Improving the Performance of DVB-T2 in High-Speed Train Communication Systems

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Received: 11 December 2024 | Revised: 25 January 2025 | Accepted: 29 January 2025

ABSTRACT

The development of Digital Video Broadcasting-Terrestrial (DVB-T2) technology has spread worldwide and been implemented in various wireless communication channel environments, including High-Speed Train (HST) communication. The HST channel's characteristics, including extremely high speeds of up to 300 km/h and the presence of numerous multipaths, significantly degrade the performance of DVB-T2. This paper proposes a method to address these challenges by employing Bose-Chaudhuri-Hocquenghem (BCH) and block code LDPC channel coding, along with Minimum Mean Squared Error (MMSE) channel estimation and equalization. The proposed approach integrates HST channel modeling with a DVB-T2 communication system that has been modified to mitigate the effects of Doppler and multipath fading. The BCH outer code is designed to address burst errors, while the LDPC inner code is engineered to handle random errors. The efficacy of the channel estimation and MMSE equalization methods in HST channels has been demonstrated, ensuring the preservation of the orthogonality of the Orthogonal Frequency Division Multiplexing (OFDM) subcarriers used and the mitigation of Inter-Carrier Interference (ICI). To this end, we have simulated the performance of this research on HST channels with various digital modulation types (16-QAM, 64-QAM, and 256-QAM) and also the effect of the number of multipath fading scatterers and the variation of train speed. The results of this research demonstrate a significant BER reduction at Signal-to-Noise Ratio (SNR) 15 dB, where the BER value reaches 10-3 when using 16-QAM. Among the various modulation options examined, 256-QAM emerged as the most effective, demonstrating a performance enhancement of up to 85% compared to the baseline scenario without the proposed mitigation. The research findings underscore the significance of train speed in Bit Error Rate (BER) performance, indicating that an increase in train speed leads to a deterioration in BER performance. Furthermore, the study highlights the impact of the number of scatterers on BER performance, demonstrating that an increase in scatterers results in a decline in BER performance. The findings of this research further reinforce the efficacy of DVB-T2 integrated with high-speed rail transportation applications, which have begun to show significant growth in numerous countries.

Keywords-Digital Video Broadcasting-Terrestrial (DVB-T2); Doppler effect; High-Speed Train (HST); Minimum Mean Squared Error (MMSE); Orthogonal Frequency Division Multiplexing (OFDM)

I. INTRODUCTION

DVB-T is the most prevalent digital terrestrial television system. Primarily designed for fixed environments, its performance in mobile or portable scenarios was inadequate, rendering it unsuitable for moving vehicles applications [1]. To enhance spectral efficiency, the DVB consortium developed an upgraded standard called DVB-T2, 2nd generation. This standard incorporates modern coding, interleaving, and modulation techniques, resulting in substantial improvements in transmission capacity and reliability for a range of devices, including HST [2]. Recent advancements in the field of modern transportation technology have led to a significant development, marked by the integration of traditional transportation facilities with advanced telecommunications technologies, giving rise to the concept of Intelligent Transportation Systems (ITS) [3]. This development signifies a substantial advancement for the nation's transport infrastructure. However, it concomitantly introduces novel communication technology challenges, including the integration of such solutions within an HST that can travel at speeds of up to 500 km/h. At these elevated velocities, the HST is estimated to generate a substantial Doppler effect on communications systems [4]. These effects result in Doppler shifts of sufficient magnitude to jeopardize communication systems, including digital television broadcasting employing the DVB-T2 standard. The Indonesian government has developed an advanced DVB-T2 standard, which will be implemented during the transition from analog to digital television [5]. The digitalization of television in Indonesia offers significant benefits, including improved frequency efficiency and enhanced broadcast video quality. However, the Orthogonal Frequency Division Multiplexing (OFDM) in DVB-T2 has significant disadvantages when used in the HST with a high-mobility profile due to the Doppler effect that causes Intercarrier Interference (ICI). Earlier studies have demonstrated that the Doppler effect on mobile communication systems operated in HST is significantly more pronounced than that on conventional cellular or vehicular communication systems [8]. Findings from a few studies recommend MIMO methods to mitigate Doppler-induced inter-channel interference [9] and beamforming-based approaches to combat fast channel changes due to high mobility [10]. The Noise2noise (N2N) algorithm is employed to denoise the pilot signal received by the base station, thereby enhancing the estimation performance [11]. Recent studies on adaptive equalization have indicated that the synergy between equalizer and channel estimator enhances communication performance in time-varying channel conditions [12]. Other studies have also identified the potential benefits of employing Polar Code as a channel coding scheme, particularly in rapidly varying channels such as HST scenarios [13]. However, prior studies are constrained to simulating static channels, overlooking the challenges posed by time-variant frequency selective characteristics resulting from HST [14].

