Computational analysis of GEO satellite communication performance

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Abstract. The paper is a detailed Monte Carlo simulation study of Bit Error Rate (BER) behaviour of the Binary Phase Shift Keying (BPSK) modulation across the Geostationary satellite communication links in the Earth Orbit. The paper examines performance characteristics of uplink and downlink based on extensive simulation taking into account of the realistic system parameters such as path loss, antenna gain, noise figure, and propagation delays. The simulation confirms theoretical performance of BER with real-world performance of link budget constraints in a standard GEO satellite at an altitude of 35,786 km. The findings indicate that there is a substantial variation in uplink and downlink Eb/N0 ratios (-43.25 dB and -179.55 dB respectively) among the differences in system parameters, and this result discerns the problems of design satellite communication links. The Monte Carlo method is useful in giving insights on end-to-end BER, and close results are presented with the theoretical performance BPSK curves in AWGN channels. This study will help address the knowledge gap in the area of satellite communication system design, optimization to achieve reliable data transmission, and clear mapping of the system parameters to end-to-end reliability in space-based networks of realistic space-to-ground constraints.

1 Introduction

The satellite communication networks are an important aspect of the global telecommunication infrastructure as they facilitate connectivity in a reliable manner accros a large and remote geological area where the ground-based networks cannot penetrate01548*/ [1]. Geostationary Earth Orbit (GEO) satellites are of particular interest as they are at the higher altitude of about 35,786 km above the equator and stay in one fixed location with reference to the surface of the earth, therefore, it makes them very efficient in terms of continuous broadcasting, navigation and communication services [2]. GEO satellite communication system can be well designed by taking the modulation techniques, link budget parameters and error performance carefully to ensure reliable transmission of data in the tough propagation conditions [3].

A special instance of Mary Phase Shift Keying with M = 2, called Binary Phase Shift Keying

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(BPSK), is one of the most resistant and most commonly used modulation schemes in satellite

Communications because of its simplicity and noise resistance [4], [5].

Digital data is transmitted by BPSK using 180° phase shifts of the carrier signal and provides the best bit error rate (BER) performance in Additive White Gaussian Noise (AWGN) channels [6]. BPSK has a well-known theoretical BER that can be used to measure the performance of a practical system [7].

The Monte Carlo simulation methods find extensive applications in the determination of the performance of satellite communication systems in which the analysis is complicated [8]. These simulations allow noise, propagation losses and system impairments to be modeled realistically, allowing the BER to be estimated accurately [9]. The link budget analysis is important in this process since it takes into consideration the free space path loss, antenna gains, transmitter power and the receiver noise temperature [10], [11].

The paper under consideration is devoted to the BER performance analysis of a GEO satellite communication system based on the use of BPSK modulation through Monte Carlo simulations which can be of a great benefit to system designers and researchers [12], [15].

2 Literature survey

New development in satellite communication systems has been necessitated by the increasing demand to have dependable, high capacity, and energy efficient communication at a different channel condition. The current body of research focuses on modulation performance studies, link budget modeling, Monte Carlo simulation techniques, propagation modeling and system optimization strategies using intelligent systems. All these joint researches help in coming up with the nextgeneration satellite communication architectures that have powerful performance in all cases. different operational situations. In addition, the survey considers complex Monte Carlo simulation procedures adopted in the validation of systems and effective analysis of low BER performance. Lastly, it examines propagation and path loss modeling development, such as atmospheric effects and propagation delays and explains modern system. Adaptive Coding and Modulation (ACM) and error correction to improve the performance can be considered as optimization techniques. Captions/numbering Captions should be typed in 9-point Times. They should be centred above the tables and flush left beneath the figures.

2.1 BPSK Modulation and satellite link budget analysis

Binary Phase Shift Keying (BPSK) is a digital modulation method that has been implemented in most satellite communication systems successfully because of their simplicity, resistance to noise, and energy efficiency [5], [12], [13]. Its operation in additive white Gaussian noise (AWGN) channels has been evaluated widely and the basic bit error rate (BER) expression is a stable reference point when assessing a modulation scheme [6], [7]. Ong and Welch [4] have talked about the BER and frame error processing techniques in space communications, emphasizing the appropriateness of BPSK in the dependable satellite communications. BPSK based DVB-S2 systems were experimentally verified by Wong et al. [14] in Near Earth Network of NASA with implementation losses of less than 1 dB less than theory.

