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How Combining Automatic Repeat Request and Forward Error Correction Improves Throughput in Low Earth Orbit Satellite Communications

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Abstract

This paper investigates the throughput performance of Automatic Repeat Request (ARQ) and hybrid Automatic Repeat Request–Forward Error Correction (ARQ+FEC) schemes in a Rayleigh fading environment, representative of Low Earth Orbit (LEO) satellite communications. While traditional FEC-only schemes have been favored in high-latency systems, the short round-trip delays in LEO enable the practical use of ARQ. However, it remains unclear whether typical Bit Error Rate (BER) levels in LEO channels—caused by fading and path loss—fall within the correction capabilities of ARQ+FEC configurations. This study fills that gap by analytically modeling and simulating the performance of BCH-coded FEC integrated with Selective Repeat ARQ. At an $\frac{E_b}{N_0}$ of 20 dB, the hybrid system reduces the average transmissions per block from 1.5 (ARQ-only) to 1.2, and improves normalized throughput from 0.67 to 0.79—an 18% gain. These findings demonstrate that moderate error correction levels are well-suited to the BER ranges typically observed in LEO, confirming the hybrid scheme's capability for improving throughput and reliability in next-generation satellite systems.

Keywords

Automatic Repeat Request
Forward Error Correction
Low Earth Orbit
Rayleigh Fading
Throughput

1. Introduction

The reliable transmission of data over noisy and fading channels is of paramount importance in modern digital communication systems. Traditionally, satellite communications have relied on forward error correction (FEC) techniques—often employing block codes, such as Bose–Chaudhuri–Hocquenghem (BCH) codes—to correct errors without the need for retransmissions, a critical consideration for high-latency geostationary links [1, 2]. However, the advent of low Earth orbit (LEO) satellite constellations has introduced a new paradigm characterized by significantly reduced propagation delays. These lower delays now permit effective integration of automatic repeat request (ARQ) protocols with FEC, potentially enhancing both the Bit Error Rate (BER) and overall throughput.

Another technique used to enhance BER and throughput is diversity, mitigating the harmful effects of multipath fading. Among the various approaches, selection combining is widely favored for its simplicity and ease of implementation [3]. When combined with error control strategies, this technique can further improve signal reliability under fading conditions. Although traditional satellite systems have predominantly employed FEC-only schemes to accommodate the latency constraints of high-orbit systems, the low-latency environment of LEO satellites permits the exploration of hybrid error control strategies that leverage ARQ protocols [2]. In particular, Selective Repeat ARQ is especially suited to LEO scenarios, as it minimizes unnecessary retransmissions by selectively requesting the retransmission of only those packets that are erroneous, thereby optimizing the overall system efficiency [4-6].

Despite extensive research on FEC and diversity techniques in both terrestrial and satellite communications, the potential benefits of integrating ARQ with FEC in LEO systems remain underexplored. Existing literature has largely focused on FEC-only schemes, driven by the latency constraints of traditional satellite environments. The current low-latency nature of LEO systems creates an opportunity to implement and assess the performance of a hybrid ARQ–FEC approach. Moreover, the effect of error correction granularity—such as the differences in performance when employing BCH codes capable of correcting one error versus two errors—has not been thoroughly quantified in the context of a hybrid ARQ–FEC scheme. Recent studies [7, 8] have explored adaptive hybrid ARQ strategies in satellite and mobile communication scenarios; however, their performance implications for LEO-specific links remain insufficiently quantified.

