ENHANCING BEST SOURCE SELECTOR OUTPUT QUALITY WITH FEC

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ABSTRACT

Best Source Selectors are now widely used to deal with the increasing need for range coverage in flight test activities. They are known to provide higher telemetry link availability and reliability. The Maximum Likelihood Bit Detection algorithm is commonly used to perform bit by bit combining in order to minimize the bit error probability. However, it requires at least three Data Quality Encapsulated streams with DQM information. Additionally, it does not exploit the benefits of Forword Error Correction algorithms such as LDPC codes since a basic best frame selection is usually implemented. This paper presents a new approach to improve the combined output quality when FEC frames are provided, starting from two DQE streams using FEC algorithms after combining. We present full system simulation results with AWGN channels, showcasing 1dB gains for two streams and higher than 3dB for more, as compared to the traditional MLBD combiner.

INTRODUCTION

Telemetry systems in military test ranges play a critical role in the validation of airborne platforms. During flight tests, aircraft transmit telemetry data continuously to ground infrastructure composed of multiple geographically distributed receiving stations. This spatial diversity ensures maximum link availability across the entire flight path, despite obstructions or local fading at individual stations.

To efficiently exploit this multi-station architecture, a centralized component known as the Best Source Selector (BSS) is typically employed. Its role is to select, at each time instant, the stream from the station deemed to offer the highest reception quality. This approach ensures robustness in the face of localized channel degradations.

A. Current Architecture

In the current state-of-the-art telemetry infrastructure, each ground station independently demodulates and decodes the received signal. The BSS collects these decoded bitstreams and selects

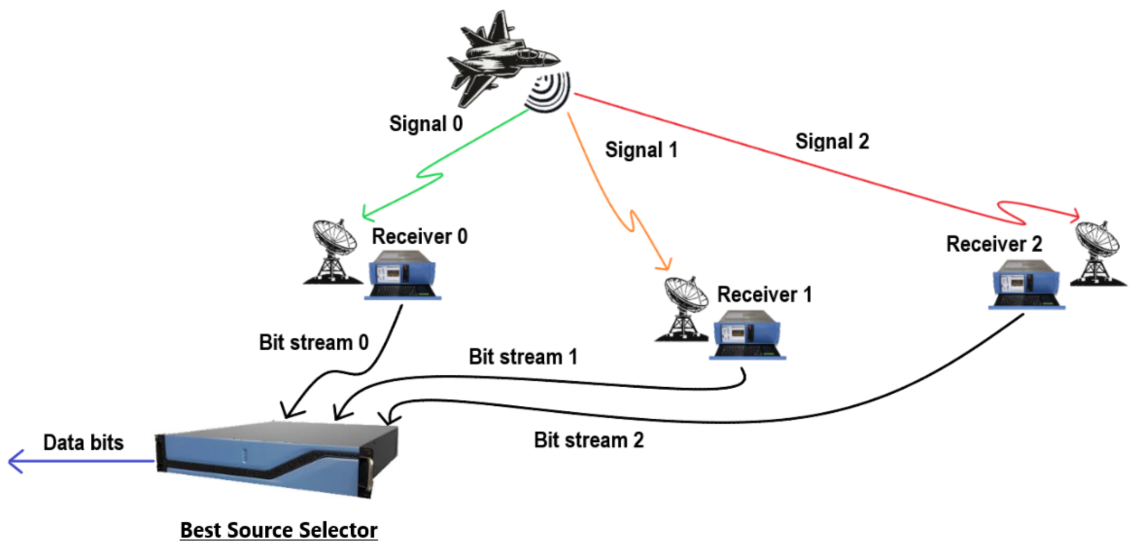

Figure 1: The state of the art telemetry framework.

one based on a data quality metric (DQM). This DQM can be based on the signal-to-noise ratio (SNR), the opening criterion of the eye diagram, or other techniques as such. In some enhanced variants, multiple decoded streams are combined using voting mechanisms, weighted majority rules to improve the final output robustness.

