier. The individual component is described in detail in the following section.

- **Oscillator:**
  Heart of any transmitter is an oscillator, the main function of oscillator is to generate carrier signal. The main requirement on oscillator circuits is that it should be stable, it should not start drifting or
else the output of the signal gets change. There are different kinds of oscillator are used, depending upon the final requirement on the system say for low power application, crystal oscillator is used, which is known for its stability.

- **Data generator:**

Data sequence is generated by using transient voltage linear feedback shift register (VT-LFSR), voltage source with pseudo random pulses that are defined at discrete time steps. Linear feedback shift register (LFSR) is used to generate sequence with user-defined relation. A shift register is a group of flip flop, with their input and output are connected in such a way that data is shifted down the line when circuit is activated.\(^7\)

A LFSR is a register of ‘N’ bits. Assigned bit values of TAPS are XOR’d together to create a new bit. This new bit is positioned to the left of the register and sequences of bit are shifted to the right with previous right most bits being assigned as output bit. This process is repeated to produce random stream of bits.\(^3\)

![Figure 10: Linear feedback shift register used to generate data sequences.](image)

TAPS are XOR’d sequentially with the output bit, and feedback into the leftmost bit, the sequence of bits on the right most position is called as output bit stream.\(^7\) The source generates different random bit sequence, since they have different value for TAPS and SEED.

SEED= Initial values of LFSR.
TAPS= Bit position, that affect the next stage.

- **Band pass filter:**

Modulated signal at the output of FM modulator will pass through the band pass filter, the filter which is at the output of modulator confines the power spectrum of a signal within an allocated band.\(^4\) This prevents the spillover of signal energy into adjacent channels and also removes out of band spurious signals that are produced during modulation process. Since filter are not very ideal, there will always be some form of unwanted signal. Power amplifier will improve the strength of the signal, but at the same time it also improves the unwanted signal present near the original signal resulting in generation of harmonics in the signal.

Band pass filter at the output of a power amplifier will make sure that all the spurious products and
harmonics, which are present in the signal are eliminated or it try to keep it to a certain minimum level, while making sure that the original signal is interference free.

- **Power amplifier:**

Power amplifier at the output of band pass filter will help improve the strength of the weak signal. But it will also improve the unwanted signal which is near the wanted signal. Thus giving rise to the spurious products or harmonics.

For low power application, to maximize the lifetime of battery, it is necessary to ensure that maximum amount of DC power entering into the amplifier is converted to RF power. Gain of the amplifier plays a vital role, first of all, if an amplifier is having high gain, then the distance between two vectors in the constellation plot increases, which means that it would be easy to recover and identify the symbol. Secondly, BER value decreases as the performance of the system increases.

**6.2 Implementation:**

The following figure 11 shows the schematic design view of FSK transmitter implemented in Agilent advance design system.

![Schematic of FSK transmitter in ADS](image)

**Figure 11: Schematic of FSK transmitter in ADS.**

**FM-Mod:** FSK Transmitter is realized using FM modulation technique. This is a tuned modulator, where carrier is injected at pin 1, modulating signal at pin 3 and the resulting output is at pin 2. The RF carrier which is generated at pin1 should be a frequency domain source while modulating signal at pin 3 should be a time domain source. A frequency domain sources generate a superposition of periodic waveform.

**P_1Tone:** Power source is used to generate carrier frequency. It is defined by its frequency, power and impedance, which is being fixed at center frequency of 403.5MHz at 0.1mW.

**VtFSR_DT:** This is a discrete time source, which is used to generate data sequence. The input to data generator is a binary sequence. Two register implemented will produce same sequence of bit stream, since both have identical feedback weight. Therefore, initial state of register i.e. SEED must be different for the two sequences to have identical phase.
**Band pass filter:** Band pass filter is a Butterworth 1st order filter with center frequency equals to carrier frequency. For system modeling behavioral response is ideal, as no ripples are produced in the pass band. It has two important parameters like Bwpass and Bwstop. Bwpass indicates the sharpness through which a pass band goes to stop band, while Bwstop defines the range, where frequency lies outside the pass band.

Butterworth filter has been selected because:

- Its linear phase that makes it desirable for modulation.
- It has good selectivity.
- Maximally flat magnitude response in pass band.
- Good filter performance and better pulse response.

**Power amplifier:**

Power amplifier improves the strength of the signal. Gain of amplifier $S_{21}$ is taken as ‘0 dB’. This shows the minimum gain limits of power amplifier. While return loss $S_{11}$ and $S_{22}$ and reverse gain $S_{12}$ is also taken as ‘0 dB’. Return loss value is ‘0’; because we don’t want output current to flow back in to the input. Increase in the value of reverse gain will lead to leakage and overall performance degradation.

