GMSK Modulator Implementation for Earth Exploration Satellite Service (EESS) Application

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***Abstract* – Due to restriction of the spectrum for Earth Exploration Satellite Service (EESS) at 8.5 GHz X-Band allocation, the mission for EESS are looking higher order modulation scheme instead of traditionally phase shift keying (PSK)such as QPSK, OQPSK and 8-PSK. The main problems with the current modulation are the Bandwidth efficiency and the Inter-symbol Interference Tolerance. The objectives of this paper are to analyze GMSK perform in EESS, to identify the best BT value, to analyze the filtering effect to BW in GMSK, to simulate GMSK in satellite communication using matlab and to compare the performance of GMSK with the OQPSK filtering with square root raised cosine (RRC) in satellite communication. The methodology used in this paper is identify the current OQPSK method used, designed and simulate the GMSK modulation by using the same method used in OQPSK in Matlab and finally compare the simulation result of GMSK with the OQPSK filtered with RRC. The result shows that the GMSK performace is almost same as OQPSK in term of bit error rate (BER). However, the GMSK performance in terms of bandwith efficiency is better compare to the OQPSK. Inconclusions, the GMSK could be used at lower data rates with a performance almost similar to the OQPSK filtered with OQPSK.**

Keyword - Gaussian Minimum Shift Keying (GMSK), Offset Quadrature Phase Shift Keying (OQPSK), Bit Error Rate (BER), Power Spectrum, Eye Diagram and Constellation Diagram.

I. INTRODUCTION

Limitation on the X-band spectrum allocation for Earth Exploration Satellite Services (EESS) which had been set by the International Telecommunication Union (ITU), many EESS missions is looking for higher order modulation scheme to replace the current modulation technique [1] which is still having higher tolerance of Inter-symbol Interference (ISI) and Less Bandwidth efficiency. This will contribute to the inconsistency of data receive to the ground station.

As we know that the current QPSK, OQPSK and 8-PSK is used for the EESS mission which is low tolerance in ISI. To reduce this ISI QPSK and OQPSK is used to RRC filter at significant roll-off factor (α). However the ISI tolerance for GMSK is still better than the OQPSK and QPSK with value of Gaussian filter (B.T) at suitable value for certain EESS requirement.

Quadrature Phase Shift Keying (QPSK) [2] is currently used in applications such as cable modems and the IS-95 (CDMA) system. QPSK is predominantly noted for its power efficiency and robustness against phase noise. Another type of modulation scheme used in mobile radio systems is Gaussian Minimum Shift Keying (GMSK), which is very popular in Europe’s GSM cellular standard. In addition, narrow bandwidth and its ability to use coherent detection characterize GMSK, a constant envelope modulation technique. QPSK originates from Quadrature Amplitude Modulation (QAM). QAM combines phase changes with signal amplitude variations that enable more information to be carried over a limited channel bandwidth. Several varieties of QAM modulation exist, such as PSK, BPSK, and QPSK, providing various levels of bandwidth efficiency. In QPSK, two data channels modulate the carrier. Transitions in the data cause the carrier to shift by either 90° or 180°. This allows two discrete data streams, identified as I channel (in phase) and Q channel (quadrature) data

GMSK is from the Minimum Shift Keying (MSK) modulation family. GMSK differs from MSK in the aspect of filter use, hence the name Gaussian MSK. GMSK resulted from an attempt to improve the MSK power spectrum. However, one of the advantages of MSK is that it does not produce Inter-symbol Interference (ISI). The transmitted pulse is confined within its bit duration resulting in no adjacent channel interference. Nevertheless, GMSK possesses a more compact spectrum, with the application of a lowpass filter, helping to reduce its spectral sidelobes.

Most digital transmitters operate their power amplifiers at or near saturation to achieve maximum power efficiency. At saturation, it poses a threat to the signal, exposing it to phase and angle distortions. These distortions spread the transmitted signal into the adjacent channel, causing interference. To resolve this issue, a filter is used to suppress the sideband lobes. Nyquist pulse-shaping techniques, such as the Raised Cosine (RC) filter and Gaussian filter, are used to reduce ISI.

This paper is organized as follows. In section 2 GMSK comunication used in this paper are presented. In section 3 GMSK designing methodology are presented. In section 4, Simulation and result for GMSK, in section 5 the results are discussd. In section 5, conclusions are reached.

II. GMSK COMMUNICATION

In designing GMSK modulation used for the satellite communication, at first we have to familiarrize the GMSK signal and how the signal model of the GMSK modulation.