FEC and ARQ protocols each offer distinct advantages in error control. FEC enables error detection and correction at the receiver without requiring retransmissions, making it well-suited for high-latency links, such as deep-space communications where round-trip delay is prohibitive [9, 11]. However, this comes at the cost of increased bandwidth consumption and reduced effective data rates due to added redundancy [11]. In contrast, ARQ improves reliability by selectively retransmitting erroneous blocks, which can be more efficient in low-latency environments [12]. The main trade-off lies in balancing redundancy, reliability, and latency. In LEO satellite systems—characterized by short propagation delays—the use of ARQ becomes viable, enabling hybrid ARQ+FEC strategies that leverage the benefits of both approaches. These hybrid schemes are particularly promising for enhancing throughput and robustness under fading conditions while maintaining spectral efficiency [13, 14]. Figure 1 illustrates the structural difference between a traditional FEC-only communication system and a hybrid ARQ+FEC system. In the FEC-only configuration (Figure 1a), error correction is performed solely through a one-way application of redundancy bits added at the transmitter side, with no mechanism for feedback or retransmission. This approach is typically favored in high-latency environments like GEO satellite links, where retransmission delays would be prohibitive.

In contrast, the ARQ+FEC system architecture (Figure 1b) introduces a feedback path that allows the receiver to request retransmission of corrupted packets. This configuration leverages the low round-trip time of LEO satellites, enabling the use of less complex or lower-redundancy FEC codes (e.g., BCH) while maintaining robust error correction via ARQ. This architecture not only reduces the overhead introduced by heavy FEC but also improves the overall throughput by selectively retransmitting only erroneous data.

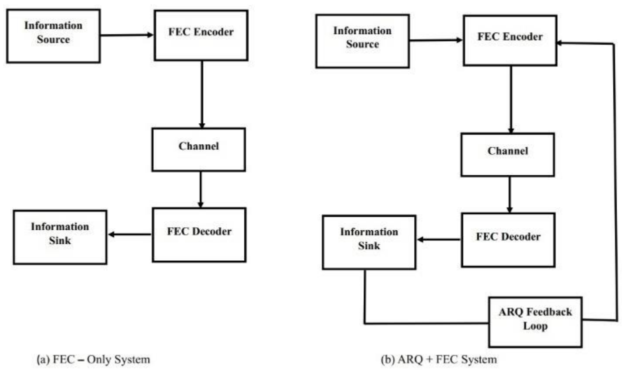

Figure 1. Comparison of FEC-only and ARQ+FEC system architectures.

In both configurations shown in Figure 1, the forward channel between the LEO satellite and ground station is modeled using Rayleigh fading to reflect the multipath effects and rapid Doppler shifts that characterize LEO passes over varied terrain and urban environments. This choice enables a realistic analysis of signal impairment and error resilience under typical LEO channel dynamics.

This study investigates the impact of combining ARQ and FEC on the BER and throughput performance in LEO satellite communication systems, with a specific focus on comparing a traditional FEC-only scheme to a hybrid ARQ–FEC approach. In the ARQ-only scenario, a Selective Repeat ARQ protocol is employed whereas in the hybrid scenario, ARQ is combined with BCH-based FEC, with performance evaluated under various error correction capabilities and different configurations of diversity links. Analytical models are developed to derive theoretical expressions for BER and throughput, and these models are validated through simulation studies that replicate realistic LEO channel conditions.

While ARQ and FEC have been extensively studied in terrestrial and generic wireless contexts, their combined performance in the unique operating conditions of LEO satellite systems remains underexplored. The relatively short propagation delays in LEO make ARQ mechanisms more feasible compared to traditional satellite environments, opening up new opportunities for hybrid error control strategies. However, it is essential to verify whether the bit error rates typically encountered in LEO channels—affected by Rayleigh fading and path loss—fall within the practical correction range of moderate FEC schemes. Figure 2 provides a reference framework to assess this question by comparing expected BER levels in LEO with the correction capabilities of BCH codes for various error thresholds. This contextual justification underscores the need to quantify ARQ+FEC performance specifically for LEO satellite communications, as attempted in this study.

