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Comparative Performance Analysis of Forward Error Correction Schemes in AX.25-Based APRS Communication Systems with AFSK Modulation using GNU Radio Simulation

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ABSTRACT: This paper presents a comparative analysis of Forward Error Correction (FEC) schemes in AX.25-based Automatic Packet Reporting System (APRS) communications using AFSK modulation through GNU Radio simulations. The study evaluates uncoded transmission, Reed–Solomon (255,223), several convolutional code configurations, and concatenated Reed–Solomon + convolutional coding under both Additive White Gaussian Noise (AWGN) and Rayleigh fading channels. Results show that convolutional coding with rate 1/3 and constraint length K=7 achieves the best trade-off, reaching error-free performance at Eb/No = -2.5 dB under AWGN and maintaining robustness under fading. Reed–Solomon codes proved effective for correcting burst errors, while concatenated coding showed strong potential but required interleaving for stable operation. These findings highlight that convolutional coding offers the most practical balance between performance and complexity for real-world APRS and satellite systems, providing insights for future enhancements in robust low-SNR communication links.

ABSTRAK: Kajian ini membentangkan analisis perbandingan bagi skim Forward Error Correction (FEC) dalam komunikasi Automatic Packet Reporting System (APRS) berasaskan protokol AX.25 dengan modulasi AFSK melalui simulasi GNU Radio. Penyelidikan ini menilai penghantaran tanpa FEC, kod Reed–Solomon (255,223), beberapa konfigurasi kod konvolusional, serta kod gabungan Reed–Solomon + konvolusional pada saluran Additive White Gaussian Noise (AWGN) dan Rayleigh fading. Dapatan menunjukkan bahawa kod konvolusional dengan kadar 1/3 dan panjang kekangan K=7 memberikan prestasi terbaik, mencapai komunikasi bebas ralat pada Eb/No = –2.5 dB dalam saluran AWGN dan kekal teguh di bawah keadaan fading. Kod Reed–Solomon berkesan untuk pembetulan ralat berurutan, manakala kod gabungan menunjukkan potensi yang kukuh namun memerlukan interleaver untuk operasi yang stabil. Hasil ini menegaskan bahawa kod konvolusional menawarkan keseimbangan paling praktikal antara prestasi dan kompleksiti bagi aplikasi APRS dan sistem satelit, di samping memberikan panduan untuk pembangunan komunikasi yang lebih boleh dipercayai dalam keadaan SNR yang rendah.

KEYWORDS: *APRS, AX.25, AFSK, Forward Error Correction, Reed–Solomon, Convolutional Codes*

1. INTRODUCTION

The Automatic Packet Reporting System (APRS) is a digital communication system commonly used by amateur radio operators to exchange real-time information, such as location, weather, and short messages [1]. In addition, APRS can be used as a satellite payload for radio communication. The LAPAN-A2 satellite uses APRS and a voice repeater for amateur radio communication missions. Establishing connections between the Indonesian Amateur Radio Community (ORARI) uses amateur radio frequencies for position monitoring, communication from distressed areas, and disaster mitigation through APRS [2]. Satellites have wide coverage that crosses geographic boundaries, provide reliable communication access even in remote areas, and support communication independent of terrestrial infrastructure. [3].

The AX.25 protocol is used for APRS communication. AX.25 is a data-layer protocol designed for amateur packet radio networks. The AX.25 protocol has three types of frames: information frames for data transfer, supervisory frames for transfer acknowledgment, and unnumbered frames for establishing link contact. The use of AX.25 on small satellites can cause significant redundancy and overhead, which is why more efficient protocols with lower redundancy are being developed [4]. As shown in Table 1, an AX.25 frame comprises several main fields, including the flag, address, control, information, and frame check sequence (FCS) fields [5]. AX.25 frames are transmitted using AFSK (Audio Frequency Shift Keying), which is FSK-FM with a 1700 Hz subcarrier and a ±500 Hz deviation on the amateur UHF frequency (437 MHz) [6].