A. GMSK Signal

GMSK as in [2] signals are partial CPM signals (with modulation index h = 0.5 and Gaussian frequency shaping) defined as:

$$x(t) = A\cos(2\pi f_c t + \Phi(t,a)), \quad t \in R \tag{1}$$

Where f_c is the carrier frequency and Φ (t, a) is the so-called excess phase. The transmitted data sequence of M-ary symbols selected from the alphabet ±1, ±3,...,±(M - 1) denoted as a = {a_k} is embedded in the excess phase;

$$\Phi(t,a) = 2\pi h \sum_{k=-\infty}^{\infty} a_k q(t-KT) \tag{2}$$

Where $q(t) = \int_{-\infty}^{t} g(\tau)d\tau$ and T is the symbol duration. The frequency shape pulse g(t) has a smooth phase shape over finite time interval 0 ≤ t ≤ LT (where L is the pulse length) and is approximately zero outside this interval. For a GMSK signal, g(t) is defined as:

$$g(t) = \frac{1}{2T}\left[Q\left(2\pi B\frac{t-\frac{T}{2}}{\sqrt{\ln 2}}\right) - Q\left(2\pi B\frac{t+\frac{T}{2}}{\sqrt{\ln 2}}\right)\right] \tag{3}$$

Where B is the 3dB bandwidth of the lowpass Gaussian filter (with 0 ≤ BT ≤ 1) and $Q(t) = \int_t^{\infty}\frac{1}{\sqrt{2\pi}}\exp\left(-\frac{\tau^2}{2}\right)d\tau$. The excess phase during interval [kT, (k+1)T] can be written as:

$$\Phi(t,a) = \theta_k(t,a) + \phi_k, \tag{4}$$

Where $\theta_k(t,a)$ is the instant phase;

$$\theta_k(t,a) = 2\pi h \sum_{t=k-L+1}^{k} a_i q(t-iT), \tag{5}$$

And ϕ_k is the accumulate phase (memory) of all symbols up to time k-L (sometimes called cumulant phase)

$$\theta_k = \pi h \sum_{t=-\infty}^{k-L} a_i \quad (mod\ 2\pi) \tag{6}$$

The cumulant phase represent the constant part of the total excess phase in [kT, (k+1)T], and is equal to the sum of the maximum phase changes contributed to each symbol, accumulated along the time axis up to the (k-L)th symbol interval. It can be recursively computed as:

$$\delta_k = (\emptyset_k, a_{k-1}, a_{k-2}, \dots, a_{k-L+1}) \tag{7}$$

Each state corresponds to a specific value of the excess phase.

B. SIGNAL Model

The baseband GMSK signal can be written as $u(t) = \exp[j\Phi(t,a)]$ where the phase $\Phi(t,a)$ has been defined as in (1). The baseband signal is modulated by a local oscillator exp $(j\omega_c t)$. The signal is corrupted by additive white Gaussian noise $\omega(t)$, with spectral density $N_0/2$. At the receiver side, the received signal is multiplied by the synchronous carrier $\exp(-j\omega_{ct})$, followed by low pass filters to generate the real and imaginary parts of the complex envelope of the received signal. After down conversion, we obtain the received baseband signal

$$y(t) = u(t) \otimes f(t) + z(t), \ t \in R, \tag{8}$$

Where f(t) is the impulse response of the lowpass filter $z(t) = \omega(t) \otimes f(t)$ is normalized complex-value additive Gaussian noise process with variance σ_z^2 *and* " ⊗ " denote convolution. The baseband complex envelope of the received modulated signal sampled at one sample per symbol (t=kT) at the output of the lowpass filters can be written as:

$$y(k) = u(k) \otimes f(k) + z(k), \ k = 1, \dots, N_s \tag{9}$$

Where N_s is the number of symbols in the observation interval. Two GMSK signal “constellations” obtained at the output of a square root raised cosine filter (roll-off factor, α=0.35 and cutoff frequency adapted to symbol duration) in the absence of noise are shown in Figure 1. The two constellations are clearly similar even if they are obtained from two distinct GMSK modulations.