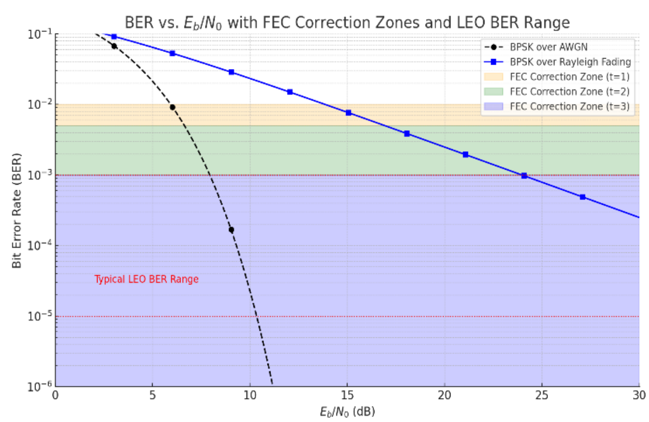

Figure 2. BER performance under AWGN and Rayleigh fading with FEC correction zones relevant to LEO satellite conditions.

The integrated analysis presented herein is expected to provide valuable insights into the performance enhancements achievable through the hybrid ARQ–FEC approach compared to conventional FEC-only implementations. The findings of this study aim to inform the design of next-generation error control protocols that optimize both reliability and throughput in LEO satellite communications.

2. Method

This study employs a combined analytical and simulation-based approach to evaluate the performance of hybrid ARQ–FEC schemes LEO satellite communication systems. The overall system model consists of a transmitter that encodes data using FEC based on Bose–Chaudhuri–Hocquenghem BCH block codes and, when applicable, an automatic repeat request (ARQ) protocol operating in Selective Repeat mode. At the receiver, selection combining diversity is implemented to mitigate the effects of multipath fading. Two main scenarios are considered: an ARQ-only configuration and a hybrid ARQ–FEC configuration.

In both configurations, digital data is modulated using a conventional modulation scheme and transmitted over a channel modeled to reflect realistic LEO satellite conditions. The channel model incorporates fading to capture the rapid time variations typical of LEO environments. In order to isolate the effects of error control, the simulation framework assumes that the underlying modulation is sufficiently robust, while the primary focus remains on analyzing BER and throughput performance.

Analytical expressions for BER and throughput serve as the foundation for the performance evaluation. For the ARQ-only scenario, the effective error probability is modelled based on the performance of the Selective Repeat ARQ (SR-ARQ) protocol. The SR-ARQ scheme is chosen over Stop-and-Wait and Go-Back-N variants due to its superior efficiency in low-latency environments, as it minimizes unnecessary retransmissions by selectively requesting only those packets that contain errors [4, 13].

The performance of the digital communication system is evaluated using both analytical derivations and simulation experiments. The key performance metrics are the BER and the effective (normalized) throughput for systems implementing ARQ with and without FEC. For the hybrid ARQ–FEC configuration, the FEC module employs BCH codes with different error correction capabilities. The effective error probability in this configuration is derived by combining the inherent error correction capability of the BCH code with the retransmission mechanism of the FECFEC protocol. This integration is modeled by modifying the BER expressions to account for the reduction in errors provided by FEC, while incorporating the probability of successful retransmission by ARQ.

Selection combining diversity is incorporated in both scenarios to further improve the reliability of the received signal. This technique selects the branch with the highest Bit-energy to Noise Ratio $\frac{E_b}{N_0}$ among multiple diversity branches. In the present analysis, configurations with one and two diversity links are simulated. The impact of diversity is incorporated into the analytical models by adjusting the effective $\frac{E_b}{N_0}$, which in turn influences the BER calculations.

Simulation studies are performed using a suitable simulation platform (e.g., MATLAB/Simulink) to validate the theoretical expressions. The simulations replicate LEO satellite channel conditions over an $\frac{E_b}{N_0}$ range representative of practical scenarios. Key simulation parameters include the $\frac{E_b}{N_0}$ range, fading statistics, Doppler shift characteristics, block length of the BCH code, and the number of diversity branches. For each configuration—ARQ-only and hybrid ARQ–FEC—the BER and throughput are measured and compared. The trade-offs between increased error correction capability (e.g., correcting one versus two errors) and the associated complexity, as well as the benefits of additional diversity branches, are quantified through these simulations.

