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Modeling and Analysis of Error Process in 5G Wireless Communication Using Two-State Markov Chain

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ABSTRACT In fifth-generation wireless communications, data transmission is challenging due to the occurrence of burst errors and packet losses that are caused by multipath fading in multipath transmissions. To acquire more efficient and reliable data transmissions and to mitigate the transmission medium degradation in the 5G networks, it is important to study the error patterns or burst the error sequences that can provide insights into the behavior of 5G wireless data transmissions. In this paper, a two-state Markov-based 5G error model is investigated and developed to model the statistical characteristics of the underlying error process in the 5G network. The underlying 5G error process was obtained from our 5G wireless simulation, which was implemented based on three different kinds of modulation methods, including QPSK, 16QAM, and 64QAM, and was employed using the LDPC and TURBO coding methods. By comparing the burst or gap error statistics of the reference error sequences from the 5G wireless simulations and those of the generated error sequences from the two-state Markov error model, we show that the error behaviors of the coded OFDM 5G simulations can be adequately modeled by using the two-state Markov error model. Our proposed two-state Markov-based wireless error model can help to provide a more thorough understanding of the error process in 5G wireless communications and to evaluate the error control strategies with less computational complexity and shorter simulation times.

INDEX TERMS 5G, burst error statistics, two-state Markov model, wireless error model.

I. INTRODUCTION

The fifth generation of wireless technology promises to greatly enhance the speed, coverage and responsiveness of wireless networks [6]. Users have high expectations for future 5G mobile networks with respect to the technology being as simple as possible and providing more functions.

To achieve improvements in network facilities with respect to bandwidth, spectral, energy and signalling efficiencies and reliability, fifth generation network technology needs to utilize an efficient waveform in order to meet the user demands [7]. Orthogonal frequency division multiplexing (OFDM) is obviously a powerful multiplexing technique that is a baseline standard technology of high performance wireless transmissions. Although OFDM can reduce the effects of multipath fading and intersymbol interference (ISI) by inserting the cyclic prefix (CP), the intrablock OFDM symbol interference has remained as an important factor in degrading the error performance of OFDM systems [22]. A major solution is to combine a coding method with the OFDM system in order to improve the bit error rate (BER) performance of the data transmission system by recovering the data symbol losses. Another major drawback of OFDM systems is their large peak to average power ratio (PAPR), which causes nonlinear distortions in the transmission process. Performance degradation followed as a consequence. To reduce OFDM errors, such as subcarrier losses, large PAPRs, data symbol losses, intersymbol interference (ISI), etc., channel coding methods become a major solution in this research area. Turbo-code, LDPC code and convolutional code are significant coding methods in the existing studies [20]–[23].

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To evaluate the performance of channel coding methods in next generation wireless communications networks, it is important to explore the behavior of enhanced physical channels and the impacts of the errors in binary data transmissions. There are two types of channels in the wireless data transmission system: physical channels and binary channels. The performance of physical channel models, such as Rayleigh and Rice models, is evaluated using parameters such as the received signal strength, the signal to noise ratio, etc. [26]. For the binary channel models, the channel is characterized using error statistics in terms of burst errors or error clusters. The performance of binary channels is evaluated using the bit error rate (BER) or packet error rate (PER) [16]–[18]. For the performance evaluation of the binary data transmission system, the study of the underlying burst error process and the exploration of the statistical dependencies among errors are important prerequisites.

The statistical and deterministic approaches are employed to model the physical channel characteristics of 5G wireless channels and the statistical characteristics of the error patterns are investigated in order to model the binary channels in 5G wireless transmissions. Knowledge of the error patterns, such as single bit error patterns and burst error patterns, can promote the optimization of wireless data transmissions. For modeling the burst error sequence, the mathematical channel model, which can be divided into the descriptive and generative models, is needed [27]. The statistics of the burst error sequences, which are obtained directly from real digital wireless channels or from computer simulations implementing the entire communication link, can be expressed by using descriptive models. By assessing the error statistics of the descriptive model, the generative models can generate similar burst error sequences [28], [29].

In this work, a simulation model was established and evaluated [8] in order to support the design of the coded OFDM 5G simulation. The statistical behaviors of the reference error sequences produced by this simulation model were studied in a descriptive way in order to achieve a better and more reliable communication model. Then, the precise generative error model was proposed using the discrete time, two-state Markov model in order to find more accurate burst error statistics and the optimal way to improve the bit error rate (BER) performance in 5G wireless communications. After comparing the error burst and error gap statistics of the descriptive model and those of the generative model and discovering similar characteristics, it could be concluded that the error process of the coded OFDM 5G simulation can be effectively modeled using a two-state Markov chain.

The main motivation of this paper is to investigate and model the errors in the coded OFDM 5G simulation model in order to achieve more accurate and better performance for the data transmissions of 5G networks. The contributions of this paper are the coded OFDM 5G simulation based on LDPC and Turbo coding [8], analyzing the error process in a descriptive manner based on the reference error sequences of 5G simulations and proposing the generative error model based on two-state Markov chains. The results show that our error models can accurately represent the errors of coded OFDM 5G networks. These error models can be applicable to evaluating and implementing error control mechanisms in order to save both costs and time because we don't need to execute the whole simulation and can generate the accurate error sequence by using proposed error model.

This paper is organized as follows. In section 2, some work related to our studies is reviewed. In the next section, the coded OFDM 5G simulation model that we have proposed [8] is briefly explained. In section 4, the analysis and results of the LDPC and Turbo coding methods for 5G OFDM simulations are discussed. Then, the two-state Markov-based error model and our proposed error model are explained in section 5. As a final subsection of section 5, the parameter estimation model is described. In section 6, our simulation results and analytical results are discussed. Finally, the conclusions that show that our simulation model is consistent with the proposed analytical model are described in section 7.

II. RELATED WORK

In next generation wireless communications, the fifth generation technology has evolved as a basic standard technology with prominent high performance characteristics such as a high data transmission rate, low latency, manifold increase in system capacity, energy savings and new, improved QoSs [24], [25], [30]. Although the existing studies have assessed the developments of the above potential key technologies, many challenges still remain, such as interference management, channel modeling and the signal processing complexity in data transmissions [24].

Previous research has determined that the modulation constellation, coding scheme, and channel and resource allocation are key drivers for improving the transmission technology and the above research challenges depend on factors such as the transmission power, transmission time, channel conditions, coding and modulation [30]. To overcome these challenges, channel coding schemes and the combination of channel coding with the OFDM system in next generation wireless transmissions have been analysed in the previous studies [8], [20]–[22].