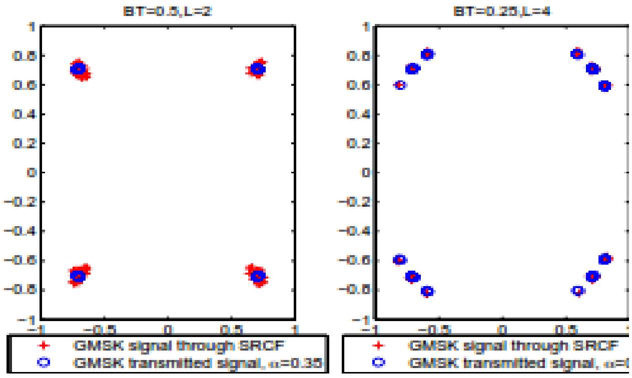

Figure 1: GMSK constellation (one sample per symbol)

The received signal y(k) can be modeled as the probability function of an hidden state at the time k which is represented by a first order HMM. This model will be used efficiently for classifying two non-linear GMSK modulations with different bandwidths (denoted as λ_1, λ_2). The main HMM characteristics are summarized below:

- The state of the HMM at time instant k is δ_k which belongs to an alphabet denoted as {s(1), s(2),…,s(N)} of size $N=4M^{L-1}$, where s(j) is the jth possible value of δ_k . As an example, for binary symbols and GMSK modulations with BT=0.5, L=2, hence N=8 different states. For binary symbols and GMSK modulation with BT=0.25, L=4 yielding N=32 different states.
- The state transition probability distribution is

$$d_{ij} = P[s_{k+1} = s(j)|s_k = s(i)] \qquad (10)$$

  Which is equal 1/M when all symbols are equally likely.
- The initial state distribution vector $\pi = (\pi_1, \dots \dots, \pi_n)^T$ defined by $\pi_i = P[s_1 = s(i)] = \frac{1}{N}$, $i = 1, \dots ., N$.
- The pdf of the observation $y(k) \triangleq p(y,k)|\, s(i)$ can be written

$$P_i\big(y(k)\big) = \frac{1}{\sigma_z\sqrt{2\pi}} \exp\left(-\frac{|y(k)-m_i|^2}{2\sigma_z^2}\right) \qquad (11)$$

  For i=1,…..,N, where m_i is the *i*th value of $e^{j\Phi(kT,a)}$. We denote as $m=[m_1,\dots,m_N]^2$ the vector containing all possible "constellations" points.

Given the above HMM, the BW algorithm can be used to determine the posterior probability of the observation sequence y given the model $\lambda \in \{\lambda_1, \lambda_2\}$ and estimate the unknown parameters m and σ_z^2 . The BW algorithms model based on a forward-backward procedure which estimates iteratively the unknown model parameters maximizing the posterior probability of the unknown parameters. After convergence, the BW algorithm provides MAP estimates of the m and σ_z^2. such that:

$$(\hat{m}, \hat{\sigma}_z^2) = \arg\max_{m,\sigma_z^2} P(m, \sigma_z^2|y, \lambda) \qquad (12)$$

The algorithm needs a forward operation to compute $P(m, \sigma_z^2|y, \lambda)$whereas a forward/backward procedure is necessary to estimate the unknown parameters m and σ_z^2. This section describes the principles of the standards BW algorithm detailed for instance in [3]. An LMS-type update BW algorithm is also presented.

III. GMSK MODULATOR DESIGN

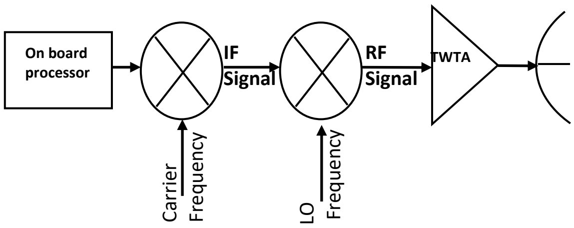

Figure 2: Satellite downlink from baseband processor to antenna

It is similar to standard minimum shift keying (MSK) [4], however the digital data stream is first shaped with a Gaussian filter before being applied to a frequency modulator. This has the advantages of reducing sideband power, which in turn reduces out-of-band interference between signal carriers in adjacent frequency cannels. However, the Gaussian filter increases the modulation memory in the system and causes inter-symbol interference, making it more difficult to discriminate between different transmitted data values and requiring more complex channel equalization algorithms such as an adaptive equalizer at the receiver. To generate the GMSK waveform as follows (Figure 3 and Figure 4):