The combined analytical and simulation-based evaluation facilitates a comprehensive comparison between the ARQ-only and hybrid ARQ–FEC approaches, with performance metrics focused on BER and throughput. This methodology aims to determine whether the integration of ARQ with FEC, supported by selection combining diversity, offers a significant performance advantage over traditional FEC-only schemes in the context of LEO satellite communications.

In this section, the system model is described, key equations derived, and simulation approach outlined. The system employs Binary Phase Shift Keying (BPSK) modulation. BPSK is chosen because of its robustness and simplicity; it transmits one bit per symbol and exhibits well-established analytical performance in additive white Gaussian noise (AWGN) channels. Data is organized into blocks of n bits (for example, n=127 bits). Two channel models are considered: AWGN only (no fading) and AWGN combined with Rayleigh fading.

For BPSK transmitted over an AWGN channel, the theoretical bit error rate is given by

$$BER_{AWGN} = Q\left(\sqrt{2\gamma}\right) \tag{1}$$

where $\gamma = \frac{E_b}{N_0}$ is the bit energy to noise ratio in the linear scale.

While $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} \exp\left(-\frac{t^2}{2}\right) dt$ where $Q(.)$ is a Gaussian Q-function [9].

In a Rayleigh fading channel, the instantaneous SNR γ (which is the same as bit-energy-to-noise ratio for BPSK with bit rate equals to channel bandwidth) is a random variable with an exponential probability density function (PDF) [3]:

$$f_\gamma(\gamma) = \frac{1}{\bar{\gamma}} \exp\left(-\frac{\gamma}{\bar{\gamma}}\right) \tag{2}$$

where γ is the average SNR (or average $\frac{E_b}{N_0}$).

The average BER is then obtained by averaging the AWGN BER over this distribution to obtain:

$$\mathrm{BER}_{\mathrm{Rayleigh}} = \int_0^{\infty} Q\left(\sqrt{2\gamma}\right) \frac{1}{\bar{\gamma}} \exp\left(-\frac{\gamma}{\bar{\gamma}}\right) d\gamma. \tag{3}$$

A closed-form expression for the above integral is

$$\mathrm{BER}_{\mathrm{Rayleigh}} = \frac{1}{2}\left(1 - \sqrt{\frac{\bar{\gamma}}{1+\bar{\gamma}}}\right). \tag{4}$$

When selection combining diversity with L independent branches is employed, the effective SNR is the maximum of the SNRs across all branches. The cumulative distribution function (CDF) of the maximum SNR is

$$F_{\gamma_{\max}}(\gamma) = \left[1 - \exp\left(-\frac{\gamma}{\bar{\gamma}}\right)\right]^L. \tag{5}$$

Differentiating (5) with respect to γ yields the probability density function (PDF)

$$f_{\gamma_{\max}}(\gamma) = L \cdot \frac{1}{\bar{\gamma}} \exp\left(-\frac{\gamma}{\bar{\gamma}}\right)\left[1 - \exp\left(-\frac{\gamma}{\bar{\gamma}}\right)\right]^{L-1} \tag{6}$$

Thus, the average BER with diversity is

$$\mathrm{BER}_{\mathrm{diversity}} = \int_0^{\infty} Q\left(\sqrt{2\gamma}\right) f_{\gamma_{\max}}(\gamma) d\gamma.. \tag{7}$$

For $L = 1$, (7) reduces to the Rayleigh BER in (3).