Likewise, channel modeling or error modeling and exploring the error statistics have become promising research topics in this area. To improve the BER performance of digital wireless transmissions, the error patterns and their statistics have been explored and error models have proposed [15]–[18]. The influence of the bit error process on packets based on their length was analysed by investigating the packet error process and establishing a 2-state Markov process over a 2-state Markov error channel [1]. The modeling of the performance of error correction codes was performed under random and burst errors. A closed form solution provided the parameterization for the 2-state Markov model.

Ling-Jyh and Hao-Hsiang [2] investigated the two error models for Bluetooth networks by using two FHSS kernels, the ordinary hopping kernel and the AFH hopping kernel.

The Markov Chain Monte Carlo (MCMC) method was used to evaluate the proposed model and to prove the consistency of the simulation and analytical methods.

The BER analysis of the Digital Audio Broadcasting (DAB) system for convolutional coded and turbo coded OFDM in an Additive White Gaussian Channel (AWGN) was performed in [3].

The burst error behavior and error profile of Discrete Time simulations were studied for fading channels by applying a tri-state memory-less Markov Model in [4], which evaluated the performance of the error-correction code over the different packet sizes with the bit error rate. The research proved that the longer the data packets, the longer the burst errors and that the larger the packet size, the larger the Bit Error Rate (BER). The experiment was conducted using different packet sizes, such as 300 bits, 1200 bits, 4800 bits and 19200 bits.

The burst errors were modeled by using generative and descriptive (analytical) methods with real wireless transmitted packages in [5]. To capture the error behavior of error bursts and error gaps, Elliot's model was applied for the generative and gamma distribution models and the Markov modulated Poisson process (MMPP-2) was applied for descriptive methods. According to the experimental result, the MMPP-2 model is closer to the channel trace and theoretically can be even more precise than Elliot's model.

The generative error models have proposed based on three widely used generative models, namely, the Simplified Fritchman Model (SFM), the Baum-Welch based Hidden Markov Model (BWHMM), and the Deterministic Process Based Generative Model (DPBGM), and by considering factors such as the detection threshold, parameterizations and parallel mapper [16]–[18]. They proved the effectiveness of their proposed models by showing the well-matched characteristics when comparing the reference error statistics of the underlying descriptive models with those of the generative models with respect to both the burst error statistics and BER performance of the coded digital wireless transmission system.

According to the literature reviews, error modeling using the real simulation model is the most prominent research area for improving wireless data transmissions in future network technologies. For the purpose of assisting the error control schemes in order to reduce transmission errors and attain better performance in 5G networks, the two-state Markov error model is proposed and evaluated based on our coded OFDM 5G simulation in this paper.

III. DESCRIPTION OF THE CODED OFDM 5G SIMULATION

A simulation framework of the coded OFDM system that conforms to the 5G specifications was presented in our previous work [8] and is shown in Fig. 1. The 5G specifications were released by the Verizon 5G Technology Forum (Verizon 5th Generation Radio Access; Test Plan release 1) [14]. As the coding methods, the LDPC and Turbo coding methods were employed and analysed using this simulation framework.

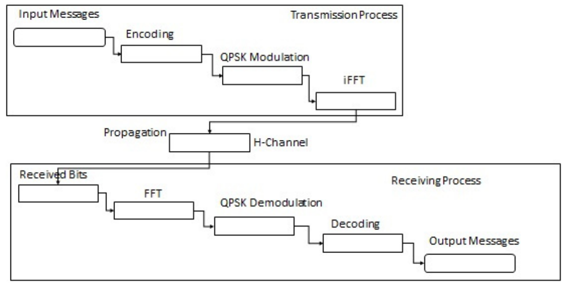

FIGURE 1. Coded OFDM system flow diagram.

For the coded OFDM 5G system, OFDM propagation in the AWGN channel with multi path fading was considered. OFDM was performed using a 28 GHz frequency band and a bandwidth of 100 MHz. OFDM with 1200 subcarriers and 75KHz subcarrier spacing was selected and the QPSK, 16QAM and 64QAM modulation techniques were selected for the 5G wireless simulation and the analysis of the proposed model. According to the Verizon 5GTF release 1, the experiment was conducted using these three modulation schemes over a 5G OFDM simulator with an FFT size of 2048 because the FFT size of 2048 is the standard FFT size of the Verizon 5G specifications.

In the coded 5G data transmission system, the input data signals are binary series of digital signals. The input signals, which include k information bits, are encoded by the encoder. The coded information ((k bits) plus extra bits (x bits)) is modulated using three kinds of modulation methods, QPSK, 16 QAM and 64 QAM, and then serial to parallel conversion is performed for the mapping with the N subcarrier channels. Inverse fast Fourier transform (iFFT) is carried out to convert the information from the frequency domain to the time domain. In a multipath environment, the OFDM transmission process is performed over the AWGN channel. After converting the received time domain signals to frequency domain signals by using the FFT, the information bits are demodulated employing demodulation methods. The original bits are restored after decoding the demodulated signals.

In the proposed coded 5G data transmission system, we represent the code rate as $R = k/n$, where n is the number of variable nodes and m is the number of check nodes for both coding methods. The parity check matrix H is constructed using the code word length (m,n). K is the information bits, where $K = \{K_o, K_1, K2, \ldots, K_{n-1}\}$, and the code word is represented by C, where $C = \{C_o, C_1, C_2, \ldots, C_{n-1}\}$. The length of the encoded bits is $L = K^* 1/R$, and the encoded bits are represented by E, where $E = \{E_o, E_1, E_2, \ldots, E_{L-1}\}$. The modulation process is conducted in order to map the encoded bits using the number of sub carriers N. According to the modulation factor F, the length of the modulated bits can be calculated by the following equation 1:

$$L(\text{mod } i) = E/F_i, \tag{1}$$

where i is the modulation method of $F_i = \{F_1, F_2, F_3\}$, which includes the three modulation methods of QPSK, 16 QAM and 64 QAM that are used in our simulation. The OFDM 5G wireless simulation is conducted with these modulation methods.

In 5G specifications, the actual number of subcarriers N does not map with the modulated bits and it has n fewer bits than the number of sub carriers N. To map it with the N sub carriers in OFDM 5G propagation, we use

$$L_c(\text{mod } i) = E/F_i + N/2 \tag{2}$$

In uncoded OFDM 5G communications, the number of information bits in the input signal is represented as B, where $B = \{B_0, B_1, B_2, \ldots, B_{n-1}\}$. According the modulation factor, F, the length of modulated bits can be determined by equation 3.

$$L_u(\text{mod } i) = B/F_i \tag{3}$$

Here, $L_c > L_u$.