B. Limitations of the State of the Art

While some level of diversity gain can still be achieved—especially when leveraging station-level quality indicators to weigh bit contributions—the demodulation process itself discards a significant portion of the signal's soft information. Once the received symbols are converted into hard bits, fine-grained confidence values that would normally guide optimal FEC decoding are irreversibly lost.

As a result, even advanced hard-decision combining schemes remain fundamentally limited in their ability to extract the full coding and diversity gain embedded in FEC-encoded transmissions. What is lost at the demodulation stage cannot be recovered by downstream logic, which motivates the need for reconstructing soft information from the available hard decisions.

C. Contribution

We propose a combine-then-decode strategy that leverages the FEC structure of the transmitted signal. Instead of decoding each ground station's bitstream independently, we combine the hard-demodulated bits from all stations to reconstruct soft information in the form of pseudo-LLRs. These are computed using each station's DQM to assign a confidence level to each bit. The resulting soft stream is then decoded centrally using a soft-input FEC decoder. This approach enables improved coding and diversity gain without requiring access to soft symbols or changes to existing ground station infrastructure.

THE STATE OF THE ART IN MULTI-STATION TELEMETRY RECEPTION

Telemetry reception in military test ranges typically relies on a network of geographically distributed ground stations to ensure continuous coverage of airborne platforms. Each station independently receives, demodulates, and decodes the transmitted signal. To consolidate these parallel receptions, a centralized BSS is used to select or combine the decoded outputs based on predefined quality metrics. This section reviews the main approaches used in current systems, from single-source selection to enhanced hard-decision combining techniques.

D. Hard-Decision Combining in Current Multi-Station Systems

In its classical form, the BSS performs a per-frame or per-packet selection based on a DQM. Let $\mathbf{b}_i \in \{0,1\}^N$ denote the decoded bitstream from station i, and let q_i be its associated quality metric (e.g., received signal strength indication, SNR, or BER). The selected output is then:

$$\mathbf{b}_{\text{BSS}} = \mathbf{b}_{i^\star}, \quad \text{where} \quad i^\star = \arg\max_i q_i. \tag{1}$$

This method, widely used in operational systems compliant with IRIG-106 Chapter 10 standards [**?**], is optimal in the absence of channel diversity or when one link clearly dominates the others in quality.

To improve resilience, enhanced combining strategies have been proposed. One common approach is bitwise majority voting, defined as:

$$\mathbf{b}_{\text{MV}}[n] = \begin{cases} 1, & \sum_{i=1}^{M} \mathbf{b}_i[n] > M/2 \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

