COMPARISON OF ADVANCED MODULATION SCHEMES FOR LEO SATELLITE UPLINK COMMUNICATIONS

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Abstract: - The M.Sc. degree project, whose one major part is explained in this paper, has been accomplished at the University of Surrey by the financial support of TUBITAK-BILTEN inclusive to the remote sensing satellite project BILSAT-1*, which is currently being carried out by Surrey Satellite Technology Limited in the UK, in collaboration with TUBITAK-BILTEN. The thesis investigates possible improvements for Low Earth Orbit (LEO) satellite communications and compromises of two major parts: Uplink and downlink cases. This paper explains the methodology and the simulation results of the performances of advanced modulation techniques under the implications of highly dynamic LEO satellite uplink. Modulation schemes that can possibly serve the objectives are the phase shift keying type modulations. Hence, the performance of binary phase shift keying (BPSK), quadriphase shift keying (QPSK), offset QPSK (OQPSK), π/4 shifted QPSK, and octaphase shift keying (8PSK) have been deeply investigated through simulations considering the LEO satellite communication uplink channel properties. The modulators and demodulators were synthesised using computer programs. The simulations were carried out regarding the dominant properties of uplink. In real world, the demodulators include all the essential parts together with the carrier and symbol timing recovery circuits. Therefore synthesised demodulators need to cover these two crucial blocks as well. It was illustrated by the simulation results that it would be beneficial to implement the hard limited Costas loop demodulator of Quadriphase Shift Keying (QPSK) for the uplink rather than other modulation schemes and demodulators compared.

Key-Words: Satellite communications, advanced modulation techniques, phase shift keying, little LEO uplink

1 Introduction

Low Earth Orbit (LEO) microsatellites are manufactured and operated for many years by different companies all over the world. There are various applications of these satellites, such as digital store and forward communications, imaging for disaster surveillance, environment monitoring, and email systems. As the payloads on the spacecrafts advanced, the demand for reliable communication with higher data rates increased. However, achieving higher data rates with the limited frequency band has some challenges to be considered.

Investigation of possible improvements of the LEO satellite communication systems by advanced modulation techniques was the focus of the research. When LEO communication is considered, reliability and robustness of the link should have the highest priority. Therefore, achieving high data rates has to be accompanied by a robust and reliable system.

In order to study the performance of various modulation schemes, it is essential to understand clearly the constraints applied by the LEO communication link. Hence, the characteristic properties of uplink have to be examined carefully, which was one of the necessary parts of the research.

Modulation schemes that can possibly serve the objectives are the phase shift keying type modulations. Hence, the performance of binary phase shift keying (BPSK), quadriphase shift keying (QPSK), offset QPSK (OQPSK), π/4 shifted QPSK and octaphase shift keying (8PSK) have been deeply investigated through simulations considering the LEO satellite communication channel properties. The modulators and demodulators are synthesised by computer simulation tools keeping in mind the real world implementation challenges such as the carrier and symbol timing recovery circuits. Therefore synthesised demodulators need to cover these two crucial circuits.

Final objective was to compare the performances of the mentioned modulation schemes under LEO satellite communication environment and, if it is possible, to demonstrate better one or ones that might be used in future missions.

* The BILTENSat-1 microsatellite flight model has been designed and constructed by Surrey Satellite Technology Limited for TUBITAK-BILTEN of Turkey in conjunction with engineers from TUBITAK-BILTEN during a collaborative program comprising the manufacture of the BILTENSat-1 microsatellite and training at the University of Surrey, Guildford, Surrey GU2 5XH, England.

2 Synthesized Modems

During the early days of deep space program, phase shift keying (PSK) was developed. Today, PSK is widely used in both military and commercial communications. PSK is considered to be efficient for these applications due to the fact that it offers the lowest probability of error. As a result this type of modulation schemes could possibly serve the aims of LEO satellite communications.

In this paper, only the synthesised demodulators are summarised due to the fact that usually demodulator determines the performance and the applied modulators are the well-known classical ones.