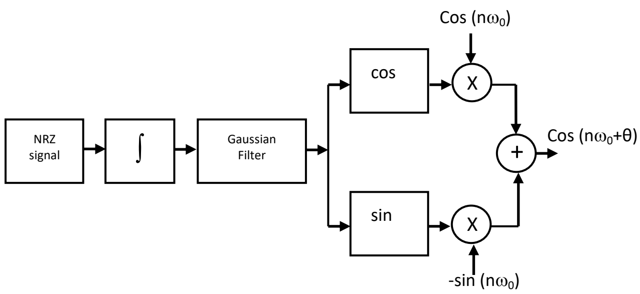

Figure 3: Block diagram of GMSK waveform generator

$$H_G f = \exp\left(-\alpha^2 f^2\right) \tag{13}$$

Where , α⇔B = 3dB Bandwidth
= 0.5887/B
f = frequency in Hz

GMSK as implemented by quadrature signal processing at baseband followed by a quadrature modulator;

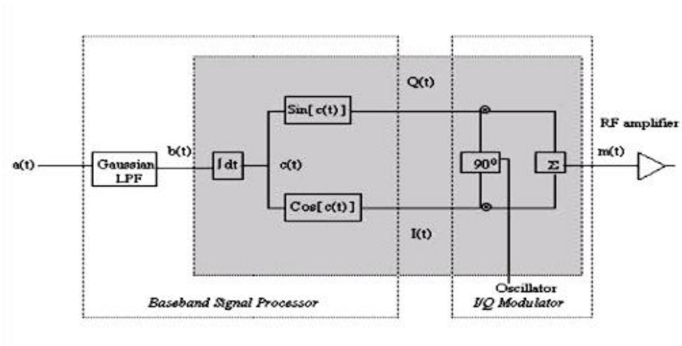

Figure 4: GMSK waveform generator

After that the waveform is going to the pulse shaping process. Which is involve, input binary pulse train (+1/-1) where each binary pulse goes through Lowpass filter (LPF) with a Gaussian impulse response. Through this process the filter smoothes the binary pulses and the filter output is truncated and scaled. This process results in a train of Gaussian shaped pulses, as Figure 5 below.

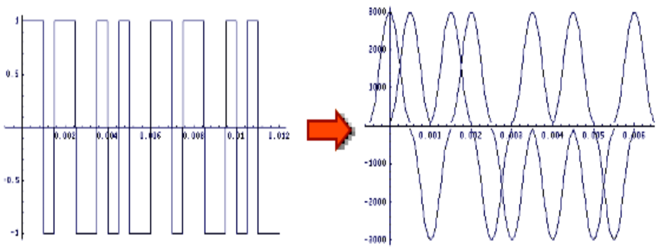
Figure 5: GMSK waveform after pulse shaping

Furthermore, the pulses are summed together. The signal is integrated over time to obtain a continuous waveform which captures the bit transition information as in Figure 6 and Figure 7.

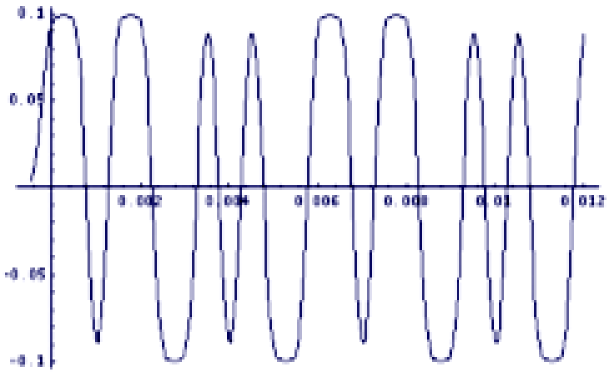
Figure 6: Pulses is summing

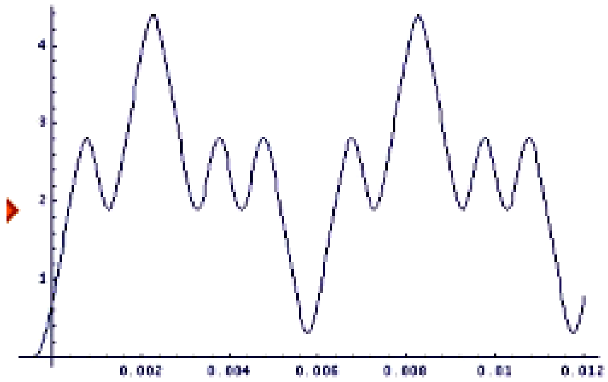
Figure 7: Integrated pulses

The resulting waveform is divided into In-Phase and Quadrature component as in Figure 8 and Figure 9 repectively. The two signal components are the up-converted to the carrier frequency.