This study proposes a novel approach to enhance the performance of DVB-T2 in high-mobility conditions for HST communication systems. The integration of BCH-LDPC coding with MMSE channel estimation establishes a novel framework for error correction and estimation. Previous research has predominantly focused on static channels or low-mobility scenarios. However, the proposed framework addresses the challenges posed by random and burst errors, which are produced by the Doppler effect and multipath fading, in high-speed mobility scenarios. The study uses a high-fidelity HST channel model with Doppler shifts, train velocities up to 300 km/h, and varied scatterer densities to emulate real-world HST scenarios. The paper also examines DVB-T2 performance under varied train velocities and multipath conditions employing 16-QAM, 64-QAM, and 256-QAM modulation techniques. The results demonstrate that the proposed technique significantly enhances the BER performance, particularly for higher-order modulation schemes and faster trains. This research offers a more realistic and resilient solution for high-mobility DVB-T2 applications by evaluating in dynamic HST conditions, a departure from earlier studies that employed static channel models or simplified mobility scenarios. It is anticipated that the implementation of this solution will have a significant impact on the quality of DVB-T2 reception within HST, thereby enabling reliable digital broadcasting even at high speeds. In addition to advancing intelligent transport technology in Indonesia, the findings may provide innovative solutions for the same problems that have occurred in HST systems. This paper examines the performance of high-speed train services, modeled using the HST channel framework. It is therefore imperative to emphasize that suitable channel coding and adaptive equalization methodologies will assume a pivotal role in addressing the Doppler effect predicament that arises in HST scenarios involving the implementation of DVB-T2 technology.

II. RESEARCH METHOD

This research uses simulation to analyze the performance of DVB-T2 applications in the communications systems of HST. The objective of this research is to enhance the performance of DVB-T2 within HST communication systems. The research methodology employs a simulation-based system using a HST channel model that incorporates essential parameters, including the Doppler effect and multipath fading, which are frequently encountered in high-mobility environments. The simulation framework encompasses a comprehensive system-level model of DVB-T2, in accordance with ETSI specifications that delineate the technical parameters for DVB-T2 systems. These parameters include modulation schemes, coding techniques, and pilot patterns, which represent the principal data used in this research. This includes the implementation of sophisticated error correction methodologies, including BCH and LDPC codes, in conjunction with MMSE channel estimation and equalization. These methodologies have been meticulously selected to address the unique challenges posed by high-velocity environments, particularly the notable Doppler effect and the recurrent occurrence of multipath fading.

A. System Model

As presented in Figure 1, a block diagram of a DVB-T2 setup that functions with HST channels reveals the architecture of a DVB-T2 system, specifically highlighting the transmitter and receiver components. The process initiated by the transmitter begins with the processing of input data, followed by channel encoding (employing BCH and LDPC encoding), QAM mapping, and OFDM signal generation. Conversely, the receiver side of the system performs operations such as the Fast Fourier Transform (FFT), channel estimation, equalization, and decoding to reconstruct the original input data. The primary function of the channel encoder is to add redundancy to the information sequence, thereby enabling the receiver to counteract the effects of noise and interference, thus enhancing transmission reliability. This increased capacity is primarily achieved through the use of advanced channel coding with higher error correction capabilities. The DVB-T2 standard employs multicarrier OFDM and 64-QAM to enhance image quality and mitigate signal loss. Within the transmitter, a bit stream is generated and processed via a QAM mapper to modulate it onto a 64-QAM carrier. Subsequently, the data undergoes a conversion from serial to parallel, with the incorporation of pilots, and a cyclic prefix (1/4 of the FFT size) is included to reduce ISI. The signal undergoes a transformation from the frequency domain to the time domain via an Inverse Fast Fourier Transform (IFFT) prior to transmission through the channel. At the receiver, the signal traverses a QAM detector, the pilots are eliminated, and the data undergoes a conversion back to parallel form. Subsequently, the QAM demapper performs a demodulation of the signal, thereby ensuring reliable transmission and delivery of high-quality video.

