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OVERVIEW OF MODULATION SCHEMES SELECTION IN SATELLITE BASED COMMUNICATION

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Abstract

Satellite based communication either in GEO or LEO based system are prominently employed for voice, video, data communication. Demand of more traffic necessitates the data rate of satellite to be enhanced which can be implemented by the proper choice of modulation scheme. Presently ground systems are also wireless based which include direct broadcast satellite (DBS),television service, wireless local area networks (WLANs), global positioning satellite (GPS), radio-frequency identification systems which is either point-to-point or point-to-multipoint. Modern day communication systems are digital; based rather than analog to have better noise immunity. Further with the limited spectrum availability the choice of modulation scheme plays an important role for faithful transmission of the signal. The digital communication can be categorized as Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), Phase Shift Keying (PSK) whereas for higher bit data rate Phase Shift Keying (PSK) such as BPSK, QPSK and OQPSK are employed. This article overview of various modulation schemes which are employed in satellite communication apart from its selection criteria along with the concept of bit error rate.

Keywords:

Modulation Scheme, Communication System, Noise, Radio-Frequency

1. INTRODUCTION

Radio frequency links are employed in the satellite operations such as controlling, receiving, health monitoring, spacecraft parameters checking, rate ranging, payload operations in the form of tele-command and telemetry signals which are perceived to be complex and are having restricted information. Various modulation and multiplexing techniques in advanced communication systems are employed keeping into considerations of various parameters such as data rate, BER, spectral efficiency, susceptibility to interference etc. Particularly modulation techniques are critical and employed for securing the data and enabling to establish reliable link margin and highly efficient on-board system. In the present scenario, analog modulation schemes are replaced with the digital based techniques where digital bits represent information. Analog systems employed in the past are prone to performance variations due to routing and bunching of wires, device placement, interconnections, improper grounding and shielding along with various radiation effects encountered due to closed loop formation. Digital based technology overcome the bottlenecks faced in the analog based system [1]-[2] mainly usage of large spectrum for transmit/receive information whereas digital systems are more efficient.

Basic modulation techniques (Fig.1) show that analog modulation scheme based on sinusoidal waveform is easily implementable but prone to variations and noise. Phase modulation in comparison to frequency modulation is having stable carrier power which is preferable in the down link chain [3]. The main criteria for choosing the modulation scheme is based on maximizing data rate and minimizing transmitted power, channel bandwidth, symbol error apart from resistance to interference signal. Present day satellite communication uses number of antenna beams which in turn increases interferences arising from frequency reuse. The methodology to overcome this challenge is to employ digital modulation with coding together with on board demodulation and re-modulation to separate uplink and down link signal degradation. Digital modulation and demodulation techniques demand increase complexity and high level of integration to transfer large amount of data and information. Excessive filtering to improve spectral efficiency can reduce interferences but increases BER (bit error rate) due to blurring of transmitted symbols. This also contributes in making the system bulkier and increases the footprint. The main parameters in analog modulation is characterized with the parameter SNR (signal-to-noise ratio) whereas in digital modulation is characterized by BER (bit error rate). The requirement for minimum BER for voice is 10^{-3} and for data 10^{-6}. The selection of the particular modulation scheme involves consideration of several requirements of the system such as BER, power consumption, linearity, bandwidth, reliability and complexity factor apart from weight and cost.