2.1 BPSK

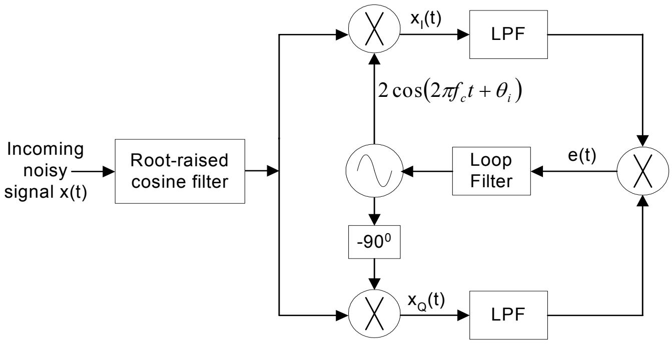

Fig.1 BPSK Costas loop demodulator

Costas loop, which is widely used, solves the carrier recovery problem while demodulating the incoming signal without extra circuitry. Costas loop demodulator for BPSK is illustrated in Fig.1. It is assumed that an RRC filter is used at the output of the modulator. The quadrature arm ($x_Q(t)$ arm) works similar to a phase locked loop (PLL), but its output reverses each time modulated signal changes sign while in-phase arm ($x_I(t)$ arm) produces the data messages [5].

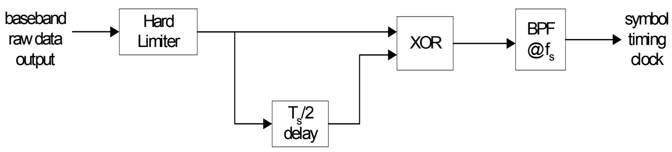

Fig.2 XOR gate symbol timing recovery circuit

Receiver of any communication system has to know the time instants when the modulated signal may alter its state. In order to determine the sampling time and the reset time for integrators, the separate symbols start and finish points has to be known. The estimation of these important times is called clock recovery or symbol timing recovery (STR).

Fig. 2 demonstrates the synchroniser with the XOR gate, which is one possible realisation of STR. The input to the revealed circuit has to be the base band raw data, which is the output signal at the in-phase arm low pass filter for BPSK Costas loop. First this signal is hard limited to get the non-return to zero (NRZ) stream. Then, with the XOR gate, it is processed with a delayed replica of itself to get return to zero (RZ) signal, which has a spectrum that consists of discrete spectral lines at multiples of the symbol rate ($1/T_s$). Therefore, filtering the output signal of the XOR gate with a narrow band bandpass filter centred at the wanted symbol rate results in the required synchronised clock [4]. Optimum performance is achieved with a delay equal to half the symbol duration, T_s. All the synthesised demodulators use this symbol timing recovery circuit.

2.2 QPSK

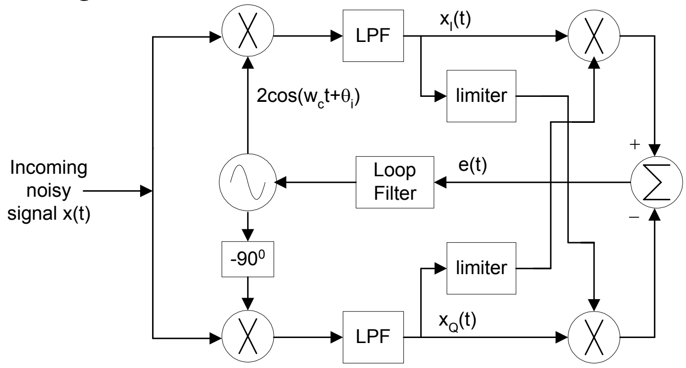

Fig.3 QPSK hard limited Costas loop

Similar to BPSK, it is also possible to recover the carrier and to demodulate the QPSK signal simultaneously. The structure is called hard limited Costas loop, which is illustrated in Fig.3 [5]. The hard limiters shown are used to remove the biphase modulation from $\sin\theta_e$ term, present in the error signal e(t). Hence together with the subtraction operation the dc voltages present at the error signal is removed apart from the loop phase error $\sin\theta_e \approx \theta_e$ [11]. Another result of using the hard limiters is the introduction of the signal suppression, which depends on the signal-to-noise ratio. Due to this suppression, the loop gain and the loop bandwidth is reduced [9].