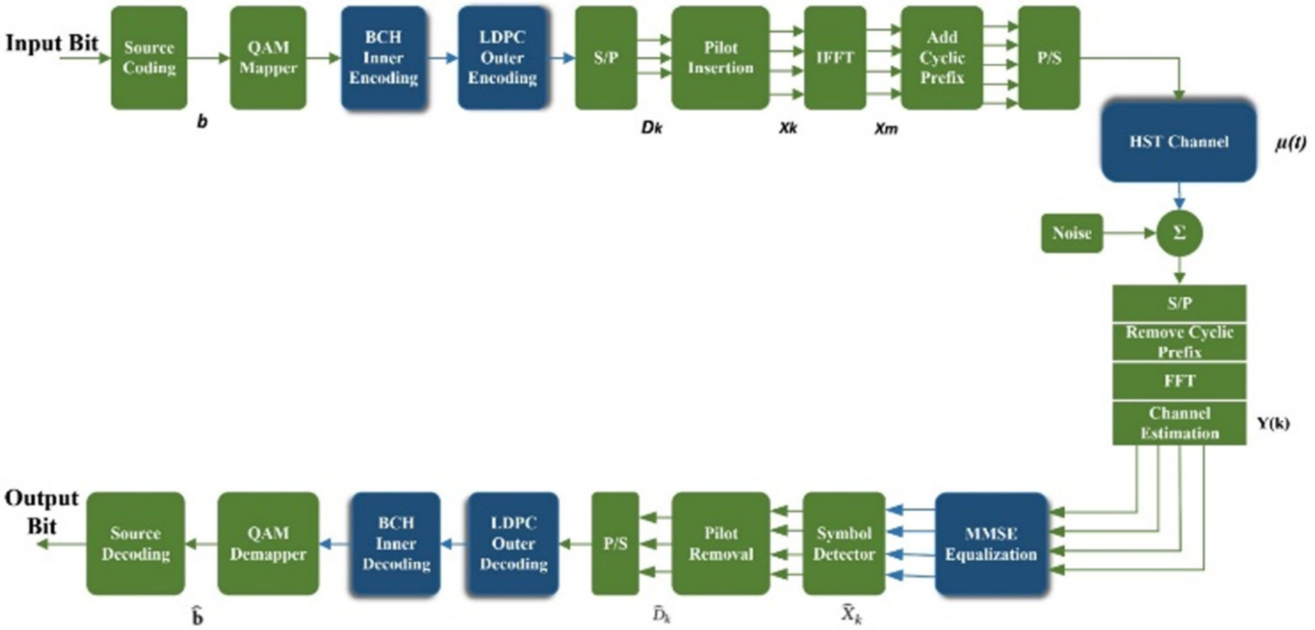

Fig. 1. DVB-T2 system model using Doppler effect mitigation methods.

B. HST Channel Model

The accelerated development of HST has profoundly transformed modern travel, enhancing its speed and efficiency, as shown in Figure 2.

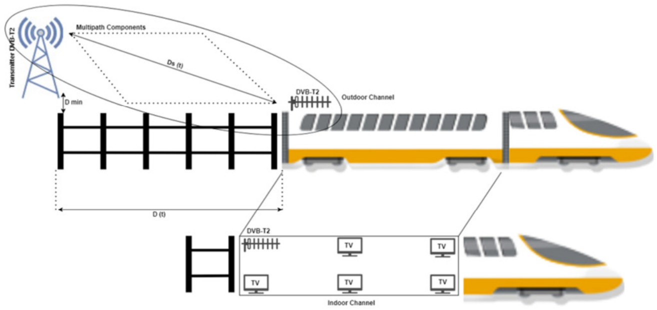

Fig. 2. HST system model.

In this HST system model, a DVB-T2 antenna functions as the receiver, whereas the BS serves as the transmitter. The communication system is classified into two distinct channels: an outdoor channel and an indoor channel. The outdoor channel facilitates communication between the base station and the DVB-T2 antenna, while the indoor channel handles communication between the DVB-T2 antenna and user devices (televisions). One of the primary challenges encountered by HST is the heterogeneity of its operational environments, which encompass Rural Macrocells (RMa), tunnels, bridges, hilly terrains, and U-shaped areas. To address these challenges, the channel model employed for HST communication systems incorporates Correlation Functions (CF) of non-stationary wideband MIMO channels. Furthermore, it employs a Geometry-Based Stochastic Model (GBSM) to effectively address the complexities associated with the varying HST environments and ensure reliable communication [15]. As shown in Figure 3, the channel will be modeled in geometric form base, according to (1) to (4). The system comprises multiple components, including Line of Sight (LOS) and Non-Line of Sight (NLOS) [15]:

$$h_{1,pq} = (t) = h_{1,pq}^{LOS}(t) + h_{1,pq}^{SB}(t) \tag{1}$$

$$h_{1,pq}^{LOS}(t) = \sqrt{\frac{K_{pq}}{K_{pq}+1}}\, e^{-j2\pi f_c \sigma_{pq}(t)} e^{-j2\pi f_{max} t\cos(\phi_{Tp}^{LOS}(t)-\beta_R)} \tag{2}$$

$$h_{1,pq}^{SB}(t) = \sqrt{\frac{\Omega_{1,pq}}{K_{pq}+1}} \lim_{N1\to\infty} \sum_{n1=1}^{N1} \frac{1}{\sqrt{N1}}\ e^{j(fn_1-2pf_c\sigma_{pq},n_1(t))} \times e^{j2\pi f_{max} t\cos(\phi_R^{(n_1)}(t)-\beta_R)} \tag{3}$$

$$h_{i,pq}(t) = h_{i,pq}^{SB}(t) = \sqrt{\Omega_{i,pq}} \lim_{N1\to\infty} \sum_{n_1=1}^{N_1} \frac{1}{\sqrt{N1}}\ e^{-j(fn_1-2pf_c\sigma_{pq},n_1(t))} \times e^{j2\pi f_{max} t_{cos}(\phi_R^{(n1)}(t)-\beta_R)}, 1 < i \ \leq I \tag{4}$$

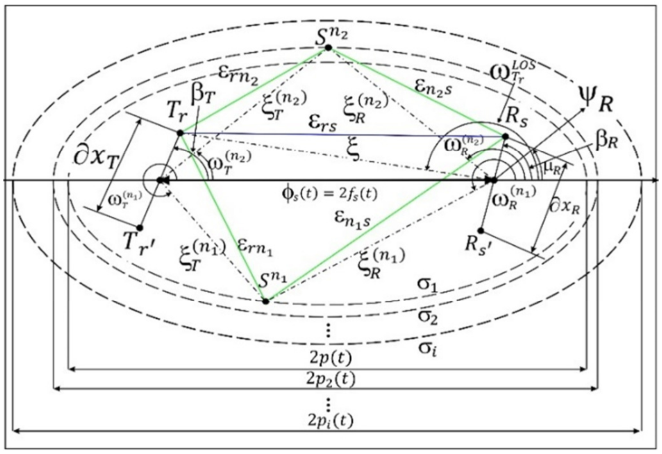

Fig. 3. HST channel model.