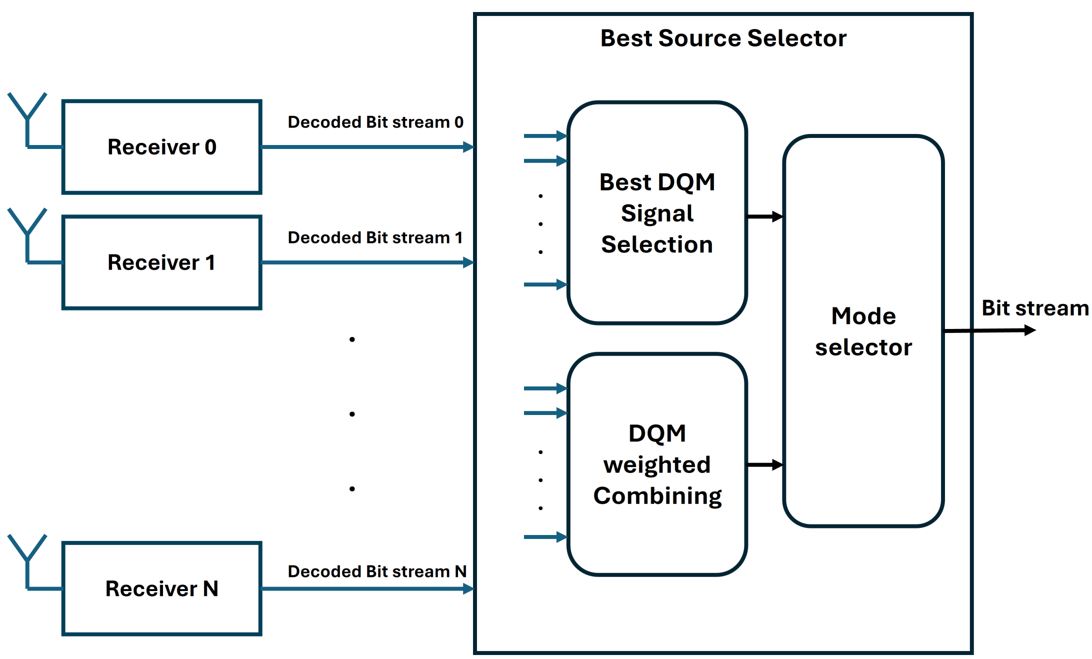

Figure 2: The state of the art telemetry framework.

where M is the number of stations and n indexes the bit position. This method assumes equal reliability across all stations and is vulnerable when stations exhibit unequal SNR.

To account for reliability differences, weighted combining has been introduced. Here, each bit is assigned a confidence weight based on station-level metrics:

$$\mathbf{b}_{\text{WC}}[n] = \begin{cases} 1, & \sum_{i=1}^{M} w_i \cdot \mathbf{b}_i[n] > \sum_{i=1}^{M} w_i/2 \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

where w_i is a weight proportional to the estimated reliability of station i (e.g., $w_i = \log \text{SNR}_i$) [**?**].

Despite these improvements, all of the above techniques operate on hard-decoded bits. The transformation from soft demodulated symbols to hard bits is irreversible, and with it, critical information about symbol reliability is lost. This restricts the ability of downstream decoders to perform optimal error correction, particularly under low-SNR or asymmetric channel conditions. Thus, while diversity gain continues to grow with the number of stations, the coding gain saturates unless soft information is reintroduced.

PROPOSED APPROACH: RECONSTRUCTING LLRS FROM HARD BITS

The limitations of hard-decision combining stem from the loss of symbol-level reliability during demodulation. To address this, we propose a method that reconstructs soft information—specifically, pseudo-log-likelihood ratios (LLRs)—from the hard-demodulated outputs of multiple ground stations. These reconstructed values enable soft-input decoding at the centralized BSS, unlocking additional coding gain without requiring access to raw symbols or modifying ground station hardware.

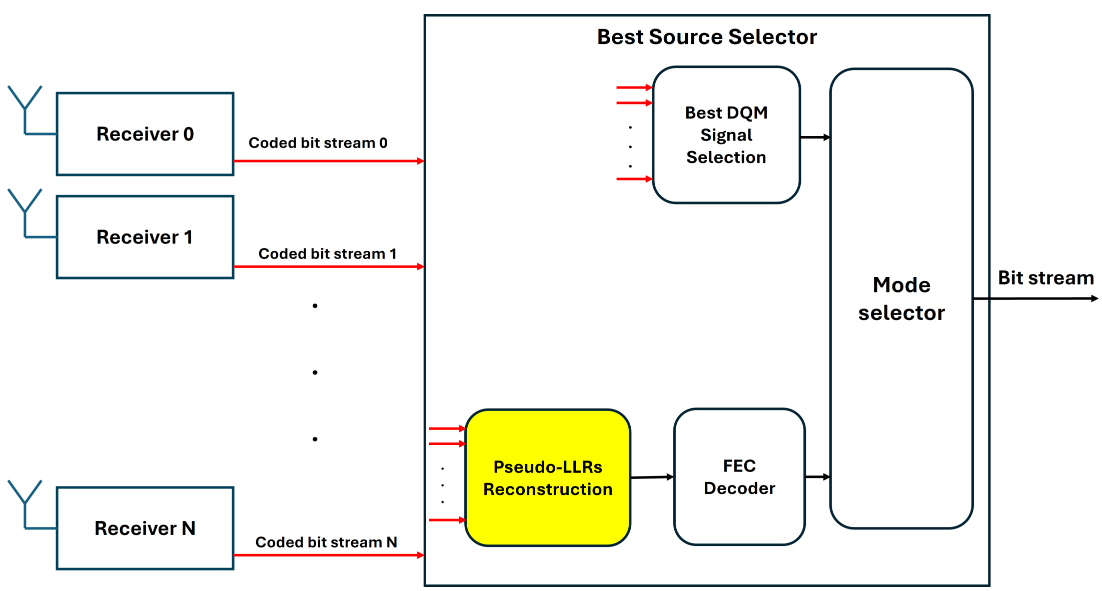

Figure 3: The proposed telemetry framework.