Next, the modulated bits are converted into the time domain using iFFT with the FFT size. These coded OFDM 5G simulations are tested using both FFT sizes of 1024 because of the fast running time and 2048 because of it being a 5G standard. In the receiving process, the reverse operation for the bit sequence operations was performed.

In coded OFDM, the LDPC encoder generates the code word and parity check matrix H and the encoded bit length is twice that of the original input signal length n if we use the code rate 1/2. For example, for the input signal length of 1200 bits, the fft size is 2048 and the number of encoded bits is 2400. This observation reflects the close relationship between the coding theory, modulation techniques and Fast Fourier Transform (FFT).

IV. ANALYSIS OF LDPC AND TURBO CODING METHODS ON OFDM 5G SIMULATION

In OFDM modulation, the input data bits are converted so that they can be mapped into the sub carrier's amplitude and phase using modulation techniques such as BPSK, QPSK or QAM. In this work, according to the Verizon 5GTF release 1, the three modulation schemes of QPSK, 64 QAM and 16 QAM are considered as the physical channels. The simulation parameters for the coding process are as given in Table 1. The LDPC-coded 5G OFDM simulation is compared with the uncoded 5G OFDM simulation based on the three modulation techniques and the results are shown in Fig. 2.

According to the simulation results, it can be found that QPSK provides the best performance as measured by the BER among the three modulation methods. Moreover, we discover that the BER performance is better for the LDPC-coded OFDM with an FFT size of 2048 compared to the uncoded OFDM with the same FFT size for all modulation methods. In addition, the simulation was also performed using these three modulations schemes for the Turbo-coded OFDM simulation. The obtained simulation results were compared with the uncoded OFDM in 5G, as depicted in Fig. 3.

TABLE 1. Simulation parameters.

Parameter		Values
Coding Schemes		LDPC & Turbo
Code Rate		1/2
Code length/FFT size		1200/2048
Decoding Methods	LDPC	Sum-product decoder
	Turbo	BCJR

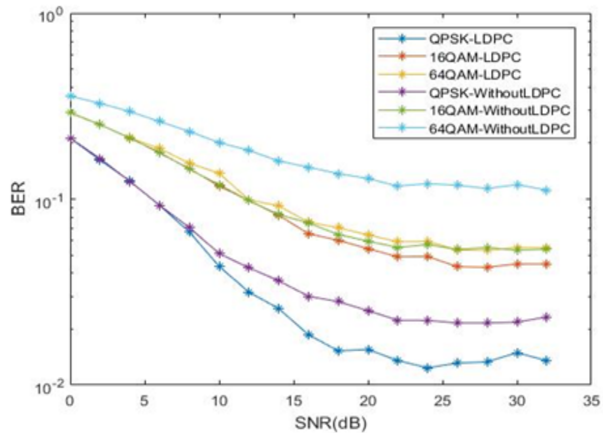

FIGURE 2. BER comparison of the LDPC coded OFDM and uncoded OFDM (fft = 1024).

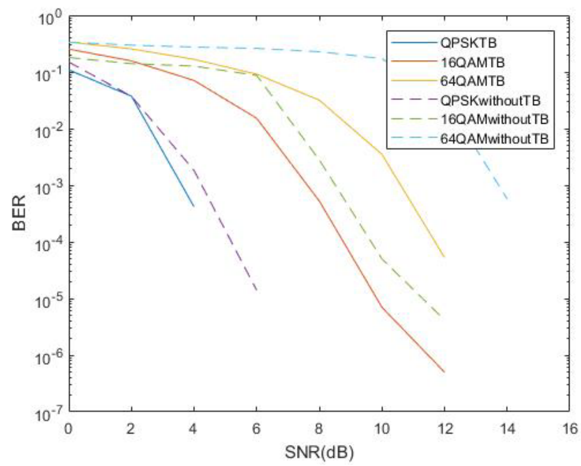

FIGURE 3. BER comparison for the TURBO coded OFDM and uncoded OFDM (fft = 1024).

By comparing the Turbo-coded OFDM with the uncoded OFDM in 5G, it can be discovered that OFDM in 5G using the Turbo performs better for the three modulation methods than the OFDM in 5G without using the coding technique. QPSK gives the lowest BER for the three different modulation methods in both FFT sizes. With respect to the two different FFT sizes, the Turbo-coded OFDM simulation results have a lower

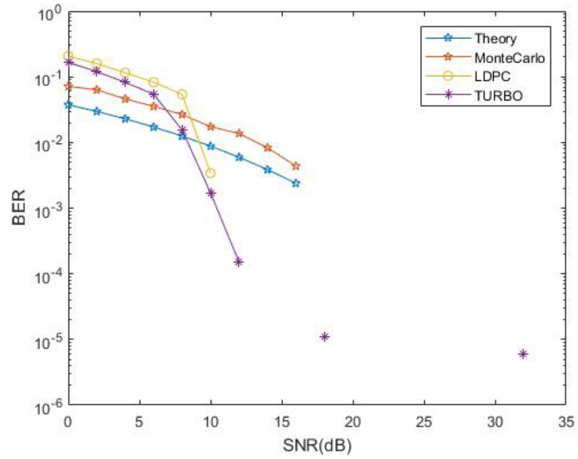

FIGURE 4. BER comparison for the LDPC-coded OFDM Vs turbo coded OFDM (fft = 2048).

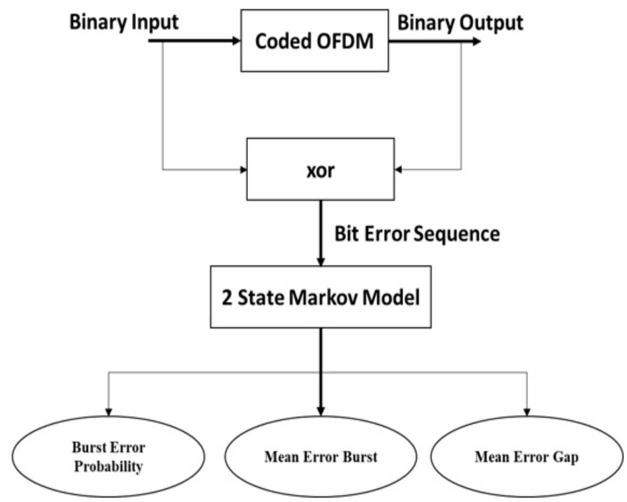

FIGURE 5. Two-State markov-based wireless error model.