C. BCH and LDPC Coding

The DVB-T2 standard, established by ETSI [16], is a digital television broadcasting standard that employs BCH codes and LDPC codes for FEC. The selection of the BCH outer code and the LDPC inner code was driven, in part, by their capacity to approach Shannon's limit within just a few hundredths of a decibel [17, 18]. The proposed method integrates BCH and LDPC channel coding with MMSE channel estimation to enhance the reliability of DVB-T2 in HST communication systems. The proposed approach employs a two-layer FEC framework, where BCH serves as the outer code and LDPC as the inner code. This combination is designed to address different types of errors in high-mobility scenarios: the BCH code effectively handles burst errors caused by abrupt changes in channel conditions, such as when the train enters or exits a tunnel, while the LDPC code mitigates random errors in the channel. The efficacy of this approach is further enhanced by the incorporation of MMSE channel estimation, which serves to minimize the mean squared error between the transmitted and received signals. This estimation technique has been demonstrated to be highly effective in suppressing noise and compensating for Doppler-induced distortions, which are particularly salient challenges in high-speed environments.

1) BCH

The encoding process involves the generation of check bits to ensure the integrity of transmitted information. This process commences with the definition of the system within the Galois Field GF (2m) and the determination of the minimal polynomial of degree 2t–1. Using this minimal polynomial, the generator polynomial g(*x*) is constructed, and the message bits are then augmented by appending a sequence of zeros equal to the degree of g(*x*). A binary division is then performed on the augmented message using g(*x*), and the remainder from this operation serves as the check bits. Finally, the check bits are appended to the original message bits to form v(x), the complete encoded data ready for transmission. This process ensures reliable communication by enabling error detection and correction at the receiver's end. The pseudocode for the BCH encoding process is:

```
Algorithm 1: BCH Encoding
Input: Message bits m(x)
Output: Encoded message with check bits v(x)
Initialize Galois Field GF(2^m).
Determine the minimal polynomial for 2t-1 error correction capability.
Generate the generator polynomial g(x) using the minimal polynomial.
Append n zero bits to the end of the message m(x)where n is the degree of g(x).
m'(x) = m(x) * x^n
Perform binary division of m'(x) by g(x).
Compute the remainder r(x).
Concatenate the remainder r(x) (check bits) with the original message m(x).
v(x) = m(x) || r(x)
Return the encoded message v(x).
End
```

In the event that the remainder of the division is found to be zero, the transmission is deemed to be error-free. Conversely, if an error is detected, the correction process is initiated. The error correction procedure involves the definition of 2t minimal polynomials and the calculation of the syndromes S1, …, S2t from the received codeword. The subsequent step involves the generation of a FEC frame, which is achieved by incorporating the base-band frame as the input to the BCH encoder, along with the parity check bits, to yield a FEC frame of the specified length for the BCH encoder. The BCH encoder is responsible for decoding and error correction of the input from the LDPC encoders at the receiver [19].

2) LDPC

LDPC codes were initially developed as linear binary codes by Robert Gallager in 1962. They are an error correction technique that has been shown to closely approach the channel's capacity. LDPC codes are defined by a matrix constructed with a small number of 1's compared to the amount of 0's. They can be created at nearly any rate and block length, specifying the number of information and parity bits in the parity check matrix H. The generator matrix G is computed only after the construction of the parity-check matrix H [20]. LDPC codes offer reduced computational complexity and are effective for downscaled applications. There are two kinds of LDPC: regular LDPC, which has a constant number of 0s in each row and column, and irregular LDPC. From a capacity standpoint, irregular LDPC codes outperform regular LDPC, but they are more complex. Irregular LDPC codes have been shown to significantly outperform comparable regular LDPC-based codes [21]. LDPC codes are employed in channel coding for error correction by using a large generator matrix with fewer elements of 1 than 0, resulting in low-density codes [22]. Element 1 demonstrates the relationship between input bits and output bits of LDPC codes. The LDPC codes matrix generator (G) functions as a codeword generator, transforming information bits from the sender side and the parity check matrix (H) to restore the codeword into information bits. It is imperative that both fulfill (5) [16]:

$$GH^T = 0 \tag{5}$$

In the event that (5) is not satisfied, LDPC codes are incapable of detecting and correcting errors present in the received codeword. The configuration of the parity check matrix of LDPC codes is modified in accordance with the block length (N), dimension (K), redundancy (M), degree of variable node (dv), and degree of check node (dc) as [16]:

$$M = N - K \tag{6}$$

then the parity check matrix of LDPC codes has dimension $M \times N$. The LDPC code rates available in DVB-T2 are a selection of the code rates of the DVB-S2 code. Specifically, 1/2, 3/5, 2/3, 3/4, 4/5, and 5/6 are used for PLP protection, while 1/4 is used for short code length only in L1 signaling protection. The LDPC codes used in DVB-T2 are characterized by irregularity, with the error protection level of each code bit exhibiting variability and being dependent on the column weight of the parity check matrix. To address this variability, Bit Interleaved Coded Modulation (BICM) has been employed to map the coded bits onto constellation symbols. This is achieved through a cascade of an interleave and a demultiplexer between the coder and the mapper [23]. The defining characteristics of LDPC codes are often attributed to the properties of the parity check matrix $\boldsymbol{H}$, or alternatively, the properties of the bipartite graph. However, a direct method for performing the LDPC encoding from $\boldsymbol{H}$ does not exist. The source bit sequence $x=[x_1, x_2, \ldots\ldots, x_k]$ is encoded by an LDPC encoder into an n-bit intermediate. The LDPC-encoded bits are expressed as [23]:

$$b = x.\boldsymbol{G} \tag{7}$$

where $\boldsymbol{G}$ is generator matrix obtained from $\boldsymbol{H}$ as $[I_k|P]$. To obtain the generator matrix $\boldsymbol{G}$, the matrix parity $\boldsymbol{H}$ is transformed into the form $[-P^T|I_{n-k}]$ through a series of row and column operations. For LDPC decoding, we implement both hard decision and soft decision decoding algorithms. In the hard decoding process, we use the peeling decoding algorithm, while for soft decoding, we employ the log LLR-based decoding algorithm. The iterative processes involved in decoding methods that use Tanner graphs exchange information between parity check nodes and variable nodes. To enhance the efficiency of encoding and decoding LDPC codes in DVB-T2, the sparse portion of the parity check matrix is designed in a quasi-cyclic manner. Consequently, efficient manipulation of the parity checks matrix's structure can render it suitable for layered decoding. The following is the pseudocode for LDPC decoding:

```
Algorithm 2 LDPC Decoding
Input: Received message r, Parity check matrix H
Output: Decoded message m_dec
Initialize maximum number of iterations max_iter.
Set the initial log-likelihood ratios (LLRs) for all received bits LLR(r).
Construct Tanner graph.
Map variable nodes (bits) to columns of H.
Map check nodes (parity equations) to rows of H.
for iteration = 1 to max_iter do
    Check node update: Compute messages from check nodes to variable nodes using parity constraints
    Variable node update: Update LLR values using messages from check nodes.
    Hard decision: m_dec = 1 if LLR(r) > 0, else m_dec = 0.
    Syndrome check: Compute s = H * m_dec^T.
    Syndrome check: if s = 0 (all parity checks satisfied), exit decoding.
End for
Return the decoded message m_dec.
End
```

LDPC codes represent the inner coding of the DVB-T2, with the code rate of LDPC codes adhering to the standards outlined in ETSI TS 102 831. LDPC codes are classified into six categories [21]: 1/2, 3/5, 2/3, 3/4, 4/5, and 5/6. The code rate of ½ offers maximum protection and minimum data rate, while the code rate of 5/6 offers minimum protection and maximum data rate. According to ETSI standards, LDPC codes of DVB-T2 employ a cyclic structure in the information section and a staircase structure in the parity section. The block length of LDPC codes can be configured to 16,200 for short frames, which is advantageous for low data rates, or 64,800 for long frames, which is optimal for higher data rates. The decoder employed integrates a technique known as layered decoding, which regards the parity check matrix as a succession of elementary matrices or layers. This method modifies the soft-decoding algorithm to operate on these layers. The conventional iteration performed on all parity check nodes is partitioned into QLDPC distinct sub-iterations, where QLDPC denotes the quantity of layers present in the parity check matrix H.

D. Channel Estimation and Equalization

The pilot pattern is typically selected based on parameters such as maximum multipath delay and maximum Doppler frequency. Pilot pattern design is important in OFDM because the bandwidth efficiency and channel estimation accuracy depend on the number of pilot symbols. When comparing different pilot patterns in DVB-T2 systems, it can be concluded that there are more pilot cells distributed in the OFDM symbol in PP1 than in PP1, which means that the system using PP1 can obtain more accuracy of frequency response for the frequency selective channel [24]. In the DVB-T2 system with pilot pattern (PP1), the scattered pilots used for channel estimation are distributed in both time and frequency domains. For the channel estimation method, LS is typically used in DVB-T, while MMSE is used in DVB-T2 [25]. The MMSE channel estimation is often considered as the reference method because its performance is almost as accurate as the perfect estimation [26, 27]. MMSE is a channel estimation method designed to minimize the mean square error between the estimated signal and the actual signal. This method exploits the statistical properties of the signal and noise to produce an accurate channel estimate. MMSE is effective in suppressing noise for known channel characteristics. The MMSE-based channel estimation $\widehat{\boldsymbol{H}}_{\boldsymbol{MMSE}}$is achieved by minimizing the MSE [28]:

$$\min E\{\|\widehat{\boldsymbol{H}}_{\boldsymbol{MMSE}} - \boldsymbol{H}\|^2\} \quad (8)$$

where E is the expectation operator. Using the LS-based channel estimation, the MMSE-based channel estimation method can be derived as [28]:

$$\widehat{\boldsymbol{H}}_{\boldsymbol{MMSE}} = \boldsymbol{R}_{\boldsymbol{HH}}(\boldsymbol{R}_{\boldsymbol{HH}} + \sigma_z^2 I_N)^{-1}\widehat{\boldsymbol{H}}_{\boldsymbol{LS}} \quad (9)$$

where $\boldsymbol{R}_{\boldsymbol{HH}}$ is the autocorrelation of the channel frequency response, where the LS channel estimation is [28]:

$$\widehat{\boldsymbol{H}}_{\boldsymbol{LS}} = \frac{1}{N_s}\sum_{i=0}^{N_s-1}[\boldsymbol{H} + \boldsymbol{X}^{-1}(i)\boldsymbol{z}(i)] \quad (10)$$

with $\boldsymbol{X}(i)$ is $N \times N$ diagonal matrix, $\boldsymbol{H}$ is the vector of channel frequency responses across N sub-carriers, and $z(i)$ is AWGN vector. The MMSE is regarded as an effective method for equalization due to its reliable performance (26). The implementation of MMSE in the DVB-T2 system utilizing HST channels represents an advancement to previous research (29). The MMSE mitigation framework, as part of the proposed system model, is presented in Figure 4.

III. RESULTS AND DISCUSSION

A. BER vs SNR Performance in Terms of Speed Variation using HST Channel

The collective impact of the aforementioned HST channel attributes is evidenced by the BER versus SNR outcomes presented in Figure 5. The Doppler effect is relatively weak at lower train speeds (10 m/s to 30 m/s), which enables the system to attain lower BER at moderate SNR values. Nevertheless, the Doppler shift becomes more pronounced as the train speed increases to 100 m/s, resulting in a higher BER, particularly at low SNR values. The limitations of standard OFDM in maintaining signal fidelity under extreme mobility conditions are underscored by this degradation. The highly dynamic nature of the HST channel, marked by severe Doppler shifts and multipath propagation effects, poses unique challenges. These factors are a result of the train's high mobility (up to 100 m/s in the study presented) and the diverse environmental conditions it encounters, including rural macrocells, tunnels, mountainous terrains, and urban areas. The orthogonality of OFDM subcarriers is significantly impacted by the Doppler shift in HST environments, leading to ICI and a decline in system performance. Additionally, the non-stationary characteristics of the channel result in time-variant frequency selectivity, further complicating signal transmission and reception.

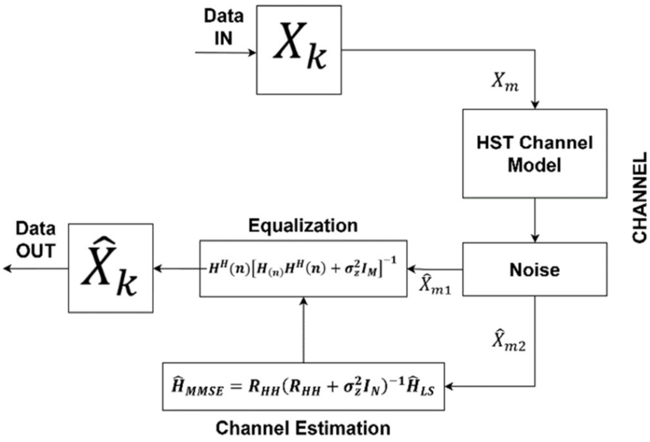

Fig. 4. The MMSE mitigation system.

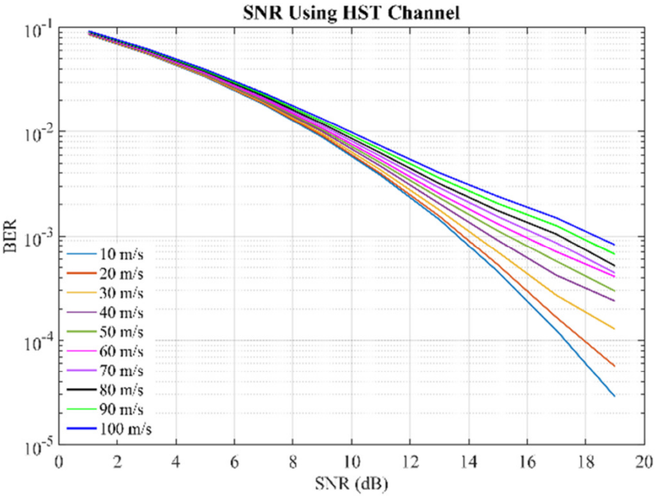

Fig. 5. BER vs SNR performance at various speeds using HST channel.