2.3 OQPSK

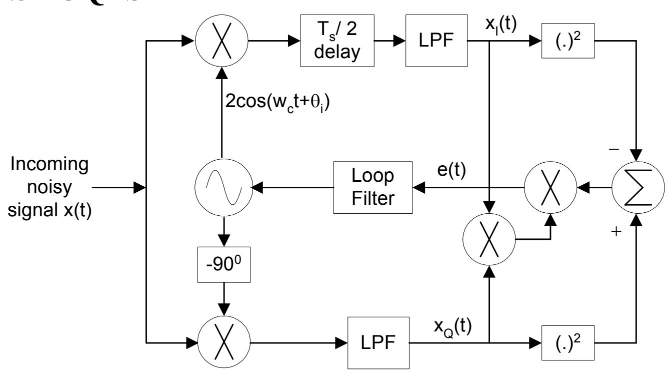

Fig.4 Offset QPSK Costas loop demodulator

If an offset modulation is used, the noise components in the in-phase and quadrature channels of the neighbouring symbols overlap, resulting in a dependent error signal from symbol to symbol. On the other hand, with the offset scheme, it is possible to reduce the phase ambiguity. For example, for OQPSK, the phase ambiguity could be 180°, not 90° as it is the case for QPSK [10]. The loop demonstrated in Fig.4 is an example of the OQPSK Costas loop, which was synthesised.

2.4 π/4 shifted QPSK

Fig.5 illustrates the limiter discriminator detector. The root raised cosine filter passes the signal and band limits the noise. Moreover, together with the possible RRC filter used at the output of the modulator, no ISI condition is achieved. The hard limiter is the second block of the demodulator. The transitions between the message points in the signal-space diagram take place directly, not following the outer circle of the diagram. The hard limiter assures that the signal keeps the outer circle during the transitions. Hence, the amplitude of the signal stays constant, which is essential for proper operation of the frequency discriminator. The instantaneous frequency of the signal, which is the information carrying part, is extracted by the discriminator block.

Fig.5 Limiter discriminator demodulator of π/4 shifted QPSK

2.5 8PSK

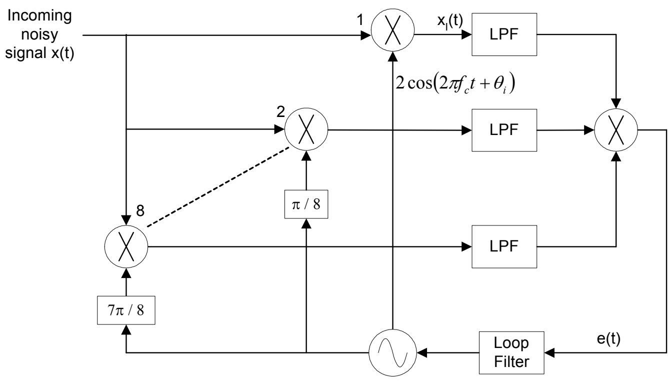

Fig.6 8PSK Costas loop demodulator

Due to the fact that Costas loop demodulators used for BPSK, QPSK and OQPSK, in order to be able to compare the performances, eight phase Costas loop, shown in Fig.6, was synthesised as 8PSK demodulator. The degradation of performance of the 8PSK Costas loop, mentioned above, is higher than the similar circuits for BPSK and QPSK, which is illustrated in [6].

3 Implemented Uplink Model

The difference between the observed frequency and the transmitted frequency in a communication system is called Doppler frequency shift (D_f), which is the result of the relative motion of the satellite and the ground station. D_f is given by the well-known formula [8].

$$D_f = \frac{v}{c} \times f \quad (1)$$

where v is the relative velocity, f is the transmit frequency and c is the velocity of the light. The relative velocity (v) of a LEO satellite is high enough to cause significant amount of Doppler shift even at VHF and UHF frequencies. For a carrier at 400 MHz, a maximum Doppler shift of ± 8.8 kHz can be experienced for LEO satellites at around 800 km altitude [2].

Since high amount of frequency shift is seen in LEO satellite communication, it is essential to compensate that shift to maintain the narrow band communication system. Therefore, active Doppler compensation using predictive tracking models is generally employed. The ground stations utilize Doppler compensation for both uplink and the downlink since it is not proper to implement this compensation on-board the satellite when there are two or more ground stations in the footprint of the satellite [2]. Hence, frequency shift of a few hundred Hz as the Doppler compensation block operation error was applied to the simulations.

Man-made interference is the dominant factor affecting the uplink of the LEO satellite communication. Although, interference is unpredictable, it strongly depends on the geographical location and local time of the day. Industrialised areas impose higher interference noise. Locations, where high power mobile radio systems used, reveal peaks of interference for VHF little LEO uplink frequencies. On the other hand, polar regions and the central pacific regions are the locations where no severe interference is present [1].

In order to understand the characteristics of the interference, in-orbit measurements are carried out by SSTL satellites. These measurements revealed that a dynamic range of 45 dB is possible, which proves that interference is the main factor to be considered in the uplink design for LEO satellite communications [2].