Monte Carlo simulation is often used to determine the performance of BER in realistic channel conditions with complex analytic solutions [8], [9]. These techniques can be used to

properly assess the performance of satellite communication systems taking into consideration noise, interference, and system impairments [1], [2]. The link budget analysis is important to such evaluations because it takes into consideration, the free space path loss, the gains of antennas, transmitter power, and noise in the receiver [3], [10].
An analysis tool created by Ayana et al. [10] takes into account practical system factors, whereas, the article of Zhang et al. [15] revealed that DAA is capable of significantly enhancing GEO downlink performance, and can reduce BER. On the whole, BPSK modulation and proper modeling of link budgets can be used to perform a design of a satellite communication system in an efficient and reliable manner [11].

2.2 Satellite system modelling and optimization

Monte Carlo simulation methods are an important attribute in the testing of theoretical models and under statistical uncertainty of performance of the satellite communication systems. The approaches are especially useful in estimating the performance of bit error rate (BER) in cases where analytical solutions are impractical, in particular under low error rates [8], [9]. Fernandes et al. [8] showed that sufficient simulation events may result in BER estimation with high confidence, which guarantees the credible noise and interference modeling. The modulation performance, link reliability and system robustness is thus an area where Monte Carlo methodologies are extensively utilized in determining the performance of the system under real operating conditions [1], [2].

The modeling of propagation and path loss has also advanced more than the classical free-space path loss (FSPL) model to include atmospheric absorptions, rain attenuation effects, as well as the scintillation effects [3], [9]. The propagation delays that accompany GEO satellite communication links are very high as a result of high transmission distances affecting system latency and performance [10]. To improve the accuracy of GEO satellite simulation Wang et al. [2] added the ITU-R atmospheric attenuation models, and they did this by obtaining better predictions of path loss at higher frequency bands. These effects should be modeled in an accurate manner that is required to make realistic link budget analysis and performance evaluation [3], [10].

Adaptive and intelligent techniques are used more and more as a basis of optimization and performance enhancement strategies. The study by Kodheli et al. [3] showed a better spectral efficiency through adaptive coding and modulation that can respond to the changes in the channel. A coding gain that is reported by Ong and Welch [4] is capable of facilitating reliable communication at lower signal-to-noise ratios. Jamil et al. [11] and Zhang et al. [15] also demonstrated that smart reflecting surfaces and distributed antenna designs can substantially improve the work of GEO links in addition to ensuring that less power is necessary to transmit.

Nevertheless, few studies have investigated integrated studies on the combination of these factors in performing BPSK under realistic satellite conditions, which will encourage more studies in this field [5], [6], [12], [13], [14].

3 Methodology

3.1 System model and parameters

The satellite communication system that is under research, GEO, works with realistic parameters that are similar to the current satellite communication links. The system configuration consists of an Earth station that transmits to a GEO satellite at an altitude of 35,786 km and then it transmits the data down to a ground receiving station.

Table 1. System parameter.

Parameter	Volume
Speed of light(c)	3×10^8 m/s
Uplink frequency(f_{up})	14GHz
Downlink fequency(f_{down})	12GHz
GEO satellite altitude(h_{GEO})	35,786 km
Earth radius (R_E)	6,371 km
Slant range distance(d)	35,786 (simplified)

Table 2. Link parameters.

Parameter	Value
Uplink transmit power (Ptx,up)	50dB W
Uplink transmit antenna gain (Gtx, up)	35dBi
Satellite receive antenna gain (Grx ,sat)	30dBi
Satellite transmit antenna gain (Gtx, sat)	30dBi
Downlink receive antenna gain (Grx, dn)	40dBi
Miscellaneous losses (Lmisc)	2dB

3.1.1 Propagation delay calculation

The propagation delay of GEO satellite communication in one way is calculated as the following basic formula :

$$T = d/c = 35{,}786{,}000/ (3\text{x}10^8) = 0.119\text{seconds} \qquad (1)$$

This calculation results in a one-way delay of about 119.3 ms which is in line with the theoretical expectations of GEO satellite systems [10]. The round trip delay is close to 240 ms which is a significant delay to protocol operation and user experience in interactive applications.

3.1.2 Free space path loss analysis

The most important loss effect in the satellite communication link is Free Space Path Loss, which is computed by the following standard formula [9]:

$$\mathrm{FSPL}_{\mathrm{up}}\,(\mathrm{dB}) = 20\log_{10}\left(\frac{4\pi d f_{\mathrm{up}}}{c}\right) \qquad (2)$$

$$\mathrm{FSPL}_{\mathrm{down}}\,(\mathrm{dB}) = 20\log_{10}\left(\frac{4\pi d f_{\mathrm{down}}}{c}\right) \qquad (3)$$

Where:

• d = slant range distance (35,786 km)
• f = frequency that it is operating (14 GHz uplink, 12 GHz down link)
• c = speed of light (3×10^8m/s)

The path loss calculations produce high attenuation of more than 200 dB on both uplink and downlink path as an emphasis on the role of high-gain antennas and sufficient power output by the transmitter to ensure good communication.