Table 1. Structure of the AX.25 Frame

Flag	Address	Control	Info	FCS	Flag
01111110	112/224 bits	8/16 bits	N*8 bits	16 bits	01111110

The APRS communication system operates with packet data transmitted over amateur VHF/UHF frequencies. Although AX.25, the standard data link layer protocol for amateur packet radio communications, has been shown to produce very low error rates in HF bands [7], when used in the VHF band, communication becomes less reliable and results in a relatively high error rate. This problem directly affects the reliability of data transmission, which is a key performance indicator for APRS utilization. Figure 1 illustrates the overall workflow and infrastructure of APRS. An APRS tracker, or mobile tracker, is a device mounted on a moving object, such as a vehicle or person, that transmits position, message, or status data in an AX.25-based packet format [8].

Forward Error Correction (FEC) techniques are crucial for addressing the problem of noisy channels. FEC is a technique used to detect and correct errors that occur during data transmission by adding redundant data. This is crucial because wireless communication channels are often affected by various noise sources such as white noise, impulse noise, and other interference [9]. With FEC, devices can automatically correct errors, thereby increasing the efficiency and reliability of communication systems without requiring the retransmission of data. Based on the test data, the AX.25 protocol without FEC is susceptible to bit errors and can cause up to 30% packet loss at low signal-to-noise ratio (SNR) conditions (≤10 dB). FEC consists of three types: linear block codes, cyclic codes, and convolutional codes. Linear block codes are a basic form of FEC. This code uses the mathematical structure of vector spaces and subspaces to construct codes that detect and correct errors in transmitted data. Cyclic codes are a subset of linear block codes that have the property that if a codeword is part of the code, then every rotation of the codeword is also part of the code. Cyclic codes include BCH and Reed–Solomon codes [10].

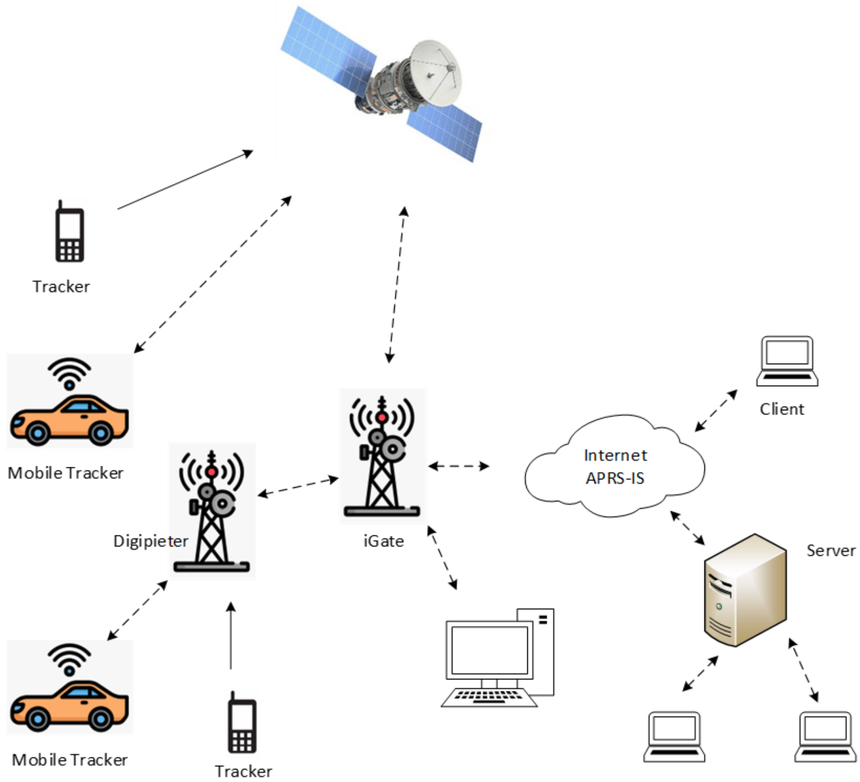

Figure 1. APRS infrastructure

Previous studies generally focused on BCH codes [11] or other more complex FEC codes, such as LDPC and turbo codes [12], but were still limited in their evaluation of Reed–Solomon and convolutional codes in the context of AX.25-based APRS. Furthermore, most performance analyses have been conducted on simple AWGN channels without considering the effects of multipath fading, which is common in satellite communications and dense terrestrial environments. The trade-off among BER performance, complexity, and latency in APRS systems has rarely been discussed. Convolutional codes are widely used in modern communication standards, such as WLAN (802.11ax), LTE, and satellite communications [13]. Meanwhile, Reed-Solomon codes are highly effective block codes for correcting burst errors that often occur in wireless environments [14]. A Reed-Solomon code improvement scheme for distributed storage systems aims to reduce bandwidth requirements. The results show that mathematical optimization can reduce the overhead without compromising the system's error-correcting capabilities of the system [15].