In order to overcome these challenges, it is imperative to incorporate powerful channel coding and estimation techniques, such as LDPC and BCH coding, in conjunction with MMSE channel estimation. LDPC coding has been shown to effectively mitigate random errors by providing robust FEC, even in the presence of severe ICI, due to its sparse parity-check matrix. The adaptability of LDPC to variable channel conditions is attributable to its capacity to support diverse code rates, thereby achieving an equilibrium between the intensity of error correction and the rate of data transmission. The efficacy of BCH coding in mitigating burst errors, a prevalent phenomenon in HST channels due to sudden variations in channel conditions, is noteworthy. Such conditions may arise during transitions from open areas to tunnels. The two-stage FEC process employs BCH as the outer coding and LDPC as the inner coding, facilitating the effective correction of both random and burst errors. This, in turn, results in a substantial reduction in the total BER. The system's capacity to accommodate the HST channel's time-varying nature is further enhanced by MMSE channel estimation, which compensates for Doppler-induced distortions and assists in preserving subcarrier orthogonality by precisely estimating the channel's frequency response using pilot symbols. Adaptive equalization, which dynamically modifies the receiver parameters to mitigate the residual effects of multipath fading and Doppler shift, is particularly effective when combined with this estimation. The results illustrate the synergy between estimation and channel coding in surmounting the inherent obstacles of the HST channel. For instance, the BER curves for all train speeds converge at higher SNR values (>15 dB), which suggests that the combined mitigation techniques are effective in stabilizing system performance. This convergence underscores the efficacy of the proposed system design in facilitating reliable communication by employing precise channel estimation and robust error correction, despite the adverse conditions of the HST channel. Collectively, these methods enhance the resilience of DVB-T2 systems, ensuring high-quality digital broadcasting in challenging environments and during extreme train velocities.

B. BER vs SNR Performance in Terms of Modulation Type Variation

As shown in Figure 6, the BER performance of DVB-T2 systems employing diverse modulation methods (16-QAM, 64-QAM, and 256-QAM) is demonstrated. The simulations were executed in a HST channel configuration with a velocity of 10 m/s and 10 scatterers, using LDPC and BCH channel coding, as well as MMSE channel estimation. This research demonstrates the trade-off between spectral efficiency and noise tolerance for each modulation technique. At lower SNRs, higher-order modulation schemes, such as 256-QAM, have a much larger BER than 16-QAM and 64-QAM. This is due to greater symbol density in higher-order constellations, which reduces the Euclidean distance between symbols, making them more vulnerable to noise and channel impairments. For instance, at a SNR of 5 dB, the BER for 256-QAM is approximately one order of magnitude greater than that of 64-QAM and two orders higher than that of 16-QAM. However, at higher SNR values (>15 dB), the BER performance of all three modulation techniques increases, indicating the efficacy of the combined LDPC and BCH coding in error mitigation. The application of LDPC and BCH coding is imperative for enhancing the resilience of DVB-T2 systems in such challenging scenarios. LDPC coding uses a sparse parity-check matrix, which facilitates robust error correction, ensuring successful transmission even in the presence of substantial noise and interference. BCH coding serves to complement LDPC by addressing burst errors, particularly those arising from rapid channel fluctuations due to the Doppler effect in HST contexts. The integration of these two coding methods establishes a multifaceted FEC framework, thereby ensuring the effective mitigation of BER across a comprehensive range of modulation schemes. The MMSE channel estimation technique has been shown to reduce the influence of multipath fading and Doppler-induced distortions by precisely estimating the channel response. This technique ensures the orthogonality of OFDM subcarriers, thereby reducing ICI and improving overall system performance. In comparison with prior investigations on DVB-T2 systems in high-mobility situations, the results presented here demonstrate a substantial enhancement in BER performance. For instance, authors in [11] employed adaptive equalization methods to demonstrate substantial BER reduction for 256-QAM at low SNR values in HST scenarios. Similarly, authors in [15] observed that higher-order modulation schemes, such as 256-QAM, were nearly ineffective in channels with a substantial number of scatterers in the absence of robust channel coding. In contrast, the present study's usage of LDPC and BCH coding facilitates 256-QAM attaining an acceptable BER (below 10^{-3}) at an SNR of 15 dB, thereby substantiating the efficacy of the proposed mitigation measures.

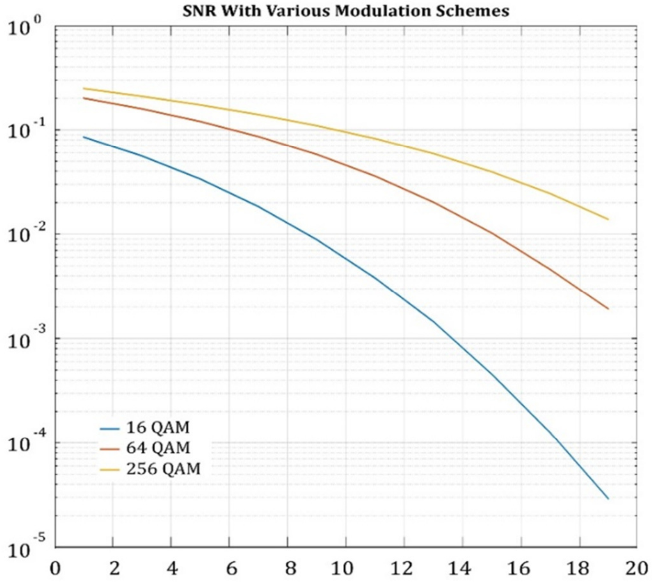

Fig. 6. BER vs SNR performance with various modulation schemes.