E. System Model

We consider a point-to-multipoint telemetry system in which an airborne transmitter sends a forward error correction (FEC) coded binary sequence $\mathbf{c} \in \{0,1\}^N$ to M geographically distributed ground stations. The transmitted sequence is modulated into a signal $x(t)$, and each station $i = 1, \ldots, M$ observes a received signal of the form:

$$r_i(t) = h_i(t) \cdot x(t - \tau_i) + n_i(t)$$

where: - $h_i(t)$ is the channel gain, - τ_i is the propagation delay to station i, - $n_i(t)$ is additive white Gaussian noise (AWGN) or potentially a fading process.

Each ground station demodulates $r_i(t)$ and produces a hard-decision bitstream:

$$\mathbf{b}_i = [b_i[1], b_i[2], \ldots, b_i[N]], \quad b_i[n] \in \{0,1\}$$

Additionally, each station reports a scalar DQM q_i, representative of channel reliability. These DQMs are, by definition, normalized to a common scale and assumed to be available to the centralized BSS. Which in turn, collects all bitstreams $\{\mathbf{b}_i\}_{i=1}^M$ and quality metrics $\{q_i\}_{i=1}^M$ to generate a soft bit estimate in the form of a pseudo-log-likelihood ratio (LLR) for each bit index n:

$$L[n] = \sum_{i=1}^{M} w_i \cdot (2b_i[n] - 1)$$

where: - $w_i = f(q_i)$ is a weight derived from the quality metric of station i, - $2b_i[n] - 1 \in \{-1, +1\}$ maps bit values to bipolar form.

The resulting soft sequence $\mathbf{L} = [L[1], \ldots, L[N]]$ is passed to a soft-input FEC decoder. This reconstruction enables improved error correction performance using only hard bitstreams and quality metrics, without access to the original demodulated soft symbols.

The following assumptions hold:

- All receivers are time-aligned at the bit level (τ_i compensated).
- Channel realizations $h_i(t)$ are independent across stations.
- Each ground station produces FEC coded hard decision outputs and a single DQM per DQE frame.

F. Numerical Results

To evaluate the performance of the proposed pseudo-LLR reconstruction method, we simulate a telemetry reception scenario with two input channels subject to independent additive white Gaussian noise (AWGN). The transmitted signal is encoded using LDPC codes of rate $R = 4/5$ and $R = 1/2$, and modulated using ARTM Tier-I waveform (SOQPSK-TG).

Each receiver performs hard demodulation, and the resulting bitstreams are combined using the pseudo-LLR reconstruction method described in the previous section. Two configurations are tested for each LDPC code rate: (1) a symmetric case where both channels have equal SNR, and (2) an asymmetric case where the second channel has a 3dB SNR disadvantage relative to the first.

Four sets of results are presented:

- **Figure 4:** Proposed pseudo-LLR combining with DQM-based weighting and LDPC rate $4/5$. Includes both the symmetric and asymmetric SNR cases.
- **Figure 5:** Same as Figure 1, but with LDPC rate $1/2$.
- **Figure 6:** Pseudo-LLR combining without using DQM (i.e., equal weighting of both channels), LDPC rate $4/5$.
- **Figure 7:** Same as Figure 3, but with LDPC rate $1/2$.

Results confirm that the proposed method yields significant coding gains in both symmetric and asymmetric scenarios, particularly when DQM information is used to weight the contributions of each channel. The advantage is more pronounced in high-rate codes, where performance is otherwise more sensitive to decoding quality.

An important result is that, when DQM-based weighting is applied, the proposed combining strategy consistently outperforms both individual channels across the entire SNR range. This demonstrates that the reconstruction of pseudo-LLRs from hard decisions, when guided by accurate reliability metrics, enables the decoder to exploit the full spatial diversity of the system.