This study aims to evaluate and compare the performance of various Forward Error Correction (FEC) schemes in APRS communication systems based on the AX.25 protocol with Audio Frequency Shift Keying (AFSK) modulation through GNU Radio simulations. The analysis focuses on the Bit Error Rate (BER) performance of several configurations: systems without FEC, systems with Reed-Solomon FEC, systems with convolutional codes in various configurations, and systems with combined coding schemes. The main contribution is the identification of the most practical coding strategy for APRS, demonstrating that a convolutional code with a rate of 1/3 and a constraint length of K=7 offers the best balance of reliability, complexity, and robustness for satellite-based APRS links.

Although several studies have investigated the application of forward error correction in digital communication systems, systematic evaluations of Reed–Solomon and convolutional codes, specifically for AX.25-based APRS links, remain limited, particularly under realistic fading conditions. Moreover, most existing studies focus either on complex modulation schemes or on idealized AWGN channels, leaving a gap in understanding the trade-off between performance, complexity, and robustness when simple, widely adopted modulations, such as AFSK, are employed. This study addresses this gap by providing a comprehensive comparative analysis of practical FEC schemes for APRS in AWGN and Rayleigh-fading environments, drawing on the literature.

2. Communication System Simulation Methodology

The simulation chain was developed in GNU Radio with custom Python blocks for AX.25 encoding/decoding, AFSK modulation/demodulation, and FEC coding. Figure 2 shows the system-level architecture: AX.25 payloads are encoded, optionally protected with FEC, modulated using AFSK, transmitted over AWGN or Rayleigh-fading channels with calibrated noise, and finally demodulated and decoded before the BER evaluation.

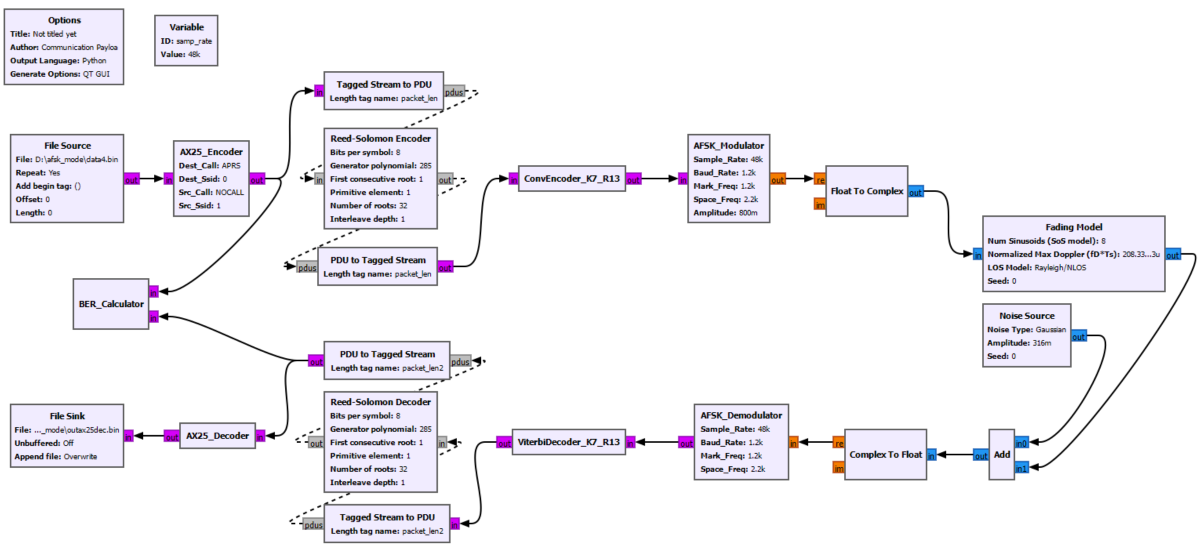

Figure 2. System-Level Simulation Chain with Noise Calibration (σ from Eb/No)

The internal implementation of the AFSK modulator and demodulator follows the standard AX.25 signal processing chain. At the transmitter, NRZI encoding is applied at 1200 bps, followed by tone generation using 1200 Hz (mark) and 2200 Hz (space) sinusoidal oscillators at a sampling rate of 48 kHz. At the receiver, band-pass filtering, tone energy detection, symbol timing recovery, and NRZI decoding are employed to recover the bitstream before AX.25 frame decoding and FEC processing.