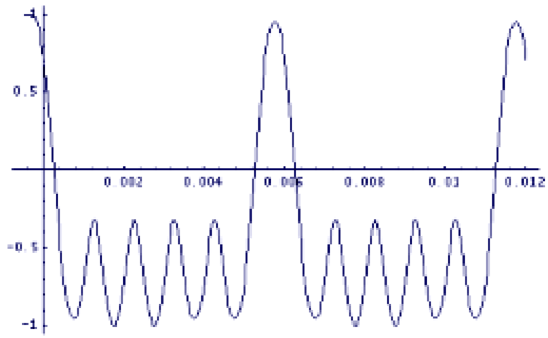
Figure 8: In-Phase

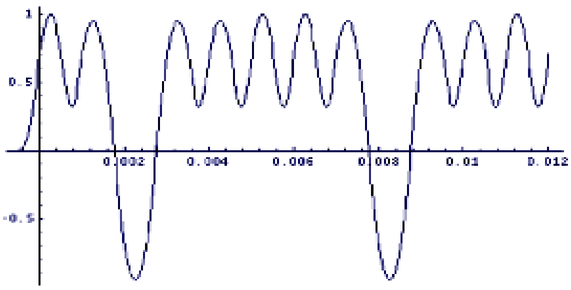

Figure 9: Quadrature component

IV. SIMULATION AND RESULT

The GMSK modulation has been design and simulates using Matlab to get the simulated performance regarding the BER, Power Spectral density, Eye diagram and Constellation diagram. The methodologist is based on the OQPSK performance simulation method. The designing process started with GMSK block diagram design as in the Figure 11. Where the simulation input is decode as in Figure 10:

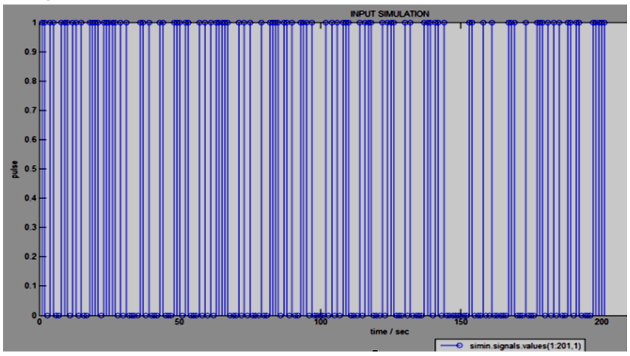

Figure 10: Simulation input data

The input is either high (1) or low (0). Simulated through the GMSK modulator circuit diagram.

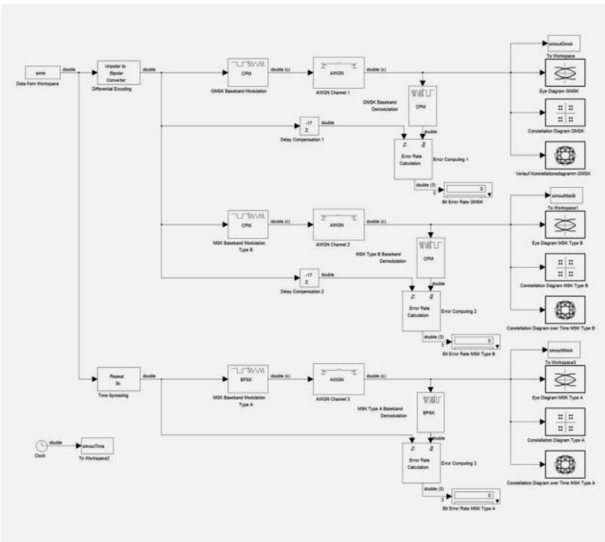

Figure 11: Matlab GMSK Modulation diagram

Few result is obtained from the simulation such as it constellation diagram, eye diagram and power spectral density below respectively.