**6.3: QPSK Transmitter:**

**Quadrature modulation technique:**

Block diagram of a QPSK transmitter is shown below in figure 12. QPSK has two independently modulated quadrature carrier even (odd) bits are used to modulate the in (I)-phase, while odd (even) bits are used to modulate the quadrature (Q)-phase of carrier. Digital modulation maps the data to a number of discrete points on the I-Q plot, these points is known as constellation points.

**Advantages:**

- Simplicity involved in the hardware design.
- Flexible structure.
- Low power consumption.
- Small and simple in size.
6.3.1 System overview:

**Low pass filter:**

In the design of QPSK transmitter, we have used root raised cosine filter as low pass filter for filtering of digital data. It works like a Nyquist filter. Root -raised cosine filter is used to shape the pulses in order to minimize bandwidth, square pulses which are generated from the signal generator requires a lot of bandwidth. By shaping the pulses, this filter will convey the same amount of information but with less bandwidth and with good ISI rejection. This filter has a parameter called Alpha ‘α’ which is known as excess bandwidth factor. Excess bandwidth factor specifies the sum of occupied bandwidth required in excess of ideal occupied bandwidth. Its job is to:

- Smoothen the transition and narrow the frequency spectrum.
- Helps to achieve cleaner and smoother sources.
- Minimize bandwidth and reduces ISI.

Higher the value of ‘Alpha (α)’, lower the amount of power consumption required.

**Band pass filter:**

The two binary sequences (I and Q) are modulated by the carrier and combined to produce a QPSK signal. The filter which is at the output of a modulated signal confines the power spectrum of a signal within an allocated band, this prevents the spillover of signal energy into adjacent channels and also removes out of band spurious signals that are produced during modulation process.
6.4 Implementation:

The above block diagram of QPSK transmitter has been implemented and simulated in ADS environment, the analysis of the design is done to evaluate the performance characteristics of transmitter.

**IQ-ModTuned:** QPSK transmitter design is realized using Quadrature modulation technique. This is a tuned modulator where RF carrier is injected at Pin 1, I data at pin 3, Q data at pin 4 and the expected output at pin 2. RF carrier generated at pin 1 must be a frequency domain source, while modulating signal must be a time domain source.

It consists of two voltage sources with pseudo random pulse sequence defined at discrete time steps. The voltage sources generate different random bit sequences because they have different values for TAPS and SEED. Tuned modulator selects the input harmonic defined by carrier frequency and then modulated it according to I (in-phase) and Q (quadrature) modulation inputs.

**LPF_Raised cosine:** This filter is used to shape the pulses in the digital modulation. It also reduces interference and bandwidth of the signal. This filter has important parameters like Roll off factor ‘α’ and symbol rate. Roll off factor defines the excess bandwidth of the signal and it is a measure of sharpness of the filter, higher the value of ‘α’, lower the power consumption.

\[ 0 \leq \alpha \leq 1 \]

![Figure 13: Schematic of QPSK transmitter in ADS.](image-url)
Chapter 7. Measured Results:

This section will present the results obtained from simulation performed at system level using Agilent advanced design system and Matlab. The schematic design view of FSK transmitter is shown in figure 11, by calculating the performance and efficiency of the system, one can estimate how good the system design is for transmission. In order to calculate efficiency and performance, most common method is to calculate BER plot and constellation plot. Lower the value of BER, higher the performance of the system.

7.1 FSK Transmitter:

7.1.1 Constellation plot:

The constellation plot shown in figure 14 is for FSK transmitter. Constellation points shows the amplitude and phase of the signal at decision points, each symbol represents the packet of data. The constellation plot provides compact characteristics of signal set with precise information about the performance of the system. FSK is represented on a pseudo –phasor diagram, the frequency is approximated as being fixed and the maximum real frequency shift is arbitrarily taken as 180° shift of phasor. Power efficiency is related to minimum distance between the points in the constellation, larger the distance between two points’ means, smaller the probability of error, and it has less probability of mistaking one signal from the other.

Figure 14: Constellation plot of FSK transmitter
7.1.2 BER PLOT:

Performance of the system is calculated by plotting BER plot. BER for 2FSK transmitter is around $= 2.8E-8$, which indicate the high performance of a FSK transmitter. High value of Eb/No indicates signal purity and quality of modulated signal.