This section emphasizes reproducibility and the rationale for parameter selection rather than procedural details. A 16-byte payload was used to represent the typical APRS beacon. AFSK tones at 1200 Hz (mark) and 2200 Hz (space), with a 48 kHz sample rate, were selected in accordance with the AX.25 TNC specification to ensure compatibility with hardware implementations. For block codes, Reed–Solomon (255,223) with a 16-byte correction capability was chosen, reflecting its common use in satellite communications. For convolutional coding, several configurations were tested:

- Rate 1/2, K = 3, generators [7, 5] (octal)
- Rate 1/2, K = 7, generators [133, 171] (octal)
- Rate 1/3, K = 4, generators [17, 15, 13] (octal)
- Rate 1/3, K = 7, generators [133, 171, 165] (octal)

By default, the configuration R=1/2, K=7, (171,133) corresponds to the CCSDS profile [16]. All the convolutional codes were non-systematic with zero-tail termination. Decoding employed a hard-decision Viterbi algorithm with a traceback depth of ≈ 5×(K–1), in accordance with communication standards. Noise injection was applied to the channel block. The noise standard deviation σ was derived from the target Eb/No using the measured signal power Ps at the modulator's output. This ensured consistent Eb/No calibration across all simulations. Further details of the custom Python blocks, including the implementation of the AFSK modulator/demodulator and AX.25 encoder/decoder, are provided in the Supplementary Material.

Table 2. Key Simulation Parameters

Parameter	Value/Range	Rationale
Payload length	16 bytes	Typical APRS beacon
Modulation	AFSK (mark 1200 Hz, space 2200 Hz)	AX.25/TNC standard
Sample rate	48 kHz	Ensures audio/TNC compatibility
Reed–Solomon code	(255,223), t = 16 bytes	Burst error correction
Convolutional codes	R=1/2, K=3 ([7,5]); R=1/2, K=7 ([133,171]); R=1/3, K=4 ([17,15,13]); R=1/3, K=7 ([133,171,165])	Trade-off analysis
Viterbi traceback depth	≈5×(K–1) (e.g., 30–35 for K=7)	Rule of thumb
Channel models	AWGN; Rayleigh fading (fD/Fs = 10^{-5} – 10^{-3})	Ideal and realistic channels
BER targets	Up to 10^{-3} (reported), extended to 10^{-5}	Satellite benchmark

AWGN was injected at the complex baseband after the AFSK modulator and before the demodulator/decoder, via a linear adder. The average signal power *Ps* was measured at the channel input with noise muted, defined as:

$$Ps = \mathbb{E}\{|s[n]|^2\} \tag{1}$$

For a system with a sampling rate *Fs* and bit rate *Rb*, the standard deviation of the Gaussian noise σ corresponding to a target energy-per-bit-to-noise ratio Eb/No is given by

$$\sigma = \sqrt{\frac{P_S F_S}{2R_b 10^{Eb/No/10}}} \tag{2}$$

This expression follows from Eb = *Ps*/*Rb* and *No* = $2\sigma^2$ for complex baseband noise. The computed σ is applied as the amplitude of the Gaussian Noise Source block. For cross-validation, the uncoded AFSK chain was simulated, and the measured BER was compared against the theoretical noncoherent FSK bound.

$$P_b \approx \frac{1}{2} exp\left(-\frac{E_b}{2\,N_o}\right) \tag{3}$$

which provides a practical sanity check to verify the absolute E_b/N_o scaling.

It should be noted that the concatenated Reed–Solomon and convolutional coding scheme implemented in this study does not employ interleaving. Consequently, the observed performance degradation at low Eb/No should not be interpreted as an inherent limitation of concatenated coding itself, but rather as a consequence of the absence of interleaving, which is essential to mitigate burst-error propagation between the inner and outer codes. With appropriate interleaving, more stable performance is expected, particularly in fading channels.

