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ORIGINAL RESEARCH ARTICLE

DEVELOPMENT OF AN IMPROVED ACM SCHEME FOR MITIGATING EARTH-TO-SPACE PROPAGATION EFFECTS

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ABSTRACT

In satellite communications, the communication link experiences propagation losses such as: Path loss, atmospheric losses, rain fading, ionosphere effects (such as scintillation), and other effects which can greatly affect the received signal strength and close the link budget in the worst case. The design of future broadband satellite systems has to be done with the challenge of more complex traffic mix and these harsher propagation conditions which mitigate the performance of the communications link. Link adaptation (LA) has been used in satellite communications applications for evaluating the performance of an adaptive modulation system in the unique space-based propagation environment. Despite the current research on improving satellite system performance, there is still a need to further develop a scheme that mitigates the effect of atmospheric impairments. This work develops an improved adaptive coding and modulation scheme that mitigates earth-to-space propagation effects. The scheme targets maximizing data throughput while staying below a Bit Error Rate (BER) threshold so as to successfully mitigate link impairment in fixed communication systems. Simulation of the work is carried out using MATLAB 2016b and System Toolkit (STK) 11.3. Simulation result showed that the iACM scheme was able to reduce the effect of path loss in time by 5% over the ACM scheme and also reduced the effect of path loss with respect to the angle of elevation by 2% over the ACM scheme and improvement in the network energy to noise ratio by 22.74% over ACM. In terms of system throughput, the iACM scheme showed an improvement in throughput by 24% over the ACM scheme. Finally, the iACM scheme has shown better performance in terms of throughput and thus, improve the performance of satellite communication.

1.0 Introduction

Satellite communication is a promising technology due to its ability to serve very large number of users with high data rate services. Despite the large deployment of optical fibre links, satellite communication technology has been seen to dominate the telecommunication industry due to its inherent advantage of extremely long-distance communication (Jayadev, 2011). The geometric increase in user-demand for higher capacity satellite links has inspired satellite operators to operate in higher frequency bands, such as Ka-band and above in order to accommodate the necessary data rates (Leshan *et al.*, 2016). The move to these higher frequency bands employs communications system designs which require the development of a link budget between the transmitter and the receiver. These designs provide an adequate signal level at the receiver's demodulator to achieve the required level of performance and availability (Pratt *et al.*, 2003). Satellite system performance of the link can be evaluated using Bit Error Rate (BER) and Carrier-to-Noise (*C/N*) ratio. Successful design of communication links involves many factors such as the various losses as well as antenna power and gain (Kilcoyne *et al.*, 2016).

The communications links described are usually configured with a fixed data rate, a static modulation and/or coding scheme, and high link margins to accommodate communications during the worst-case scenario. This worst-case planning approach ensures that communications links are maintained during even the worst expected Earth-to-Space propagation effects (Pratt *et al.*, 2003). These propagation effects include path loss, atmospheric loss, attenuation due to rain, and ionosphere loss, among others. Generally, a maximum BER is identified in a communications system and the link is designed to support that BER threshold (Pratt *et al*, 2003). The effects of these propagation impairments degrade the received signal power and are detrimental to a communications link if the BER increases above the acceptable limit for the transmitting waveform as the error correction codes would no longer be able to resolve bit errors (Kilcoyne *et al.*, 2016).

LA is a broad term that encompasses many types of adaptation on the communications link. The technique often referred to as Adaptive Coding and Modulation (ACM) is a good way for the earth-to-space communications link to select the modulation scheme that adapts to the signal energy fluctuation to maintain a desired BER (Sami *et al.*, 2011). LA is developed to track the channel variations, thus changing the modulation and coding scheme to yield a higher throughput. This is achieved by transmitting with high information rates under favorable channel conditions. (Sami *et al.*, 2011). LA has been used in satellite communications applications, evaluating the performance of an adaptive modulation system in the unique propagation environment. Some LA satellite applications consider weather impairments, such as rain-fading in the higher frequencies of Ka- and Ku-bands (Cioni *et al.*, 2008). This research work developed an improved ACM scheme to mitigate earth to space propagation effects.