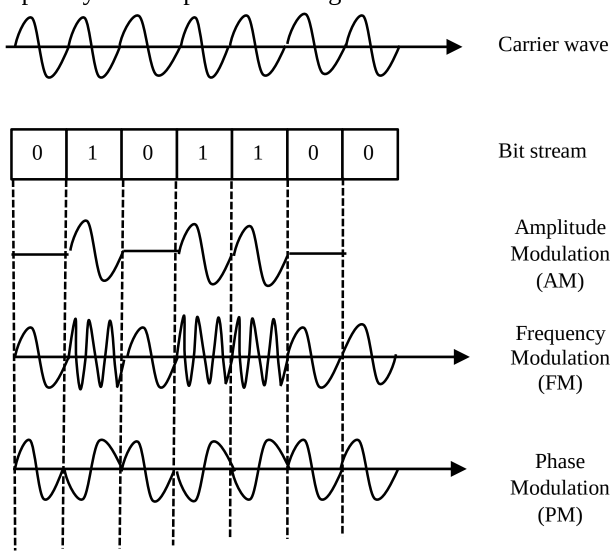

Fig.1. Basic analog modulation techniques

Satellites carry several transponders having defined bandwidth resulting in the fixed data rate which is determined by the modulation scheme and access method. The future satellites may require a large number of commands to be uplinked in a relatively short time. This may call for a command system which can handle higher bit-rates. Digital modulation scheme can be classified as constant envelope such as FSK, PSK and non-constant envelope such as ASK, QAM. M-APK (Amplitude and phase keying) and n-m PCM are the other choices. FSK is having lower bandwidth efficiency due to requirement of higher bandwidth for data modulation whereas QAM requires very high C/N ratio and is not useful for satellite communication. Mostly constant envelope scheme is preferred for satellite communication [4]-[5] and major parameters are BER, spectral efficiency and power efficiency. QPSK is the accepted modulation technique for low to medium bit rate transmission. For bulk data transmission, high density spectrum efficient modulations techniques are to be employed. Due to trade-off between bandwidth and carrier power, 4ϕ (PSK) is having widespread usage compared to FM and QPSK signals in communication systems. PSK modulation is widely used in satellite data transmission taking into consideration the spectral efficiency offered by the scheme at a given transmitted power. . BPSK, QPSK, OQPSK, MSK have inherent 3-dB advantage over coherently detected FSK technique. Further QPSK is preferred than BPSK due to doubling of data rate as carriers are in phase quadrature [6]. Also symbol energy of QPSK is more compared to the bit energy in BPSK. The data rate of a QPSK modulator is twice the data rate of I and Q data streams but the error probability is higher compared to the BPSK.MSK is a type of PSK requiring higher bandwidth and complex circuit. This article details various modulation schemes, their selection criteria, concept of BER, and implementation methodologies.

2. CHOICE IN COMMUNICATION SYSTEMS

Satellite communication mostly dependent on ground communication systems and the parameters responsible for the spacecraft communication depends on the range, frequency, size and power of ground antennas. The command and telemetry provide constant interaction with the spacecraft [7] so the modulation scheme plays an important role in telemetry and command. The huge data which is accumulated got converted in digital bit stream so as to transmit to the ground for display. Wider channel bandwidth and higher powers to establish reliable satellite links due to non-linear distortion imposes constraint on the reliable down linking of the data. Selection of the modulation technique plays critical role and various parameters such as dynamic range, linearity, minimization of interferences are important for link margin establishment. Reliable link margin establishment for the communication with the spacecraft is calculated based on link budget. Link budget needs the following information's:

- Planned data or information rate.
- Modulation type
- Forward error correction rate (1/2 or 3/4)
- Uplink and Downlink frequencies.
- Uplink and Downlink antenna sizes.
- Uplink and Downlink antenna efficiency.
- Uplink and Downlink transmit and receive gains at frequency.
- Minimum digital signal strength (E_b/N_0) for desired Bit Error Rate (BER) performance.

The main challenge in present communication system design is to avoid signal distortion, sensitivity degradation and capture signals with appropriate levels as Amplitude modulation is orthogonal to phase and frequency modulation. AM requires linearity in comparison to FM or for PM where requirement of phase linearity to be met. But interferences and thermal noise causes phase to jitter resulting in an error. BER below minimum value causes outages in link. The modulation scheme chosen for satellite communication is based on power and bandwidth efficiency. Power efficiency refers to the energy required in each bit to transmit the data at a specified BER. Channel bandwidth can be optimized by judicious selection of modulation and coding. The squeezing of maximum data into the available spectrum is the main selection criteria of the modulation scheme. The spectral efficiency parameter defined these criteria of transmission data in the assigned bandwidth defined in terms of bits per second per Hz (bps/Hz). The spectral efficiency can be enhanced by various techniques such as pre-modulation filtering, reduction in fast transition. Various filtering techniques such as raised cosine, square-root raised cosine, gaussian filtering but raised cosine filters provide better spectral efficiency. Enhancement of power results in the weight increase and lowering of power can lead to less efficient operation so the optimum solution is the selection of modulation scheme meeting all the requirements of critical components like power amplifiers. Communication satellite maximum capacity per unit weight is desired and to achieve the same output transmitter are driven hard to overcome the thermal noise. This forces amplifiers to driven at saturation and require modulation techniques having less non linearties in amplitude. Amplitude modulation is orthogonal to phase and frequency modulation but AM requires linearity in comparison to FM or PM for which phase linearity is important paremeter. But interferences and thermal noise causes phase to jitter resulting in an error. So the compromise between various modulation parameters to be carried out for the selection of modulation scheme which is primarily governed by the application and in case of satellite communication adoption of digital techniques is mostly preferred.