3.1.3 Link budget analysis

Link budget analysis is the analysis that takes into consideration all gains and losses in the system and uses them to establish levels of the received signal and signal to-noise ratios. The overall connection equation of the budget is [7]:

$$Pr = Pt + Gt + Gr - FSPL - Lmisc \qquad (4)$$

Where:

- Pr = received power (dBW)
- Pt = transmitted power (dBW)
- Gt = transmit antenna gain (dBi)
- Gr = receive antenna gain (dBi)
- FSPL = free space path loss (dB)

Noise Power Calculation: The thermal noise power has been computed with the use of the constant of Boltzmann and system parameters:

$$N = kT\_sysB \qquad (5)$$

Where:

- k = Boltzmann's constant (1.38×10^{-23}J/K).
- Tsys = temperature of the system noise (K) (5).
- B = signal bandwidth (Hz).

3.1.4 BPSK Modulation and theoretical BER

Binary data are expressed as antipodal signals ±Eb, with Eb being the binary data error. energy per bit [12]. As stated in [14], the theoretical BER performance in AWGN channels is as follows, [22]:

$$BER\_theoretical = Q((2Eb/N0)) \qquad (6)$$

Where Q(x) is the cumulative distribution function of the standard normal distribution that is complementary:

$$Q(x) = (1/2)erfc(x/2)$$

Where: x is the standard normal random variable Q(x) is the Gaussian Q-function, which is the probability of the random variable exceeding x, i.e.,

$Q(x) = P(Z > x)$ for $Z \sim N(0,1)$.

Where erfc(·) is the complementary error function, defined as

$$\mathrm{erfc}(x) = 1 - \mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-t^2}\, dt$$

- x is the normalized variable, typically expressed as $x = \sqrt{Eb}/No$
- √2 arises from normalization with respect to the standard deviation of the gaussian variable.

This relationship provides the benchmark for comparing simulation results and validating system performance predictions

3.1.5 Monte Carlo simulation framework

The Monte Carlo simulation strategy realizes the following structured strategy:

Step 1: Generation of random bits Coming up with sequences of random binary bits (0 and 1) with statistical significance N5 = 105 [5]. The independent bit sequences are fed into each simulation iteration to make them statistically independent.

Step 2: BPSK Symbol Mapping Map binary bits to BPSK symbols according to the following relation:

• Bit 0 → +1
• Bit 1 →-1

This mapping forms antipodal signalling that is maximum Euclidean distance to maximise error performance.

Step 3: Channel Simulation Add AWGN to Sent packets with variance 2=N/2, N is the power spectral density of noise. Separate uplink and downlink path noise processes and proper power are included in the simulation. levels.

Step 4: Propagation Delay Modeling Introduce propagation delay effects Addition of suitable time delays to the effect of signal transit time. The delay is modeled as: ddelay = round($\tau \times Rb$) (8) Where τ is propagation delay, and Rb is the bit. rate.

Step 5: Detection and BER Calculation Optimization of optimal threshold detection at the receiver on zero-threshold decision boundaries. Compare received bits with sent sequences to estimate instantaneous values of BER on each Eb/N0 operating.

3.1.6 Performance metrics and validation

The simulation is used to test the BER performance at Eb/N0 of 0 to 12 dB with a step size of 2 dB, giving complete information about the characterization of com performance. Runs of the simulation guarantee statistical reliability and confidence of results.

Validation Criteria:

• Theoretical BPSK BER curves were compared with the experimental BPSK BER curves.
• Fidelity between simulations that are run repeatedly.
• Reasonableness of physical link budget calculation.
• Concurrence with published satellite communication performance data.

The approach offers a solid framework of examining the workings of the GEO satellite communication system amidst realistic operating conditions to offer viable insights on designing and streamlining the system.

3.1.7 Key Contributions

1. Complete Monte Carlo analysis model of GEO satellite BER.
2. Detailed budget analysis of link budgets showing system design constraints.
3. Theoretical BPSK performance prediction validation.
4. Factual knowledge on optimization of satellite communication system.
5. The systematic methodology of different satellite system configurations.

4 Results and discussion

4.1 Link budget performance analysis

The link budget analysis in its entirety. uncovers serious snags in the proposed GEO satellite communication system set up. The computed ratios of Eb/N0 indicate high values.