The process of setting the International Space Station (ISS) orbit can be done by using the STK. The parameters necessary for characterization of the communications link environment is gotten from the STK software. Typical STK parameters are given in Table 1. The International Space Station (ISS) orbit is easily loaded after searching the STK satellite database by common name. STK uses Two Line Elements (TLEs) and the Simplified General Perturbations (SGP)-4 propagator to model the orbit. In the instant of the ISS orbit, TLE data and SGP-4 model are used to provide an accurate propagation routine. TLEs provide the position of an earth-orbiting object for a given point in time. From this data, a prediction routine, such as SGP-4, can be used to predict the position of the satellite at any point in time.

Link adaptation is a broad term for a technique that monitors a communications link and alters system parameters to meet certain conditions. The ACM is a method for carrying out LA analysis. Accurate link budgeting improves the throughput of the communications link. In order to perform LA analysis (using the ACM method) as a function of Bit Error Rate (BER), the estimated *C*/*N*is related to the received energy per symbol. This relationship is given in equation (1) as follows (Kilcoyne, (2016):

$$\frac{E_S}{N_O} = \frac{C}{N} = SNR \tag{1}$$

To measure the quality of the communication link, the probability of bit error is estimated. In this work, the adaptation algorithm has a major aim of increasing data throughput which is given in equation (2). The objective BER for data transmission on wireless channels is known to be 10^{-5}. This is because the data transmission to the fight SDR is the main objective in this work, a selected BER threshold of 10^{-5}(Usman *et al.,* 2018):

$$Throughput = \frac{File\ size}{Ttransmission\ time}(bps) \tag{2}$$

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A BER of 10^{-5}implies that the receiver must receive on average 100,000 bits before one is in error. Thus, an average of 10,000,000 bits must be received for 100 bits to be in error. In this work, all the schemes transmit a fixed symbol rate of 502 kbps. Hence, at the lowest bit rate, the receiver required approximately 19.9s to measure the BER (Kilcoyne *et al.,* (2016). From simulation, the estimated time required for each modulation scheme to receive 100 errors, assuming a BER threshold of 10^{-5}, is given in Table 1.

Table 1: BER Average Time for each Modulation Scheme (Kilcoyne*et al.,* (2016)

Modulation Scheme	Average Time to Receive 100 Error
BPSK	19.92s
QPSK	9.96s
8PSK	6.64s
16QAM	4.98s
64QAM	3.32s

During simulation process, gray coding of all modulation schemes is assumed in order to keep each neighboring symbol differs by only one bit

To check the BER probability, E_b / N_0 is used to calculate the BER for BPSK and QPSK modulation schemes. The BER probability from the work of Kilcoyne, (2016) is calculated as follows Kilcoyne, (2016)

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_o}}\right) \tag{3}$$

where Q is the Q-function of the transmitted signal

From simulation, when comparing the performance of BPSK and QPSK using E_b / N_0, it appears that the required energy to maintain the same P_b is identical. When the BER is written in terms of the modulated energy per symbol, a 3 dB increase of signal energy is evident. The process of doubling the energy used in the modulation constellation as a result of using both the quadrature and in-phase channels rather than just in-phase of BPSK accounted for the generation of this 3dB. Table 2 shows the equations used in calculating the BER for each of the modulation schemes considered in this work.