In contrast, when DQM information is not used and all channels are weighted equally, performance degradation is observed in the asymmetric case. At low BERs (i.e., high SNR), the combined stream still outperforms the better of the two channels due to residual diversity gain. However, at higher BERs (i.e., lower SNR), the lack of reliability weighting causes the poorer channel to dominate the combined output, resulting in worse performance than selecting the best channel alone.

This suggests that, under severe channel conditions, the decoding gain provided by the LDPC code dominates the system behavior, reducing the relative importance of perfect DQM accuracy. As DQM estimation itself can be challenging at low SNR, this robustness to weighting imperfections is a promising result for practical deployment.

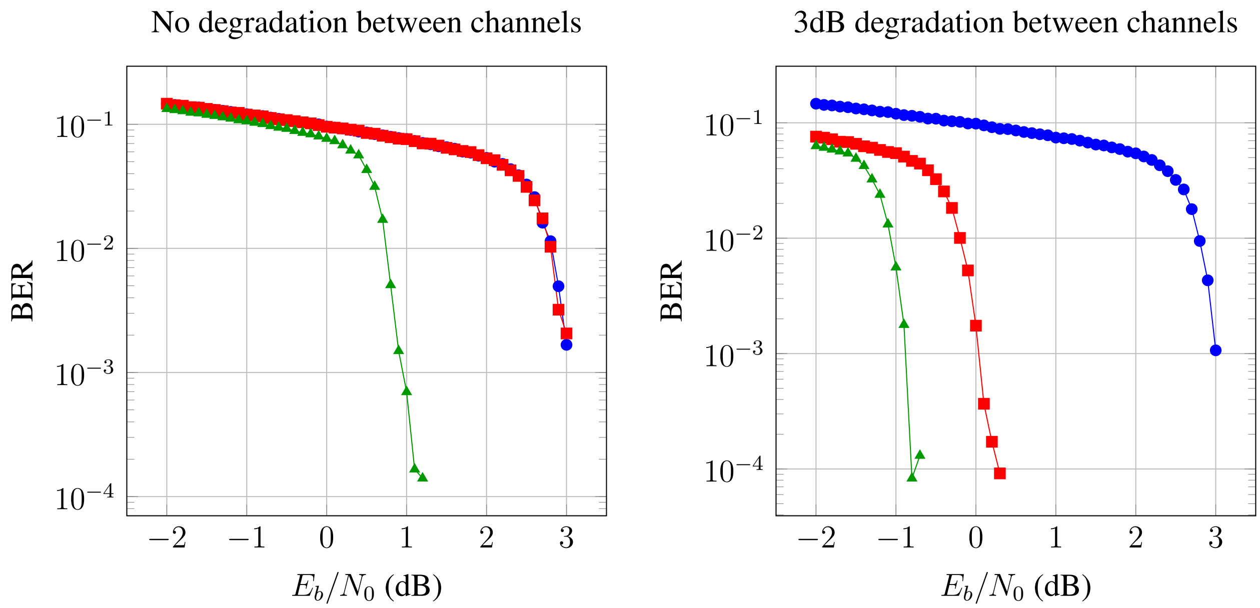

Figure 4: Bit Error Rate simulation for LDPC 4/5 ARTM Tier-I waveform. In blue and red, the two input channels, and in green the proposed DQM-weighted combined channel.