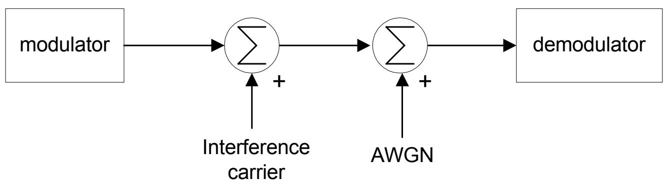

Fig.7 Uplink model used in simulations

As a result, the performance of the modems under interference had to be examined and compared. The model, which is shown in Fig.7, was used for this purpose. The interference signal simulated was a pure unmodulated carrier. The frequency of this sinusoidal was dependent on the modulation scheme. The Nyquist rate, which is equal to $1/2T_s$, was chosen as the interference carrier frequency.

One of the important features of synthesising modems with computers is not to simulate the carrier itself since carrier does not convey any information. Moreover, most of the simulation time is spent for simulating this non-information part of the signal. Therefore, none of the designed systems contained the carrier.

Table 1 reveals the frequency of the interference carrier applied for different modulation schemes. Since there was no actual carrier present in modulated signals, the spectrum occupied was the base band equivalent. Hence, the interference was applied to the base band equivalent spectrum. Not surprisingly, the interference signal frequency was reduced, as the order of the modulation format was increased, bandwidth was reduced, hence the Nyquist rate of the modulated signal (The data rate for the simulated systems was 10 kbps).

Table 1 Interference carrier frequency for different modulation schemes

Modulation scheme	Interference carrier frequency
BPSK	5 kHz
QPSK	2.5 kHz
OQPSK	2.5 kHz
π / 4 shifted QPSK	2.5 kHz
8PSK	1.67 kHz

The amplitude of the interference carrier was equal to one fourth of the actual signal. This ratio was conserved for all five different systems in order to be able to compare their performance. The magnitude response of RRC filters drop to half at the Nyquist frequency. As a result the amplitude of the interference carrier was reduced by half due to filtering, resulting $(1/8)^{th}$ of the original modulated signal. Therefore, the carrier to interference ratio C/I for the simulations carried out was calculated as 18 dB, seen below.

$$\frac{C}{I} = 20\log(8) = 18 \;\; dB \qquad (2)$$

4 Results and Discussion

The first system simulated was the modulator and the conventional Costas loop demodulator of BPSK. Fig.8 reveals the BER curves of the BPSK modem synthesised. The theoretical curve was also included. The red curve, labelled as simulated, just included the AWGN and the system itself. As it is seen from the plots, there was degradation in performance, nearly 1.5 dB, between the theoretical curve and the simulated system results. This degradation was the result of the Costas loop operation. Investigating the performance of the BPSK system under interference was the main objective of the carried out simulations. Approximately 1dB of degradation between the AWGN curve and the interference curve was encountered. [3] revealed the interference BER plots for BPSK. According to those plots, with C/I = 18 dB, the degradation was nearly 0.7dB; hence 1dB of performance failure of the synthesised modem was not surprising.