Table 2: Theoretical BER Equations for Different Schemes

Modulation Schemes	BER Equations
BPSK	$P_b = Q\left(\sqrt{\frac{2E_b}{N_o}}\right)$
MPSK	$P_b = \frac{2}{\log_2 M} Q\left(\sqrt{\left(\sin\frac{\pi}{M}\right)^2 \frac{E_s}{N_o}}\right)$
MQAM	$P_b = \frac{4}{\log_2 M}\left(\left(1-\frac{1}{\sqrt{M}}\right) Q\left(\sqrt{\frac{3}{M-1}\frac{E_s}{N_o}}\right)\right)$

To check the performance of the receiver and the quality of the received signal, Error Vector Magnitude (EVM) used as a decision statistic for QPSK and 16-QAM modes. The EVM was measured by calculating the distance between the ideal and received symbols. The distance of the ideal symbol from the received symbol is the EVM

A variety of research has been carried out to mitigating earth-to-space propagation effects in satellite communications. For instance, Sali *et al.,* (2012) evaluated link adaptation mechanisms in a reliable multicast scenario, where the challenge lied in finding the optimal transmission rate to suit all terminals in the multicast group. From the simulation results, MLA and MIN are shown to be the best link adaptation algorithms, in providing the highest user fairness and the highest throughput. The problem of this paper was that the channel conditions experienced by the terminal deteriorated as the number of terminals increased. This was due to the error signal generated by solar panel shadowing effect on the satellite antenna that eventually led to high bit error modulation by the modulation schemes adopted in the work.

Tarchi *et al*., (2012) developed three adaption algorithms (state-based ACM, state estimation, and state nested algorithms) to improve mobile communication in rural and low populated areas with narrowband access. Numerical results showed that the proposed approaches increased the link performance. The limitation of the research was that certain channel parameters like the SINR still represented a challenging scenario which in turn lowered the link margin.

Rico *et al*., (2013**)** analyzed the problem of modulation and coding scheme selection in the return link of the mobile satellite system. The work used a weighted combination of both open loop and closed loop signal quality indicators to perform the selection. Numerical results showed good performance of the proposed method compared to previous algorithms, and its robustness to environment changes. The challenge of this study was that the target BER could not be achieved in very high or very low SNR scenarios.

Al-Saegh *et al.,* (2014) presented the atmospheric impairments to the satellite signal quality in terms of performance evaluation and assessments concerning various effective atmospheric and transmission parameters during dynamic weather conditions. Their results revealed that the transmitted frequency, rainfall rates, and relative humidity were directly proportional to the signal quality degradation, whereas elevation angle θ was inversely proportional and corresponding to low BER. Although the QPSK modulation was considered the most appropriate modulation scheme in case of high atmospheric impairments but it also exhibited lower number of transmitted bits per unit time which reduced the reception time of transmitted signals to the GEO satellite.

Bruno *et al.,* (2015) designed a reinforcement learning AMC algorithm in order to address the short comings (such as the CQI feedback that sometimes resulted in throughput losses) encountered by most AMC methods in a LTE system. The designed AMC scheme exploited a reinforcement learning algorithm to adjust the MCS selection rules based on the knowledge of the effect of previous AMC decisions. Although the simulated results showed the best MCS even if the CQI feedback provided a poor prediction of the channel performance, the convergence delays of the reinforcement learning were typically long. And as such, the satellite took a longer time to decode the received signals which generally reduced the systems performance in terms of throughput.

Kilcoyne *et al.,* (2016) characterized propagation environment experienced by a software-defined radio on the NASA scantest bed through a full link-budget analysis. The work proposed, designed, and modeled a link adaptation algorithm to provide an improved trade-off between data rate and link margin by varying the modulation format as the received SNR fluctuated. The result of the work showed an improvement on the throughput of the network. To address any data that might have been demodulated incorrectly and taking into account the round-trip delay, the transmitter would re-transmit the data that was sent when the channel conditions changed thereby degrading the general performance of their system in terms of throughput and the effect of path loss was high.

It is evident from the reviewed works that most of the existing algorithms either presented LA in a broadcasting system with no direct feedback to the ground station or do not consider shadowing effects. Some LA satellite applications considered weather impairments, such as rain-fading in the higher frequencies of Ka- and Ku-bands or log-normal shadow fading. Other algorithms applied the ACM method of LA to address variations in the channel condition on the receiving antenna which can cause an interruption of data transmission. Despite the various interventions by other researchers, there is still a need for improvement with the aim of having better link budget that improves the throughput of satellite network. This research work develops a GSA based ACM scheme to mitigate earth to space propagation effects.