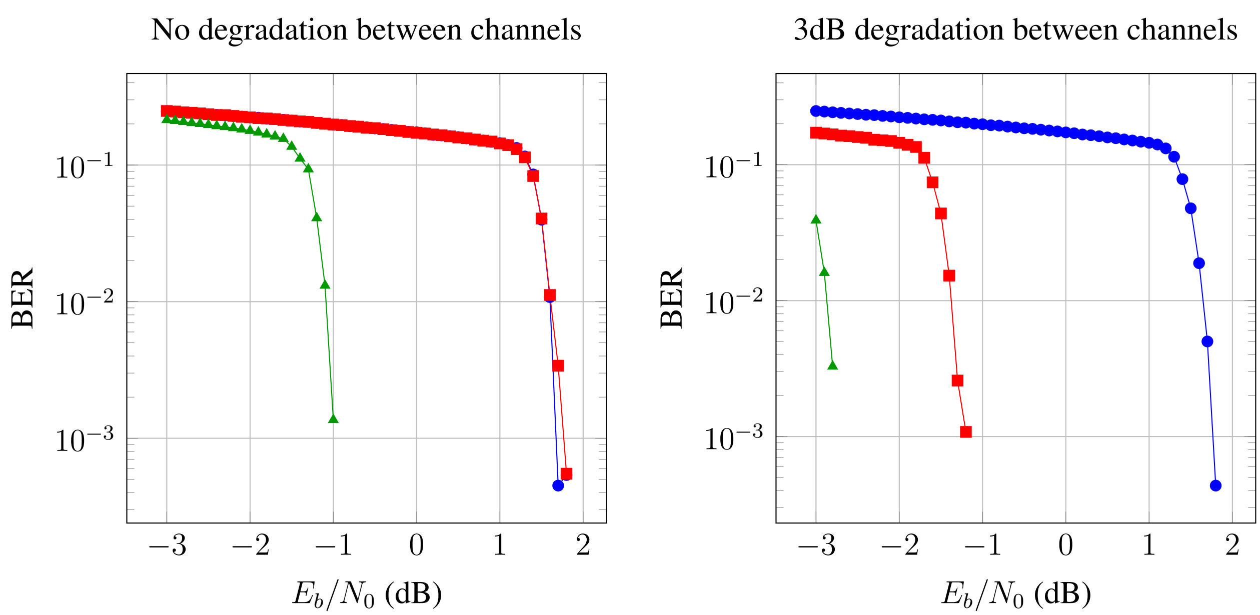

Figure 5: Bit Error Rate simulation for LDPC 1/2 ARTM Tier-I waveform. In blue and red, the two input channels, and in green the proposed DQM-weighted combined channel.

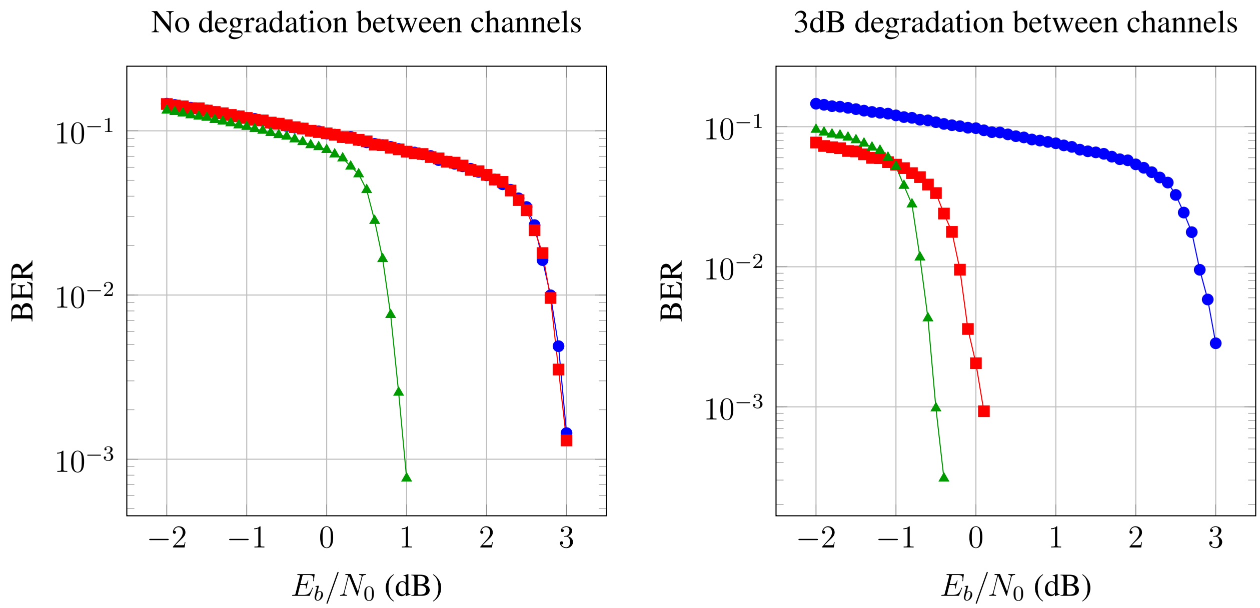

Figure 6: Bit Error Rate simulation for LDPC 4/5 ARTM Tier-I waveform. In blue and red, the two input channels, and in green the proposed equally-weighted combined channel.