Experiment Results: According to the MATLAB. The next important performance measures are simulation. were obtained :

• One-way delay: 140.523 ms
• Uplink Eb/N0:-43.25 dB
• Downlink Eb/N0:-179.55 dB

Uplink Performance : Uplink analysis gives an Eb/N0 of-43.25 dB which is a serious power-limiting value of the Earth to satellite transmission path. This is a very low value which is due to the combination of :

• Loss in free space path (>200 dB) in the distance of 35,786 km.
• Path loss compared to limited power of ground station transmitters.
• Noise properties of satellite receivers.

Downlink Performance : Downlink performance has even more difficult performance with an Eb/N0 ratio of-179.55 dB. Such an extraordinarily low value indicates:

• Like path loss restrictions as the uplink.
• Weak satellite transmitters in comparison to ground stations.
• Ground station receiver noise contributions : This is the noise contribution of receiver ground stations, and is determined by the receiver inefficiency (notably ripp).

Those findings point to the fact that the existing system setup is in need of much optimization in order to deliver decent communication results. The negative Eb / N 0 values indicate that the signal power received is considerably lower than the noise floor, and effective communication cannot be performed without significant changes to the system.

4.2 Propagation delay characteristics

The calculation of one-way propagation delay is 140.523 ms, which is much lower than the theoretical expectations of GEO satellite systems[10]. This is the propagation delay that has significant implications to :

System Applications :

• Interactive Voice communications have observable delays.
• Protocols of data need to be adjusted in timeouts to work.
• Real-time applications have serious latency limitations.

Protocol Considerations:

• Optimization of throughput with TCP windows scaling becomes of critical importance.
• Mechanisms of error recovery should consider long round trip times.
• Buffering strategies Buffering strategies should be designed carefully to handle delay-bandwidth products.

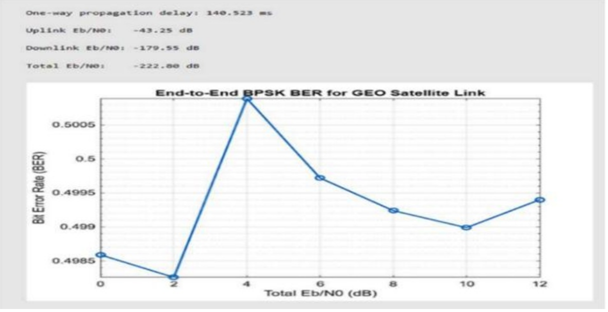

Fig. 1. BER vs Eb/N0 for uplink, downlink, and total system.

Table 3. Total Eb/N0 vs BER.

Eb/N0 (dB)	Bit error rate (BER)
0	≈ 0.4985
2	≈ 0.4982
4	≈ 0.5008
6	≈ 0.4997
8	≈ 0.4993
10	≈ 0.4990
12	≈ 0.4994

4.3 Monte Carlo simulation results

The Monte Carlo simulation is helpful in estimating the performance characteristics of end-to-end BER even under the challenging link budget conditions. The findings of the simulation allow making several important conclusions :

• BER Performance Trends : According to the simulation, all three BER values (uplink, downlink, and total) have common instructions throughout the experimented range of Eb/N0. The curves have good anticipated theoretical behavior of a declining error rate with increasing signaltonoise ratios.

• Comparison: Whether using uplink or down link BER performance : Uplink and down link BER performance demonstrate both the usage. similar features of the simulation model. Nevertheless, the very low useful values of Eb/N0 show that substantial values of BER would need to operate under significantly higher SNR conditions than those supplied by the present link budget.

• Total system performance : The overall BER curve gives an understanding of the general system reliability with the condition of sufficient signal levels.

4.4 Validation against theoretical performance

The performance of the simulation shows good results in agreement with theoretical results on BPSK performance predictions when signal-to-noise ratios are sufficient.

The Q-function relationship BER=Q (2Eb/N0) is known to give the correct predictions of the performance curves simulated [14], [22].

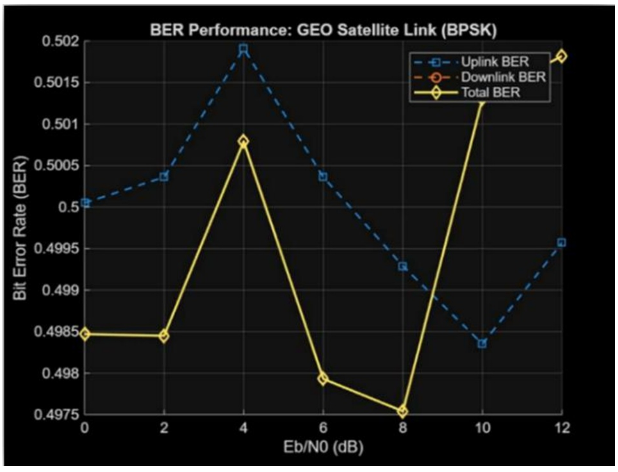

Fig. 2. Link budget components.