2.0 Materials and Methods

The following presents the materials and method used in the development of the proposed scheme.

2.1 Materials

The materials used for this work include:

(a) Laptop (hp Intel (R) Core (TM) i5-2520M CPU)

2.2 Methods

2.2.1 Flowchart of the Developed Scheme

Figure 1 shows the step-by-step process that was adopted in the development of the link adaptation algorithm. The flowchart shows how the GSA algorithm is incorporated for link budget analysis and how a normalized EVM is used for symbol analysis.

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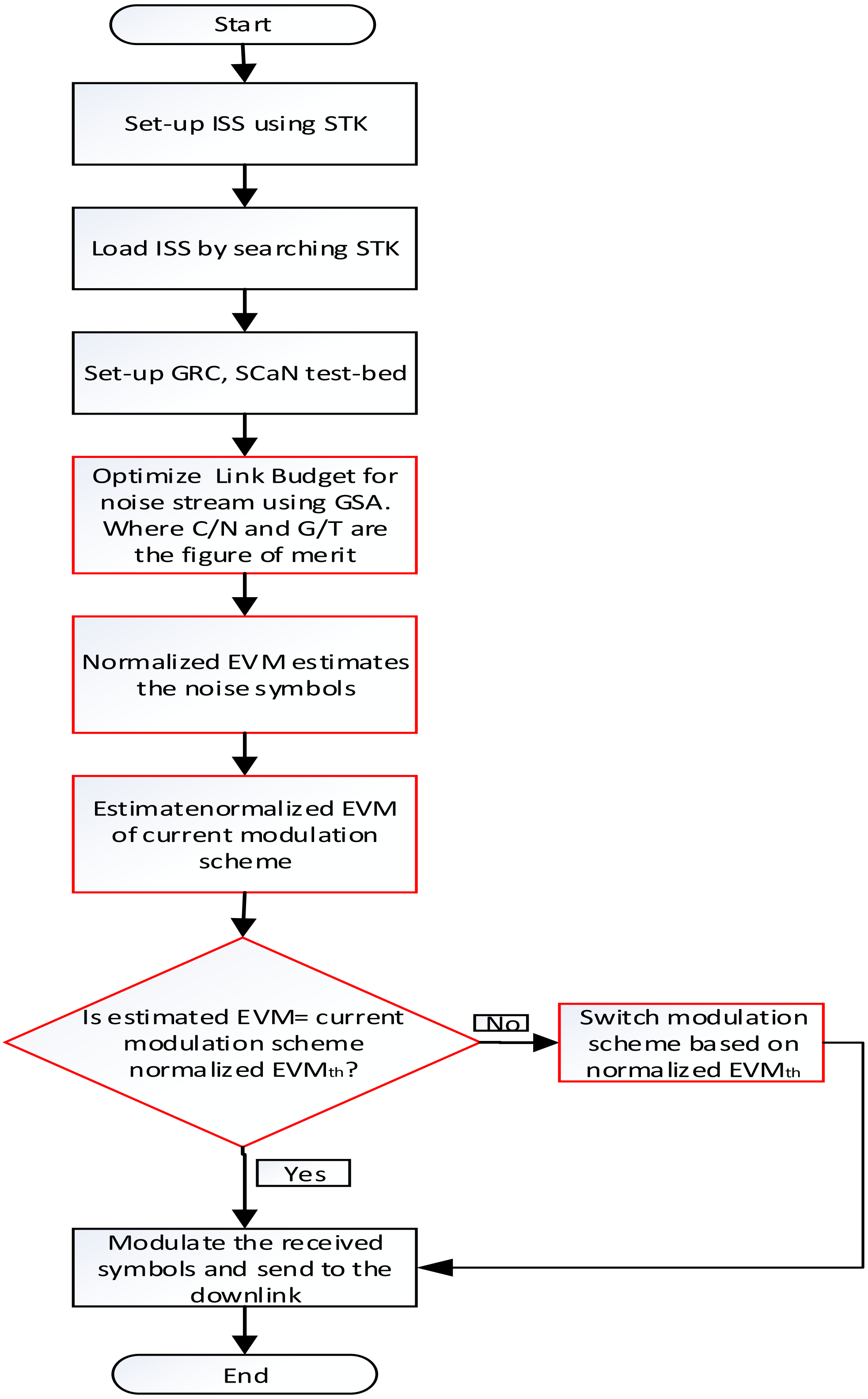