BER for the FFT size of 2048 than the uncoded OFDM with same FFT size. From this observation, it can be concluded that both coding methods can give lower BER rates and better performance than the uncoded OFDM.

Finally, the comparison of the simulation results for the LDPC-coded OFDM and the Turbo-coded OFDM for the 5G simulation is shown approved the simulation results by using Monte Carlo and theoretical BER Simulation Results in Fig. 4. In the existing research that analyses the coding methods in OFDM simulations [12], [13], turbo coding achieved a better result than LDPC coding. In this simulation, the Turbo-coded OFDM has a lower bit error rate than the LDPC-coded OFDM.

From our simulation results, one is encouraged to select the Turbo codes for the channel coding in 5G wireless networks conforming to the 5G specifications that were released by the Verizon 5G Technology Forum (Version 5th Generation Radio Access; Test Plan release 1) [14]. By using Turbo codes for the 5G channel coding, it is possible to implement 5G wireless networks with lower costs because of the backwards compatibility with 3G and 4G technology.

V. THEORETICAL BACKGROUND AND PROPOSED MODEL

A. ERROR MODELING

To assess the realistic error behaviors in the coded simulation, a statistical or deterministic precise error model is needed. By investigating the error process, useful knowledge will be gained for the error control and adjustment processes in specific situations of wireless communications. In this work, a discrete Markov model-based error analysis model is proposed, as shown in Fig. 5.

In the data transmission process, X_i is the digital input sequence and Y_i is the corresponding output sequence. As an output sequence including error sequences, Y_i can be considered a binary discrete-time stochastic process and N_i can be considered the noise sequence representing the effect of the multipath channel on the data packets. Then,

$$Y = X + N \tag{4}$$

The error process of the data transmission is considered as a binary discrete time stochastic process. The binary input is the set of X,

$X = [x_1, x_2, \cdots, x_k, \cdots]$, where $X_k \triangleq k^{th}$ is the channel input.

The binary output is the set of Y, $Y = [y_1, y_2, \cdots, y_k, \cdots]$, where $y_k \triangleq k^{th}$ is the channel output

The effective noise on the data packets is $N = [n_1, n_2, \cdots, n_k, \cdots]$, where $n_k \triangleq k^{th}$ is the channel noise.

The probability of an error occurring in the data transmission is PE, $PE = [PE_1, PE_2, \cdots, PE_k, \cdots]$, where $P_k \triangleq$ is the probability of an error in the k^{th} symbol transmission.

For a binary data transmission channel, the input-output relationship can be expressed as

$$E = X \oplus Y \tag{5}$$

where $E = \{e_1, e_2, e_3, \cdots, e_k, \cdots\}$ is a binary vector or sequence having the elements {0, 1}. A correctly received bit is defined as "0", and an incorrectly received bit is defined as "1'. Therefore,

$e_k = 0$ denotes that the k^{th} element of X, x_k, is received correctly ($y_k = x_k$) and $e_k = 1$ denotes that the k^{th} element of X that is received has an error ($y_k \neq x_k$). The error sequence can be generated randomly by threshold

$$e_k = \begin{cases} 1 & U_k \leq P_k \\ 0 & U_k \geq P_k \end{cases}$$

where U_k = the number obtained from the k^{th} call to the random number generator.

For modeling the error sequences, the model parameters can be estimated and the expressions can be derived from the burst error statistics and the burst error distributions.

The burst error statistics can be calculated by using the second order statistics, which are extracted from small parts of that error sequences. According to the literature, error sequences are composed of the two classes of consecutive errors and error-free sequences, which are called error bursts and error gaps, respectively. An error gap is a sequence of consecutive zeros between two ones that has a length equal to the number of zeros. An error burst is a series of errors that includes ones and zeros and is restricted by "1" s at the edges. They are defined over the observable length, m.

In an error sequence, $E = \{e_1, e_2, e_3, \cdots, e_k, \cdots\}$, where $e_k = 1$ indicates that a transmission error occurred in the k^{th} transmitted bit, and $e_k = 0$ indicates that the k^{th} symbol is transmitted correctly. These two natures can be expressed as follows:

$(0^m|1)$ represents that error-free transmissions occurred following an error by observing m or more consecutive bits, and

$(1^m|0)$ represents that consecutive error transmissions occurred following an error-free transmission with m or more consecutive bits.

The probabilities of occurrence of these two events are given by the sum of weighted exponentials as follows:

$$Pr\left(0^m \mid 1\right) = \sum\nolimits_{i=1}^{k} f_i \lambda_i^{m-1} \tag{6}$$

$$Pr\left(1^m \mid 0\right) = \sum\nolimits_{i=k+1}^{N} f_i \lambda_i^{m-1} \tag{7}$$

where λ_i, where $i = 1, 2, \cdot \cdot\cdot, k$, and λ_i, where $i = k+1, k+2, \cdots, N$, are the eigenvalues of the state transition probabilities A_{gg} and A_{bb}, respectively, and the corresponding values of f_i are functions of the $a_{ij,}$ elements of the state transmission matrix.

B. TWO STATE MARKOV ERROR MODEL

For modeling the error process of a coded OFDM data transmission, the discrete-time, two-state Markov model (MM) is applied, as shown in Fig. 6. In this work, wireless communication channels are considered as the discrete communication channels and the error process is a simple two-state Markov model. In this model, there are two-states: good states and bad states. If the data transmission is error free, it is assumed to be in the good state, and if an error occurs, it is considered to be in the bad state with the bit error probability of h. The state

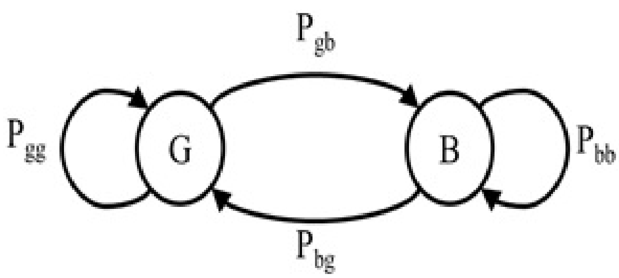

FIGURE 6. **Two-State Markov model.**

can be represented by the following set:

$$S = \{G, B\}.$$

Given that the data transmission started at the initial state St, since the time is continuous, the state will proceed to the next state S_{t+1} at time $t + 1$. We can express the discrete time T as the set of times t

$$T = [t, t+1, t+2 \cdots, t+k]$$

and the set of the states as

$$S = [S_t, S_{t+1}, S_{t+2} \cdots, S_{t+k}]$$

At the initial state, the channel might be in a good state or a bad state. At the transition of a new state for a new bit, it will change to a new state or remain in the same state. The state transition will occur with a set of transition probabilities, P_{ij} (t). We expressed the four transition probabilities as follows:

$$\begin{aligned} P_{gg}(t) &= Pr\{S_{t+1} = g|St = g\} \\ P_{gb}(t) &= Pr\{S_{t+1} = b|St = g\} \\ P_{bb}(t) &= Pr\{S_{t+1} = b|St = b\} \\ P_{bg}(t) &= Pr\{S_{t+1} = g|St = b\} \end{aligned}$$