2.1 Throughput Calculation

In an ARQ system without FEC, a block of n bits is retransmitted until it is received error-free. Let P_{success} denotes the probability that a block is received without error. Then, the average number of transmissions per block becomes

$$N_{\text{tx}} = \frac{1}{P_{\text{success}}}. \tag{8}$$

The normalized throughput (relative to a raw rate of 1 bit per second) is therefore

$$T_{\text{eff}} = \frac{1}{N_{\text{tx}}} = P_{\text{success}}. \tag{9}$$

For an AWGN channel, if the BER is BER_{AWGN} then for a block of n bits,

$$P_{\text{success, AWGN}} = (1 - BER_{\text{AWGN}})^n. \tag{10}$$

When FEC is incorporated using BCH codes, redundancy is introduced, reducing the effective data rate. The effective coding rate is approximated as [1]:

$$r_c = \frac{n - 7t}{n} \tag{11}$$

where t is the number of errors the code can correct. In an ARQ system with FEC, if the number of bit errors in a block is less than or equal to t, the FEC decoder corrects the errors and the block is considered error-free; otherwise, the block is retransmitted. The probability of successful decoding with FEC is as follows [10]:

$$P_{\text{success}}^{\text{FEC}} = \sum_{k=0}^{t} \binom{n}{k} p_b^k (1 - p_b)^{n-k} \tag{12}$$

where p_b is the bit error probability (e.g., BER_{AWGN} or $\text{BER}_{\text{Rayleigh}}$). The average number of transmissions required per block is given as

$$N_{\text{tx}}^{\text{FEC}} = \frac{1}{P_{\text{success}}^{\text{FEC}}} \tag{13}$$

Thus, the normalized throughput with FEC is

$$T_{\text{eff}} = \frac{r_c}{N_{\text{tx}}^{\text{FEC}}} = r_c \cdot P_{\text{success}}^{\text{FEC}} \tag{14}$$

2.2 Throughput under Rayleigh Fading

In Rayleigh fading scenario, the BER is higher than in an AWGN channel, thereby reducing the block success probability. For an ARQ system without FEC in a Rayleigh fading channel,

$$P_{\text{success, Rayleigh}} = \left(1 - BER_{\text{Rayleigh}}\right)^n \tag{15}$$

The normalized throughput is then given as

$$T_{\text{eff, Rayleigh}} = \left(1 - BER_{\text{Rayleigh}}\right)^n \tag{16}$$

For an ARQ system with FEC under Rayleigh fading, the throughput is

$$T_{\text{eff}} = r_c \cdot P_{\text{success}}^{\text{FEC, Rayleigh}} \tag{17}$$

With $P_{\text{success}}^{\text{FEC, Rayleigh}}$ calculated using the same method as in (12) but with the BER derived from the Rayleigh channel.

3. Results

The performance of the communication system was evaluated through MATLAB simulations, which examined both the BER and the normalized throughput as functions of $\frac{E_b}{N_0}$ over a range from 0–30 dB. The BER simulations were carried out for a BPSK system using blocks of 127 bits, and the results were averaged over a large number of blocks to ensure high statistical accuracy. The simulated scenarios included an AWGN-only channel (without fading or FEC), a channel with both AWGN and Rayleigh fading (without FEC), and channels with AWGN, Rayleigh fading, and the application of BCH forward error correction capable of correcting up to 1, 2, or 3 errors per block

Figure 3 presents the BER performance for a BPSK system (evaluated with a block length of n=127 bits) under different channel conditions and FEC configurations. The curve labeled “AWGN Only” (black circles) exhibits the best performance, with a steep exponential decay in BER as $\frac{E_b}{N_0}$ increases — confirming the expected behavior in a non-fading, noise-limited environment. As expected, the AWGN-only case exhibited the lowest BER, with the error rate decreasing steeply as $\frac{E_b}{N_0}$ increased in accordance with equation (7). The blue squares represent performance under

Rayleigh fading without any FEC. As shown, BER remains relatively high even at as $\frac{E_b}{N_0}$ >20 dB, illustrating the severe impact of multipath fading on signal quality.