Figure 1: Flowchart of the Developed Improved Developed Improved adaptive coding and modulation scheme

2.2.3 Estimate Link Budget using GSA

The developed improved Adaptive Coding and Modulation (iACM) scheme for mitigating earth to space propagation effects adopted the GSA algorithm to optimize the process for the estimation of channel link budget. The process for link budget analysis was complex and prone to error due to large number of channel parameters to be estimated. In order to improve the throughput of the satellite communication link, proper and accurate link budgeting process is

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required. The iACM scheme optimized the link budgeting process. For efficient performance analysis of the communication link, the developed iACM scheme used f *C/N* and *G/T*(dB/K) as figure of merit. The *G/T* is used in this work to describe the capability of the earth station or satellite to receive a signal. The relation between the *C/N* and *G/T* used in this work is given as follows (Rashedi *et al.,* 2009):

$$\frac{C}{N} = f\left(\frac{G}{T}\right) \tag{4}$$

where:

f is the antenna frequency
G represents the antenna gain
T denotes the system noise temperature

The antenna gain used in this work is given as follows (Kilcoyne *et al*., 2016):

$$G = 20.4 + 10\log 10\eta + 20\log 10\left(D \times \frac{f}{1000}\right) \tag{5}$$

where, η is the antenna efficiency and D is the antenna diameter

The GSA algorithm was used to optimize the link budgeting process with simulation process in the developed scheme carried out using the GSA algorithm. The simulation parameters for the GSA are given in table 3 while table 4 is the communication link design simulation parameters for the developed scheme.

Table 3: GSA Simulation Parameters

GSA Parameters	Value
Maximum-iteration.	50
Dimension of problem	4
Velocity	Clock
Number of agents	50
Acceleration.	Gateway node flag
Mass. Ma=Mp=Mi=M	Time master node flag

Table 4: Design Parameters for the developed scheme

Designs parameters	**Ranges**
Uplink frequency	[5.0 7.0] GHz
Downlink frequency	[2.04 4.4] GHz
Earth transmit Power	[26 30] dBW
Satellite transmit Power	[8 11] dBW
Earth transmit and receive antenna efficiency	70%
Earth transmit and receive antenna diameter	2.4m

2.2.4 BER Estimation

In order to improve the data transmission performance of the communication link at each satellite pass, the BER of the communication link was calculated in terms of E_b/N_0 with BER_{th} value of 10^{-5}. The objective of the developed algorithm is to maintain this BER threshold value. During the simulation process it was noticed that both BPSK and QPSK meet the BER requirement for the entire pass duration; meanwhile, 8PSK, 16QAM, and 64QAM all achieve

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the threshold for shorter periods of time. This result is to be expected as the higher order modulation schemes require stronger symbol energy to achieve the same BER. Table 5 outlines the thresholds for switching up and down a particular modulation type in the ACM scheme. As BPSK and 64QAM are the lowest and highest achievable modulation schemes, they do not have a switch-down or switch-up threshold, respectively.