This can be represented by the state transition matrix.

$$A\,(t) = \begin{vmatrix} P_{gg} & P_{gb} \\ P_{bg} & P_{bb} \end{vmatrix}$$

We define Π_t as the state probability distribution at time t. Specifically,

$$\Pi_t = [\pi_{t,g}\pi_{t,b}],$$

where π is the steady-state vector that expresses the total percentage of a state in a Markov chain. This vector can be computed by raising P to a large power:

$$P^n \rightarrow 1\pi$$

Here, the sum of πi must equal to one.
P is the probability transition matrix.
Π is the steady state probability vector.
1 is the column vector of ones: 1T = (1, 1,...).
Then, the error generation matrix is defined as

$$Er = \begin{vmatrix} \Pr\{c/g\} & \Pr c\{c/b\} \\ \Pr\{e/g\} & \Pr\{e/b\} \end{vmatrix}$$

where "c" denotes that a correct decision is made and "e" denotes that an error is made.

By simple matrix multiplication, it follows that the unconditional probability of a correct decision Pc and an error Pe are given by

$$|P_cP_e| = \Pi_t Er^T \tag{8}$$

where Π_t is the steady-state state distribution matrix and Er ^{T} is the transpose of the error generation matrix Er.

C. ESTIMATION OF MARKOV MODEL PARAMETERS

In the parameter estimation of the Markov Model, the Baum-Welch forward-backward algorithm is a well-known and obvious method [9], [10]. It supports the mitigation of the computational complexity in the evaluation of all the states of the model using the training data. The Baum-Welch algorithm was established based on the computations of two different probabilities, the forward path probability and the backward path probability. By using these probabilities, the parameters of the proposed Markov model can be estimated.

The Markov model for a discrete channel is described using the N × N state transition matrix A and the M × N error probability generation matrix E. An iterative procedure for estimating these parameters $\Gamma = \{A, Er\}$ from a given error sequence is obtained using the coded OFDM 5G simulation

$E = \{e_1, e_2, e_3, \cdots, e_t, \cdots, e_T\}$, based on the Baum-Welch algorithm [11]. This iterative algorithm is designed to converge to the maximum likelihood estimator of $\Gamma = \{A, Er\}$ that maximizes $\Pr(Er|\Gamma)$.

The parameters of BMW, which are the estimates of the elements of the state transmission matrix and the estimates of the elements of the error generation matrix, can be computed as follows:

$$P_{ij} = \frac{\text{expected number of transitions from i to j}}{\text{expected number of transitions from i}} \tag{9}$$

$$Er(e_k) = \frac{\text{expected number of times} e_k \text{is occuredin state j}}{\text{expected number of visit to state j}} \tag{10}$$

To prevent numerical underflow, the forward and backward variables of the Baum-Welch algorithm are scaled using the scaling constant vector Ct. We can define the scaling constant vectors for the forward variable αt and the backward variable βt as follows:

$$C_t = \sum\nolimits_{i-1}^{N} \alpha_t \tag{11}$$

$$C_t = \sum\nolimits_{i-1}^{N} \beta_t \tag{12}$$

Defining the stopping criteria is a critical challenge for iterative methods. Since the Baum-Welch algorithm is an iterative method, it is necessary that the optimal level of the stopping criteria be met within the given accuracy. To accurately estimate the desired parameters of Baum-Welch algorithm, A and Er, the execution of the algorithm is allowed to continue until the elements of the parameters no longer change from iteration to iteration. For this reason, the maximum likelihood solution can support the determination of the convergence for continuing the iteration until the optimal value of $\Pr(Er|\Gamma)$ is reached. The optimal value of $\Pr(Er|\Gamma)$ can be express using the scaling constant vector Ct as follows:

$$\Pr(eR/\Gamma) = \prod\nolimits_{t=1}^{T} C_T \tag{13}$$

In this experiment, the log likelihood function is illustrated in Fig. 7.

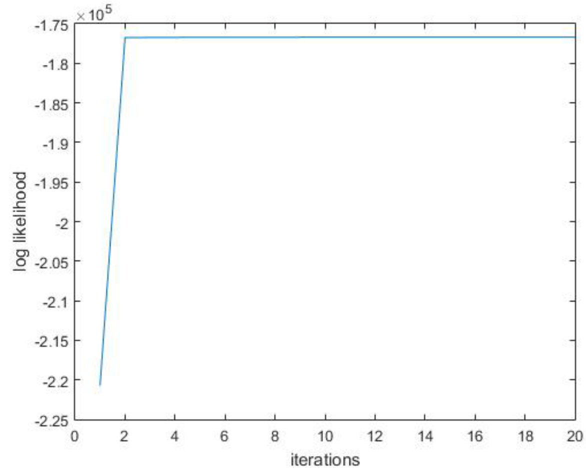

FIGURE 7. Log Likelihood function for parameters A and Er.

Fig. 7 shows the convergence of the absolute value of the log likelihood function for different iterations with Eb/No from (0 to 5) dBs. The Baum-Welch algorithm finds the local maxima and does not change considerably after the initial iterations. It can be seen that the log likelihood function reaches the optimal point for convergence in about two iterations. Note that this conclusion is consistent with the preceding computations of Ak and Bk for 20 iterations. Note also that, as discussed previously, the likelihood numbers are very small.

VI. SIMULATION RESULTS AND DISCUSSION

In this simulation, two reference error sequences are produced by the coded OFDM 5G simulation based on the LDPC and Turbo codings and used. They are represented by a blue line and labeled as 'experiment'. The error sequence generated by the simulation of the proposed Two-state Markov error model is expressed by the orange color and labeled as 'model'. The x axis represents the probabilities of error gaps, Pr{0m|1}, and error bursts, Pr{1m|0}, and the y axis represents the length of m observation intervals. The reference error sequence has 170400 bits for the training process for model simulation. The burst size is 3 for all modulation methods. The error free (gap) size changes depending on the error occurrences.