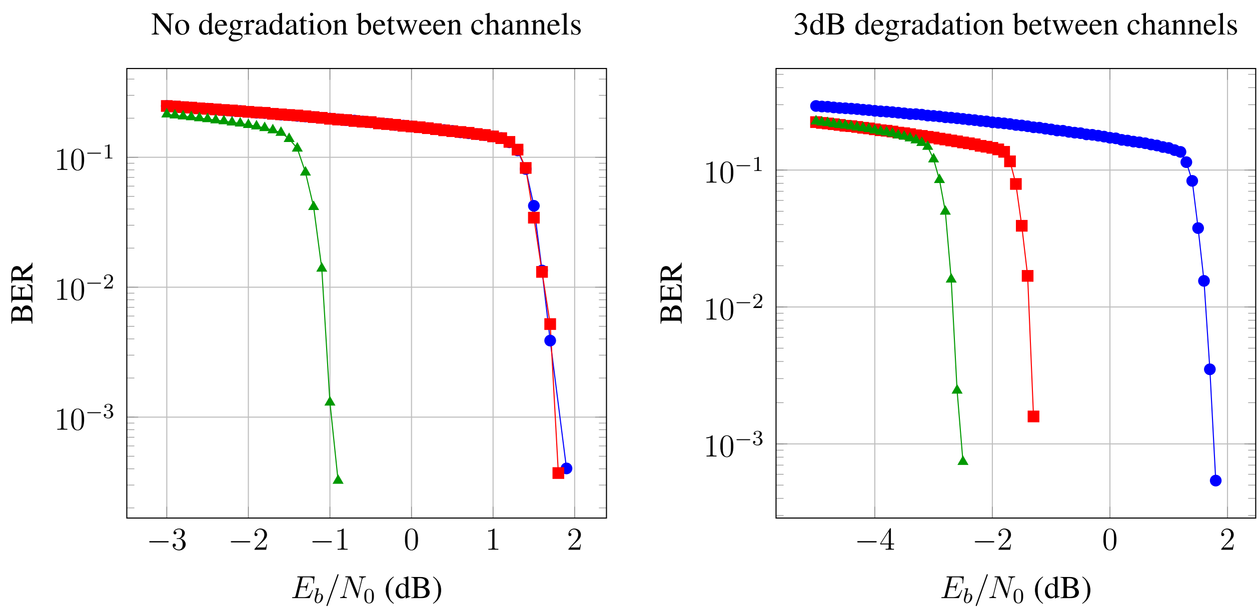

Figure 7: Bit Error Rate simulation for LDPC 4/5 ARTM Tier-I waveform. In blue and red, the two input channels, and in green the proposed equally-weighted combined channel.

CONCLUSIONS

This paper proposed a soft-information reconstruction strategy for telemetry systems relying on multiple geographically distributed ground stations. By combining hard-demodulated bitstreams using station-level quality metrics, the method reconstructs pseudo-LLRs that enable soft-input decoding at a centralized node—without requiring access to raw demodulated symbols or changes to existing ground station infrastructure.

Simulation results using LDPC codes demonstrated that the proposed approach outperforms traditional hard-decision combining techniques, particularly in asymmetric channel conditions. When DQM information is available and reliable, the combined stream achieves better performance than any individual channel. However, results also show that under low-SNR conditions, where LDPC decoding is required, the system remains robust even without precise DQM weighting, highlighting the method's practical applicability.

Overall, this strategy extends the benefits of spatial diversity into the coding domain, offering a low-complexity path toward improving link resilience in telemetry systems.

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