3. SELECTION OF MODULATION SCHEME

Selection of digital modulation scheme is based on maximizing data rate and resistance to interference along with minimizing various parameters such as channel bandwidth, probability of symbol error, transmitted power and current. There are three basic types of modulation methods for transmission of digital signals. These methods are based on the three attributes of a sinusoidal signal, amplitude, frequency and phase. The corresponding modulation methods are called Amplitude Shift Keying (ASK), Frequency shift keying (FSK), and Phase Shift Keying (PSK). The selection is based on the criteria of minimizing non-linearties and interferences for signal detection. In addition, combination of ASK and PSK is employed at higher bit rates which is known as Quadrature Amplitude Modulation (QAM).Modulation signals with constant envelope are required for reducing side-lobe regeneration [8]. The scheme that generates less amplitude fluctuation to avoid signal fidelity is an important consideration for aerospace applications (Table.1). As the selection is based on power and band-width efficiency which is governed by the E_b/N_0 criteria where bit error probability (BER) of $<10^{-5}$ is taken as reference. As shown in Table.1, digital techniques are preferred and moreover PSK technique provides better spectral efficiency compared to other techniques. Various PSK variants are possible such as BPSK, QPSK, DPSK etc.

Table.1. Parameters comparison of various modulation techniques

Parameters	AM	FM	PM	ASK	FSK	PSK
Applications	Radio signal, Navigation	Radio	GSM, Satellite television	Laser transmitters	Radiosonde	Wireless LAN, RFID
Techniques	Analog	Analog	Analog	Digital	Digital	Digital
Frequency Range	30-1605 KHz	88-108 MHz	-	-	-	-
Phenomena	Amplitude of carrier variation	Frequency of carrier variation	Signal modulation in phase or quadrature	Signal modulation variation with information	Shift in frequencies with information	Phase variation with information
Features	More noise, low data rate	Improvement in SNR, unaffected amplitude	Higher data rate	Rapidly change of amplitude	Noise immunity, High SNR	Spectral efficiency
Requirement	Less distortion	Better selectivity	Minimal interferences	Linear components	Stability at higher frequency	Length of transmission line

The BPSK demodulation process involves carrier and data recovery. The two commonly methods employed for this process are the Squaring loop technique and the Costa's loop technique. In the squaring loop technique, the incoming PSK modulated signal is squared using a mixer or a multiplier, which regenerates the carrier at twice the carrier frequency subsequently dividing this by two gives the carrier frequency, which is tracked using a PLL. The modulated PSK is again multiplied with the recovered carrier to get the data output. The Costa's loop uses two parallel tracking loops (I and Q) simultaneously to derive the product of the I and Q components of the signal

BPSK scheme is having the symbol rate equal to the bit rate whereas QPSK symbol rate is half the bit rate resulting in QPSK scheme achieving twice the band efficiency compared to the BPSK (Table.2).