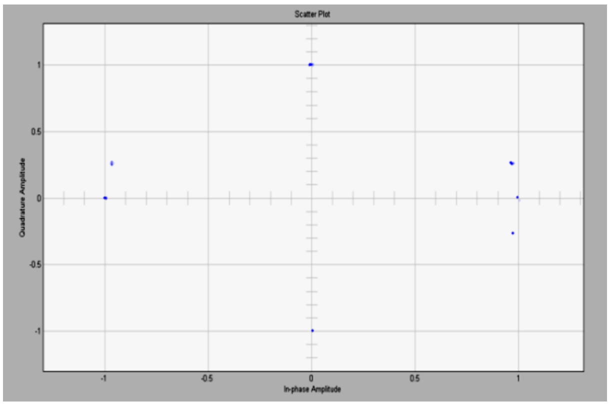

Figure 12: GMSK constellations simulation result

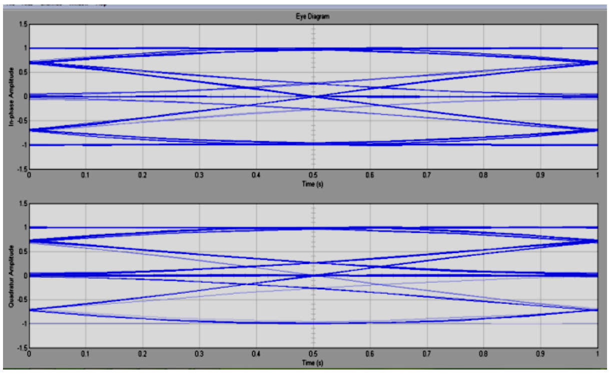

Figure 13: GMSK eye diagram simulation result at BT=0.5

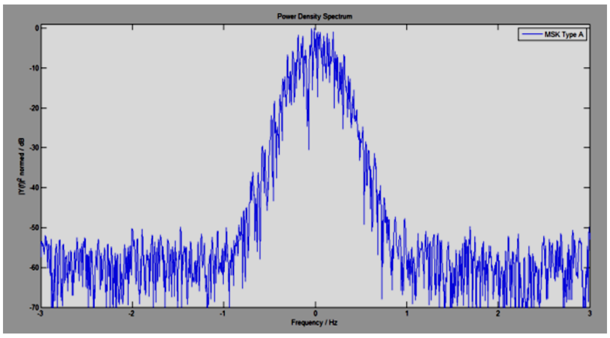

Figure 14: GMSK Spectrum density at BT=0.5

Besides that the BER also been simulated for the GMSK at different value of BT.

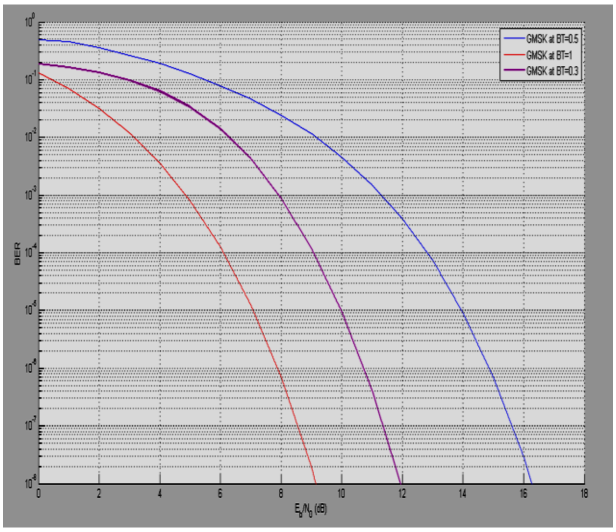

Figure 15: BER analysis for different BTs

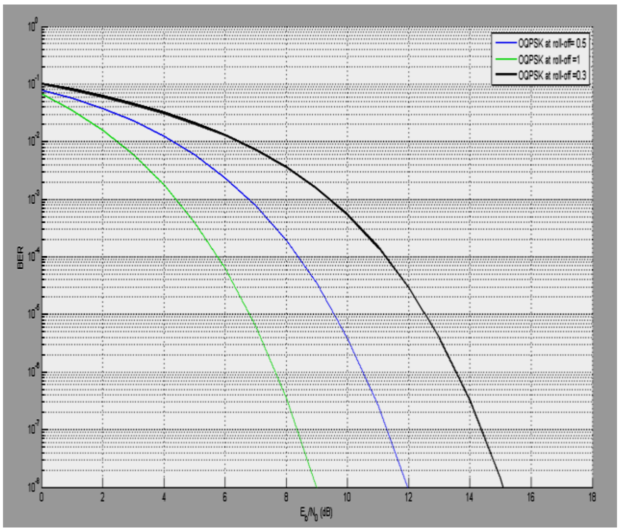

Figure 16: OQPSK BER analysis at different roll-off factor

V. PERFORMANCE COMPARISONS

As we know, OQPSK modulation is widely used in Earth Exploration Satellite Service. However due to tremendous increase of higher modulation scheme demand with limited bandwidth allocation, we need to look for modulator with higher bandwidth efficiency and low tolerance of Inter-symbol Interference.