3. Performance Analysis and Simulation Results

3.1. BER Measurement Methodology

Bit Error Rate (BER) was used as the primary metric. Noise was injected at the complex baseband after AFSK modulation, with an amplitude σ calibrated to the target Eb/No. BER calculators were placed before and after the FEC encoder and decoder to capture both the raw and corrected error rates. Both AWGN and Rayleigh-fading channels were simulated to represent ideal multipath conditions for satellite/APRS. In this study, BER was measured at two points: pre-FEC (before the encoder/decoder chain) and post-FEC (after decoding). The reported curves focus on the post-FEC BER, which quantifies the residual error rate after error correction, whereas the pre-FEC BER serves as a baseline to characterize channel impairment.

3.2. Comparative Performance on the AWGN Channel

The representative BER values are summarized in Table 3 for Eb/No points ranging from –4 to +4 dB. The convolutional code with a rate of 1/3 and a constraint length of K=7 shows the best performance, achieving an error-free condition at Eb/No -2.5 dB. Meanwhile, Reed-Solomon is proven effective at correcting burst errors but less efficient in fading conditions. The Reed–Solomon (RS) code is widely used in wireless, satellite, digital video broadcasting (DVB), digital audio broadcasting (DAB), digital subscriber line (DSL), and Ethernet communications because it can correct burst and random errors with high coding gain [17].

Table 3. Summary of BER Performance Across Coding Schemes (AWGN Channel)

Eb/No (dB)	Amp	Without FEC	RS (255, 223)	Convolutional Code R=1/3 K=7	Convolutional Code R=1/3 K=4	Convolutional Code R=1/2 K=3	Convolutional Code R=1/2 K=7	RS + Convo
-4,0	1,121	1,17E-02	1,17E-02	5,36E-03	5,76E-03	9,25E-03	1,66E-02	5,99E-02
-3,5	1,058	8,89E-03	9,01E-03	2,15E-03	3,14E-03	5,66E-03	9,28E-03	0
-3,0	0,999	6,81E-03	6,64E-03	6,37E-04	2,02E-03	4,07E-03	3,41E-03	0
-2,5	0,943	4,80E-03	4,77E-03	0	1,15E-03	2,25E-03	2,86E-03	0
-2,0	0,890	3,28E-03	3,28E-03	0	5,92E-04	7,90E-04	9,31E-04	0
-1,5	0,840	2,27E-03	1,99E-03	0	1,91E-04	1,17E-03	4,52E-04	0
-1,0	0,793	1,39E-03	1,30E-03	0	6,43E-05	3,43E-04	2,04E-04	0
-0,5	0,749	8,90E-04	6,99E-04	0	5,02E-05	0	1,20E-04	0
0,0	0,707	4,08E-04	3,82E-04	0	2,32E-05	0	0	0
0,5	0,668	1,99E-04	1,58E-04	0	0	0	0	0
1,0	0,630	1,31E-04	7,54E-05	0	0	0	0	0
1,5	0,595	6,08E-05	1,84E-05	0	0	0	0	0
2,0	0,562	2,66E-05	6,81E-06	0	0	0	0	0
2,5	0,530	8,22E-06	5,57E-06	0	0	0	0	0
3,0	0,501	4,31E-06	0	0	0	0	0	0
3,5	0,473	0	0	0	0	0	0	0
4,0	0,446	0	0	0	0	0	0	0

The combined scheme (RS + Convolutional) performs well on AWGN channels at moderate Eb/No. However, its instability at low Eb/No is mainly attributed to the absence of an interleaver, which allows burst errors at the output of the inner convolutional decoder to propagate directly into the outer Reed–Solomon (RS) decoder. This behavior should not be regarded as a fundamental weakness of concatenated coding but rather as a limitation of the current implementation. With proper interleaving, improved performance is expected, particularly in fading channels. An interleaver is crucial for improving the iterative decoding performance and reducing the probability of error bursts [18]. The combination of Reed-Solomon and convolutional codes significantly improves BER performance compared with using either code separately [19]. The concatenated code scheme offers an optimal trade-off between complexity, delay, and reliability, making it suitable for communication applications that require high reliability [20].