Table.2. Parameters comparison of various modulation techniques

Parameters	BPSK (binary)	DPSK (differential)	QPSK (quadrature)	MPSK (M-ary)
Bits per symbol	1	1	2	n
Detection method	Coherent	Non-coherent	Coherent	Coherent
Bandwidth (min)	$2f$	f	f	$2f/N$
Symbol duration	T_b	$2T_b$	$2T_b$	$N.T_b$

The PA in the transmitter needs to be a linear amplifier if the modulation is QPSK or QAM so as to faithfully reproduce the amplitude and phase information. In case of ASK, FSK, and BPSK, a more efficient non-linear amplifier to be employed. Filtering of the transmitted signal is required to avoid interference of the adjacent channel but it impacts the BER performance. The rise and fall time of the filter results in the variation in the constant amplitude envelope of BPSK and PSK signal. This variation can be taken care with the saturated mode of amplifier operations. In case of 5G, modulation and coding scheme is chosen to achieve higher data rate and spectral efficiency is an important parameter. Orthogonal frequency division multiplexing (OFDM) is preferred which is the combination of the QAM and FDM resulting in higher throughput. Relationship between the bit error rate and associated bandwidth for various modulation schemes [8] can be represented as per Table.3.

Table3. BER and bandwidth of various modulation schemes

Modulation	BER	Bandwidth
BPSK	$Q\left[\sqrt{\frac{2E_b}{N_0}}\right]$	R_b
FSK	$Q\left[\sqrt{\frac{1.217E_b}{N_0}}\right]$	R_b
DPSK	$Q\left[\sqrt{\frac{E_b}{N_0}}\right]$	$R_b/2$

where, R_b is the sampling rate × no of bits/symbol

$$Q(\alpha) = \int_{\alpha}^{\infty} e^{\frac{-x^2}{2}} dx \quad (1)$$

Typically Q function value changes from 0.5 to 0.00005 for the value of α ranging from 0.0 to 3.9.

4. CONCEPT OF BIT ERROR RATE (BER)

BER value indicates the error in transmitted bits and the measurement of BER is given in terms of carrier to noise ratio (CNR). In digital modulation the performance criteria is specified in terms of BER which is the measure of the error probability due to polarity reversal at the time of signal sampling in the receiver. It depends on the noise present and the amount of inter-symbol interference. In case of transmission of polar NRZ waveform, taking T_b as the bit period, average energy in each bit can be represented as

$$E_b = P_r T_b \quad (2)$$

So for minimum probability of error (N_0 is the noise energy per bit)

$$BER = \frac{1}{2} erfc\sqrt{\frac{E_b}{N_0}} \ (3) \text{ and } \left(\frac{S}{N}\right)_{\max} = \sqrt{\frac{2E_b}{N_0}}$$

Error probability depends inversely on the square root of the bit rate [9]. Using the above equation (3) for a given BER, the corresponding E_b/N_0 is found out in which implementation margin is added for non-ideal filtering conditions.

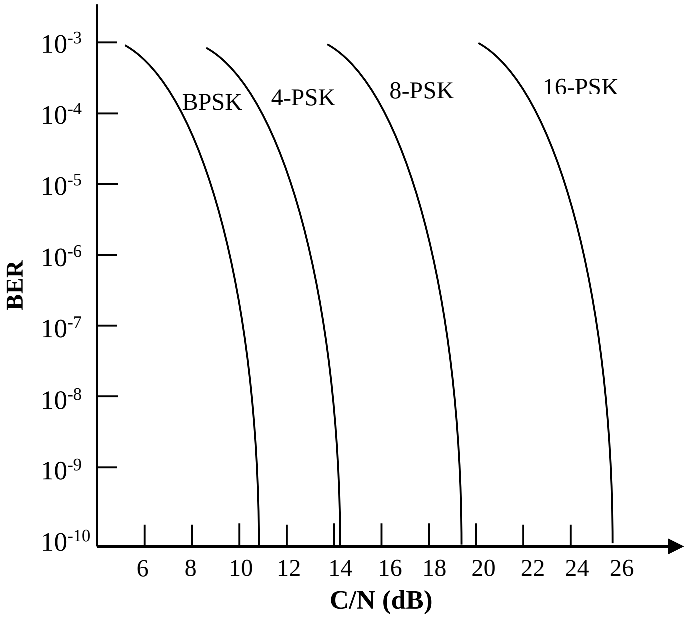

Fig.2. BER Vs CNR plot for PSK modulations [3]

As shown in Fig.2, minimum overall C/N of 13.5 dB is required for the BER of 10^{-6} but for typical satellite transponder accounting for various non-linearties and distortions, the overall C/N required is typically 16dB. The above plot shows that signal energy associated with each data bit for 4-, 8- or 16-PSK is higher compared to BPSK.