Form the analysis of OQPSK modulation, we found out that OQPSK with RRC filter is currently used to modulate data in EESS. The best roll-off factor that comply with the need of EESS is α=0.35. Nevertheless, it is very good in Bit Error Rate (BER) performance analysis as compare to other roll-off factor value. Figure 16 shows the comparison of BER for the OPSK with RRC filter. Fortunately, GMSK also showing the same result as the OQPSK as α=0.5 BER analysis at GMSK BT=0.5 as we can see on the Figure 15. From the analysis, both GMSK and OQPSK are giving the same performance in term of BER analysis see in Table 1.

Table 1: BER comparisons data for GMSK and OQPSK filtered with RRC

GMSK		OQPSK	
BT	E_b/N_0 (dB) at BER= 10^{-8}	α	E_b/N_0 (dB) at BER= 10^{-8}
1	9.2	1	9
0.3	12	0.3	12
0.5	16.3	0.5	15

For the eye diagram analysis from the GMSK simulation, we can see that the noise margin is very small (Figure 17).

This margin shows that it is the difference between the 1 level and amplitude level that divides the eye in two equal halves in the vertical direction (it is 0 for NRZ data and 50% of 1 level for RZ data).

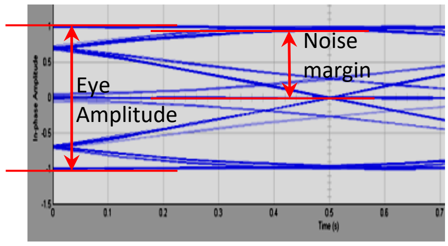

Figure 17: Eye diagram noise margin

Mean while, the Eye amplitude shows that it is the difference of level of 1 and level of 0. It represents the power in the eye actually carrying information and does not account of any noise that may be present in the signal.

All of the following result shows simulation for values of BT and roll-off factor equal to 0.2 and 1.0. For the case of GMSK, as BT decrease, the side lobe levels fall off very rapidly causing and increase in bandwidth efficiency, as seen in Figure 17 (a) and Figure 17 (b).

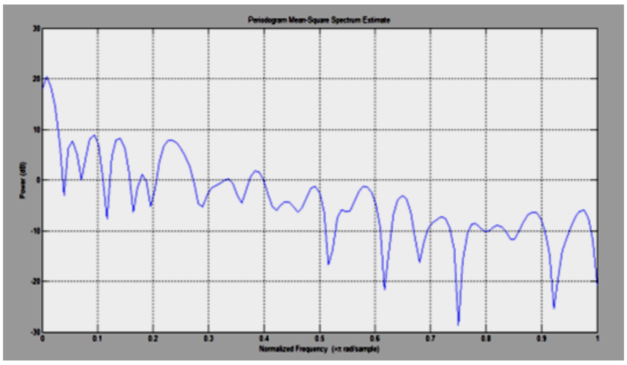

Figure 17(a): GMSK Power spectral at BT=0.5

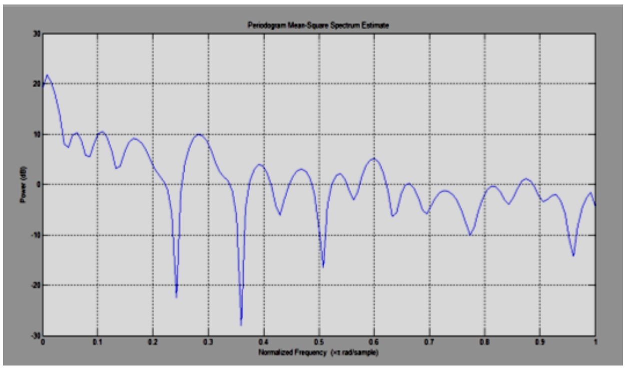

Figure 17(b): GMSK Power Spectral at BT=0.3

However, as BT increases in the Power spectral density (PSD) implementation, as in the case of BT=0.5, the graph yield a wider spectrum, indicating a loss in power efficiency. Notice the reduced side lobe energy for GMSK. Ultimately, this means channel spacing can be tighter for GMSK BT=0.5 when compared to GMSK BT=0.3 for the same adjacent channel interference.

Next, referring to the total GMSK signal output, the graph reveals a wider eye diagram for an increasing of BT's value, as shown in Figure 18(a) and Figure 18(b). This means that it is easier to recover the carrier at the demodulator. It is also shows error occurrence reduces when we increased the BT value of the GMSK modulator.