A. SIMULATION RESULTS OF THE ESTIMATED MARKOV MODEL COMPARED WITH THE LDPC CODED OFDM

In Fig. 8, the comparison of the error gap Pr{0m|1} for the error sequences of the LDPC-coded OFDM 5G simulation and the error gap Pr{0m|1} of the error sequences generated by the Markov model using the Baum-Welch algorithm are expressed. From these simulation results, it can be clearly seen that the error gap probabilities of the estimated Markov model and the LDPC-coded OFDM 5G simulations are symmetrically identical for every interval for the 16QAM modulations, although there is a slight difference in the

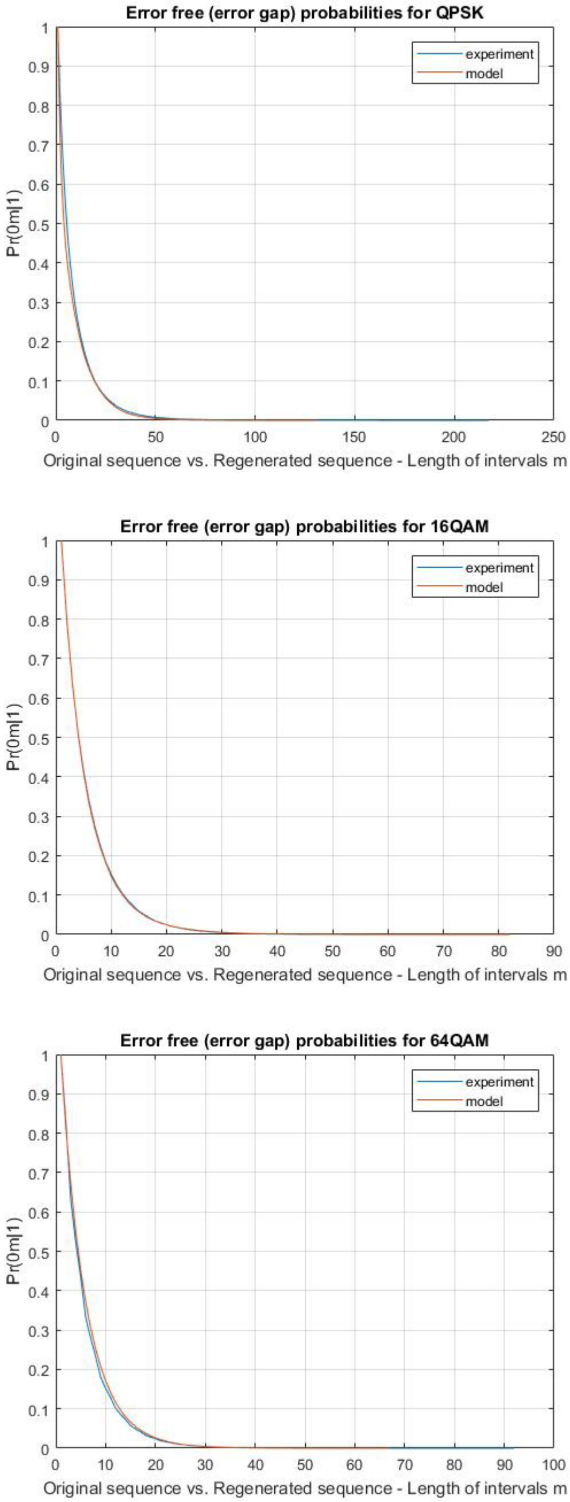

FIGURE 8. Error gap histograms for the error sequences of the LDPC-coded OFDM 5G simulation and the error sequence resulting from the 2 state Markov model.

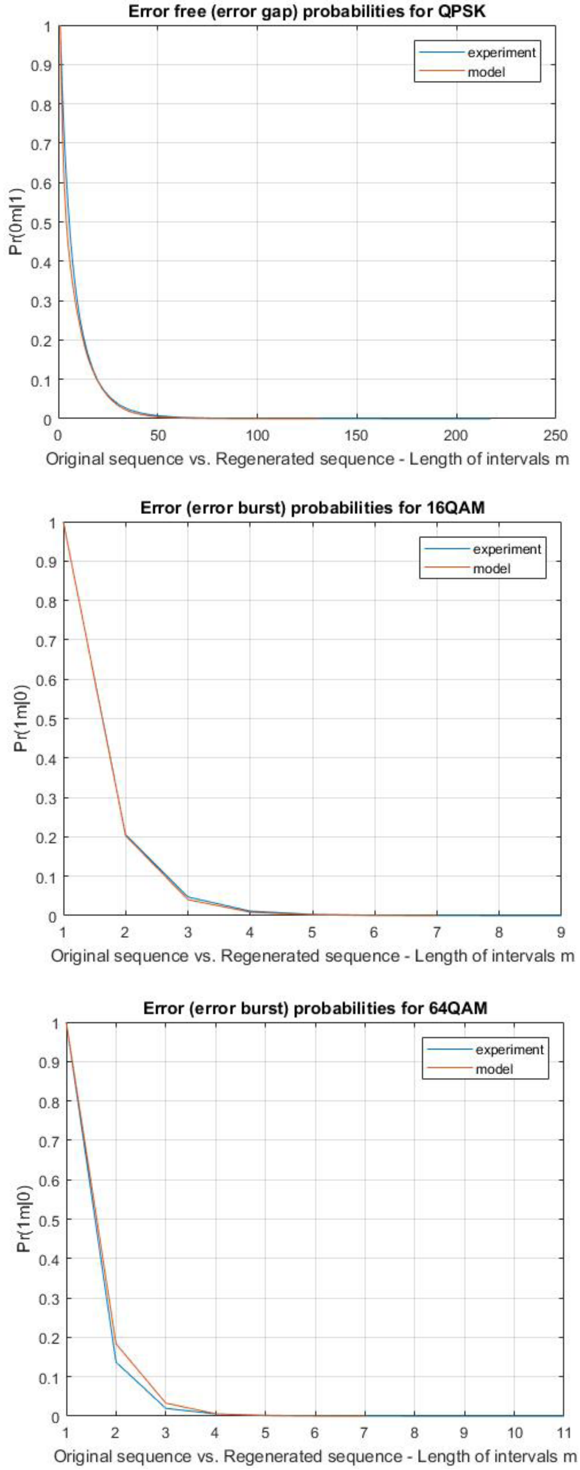

FIGURE 9. Burst error histograms for the error sequences of the LDPC-coded OFDM 5G simulation and the error sequences resulting from the 2 state Markov model.

neighborhood of m = 10 for QPSK and between m = 10 and m = 20 for the 64QAM modulation.