Introducing BCH-based FEC improves BER in Rayleigh channels significantly. The red triangles (t =1), green diamonds (t =2), and magenta down-triangles (t=3) demonstrate progressive BER reductions as the correction capability increases. At lower $\frac{E_b}{N_0}$ values (below 15 dB), higher error correction capabilities offer a marked improvement. However, beyond 20 dB, the performance gap between t=2 *and* t=3 narrows, reflecting diminishing returns due to redundancy overhead.

Notably, the t=1 configuration achieves a substantial BER reduction while maintaining a high coding rate (~0.945), making it a practical trade-off point for LEO satellite systems, where both error resilience and throughput are critical. The Figure validates that even minimal error correction capability yields significant benefits in fading environments.

Figure 4 illustrates the normalized throughput performance across varying $\frac{E_b}{N_0}$ levels for different system configurations. In the AWGN-only case, the throughput remains high across the entire SNR range due to the minimal need for retransmissions in a noise-limited, non-fading environment. However, in the presence of Rayleigh fading without any FEC (blue curve), throughput drops significantly — especially at low $\frac{E_b}{N_0}$ values — due to frequent retransmissions resulting from burst errors and signal degradation. The application of FEC mitigates this effect by enabling the correction of bit errors at the receiver, thus reducing retransmissions. As the FEC correction capability increases (from t=1 to t=3), a general improvement in throughput at low-to-moderate $\frac{E_b}{N_0}$ levels can be observed. Among these, the configuration with t = 1 (red curve) delivers the highest throughput at high values of $\frac{E_b}{N_0}$ because it retains a high coding rate (~0.945) while still correcting a meaningful number of errors.

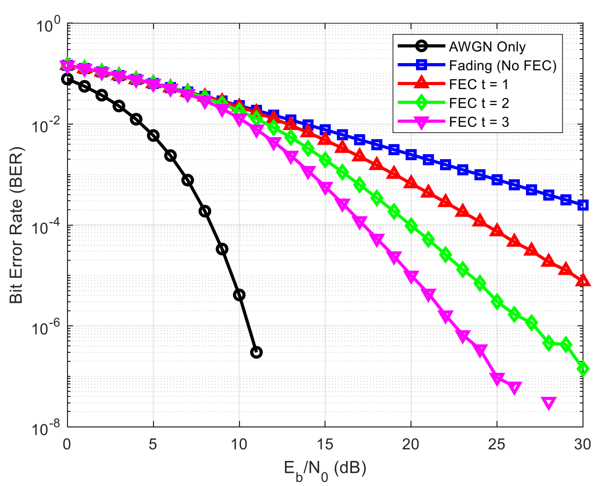

Figure 3. Probability-of-error perfomance.

Conversely, although t = 2 and t = 3 (green and magenta curves, respectively) show better resilience at lower values of $\frac{E_b}{N_0}$, their lower effective data rates—due to increased redundancy—limit their throughput at high $\frac{E_b}{N_0}$ values. This observation illustrates a key trade-off: higher error correction improves reliability in noisy environments but can degrade throughput in clean channels due to coding overhead. Figure 2 confirms that moderate FEC levels, particularly t=1, strike an optimal balance between throughput and reliability for LEO satellite links, especially under fluctuating channel conditions.

Figure 5 depicts the average number of transmissions required per data block as a function of $\frac{E_b}{N_0}$ for three scenarios: AWGN-only, Rayleigh fading without FEC, and Rayleigh fading with BCH-based FEC correcting one (t =1), two (t=2), and three (t=3) errors. Under AWGN-only conditions (black curve), the average number of transmissions remains close to one across all $\frac{E_b}{N_0}$ values, indicating that most blocks are successfully

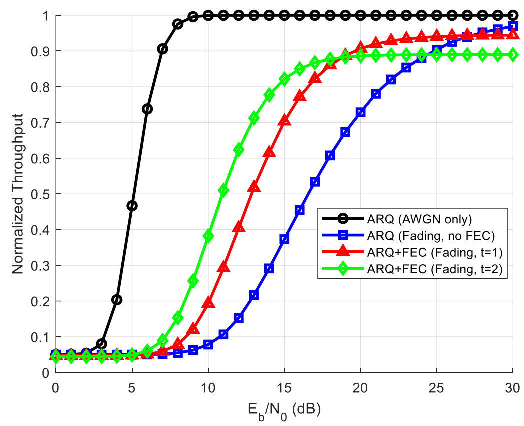

Figure 4. Normalized throughput under different channel conditions.