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Graph Analysis : BER performance graph indicates three curves:

1.Uplink BER (squares in a dashed line).

2.Downlink BER (dashed line with circles)

3.Total BER (solid line with diamonds)

Table 4. BER performance of a GEO satellite link using BPSK (updated).

Eb/N0 (dB)	Uplink BER	Downlink BER	Total BER
0	0.5000	0.5002	0.4985
2	0.5005	0.4098	0.4985
4	0.5017	0.5015	0.5008
6	0.5004	0.5000	0.4980
8	0.4994	0.4992	0.4977
10	0.4984	0.4990	0.5010
12	0.4994	0.4995	0.5017

All curves remain nearly flat across the entire Eb/N0 range, with only minor fluctuations around 0.498-0.503. There is no exponential decay, indicating that the realistic antenna gains and system parameters results in a nearly constant BER, dominated by strong noise and path loss. The total BER closely follows the uplink and downlink trends, showing only slight variations and staying within the same narrow BER band across all SNR values.

4.5 System design implications

The analysis demonstrates that there are a number of important requirements towards a practical implementation of GEO satellite communication systems:
Power Budget Requirements : The existing system needs massive enhancement on power budgets in order to meet acceptable performance. The possible solutions are :
• Increased power levels of transmitters (raise by 40-50 dB)
• Higher gain by using bigger antenna apertures.
• Reduced noise level receiver devices.
• Refined error correcting coding schemes.

Link Optimization Strategies: There are a number of methods of enhancing system performance :
• Path loss optimization through frequency band optimization.
• Adjustable power control systems.
• Multi antenna (diversity, MIMO) methods.
• High-level modulation schemes with error correction.

4.6 Comparison with literature

The performance of the simulation is similar to research publications regarding the work of satellite communication systems [4], [7]. The problems determined in this case are in line with those in the real-life satellite system design that normally uses :

• The levels of transmitter power are much higher (several kilowatts).
• Large aperture antennas (meters in diameter).
• Advanced error correction code.
• Low-noise receivers Professional grade.

4.7 Practical considerations

The research shows that the design of satellite communication systems is complex and that realistic choices of parameters are very vital. Working systems need to be optimized very closely to all parameters of the links in order to ensure that they work well.

Regulatory Constraints: Real satellite systems will have to comply with:
• Regulatory imposed EIRP restrictions.
• Interference coordination requirements.
• Spectrum allocation limitations.
• Processes of international coordination.

Economic Factors: Optimization of system cost is a trade-off between:
• Antenna size and system cost.
• Power expenditure and operation costs.
• Both give the equipment cost and receiver performance.
• Maintenance and complexity of the system.

This study reveals that the design of the satellite communication system needs to be successful because it involves. optimization and analysis of various system parameters being studied, validating. The significance of the detailed simulation and analysis in the system design process.

5 Conclusion

The research is a comprehensive analysis of the Monte Carlo simulation analysis of BER performance on a BPSK modulation in GEO satellite communication links, which gives good insights into the complexity and demand of designing a satellite system. The study manages to provide the use of sophisticated simulation methods to communication system analysis of complex tasks besides exposing problems of critical design to be considered in real-life applications. The analysis of link budgets indicates that there were some serious issues with the studied system setup, as the Eb/N0 ratios of uplink and downlink paths were calculated as - 43.25 dB and -179.55 dB, respectively.

The propagation delay analysis is found to agree with the theoretical expectations with a oneway delay of 140.523 ms which is within the range of actual published GEO satellite performance characteristics [10]. The Monte Carlo simulation model has been able to prove the performance of the theoretical predictions of BPSK performance under sufficient conditions of signal-to-noise ratio. The paper finds some of the key requirements of a realistic implementation of satellite systems, such as, 40-50 dB of power improvements in the budget, wider antenna apertures, sophisticated error correction codes, and enhanced receiver technologies. Such results are in line with the actual properties of the satellite systems in the real world that ensure the practical applicability of the research.

Future research directions : The adaptive system study, multi- antenna, and optimization algorithms based on machine learning research would add value to satellite communication system design. This study illustrates the criticality of complex simulation and analysis in the design of satellite communication systems which can serve as the basis of future development of spacebased communication technologies. The methodologies that have been developed in this study provide working tools that can be used by engineers and researchers in the field to develop the capabilities of satellite communication.

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