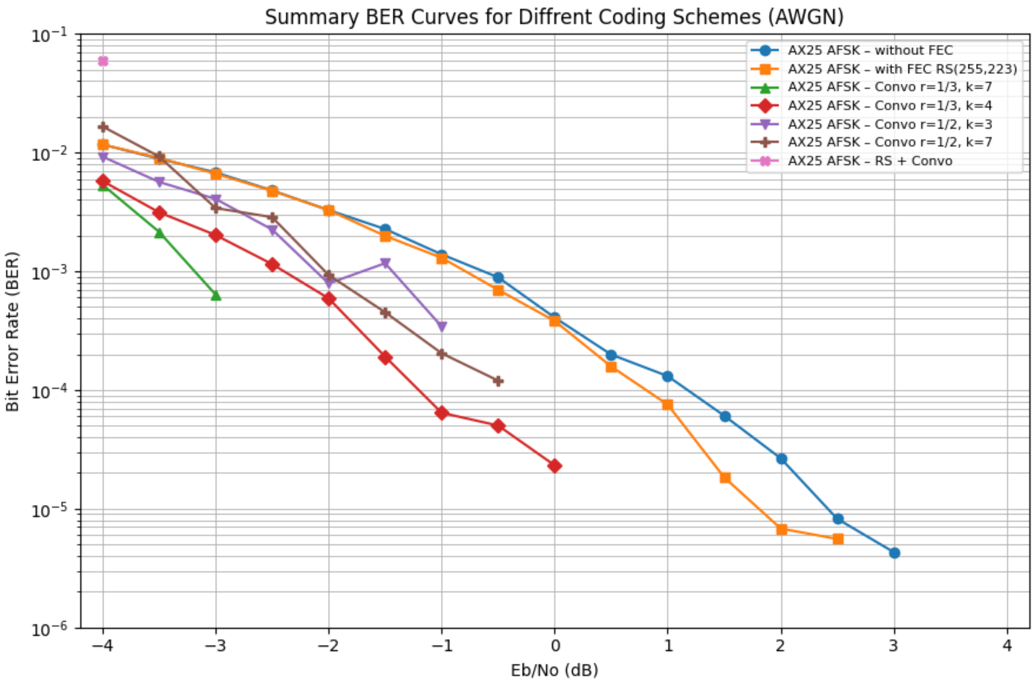

Figure 3. BER vs Eb/No AWGN Channel curve

Figure 3 shows BER curves for different coding schemes under an AWGN channel. The convolutional code R=1/3, K=7 provides the most significant performance improvement, whereas the concatenated (RS+Conv) shows instability at low Eb/No due to the absence of interleaving. It should be noted that the BER performance achieved with AFSK modulation and FEC in this study surpasses the results reported in previous works employing more complex modulation formats [21-22]. In contrast, our results show that convolutional coding (R=1/3, K=7) with AFSK achieves error-free communication at Eb/No ≈ –2.5 dB in the AWGN channel, underscoring the effectiveness of FEC integration even with a relatively simple modulation scheme.

3.3. Performance under Rayleigh Fading

This testing focused on the three most relevant FEC configurations: no FEC, Reed-Solomon FEC (255, 223), and the best convolutional code (rate 1/3, K=7). To simulate the motion conditions, the maximum Doppler value was set based on the vehicle scenario. The data analysis in Table 4 and the curves in Figure 4 show that Rayleigh fading significantly affects the system performance. Compared with testing using AWGN noise alone, the overall BER is much higher at all Eb/No levels, and the curves appear more gradual. Rayleigh fading degrades channel quality relative to AWGN, causing the modulation- or coding-switching

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points to shift to higher SNR values [21]. This confirms that the fading effect causes more significant performance degradation, which cannot be overcome by simply increasing the signal power.

The convolutional code with a rate of 1/3 and K=7 shows the best performance with the lowest BER across the entire Eb/No range. These results demonstrate that robust error-correction mechanisms, such as those implemented by the Viterbi decoder, are more effective at addressing errors caused by fading. This configuration is the only one capable of achieving zero BER at Eb/No of 35 dB and above. The Reed-Solomon scheme also shows a clear performance improvement over the system without FEC, particularly at higher Eb/No values. However, in fading scenarios, its performance is still not as strong as that of the convolutional code.