Table 5: E_b/N_0 Upper and Lower Boundaries for 10^{-5} BER

Modulation Schemes	Down	Up
BPSK	N/A	13.6 dB
QPSK	12.6 dB	18.8 dB
8PSK	17.8 dB	20.5 dB
16QAM	19.5 dB	26.6 dB
64QAM	25.6 dB	N/A

2.2.5 Normalized EVM_{th} using BER_{th}.

In the EVM calculation during the ACM process, the developed scheme adopted the normalized EVM formula. The EVM bound for modulation switching scenario is given in Table 5. The normalized EVM estimated was performed on each symbol of the transmitted signal, using the symbol closest in distance as the ideal symbol. A moving average of EVM calculations over 1000 symbols is used during simulation to estimate the EVM value. When the average EVM (rms) shifts into a different modulation region, the receiver switch modes. The initial receiver state is always BPSK, as it is the most robust to degrade channels out of the modulation scheme options used in this algorithm. Once EVM estimation has been determined, the receiver either maintains the status of BPSK or increases modulation rate/scheme, depending on the result of the estimation.

2.2.6 Selected Modulation Scheme for Symbol Modulation

The effective performance of the communication link ensure that correct information gets to the receiver at the receiving end. After the link budget process, the ACM scheme estimates the BER of the signal and selects an appropriate modulation scheme that reduces the satellite communications link impairments to achieve improved throughput of the network.

3.0 Result and Discussion

The results obtained from the simulation carried are presented and discussed below.

3.1 Free Space Loss and Elevation Analysis of Longest Access

The results show that the shortest pass is found to be 0.23 minutes while the longest access is approximately 10.8 minutes. From Figure 2, it is observed that the position of the ISS during its orbit and the elevation angle affect the length of the available communication time with the GRC ground station. It is also observed that the iACM scheme relatively shows a lower free space loss value as the elevation angle increases. This implies that the developed algorithm has a higher available duration for communication purpose.

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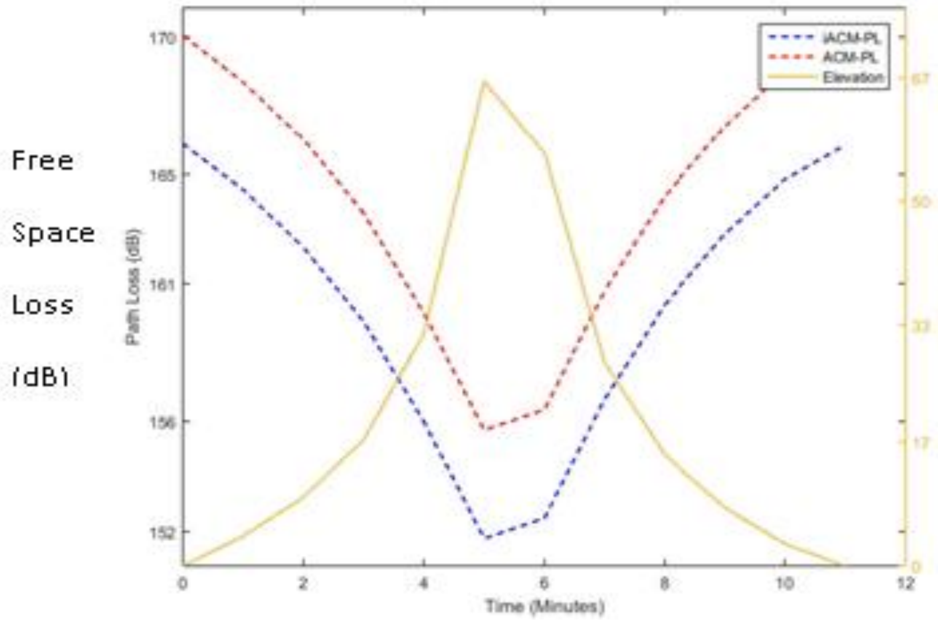

Figure 2: ACM and iACM Scheme for Free space loss and Elevation with 207 accesses

The reduction in free space loss in the developed scheme is due to the consideration of *G/T* which indicates the quality of receiving earth satellite. The iACM scheme optimized the parameters of the transmitter to cater for the possible link losses during transmission process to the receiver.