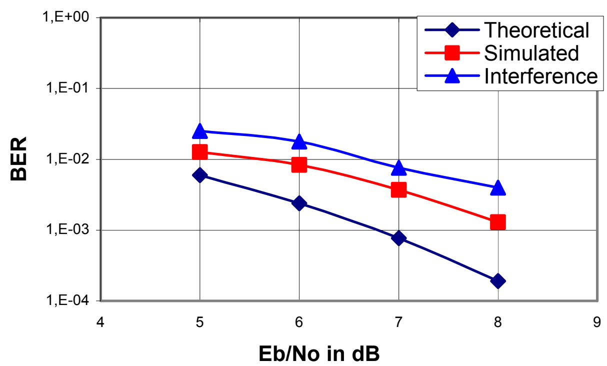

Fig.8 Performance curves of BPSK

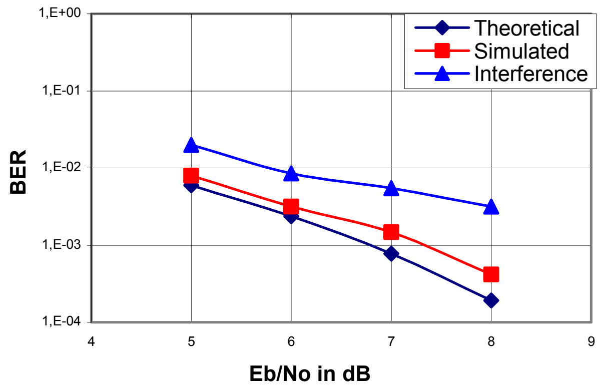

Fig.9 Performance curves of QPSK

Following BPSK, QPSK modulator and hard limited Costas loop demodulator were simulated. Fig.9 demonstrates pure AWGN channel performance curve, labelled as simulated and the interference curve of this modem. Designed loop caused a degradation of approximately 0.5 dB with respect to theoretical curve due to the loop losses. The interference simulation of QPSK resulted in the plot given in Fig.9. The degradation of performance with respect to the AWGN simulation was around 2 dB, which was consistent with the plots revealed in [3], where the performance goes worse by nearly 1.5 dB.

Fig.10 illustrates the simulation results for AWGN channel and the interference for offset QPSK. The theoretical performance curve, which is identical to BPSK and QPSK, is also revealed. The performance of designed modem degraded approximately 1 dB with respect to the theoretical curve. This degradation was expected due to the loop operation and it was depended on the SNR and the loop parameters. The interference curve was shifted above the original AWGN BER one by 2.5 dB, considering the horizontal axis. This amount of degradation was higher than the previous modulation formats tested.

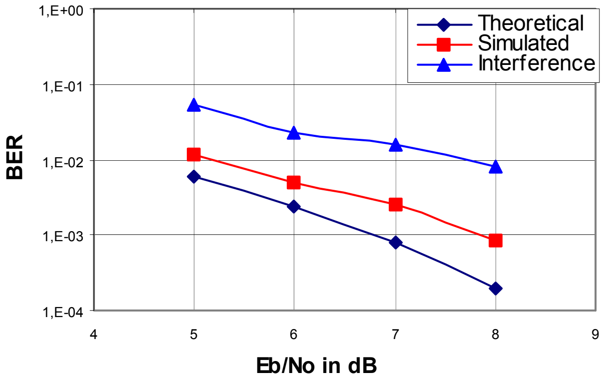

Fig.10 Performance curves of OQPSK**.**

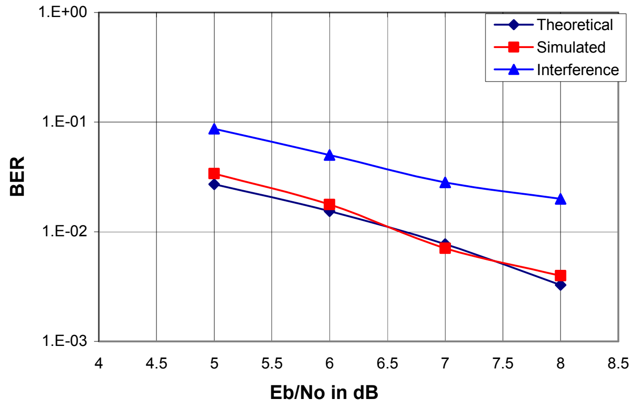

Fig.11 Performance curves of π/4 shifted QPSK

The performance of non-coherent limiter discriminator demodulator together with the π/4 shifted QPSK modulator was investigated through proper simulations. According to Fig.11, the modem worked properly and its performance was approximately identical to the theoretical one. This outcome might be surprising at first glance, but it was expected to achieve a good performance due to the fact that the demodulator simulated was formed of very accurately defined blocks, hence there were not many parameters to choose. Moreover, since there was no loop present, any loop losses or degradation did not affect the performance. BER of pure AWGN channel simulation for E_b/N_o = 7 dB was equal to 7.6 × 10^{-3}. Liu simulated a BER performance of 8.9 × 10^{-3} for the same figure of merit value [7]. Therefore, the red curve demonstrated in below graph was a little better than expected but not surprisingly perfect. Moreover, since the demodulator was non-coherent, its performance was definitely worse than the previous coherent demodulators of BPSK, QPSK and OQPSK. The influence of the inserted interference carrier was to shift the AWGN curve by 2 dB along horizontal axis. This amount of degradation was expected, since π/4 shifted QPSK was a variant of QPSK, and the amount of degradation was similar to QPSK and OQPSK