Table 4. BER Performance Data on the Rayleigh Fading Channel

Eb/No (dB)	Amp	Without FEC	RS (255, 223)	CC (R=1/3, K=7)
-3	0,999	2,97E-02	3,00E-02	3,13E-02
-1	0,793	2,48E-02	2,48E-02	2,54E-02
1	0,630	2,05E-02	2,03E-02	1,66E-02
3	0,501	1,68E-02	1,74E-02	1,31E-02
5	0,398	1,34E-02	1,36E-02	9,21E-03
7	0,316	1,16E-02	1,11E-02	6,32E-03
9	0,251	8,90E-03	9,07E-03	5,02E-03
11	0,199	7,32E-03	7,25E-03	2,61E-03
13	0,158	6,24E-03	5,93E-03	2,48E-03
15	0,126	5,06E-03	4,96E-03	1,46E-03
17	0,100	4,31E-03	4,20E-03	1,25E-03
19	0,079	3,66E-03	3,55E-03	6,31E-04
21	0,063	3,22E-03	3,07E-03	3,24E-04
23	0,050	2,90E-03	2,74E-03	7,90E-04
25	0,040	2,39E-03	2,31E-03	3,52E-04
27	0,032	1,98E-03	2,01E-03	3,99E-04
29	0,025	1,70E-03	1,78E-03	3,27E-04
31	0,020	1,64E-03	1,68E-03	2,16E-04
33	0,016	1,52E-03	1,63E-03	6,75E-05
35	0,013	1,47E-03	1,59E-03	0
37	0,010	1,46E-03	1,56E-03	0
39	0,008	1,44E-03	1,45E-03	0

Notably, the BER of the new convolutional code reaches zero at a very high Eb/No (35 dB), whereas the other configurations never reach it. This indicates that the fading channel model poses a much more challenging problem, in which emerging error patterns can exceed the code's correction capacity even when the signal power is sufficiently high. These results underscore the importance of implementing robust FEC schemes in real-world APRS applications, which typically operate in fading and multipath environments.

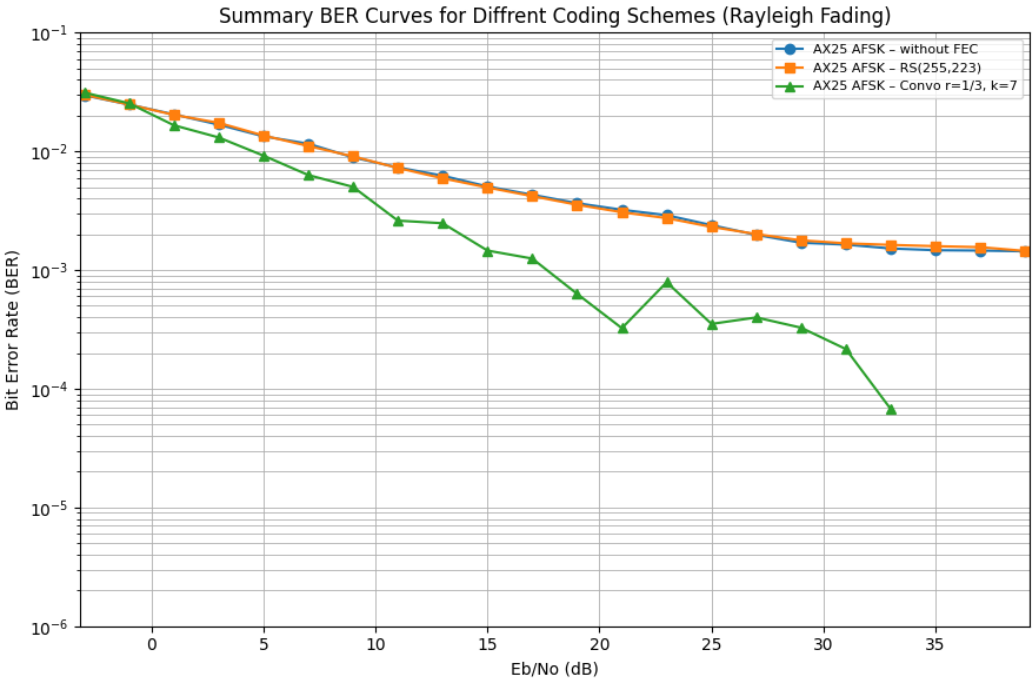

Figure 4. BER vs Eb/No curve - AX.25 AFSK (with Fading Rayleigh)

3.4. BER Floor and Practical Receiver Limitations

The presence of a BER floor in some configurations can be attributed to several factors. First, the use of AFSK modulation with noncoherent detection inherently limits performance at low Eb/No compared to coherent detection schemes. Second, the adoption of hard-decision Viterbi decoding, although computationally efficient, does not fully exploit the soft reliability information of the received symbols, thereby constraining the achievable coding gains. Finally, practical simulation constraints, such as finite traceback depth and synchronization transients, may also contribute to the residual error floor. These observations indicate that further performance improvements can be achieved by incorporating soft-decision decoding and optimized synchronization techniques, particularly for satellite-based and long-range APRS deployments.