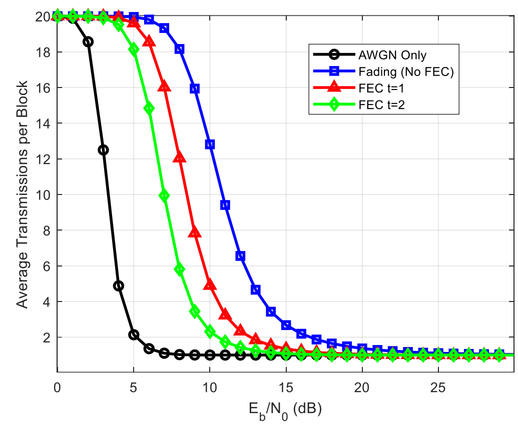

Figure 5. Average transmissions for different ARQ Scenarios (L = 1, Max Tx = 20).

received on the first attempt due to the absence of severe impairments. In contrast, the fading-only scenario (blue curve) shows a sharp increase in average retransmissions, particularly at low $\frac{E_b}{N_0}$. This highlights the significant degradation caused by Rayleigh fading, which increases the probability of block errors and thus triggers more retransmission requests.

The application of FEC dramatically reduces the number of retransmissions. At t = 1 (red curve), the retransmissions drop noticeably compared to the no-FEC case, especially above 10 dB. As the correction capability increases to t = 2 and t = 3 (green and magenta curves), further reductions are observed at lower $\frac{E_b}{N_0}$ values. However, at higher $\frac{E_b}{N_0}$ values, the benefit of correcting more than one error diminishes, and the curves tend to converge. This behaviour reinforces the idea that while stronger FEC improves error resilience at low $\frac{E_b}{N_0}$, it offers limited advantages when the channel is already reliable. Therefore, employing a moderate FEC level (t=1) provides substantial retransmission savings while maintaining higher throughput, making it an efficient choice for LEO satellite communication systems.

The simulation results demonstrate a clear trade-off between error correction and throughput. The AWGN-only channel consistently delivers the best performance in terms of both BER and throughput. However, under realistic fading conditions, the use of FEC in an ARQ system is essential for maintaining reliable communication. Although stronger FEC (with a higher error correction capability) improves the BER at low-to-moderate $\frac{E_b}{N_0}$ levels, the associated reduction in coding rate can limit the throughput at higher $\frac{E_b}{N_0}$ values. This balance is especially critical in LEO satellite communications, where low latency allows ARQ mechanisms to be effective. In such systems, the combined ARQ+FEC approach, particularly with a moderate FEC configuration (e.g., correcting one error per block), can significantly enhance throughput by reducing the frequency of retransmissions while preserving a high effective data rate.

4. Discussions

This study aimed to evaluate the performance of ARQ-based systems with and without FEC in digital communication systems, with a particular focus on applications in satellite communications. The simulation results reveal several important findings regarding both the BER and the normalized throughput under different channel conditions, namely AWGN and Rayleigh fading, and across varying FEC correction capabilities.

The integration of BCH-based FEC with ARQ dramatically improves error performance in fading channels by correcting errors within each block before a retransmission is needed. Notably, the results indicate that FEC capable of correcting one error per block (with an effective coding rate of approximately 0.945) provides a substantial reduction in BER, particularly at moderate $\frac{E_b}{N_0}$ levels, and it yields the highest throughput at high $\frac{E_b}{N_0}$ values. Although increasing the correction capability to $t = 1$ and $t = 3$ further reduces the error probability at lower $\frac{E_b}{N_0}$, the associated reduction in the coding rate (to about 0.890 and 0.835, respectively) results in diminishing throughput gains.