The results of the error burst Pr{1m|0} for the error sequences of the LDPC-coded OFDM 5G simulation and the error burst Pr{1m|0} using the data generated by the model estimated by the Baum-Welch algorithm are also nearly the same as in Fig. 9. It can be clearly observed that the burst error probabilities of the estimated Markov model and the LDPC-coded OFDM 5G simulation are symmetrically identical for every interval for QPSK and 16QAM modulations although there is a few difference between m = 2 and m = 4 for 64QAM modulation.

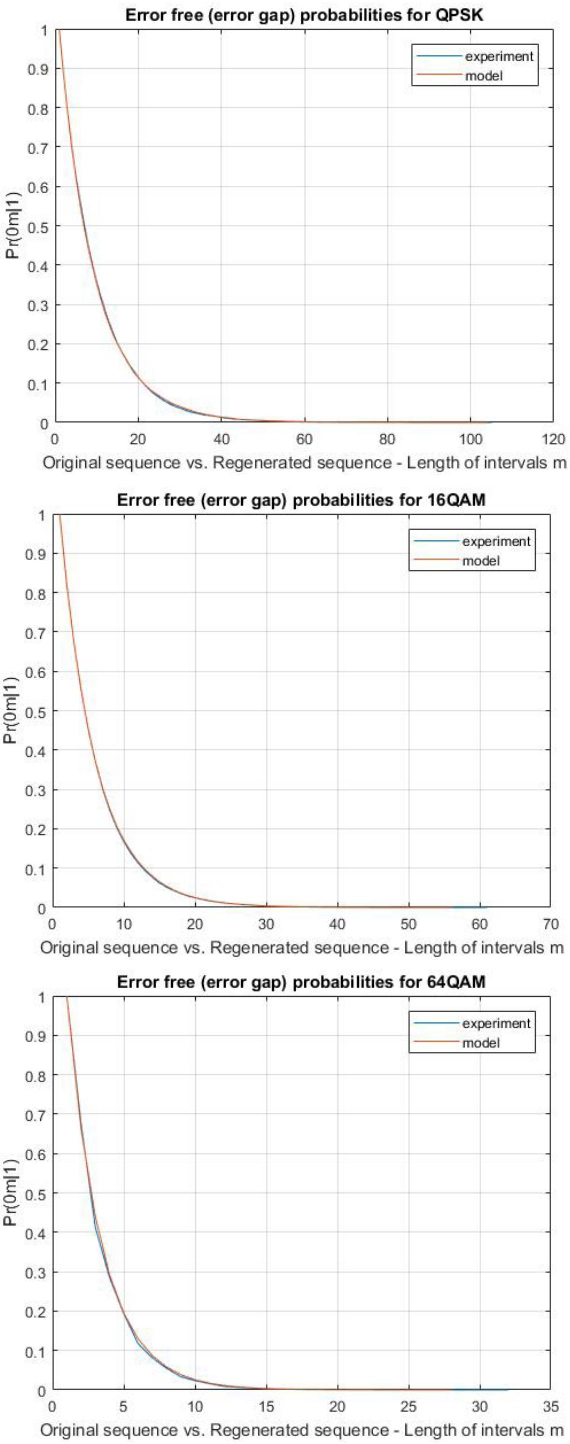

FIGURE 10. Error gap histograms for the error sequences of the Turbo-coded OFDM 5G simulation and the error sequence resulting from the 2 state Markov model.

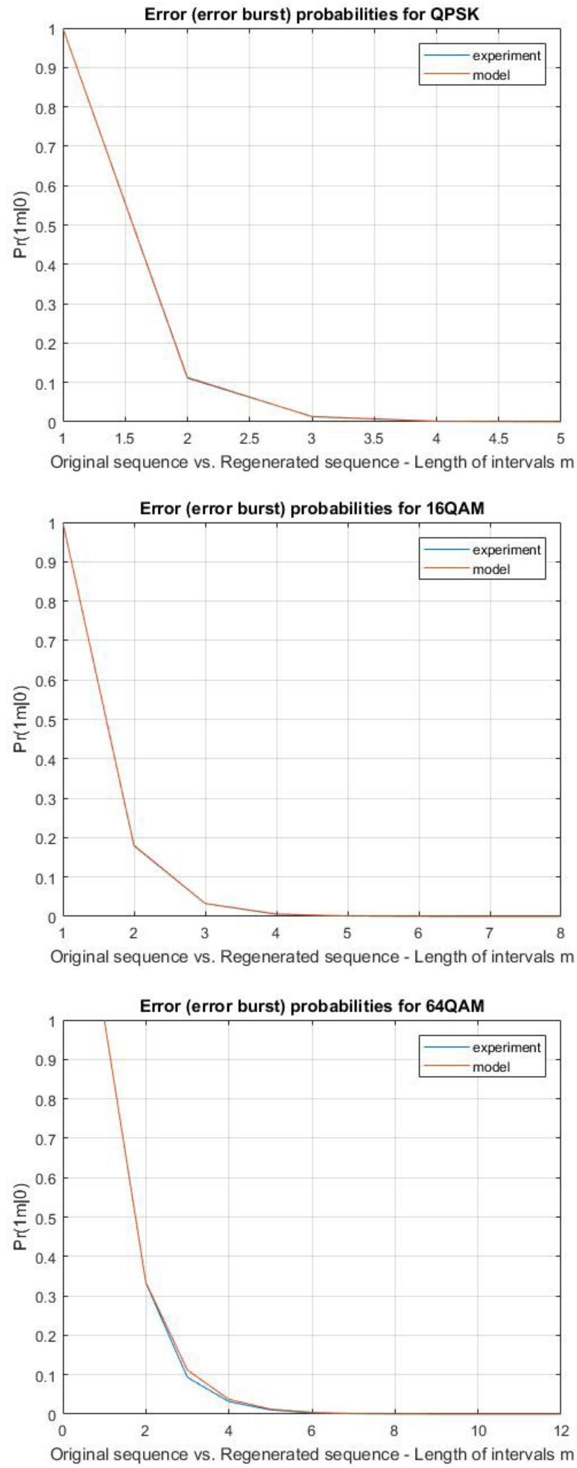

FIGURE 11. Burst error histograms for the error sequences of the Turbo-coded OFDM 5G simulation and the error sequences resulting from the 2 state Markov model.