![Figure 15: BER curve of FSK transmitter](image)

BER=2.8E-08, Since BER =$P_e$
7.2 QPSK Transmitter:

7.2.1 Constellation plot

Constellation plot for QPSK shows data is divided into pairs of 2 bit, each of 2 bit pair is known as symbol. Each symbol is equispaced at different phases of carrier such as 45°, 135°, 225°, 315°. Thus QPSK have 4 symbols, each start at 45° and then phase change by 90° each time to get next symbol. The constellation diagram shows the repetitive “snapshot” of that same burst, with the values shown only at the decision points. It provides details and effect of power levels, filtering and distortion. Constellation diagram shows us the amplitude and phase error at the decision points.

Constant amplitude modulation scheme have constant amplitude, so quadrature phase trajectory will never leave a unit circle. This is essential, mainly because it allows power amplifier device to be operated further into compression resulting in improved efficiency and output power.

Bandwidth efficiency is associated with the number of symbol vector in the constellation plot. As the constellation plot is allowed to be denser, each symbol carries more information. In case of MPSK, as the value of ‘M’ increases, bandwidth efficiency increases, as more and more data can be send in a narrow bandwidth, while at the same time power and system efficiency decreases.

![Constellation plot of QPSK transmitter](image)

Figure 16: Constellation plot of QPSK transmitter
7.2.2 BER plot:

BER plot shown in figure 17 indicate the performance of the system. QPSK system has very low BER value for high energy to noise ratio, which means that transmitted signal is a high quality signal. It has a value of BER = $3 \times 10^{-17}$, which also shows that, QPSK is less susceptible to noise. Finally, QPSK transmitter shows good power and bandwidth efficient properties compared to FSK transmitter.

QPSK : BER plot, BER=$P_e/2=3E-17$

Figure 17: BER plot for QPSK transmitter
Chapter 8: Conclusion

Comparison between FSK and QPSK scheme:

The modulation format used in the subsystem will have an effect on choice of circuitry, battery life and tolerance on signal to noise ratio. The two modulation scheme (FSK and QPSK) differ with each other in number of ways:

<table>
<thead>
<tr>
<th></th>
<th>FSK Transmitter</th>
<th>QPSK Transmitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Baseband and RF hardware is simple</td>
<td>Complex structure</td>
</tr>
<tr>
<td>2.</td>
<td>Less interference, since power density is low.</td>
<td>Less interference, high performance in a fading environment compared to FSK and ASK.</td>
</tr>
<tr>
<td>3.</td>
<td>Power and system efficient</td>
<td>Power and bandwidth efficient.</td>
</tr>
<tr>
<td>4.</td>
<td>FSK modulation has been found to provide a good compromise between data rate, complexity, and requirements on linearity</td>
<td>QPSK is a special case, which offers good performance in both power and bandwidth efficient system.</td>
</tr>
<tr>
<td>5.</td>
<td>Used in power efficient system.</td>
<td>Used in bandwidth efficient system like DAMPS cellular system and satellite communication.</td>
</tr>
<tr>
<td>6.</td>
<td>Easy to demodulate.</td>
<td>Bit difficult</td>
</tr>
<tr>
<td>7.</td>
<td>High bandwidth required</td>
<td>Low bandwidth required</td>
</tr>
<tr>
<td>8.</td>
<td>Reasonable BER performance</td>
<td>Improved BER performance with high quality signal</td>
</tr>
<tr>
<td>9.</td>
<td>QPSK is less susceptible to noise than FSK.</td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>QPSK can transmit more data in a given bandwidth. Twice as fast as binary modulation scheme.</td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>QPSK does not suffer from BER degradation.</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Comparison of FSK and QPSK transmitter scheme.
The following table shows the transmitter characteristics for ultra low power application. The BER value shown in the table states that, QPSK transmitter is less susceptible to noise than FSK.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Input power</td>
</tr>
<tr>
<td>2.</td>
<td>Frequency band</td>
</tr>
<tr>
<td>3.</td>
<td>Modulation scheme</td>
</tr>
<tr>
<td>4.</td>
<td>Raw bit rate (kbps)</td>
</tr>
<tr>
<td>5.</td>
<td>BER</td>
</tr>
</tbody>
</table>

**Table 3. Transmitter characteristics**

**FSK modulation technique is a superior technique for ultra low power application, the above presented model could be used for low power application, by replacing system model with the circuit made model. The analyzed result shows the minimum performance limit for both FSK and QPSK transmitter. More advance techniques like QPSK and MSK could be used. MSK is a special case of FSK and it is also called CPFSK. MSK is both power and bandwidth efficient and both modulator and demodulator of MSK are simple to implement.**
Chapter 9: References:


4) Michael Deluca, “QPSK modulation and error correction codes”, Temple University, Agilent technologies.