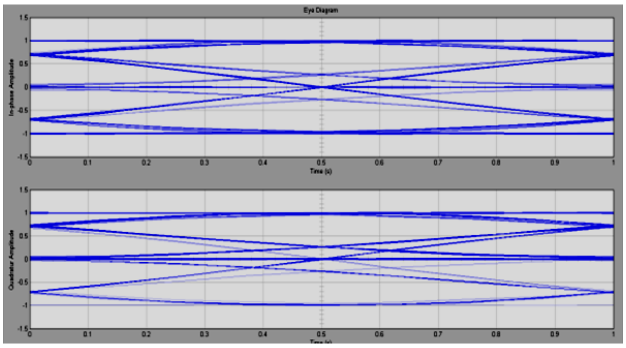

Figure 18(a): GMSK eye diagram at BT=0.5

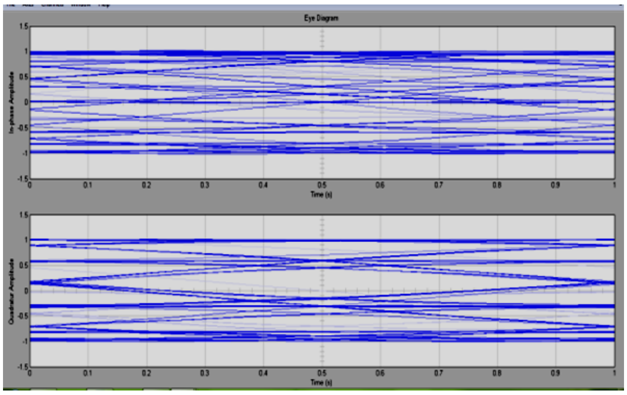

Figure 18 (b): GMSK eye diagram at BT=0.3

Implementing OQPSK with RRC filter shows that increasing the roll-off factor,α makes the spectrum more compact, causing a faster decay of the signal response as seen in Figure 19. However, our interest lies in the slow decay and this exist for smaller roll-off values, where ISI is fought more effectively.

By examining the PSD of OQPSK in Figure 20, decreasing the roll-off value expands the spectrum, requiring more bandwidth, and thus, more power. However, since OQPSK is predominantly noted for its bandwidth efficient feature, it is preferable to operate at higher data rate.

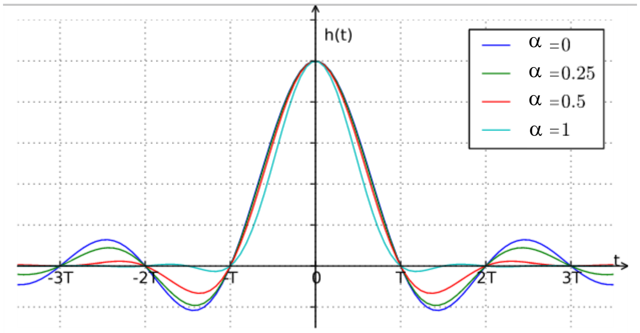

Figure 19: OQPSK RRC Filter Response

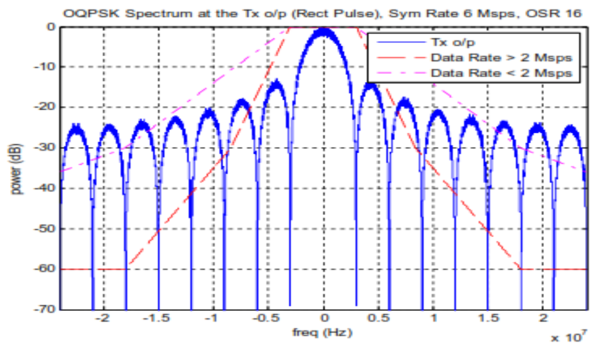

Figure 20: OQPSK power spectral density

VI. CONCLUSIONS

The result above indicates that there is no one prominent modulation scheme between OQPSK and GMSK. Both OQPSK and GMSK have strong features that provide a desirable satellite communication environment. When it comes to any one particular application, it is important to look the tradeoffs involved. Most communication products are design with class c power amplifier, which offer the highest power efficiency, yet because they are nonlinear; require the amplified signal to have a constant envelope. This reduces the desirability of implementing OQPSK in this situation. However, GMSK effectively utilizes bandwidth; whereas OQPSK requires more bandwidth to effectively recover the carrier.

GMSK obviously the improved spectral efficiency when compared to other phase shift keyed modes. It can be amplified by a non-linear amplifier and remain undistorted.

GMSK also none of the information is carried as amplitude variations. Nevertheless GMSK also produces less noise when compared with other phase shift-keying modulation schemes and GMSK is most preferable at lower data rate transmission.

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