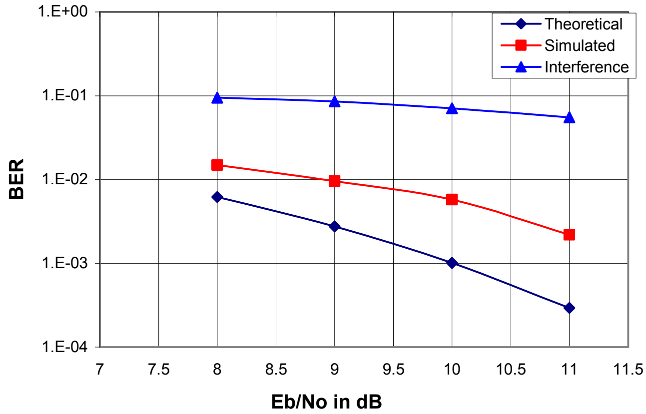

Fig.12 Performance curves of 8PSK

Table 2 Doppler performance of synthesised modems for E_b/N_o = 8 dB

Modulation format	No Doppler	200 Hz of Doppler
BPSK	1.29 × 10^{-3}	2.37 × 10^{-3}
QPSK	4.17 × 10^{-4}	4.1 × 10^{-4}
OQPSK	8.51 × 10^{-4}	1.78 × 10^{-2}
π / 4 shifted QPSK	3.98 × 10^{-3}	5.88 × 10^{-3}
8PSK	1.49 × 10^{-2}	1.32 × 10^{-1}

The simulation results of the synthesised 8PSK modulator and Costas loop demodulator of this modulation scheme are demonstrated in Fig.12. Comparing the synthesised modem performance and the theoretical curve, 2 dB of degradation was encountered. This was higher than the previous synthesised loop degradations due to the fact that this loop was operating for a higher order modulation, namely 8PSK. As [6] clarified, loop performance goes worse by using higher order modulation formats. Therefore, the performance of the synthesised modem was reasonable. Interference simulations resulted the BER curve, which is presented in Fig.12. More than 3 dB performance loss was seen due to the interference carrier. Comparing this result with the plots of [3], where the degradation was revealed to be almost 3 dB, the validity of the simulations was established.

According to simulation results and Table 2, QPSK was the most tolerant scheme for Doppler shifts. Whereas, higher order technique namely 8PSK, offered the worse performance. OQPSK performance degraded seriously too. However, BPSK and π/4 shifted QPSK showed moderate degradation, which might be possible to tolerate.

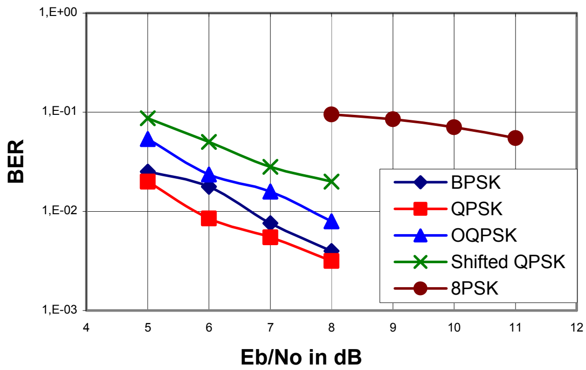

Fig.13 Performance curves with C / I = 18 dB

Above plots summarises the uplink performances of the investigated schemes. As it is seen, QPSK surpassed all the other ones, resulting in the best curve. Following it, BPSK and OQPSK might be considered for uplink of the LEO satellite communication channel. QPSK also achieved a good tolerance to Doppler shifts depending on Table 2. Since, for the uplink, the power constraints are not as serious as it is the case for the downlink, the non-constant envelope of this format could be compensated by using less efficient linear amplifiers in the ground segment, preventing the regeneration of suppressed side lobes. As a result, QPSK seems to be the best choice for the uplink of LEO satellite communication among the compared five phase shift keying type modulation formats.

5 Conclusions and Future Work

The research included performance comparison of various phase shift keying type modulation schemes under LEO satellite uplink channel constraints. Phase shift type techniques had been considered to investigate due to the fact that they theoretically offer better performance than amplitude or frequency shift keying formats.

In this research modulators and demodulators were synthesized using MATLAB® simulation tool. The outcome of the various simulations regarding uplink was the decision of implementing QPSK modem, which is expected to reveal better performance than the other ones. However, since the envelope of QPSK is non-constant, the high power amplifiers at the output of the transmitter must be forced to work in linear region, reducing the power efficiency. This is not a severe problem for the uplink due to the fact that there are no severe power constraints in the ground stations as is the case for satellite.

The meaningful future work of this research, which will start with TUBITAK BILTEN engineers in a couple of months, is the hardware implementation of the systems, possibly by employing FPGAs and integrating the system as an experimental payload with one of the future BILSAT satellites.

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