The relation between signal to noise ratio and signal energy to noise energy (digital) ratio C/N and E_b/N_0 can be found out as below:

$$\frac{E_b}{N_0} = \frac{signal.energy.per.bit}{noise.energy.in.one.cycle}$$

$$= \frac{(S/bit.rate)}{(N/noise.bandwidth)} = \frac{S}{N}\cdot\frac{noise.bandwidth}{bit.rate}$$

$$\frac{C}{N} = \frac{E_b}{N_0}\cdot\frac{f_b}{BW}$$

$$\Rightarrow \frac{C}{N_0}(dB) = \frac{E_b}{N_0} - 10\log\left(\frac{BW}{DataRate(kbps\times10^3)}\right) \quad (4)$$

$$\Rightarrow \frac{E_b}{N_0}(dB) = \frac{C}{N_0}(dB) + 10\log\left(BW\right)$$

$$-10\log\left(\frac{1}{DataRate(kbps\times10^3)}\right)$$

where data rate value are to be kept in kbps, f_b is symbol/data rate and BW is occupied bandwidth. Further symbol rate is written as

$$f_b = \frac{\text{information - rate}}{\text{modulation}\times\text{FEC}\times\text{coding}} \quad (5)$$

The parameters C/N and Pr/N are the same for constant envelope signalling (PSK or FSK) but are different for non-constant envelope signalling (ASK, QAM) [6-8].Comparison of the various modulation techniques along with the requirement of bandwidth and C/N shown in Table.4.

Table.4. Typical bandwidth and C/N for various modulation techniques

Modulation	Bandwidth	C/N
FSK	B	13 $[S/N]=[C/N]+3(\beta+1)\beta^2$
PSK	B/2 (4-phase)	10 $[C/N]=[E_b/N_0]+[R_b]$
PSK	B/3 (16-phase)	14
QAM	B/4	17

As shown in Table.4, the phase variants increase such as from 4-phase to 16-phase results in the enhancement of C/N as well as decrease in the bandwidth requirement. The selection of the modulation scheme is based on the extraction of the information from the modulated signal. The phase separation in the digital modulation needs to be maximized so as to distinguish one state from another by the receiver [9]. E_b/N_0 can be reduced by the error correction coding while maintain the required BER. Coding also reduces power requirements but information bits are changed into symbol bit resulting in the enhancement of bandwidth. Various coding techniques are applied for the digital signal transmission which are categorized under line and block coding. In satellite communication encoding is done using the convolution codes [10]-[11]. Also new coding techniques such as turbo codes and low density parity check codes are having higher efficiency of error correction. Adaptive coding and modulation (ACM) as well as variable coding and modulation (VCM) having the feature of real time FEC code rate and modulation constellation are the key system features of advanced high throughput satellite [12].

5. CONCLUSION

Present day communication satellites are having on-board switching and processing, high frequency propagation, non-linearties and distortions (due to TWTAs), synchronizing and networking to enable to meet the demands. The elements of satellite systems are earth segment and space segment. Earth segment comprises of a network of transmit and receive earth stations whereas space segment comprises of a satellite. The performance objectives of the satellite link is specified in terms of allowable (S/N) or BER for a given signal or as a minimum allowable carrier to noise power ratio C/N. Reliable link in satellite communication can be made by ensuring minimum signal-to-noise ratio(S/N) in the receiver baseband channel, optimizing transmitter power and RF bandwidth. S/N ratio is dependent on the carrier-to-noise ratio (C/N) of the RF or IF signal in the receiver, modulation type and the RF/IF bandwidth in the receiver. Present days system are replacing conventional NRZ signalling by PAM4, a modulation scheme that takes half the bandwidth to transmit the same payload data as the equivalent NRZ signal. This article briefly introduces various modulation schemes and its selection criteria along with the description of varied parameters which needs to be considered before selection.

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