Table 6: Percentage Improvement of Free space loss against access Time

Metric	ACM	iACM	Percentage Improvement
$E_s/N_{o\ (dB)}$	23	28.23	22.74%

When BER and Energy to Noise Ratio are plotted against access time, the percentage decrease in the free space loss for both schemes is shown in Figure 2. The loss was computed in Table 6. These are achieved when the angle of elevation is considered.

3.2 BER and Energy to Noise Ratio at Various Periods of Time

Figure 3 is a plot showing the relationship between BER , *Es/No* and access time at various period of time. The EVM-based algorithm conservatively switches between various modulation schemes, ensuring that the BER was maintained below the 10^{-5}threshold before switching modes. From Figure 3, it was observed that the iACM shows a lower BER and a higher *Es/No* as compared to the ACM scheme at a BER threshold of 10^{-5}. This is due to the ability of the improved scheme to efficiently find an efficient modulation type to aid better data transmission in the presence of channel impairments. The effect of a reduced BER translates to a better throughput of the network.

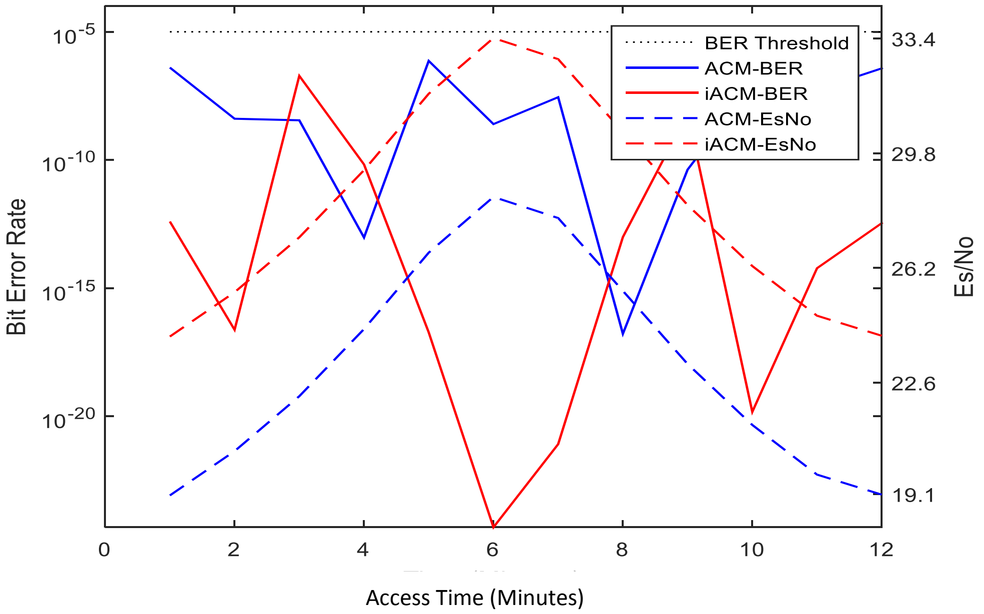

Figure 3: BER/E_s/N_o for ACM and iACM

4.0 Conclusion

In this study, an iACM scheme for mitigating earth-to-space propagation effects using GSA for link budgeting and normalized EVM at the receiving satellite station that mitigates the effect of path loss and increase data throughput has been achieved. This scheme improves the existing ACM scheme. The improved scheme focuses on improving satellite data throughput and mitigating the effects of path loss on the communications link. This iACM scheme provides a more accurate EVM value during data transmission at the satellite station which serves as a base for the selection of an efficient modulation scheme. The link budget analysis was carried out using the GSA algorithm which considered two figures of merit. The best case and worst-case link budget analyses are carried out. The improved ACM shows better improvement in terms of network throughput and reduced path loss effect than the ACM scheme.

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