C. BER vs SNR Performance in Terms of Number of Scatterers using HST Channel

As presented in Figure 7, the BER performance is characterized as a function of the SNR for a HST channel with varying scatterer counts (5, 10, 20, and 50). The simulation is predicated on a 16-QAM modulation system with a train velocity of 10 m/s, employing error correction via LDPC and BCH coding. The present study focuses on the effects of multipath scattering on system performance in high-mobility situations. As the number of scatterers increases, the BER performance degrades across all SNR values. For channels with fewer scatterers (5 scatterers), multipath effects are minimal, resulting in less severe ISI and more consistent BER performance. At higher SNR values (>15 dB), the BER for 5 scatterers approaches 10^{-5}, demonstrating strong performance in low multipath environments. Conversely, for channels with 50 scatterers, the presence of a dense multipath environment leads to substantial ISI and amplitude fading, resulting in elevated BER levels. This is evident even at an SNR of 20 dB, where the BER exceeds 10^{-3}, underscoring the constraints imposed by complex channel conditions.

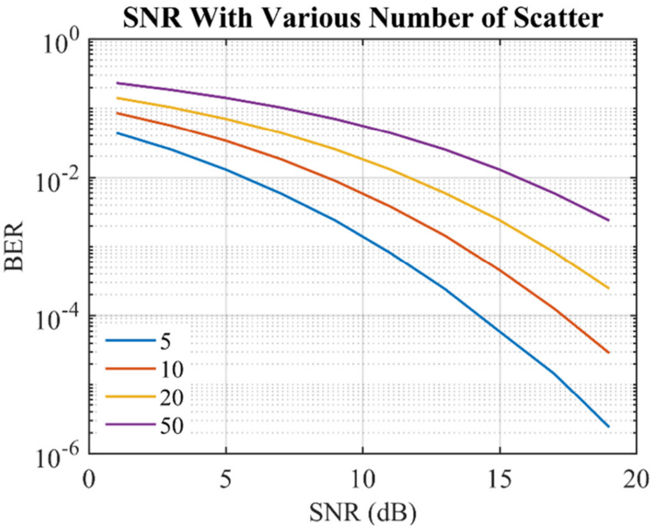

Fig. 7. BER vs SNR performance in terms of various number of scatterers.

The integration of BCH coding and LDPC is imperative for mitigating the effects of multipath fading. LDPC coding effectively corrects random errors by using its sparse parity-check matrix, whereas BCH coding resolves burst errors, ensuring reliable communication in challenging environments. In scenarios with fewer scatterers, where the multipath effects are less pronounced, these two-layered FEC mechanisms are particularly effective. The results of this study underscore the crucial impact of scatterers on the BER performance of HST channels. Although LDPC and BCH coding, when employed in conjunction with MMSE estimation, can effectively mitigate the adverse effects of multipath scattering, their efficacy is inherently constrained in highly dispersive environments. These results underscore the significance of optimizing the quantity of scatterers in channel modeling to achieve a balance between computational efficiency and realism. To further enhance system performance under variable scatterer conditions, future research should explore the potential of adaptive modulation and coding schemes. As indicated by numerous studies in the relevant literature, the number of scatterers in high-mobility channels is directly proportional to the degradation of BER performance, even when employing advanced channel estimation techniques [15].

Authors in [11] demonstrated that the presence of dense scatterers in the environment introduces higher levels of complexity in the processes of equalization and error correction, thereby limiting the effectiveness of FEC techniques at lower SNR values. In contrast to these studies, the results presented here demonstrate that the integration of LDPC, BCH, and MMSE estimation yields competitive BER performance, particularly for channels with moderate scatterer densities (10–20 scatterers). The accurate anticipation of the channel response, as facilitated by MMSE channel estimation, further enhances system performance. This estimation process mitigates ICI by compensating for Doppler-induced distortions and preserving the orthogonality of OFDM subcarriers. However, the performance disparity observed in the graph is partially accounted for by the increasing complexity of channel estimation as the number of scatterers increases.

IV. CONCLUSIONS

The present study focuses on enhancing the performance of DVB-T2 in High-Speed Train (HST) communication systems, addressing significant challenges such as Doppler shifts and multipath effects resulting from train speeds exceeding 300 km/h. The integration of advanced techniques, such as Low-Density Parity Check (LDPC) and Bose-Chaudhuri-Hocquenghem (BCH) channel coding, along with Minimum Mean Square Error (MMSE) channel estimation, has been demonstrated to achieve substantial reductions in Bit Error Rates (BER) across a range of modulation schemes, including 16-QAM, 64-QAM, and 256-QAM, under diverse environmental conditions. The efficacy of these methods is demonstrated by their ability to effectively mitigate random and burst errors, maintain the orthogonality of Orthogonal Frequency Division Multiplexing (OFDM) subcarriers, and combat the adverse effects of Inter-Carrier Interference (ICI) caused by Doppler shifts. The inclusion of equalization further enhances the system's ability to adapt to dynamic channel variations, ensuring stable communication performance even in highly dispersive environments with varying scatterer densities. The findings demonstrate a reliable framework for sustaining high-quality DVB-T2 broadcasting in extreme mobility conditions, offering practical applications for intelligent transportation systems worldwide and setting a benchmark for advanced digital broadcasting in high-speed scenarios.

ACKNOWLEDGMENT

This research is supported and funded by the Ministry of Research, Technology and Higher Education of Indonesia.

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