B. SIMULATION RESULTS OF THE ESTIMATED MARKOV MODEL COMPARED WITH THE TURBO CODED OFDM

The performance of the estimated two-state Markov model is also evaluated by comparing it with the Turbo-coded OFDM 5G simulation based on the parameters of the error gap probability Pr(0m|1), the error burst probability Pr(1m|0), and the burst error probability PE. All experiments were performed and evaluated over 20 iterations.

In Fig. 10, the curves are symmetrically close for the error gap Pr{0m|1} of the error sequences of the Turbo-coded OFDM 5G simulation and the error gap Pr{0m|1} obtained from the data generated by the model using the Baum-Welch algorithm. By comparing the estimated Markov model with the Turbo-coded OFDM 5G simulation, it can be clearly seen that the error gap probabilities are symmetrically identical

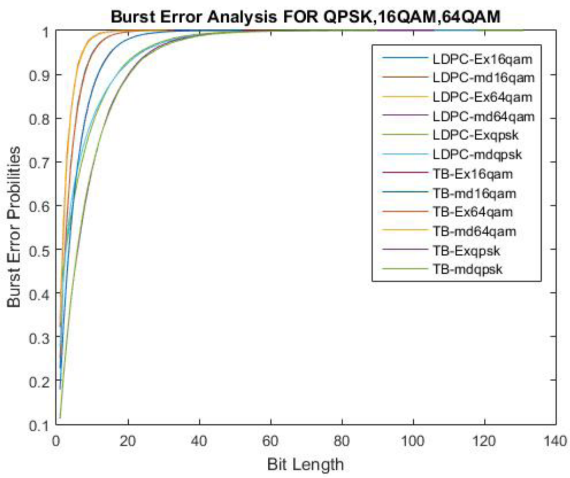

FIGURE 12. Burst error analysis for the estimated two-state Markov model compared with the LDPC- and Turbo-coded OFDM 5G simulations.

for every interval for the QPSK and 16QAM modulation methods, but the results of 64QAM have slight differences in the interval lengths (m) of 2 and 6.

The best match of the error burst Pr{1m|0} for the error sequences of the Turbo-coded OFDM 5G simulation and the error burst Pr{1m|0} using the data generated by the model estimated by the Baum-Welch algorithm is presented in Fig. 11. From the figures, it can be seen that the error gap probabilities are symmetrically identical for every interval for the QPSK and 16QAM modulation methods, although there are slight differences around m = 4 in 64QAM.

Burst error analysis was conducted for the estimated two-state Markov model and compared with the LDPC and Turbo-coded OFDM 5G simulations based on the three different modulation methods of QPSK,16QAM and 64 QAM, as shown in Fig. 12. The burst error probabilities of the estimated model are very close to those of the coded OFDM 5G simulation and there are very few differences over all modulation methods.

The probability of a burst error in the Turbo-coded OFDM 5G is 0.108374 and the burst error probability for the Markov model is 0.0.108539 using QPSK Modulation. Since the probabilities are nearly consistent, it can be said that our Markov model can well estimate the error process of the Turbo-coded OFDM. On the other hand, the burst error probability is 0.149563 with the LDPC-coded OFDM 5G and is 0.14879 with the Markov error model in the QPSK modulation. This nearly symmetrical result shows that our proposed Markov model can also effectively estimate the error process of the LDPC-coded OFDM 5G. The difference between the Turbo and the LDPC is 0.041189.

The experiments are performed for the error occurrence probability of the three modulations methods by comparing the LDPC and Turbo, as shown in Fig. 13. According to the figure, the error occurrence probabilities of our estimated model and the coded 5G simulations are nearly the same for all three modulation methods for both coding schemes. Among the three modulations, the error occurrence probability is the highest in 64QAM and the lowest in QPSK. In addition, the error occurrence probability of the Turbo-coded OFDM is lower than that of the LDPC-coded OFDM.

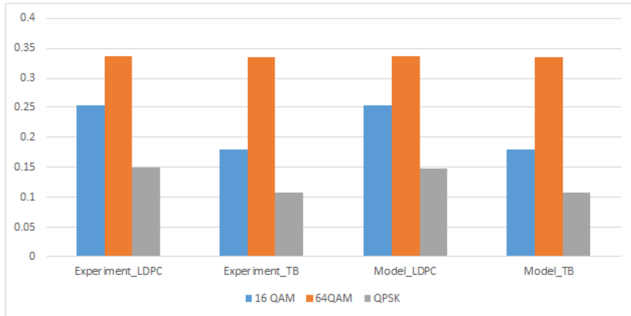

FIGURE 13. Error probabilities for the three modulation methods.

VII. CONCLUSION

In this study, the error behaviors, including the error gap and error burst statistics, of both LDPC-coded and Turbo-coded OFDM data transmissions in the 5G environment are investigated and modeled using two-state Markov chains. Moreover, the impacts of the three different kinds of modulation methods with respect to the error patterns and behavior are studied by performing burst error analysis based on the proposed two-state Markov error model. From this analysis, it can be seen that the estimation of the Markov error process model performs better in Turbo coding than in LDPC coding in the OFDM 5G environment.

From the results of the error gap and error burst analyses, it can be concluded that the error gap Pr{0m|1} and the error burst Pr{1m|0} are closely symmetrical between the estimated model and the 5G simulations of both error coding methods. These results also show that our Markov error process model works well for coded OFDM 5G simulations. The bit error occurrence probabilities are the highest in 64QAM and the lowest in QPSK. By detailed examination of the estimation process of the proposed Markov error model on the three modulation methods, the burst error occurrence probabilities of the models based on 16QAM and 64QAM are almost identical to those of the coded 5G simulations, while the burst error probability of QPSK has slight changes and very few differences from those of the coded 5G simulations.

The proposed generative error models have the advantage of significantly reducing the simulation time because they do not need to simulate the entire communication system. The Baum-Welch (BW) algorithm was mostly used to tune the hidden parameters based on the available observations, which greatly improved the accuracy of the proposed model. The main advantage of the proposed generative error model is that it can greatly reduce the computational requirements for generating long error sequences and therefore accelerate the simulations. The results show that the proposed error model can provide the best estimation of the desired burst error statistics of the reference error sequences and the desired BER of coded 5G transmission systems. Our proposed generative Markov error model for the coded OFDM 5G network can assist in designing and investigating the digital components, error control schemes or protocols by reducing complexity and saving time. In future works, more prediction models could be considered for designing error control schemes and higher layer protocols.

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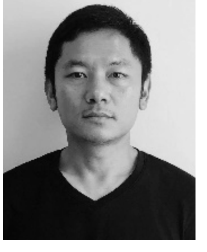

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