LEO satellites typically operate at altitudes ranging from 500 km to 2,000 km above the Earth's surface. At these distances, the free-space path loss is significantly lower than in geostationary systems, and the one-way propagation delay remains below 10 ms, making ARQ mechanisms viable for real-time error control [15, 16]. Assuming a carrier frequency in the X-band (e.g., 8 GHz) and typical transmit power and antenna gains, the resulting received $\frac{E_b}{N_0}$, under clear-sky conditions often falls within the range of 0 dB to 25 dB for ground stations equipped with modest aperture antennas [1]. In such environments, BER under Rayleigh fading has been shown to vary between 10^{-2} to 10^{-6} depending on modulation, coding, and diversity order (Figure 2).

The findings in this study demonstrate that when using BCH-coded FEC with error correction capabilities of one or two bits per block *(t* = 1 *or t* = 2*)*, the BER can be effectively suppressed to acceptable levels even under fading conditions, while maintaining high throughput. Importantly, the observed improvements in throughput and reduction in retransmissions fall well within this realistic $\frac{E_b}{N_0}$/BER operating range for LEO links. This confirms that the ARQ+FEC configurations analyzed are not only theoretically sound but also practically aligned with the channel impairments encountered in modern LEO satellite deployments. As such, this work quantifies and validates the applicability of hybrid ARQ+FEC schemes specifically for LEO systems—filling a gap left unaddressed by prior generalized or terrestrial-focused studies.

Furthermore, the trade-off between error correction and effective data rate highlighted in the results underscores the need for careful optimization of FEC parameters in satellite systems. For instance, while stronger FEC can significantly lower the error probability at low $\frac{E_b}{N_0}$ the loss in coding rate can undermine throughput when channel conditions are favorable. Hence, a moderate FEC configuration that corrects one error per block appears to strike the best balance for LEO scenarios, maximizing throughput without sacrificing reliability.

Hofmann [15] discussed adaptive ARQ+FEC schemes, introducing dynamic control mechanisms in multipoint communication environments. In contrast to proposing a new adaptive scheme, this study focuses on quantifying the performance improvements achievable by applying a standard ARQ+FEC combination in LEO satellite systems. Given the reduced propagation delays in LEO, ARQ becomes more feasible than in traditional high-latency satellite scenarios. This analysis provides new insight by demonstrating, through both analytical modeling and simulations under Rayleigh fading conditions, how hybrid ARQ+FEC can significantly enhance throughput. Such quantitative evaluation under LEO-specific constraints has not been adequately explored in prior literature.

Emerging directions in this domain include exploration of intelligent ARQ+FEC systems that dynamically respond to varying channel conditions. These systems could leverage real-time feedback or predictive models to optimize the trade-off between redundancy and throughput. Furthermore, further studies could explore the performance of higher-order modulation schemes in conjunction with advanced FEC codes under more realistic channel models that account for channel memory, interference, and non-idealities in satellite links.

5. Conclusion

This study shows that combining ARQ with FEC significantly improves both error performance and throughput in digital communication systems under fading conditions, such as those experienced in LEO satellite communications. The simulations reveal that while an AWGN-only channel naturally performs best, the presence of Rayleigh fading degrades performance, making FEC essential to reduce the number of retransmissions. In particular, a FEC scheme capable of correcting one error per block strikes the best balance between reliability and data rate, achieving higher throughput at elevated $\frac{E_b}{N_0}$ levels. Future research should focus on developing adaptive ARQ+FEC schemes that adjust error correction based on real-time channel conditions, exploring higher-order modulation and more complex channel models, and examining the impact of different retransmission limits, all of which will help advance the design of robust satellite communication systems.

CONTRIBUTIONS OF CO-AUTHORS

Moses I. Mchome [ORCID: 0000-0003-2492-6011] Conceived the idea and wrote the paper

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