4. IMPLICATIONS FOR SYSTEM DESIGN

4.1. Performance, Complexity, and Latency Trade-off

Selecting the optimal FEC scheme for a real-world APRS system requires careful consideration of trade-offs among performance, complexity, and latency. The complexity of the Viterbi algorithm increases exponentially with the constraint length of the convolutional code [24]. RS decoding with LCC (Low-Complexity Chase) provides better error correction but is time-consuming; therefore, it is not ideal for high-speed, low-latency applications [25]. Table 5 summarizes the practical trade-offs between the different FEC schemes. A convolutional code with R=1/3 and K=7 offers the best balance for APRS in resource-constrained devices, whereas concatenated codes require significant hardware support.

The choice of the FEC scheme for APRS must balance performance gains against implementation constraints. Convolutional R=1/3, K=7 emerges as the most robust, achieving error-free operation at lower Eb/No while keeping computational complexity within reach of low-power APRS trackers. Reed–Solomon (255,223) is effective in burst-error channels;

however, its block-level decoding introduces latency and memory demands that may be unsuitable for real-time emergency applications. The concatenated (RS+Conv) scheme theoretically offers the best of both worlds, but without interleaving, it becomes unstable at low Eb/No, and its implementation requires FPGA-level resources that many CubeSat payloads lack.

Table 5. Trade-off Analysis of FEC Schemes for APRS System Design

FEC Scheme	Performance (BER)	Complexity	Latency	Resource Requirement
No FEC	Poor (high BER at low Eb/No)	Very Low	None	Minimal (MCU/SDR only)
Reed–Solomon (255,223)	Strong vs burst errors, limited in fading	Moderate (block algebra)	High (block-level decoding)	Requires a memory buffer
Conv. R=1/3, K=7	Best overall, robust in fading	High (Viterbi decoding)	Low (bit-by-bit)	Feasible on DSP/MCU
Concatenated (RS+Conv)	Excellent in AWGN, unstable at low Eb/No without an interleaver	Very High (RS + Viterbi)	High (due to block + interleaver)	FPGA-level resources needed

4.2. Relevance to Real APRS Environment

An analysis of a simple AWGN channel provides a strong initial guide. However, additional testing with a Rayleigh fading channel model provides a more comprehensive picture of the system's robustness in real-world scenarios. This additional analysis with a Rayleigh fading channel is more representative of the APRS environment, which operates at VHF/UHF frequencies and exhibits significant multipath propagation [1-2,21]. The actual APRS environment is much more complex, characterized by fading, non-Gaussian noise, and various types of interference. As shown in the literature, Rayleigh fading is commonly used to model non-line-of-sight channels in satellite and urban communications, resulting in poorer BER performance than AWGN [21]. Tests on a fading channel show that convolutional codes, while very effective at addressing random errors (such as those caused by AWGN noise), also perform reasonably well against fading errors, although their performance is not as good as in AWGN channels. Thus, convolutional codes remain a solid choice for addressing challenging real-world APRS environments.

5. CONCLUSION

This study presented a comparative performance evaluation of several FEC schemes for AX.25-based APRS communication using AFSK modulation in the GNU Radio simulations. The main findings are summarized as follows: First, convolutional coding with rate R = 1/3 and constraint length K = 7 yields the best overall BER performance across both AWGN and Rayleigh fading channels, striking a favorable balance between reliability and implementation complexity. Second, Reed–Solomon coding is effective at correcting burst errors but is less robust in fading environments when used independently. Third, concatenated Reed–Solomon and convolutional coding demonstrates strong potential; however, its instability at low Eb/No in this study is primarily due to the absence of interleaving, rather than an intrinsic weakness of the coding scheme.

These results confirm that, for practical APRS and small-satellite applications, convolutional coding with R=1/3 and K=7 is the most viable solution in terms of performance, latency, and resource constraints. Future work will focus on three main directions: incorporating interleaving into concatenated coding schemes to enhance stability in fading channels, investigating soft-decision decoding to reduce the observed BER floor, and extending the study to hardware-in-the-loop experiments to validate the computational complexity, latency, and power consumption in real SDR-based APRS implementations.

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