PACKET-BASED MARKOV MODELING OF REED-SOLOMON BLOCK CODED CORRELATED FADING CHANNELS

Cecilio Pimentel

Department of Electronics and Systems
Federal University of Pernambuco
Recife, PE, 50711-970, Brazil
Email: cecilio@ufpe.br

Fady Alajaji

Department of Mathematics and Statistics
Queen's University
Kingston, ON K7L 3N6, Canada
Email: fady@mast.queensu.ca

ABSTRACT

This paper considers the transmission of a Reed-Solomon (RS) code over a binary modulated time-correlated flat Rician fading channel with hard-decision demodulation. We define a binary packet (symbol) error sequence that indicates whether or not an RS symbol is transmitted successfully across the discrete channel whose input enters the modulator and whose output exits the demodulator. We then approximate the discrete channel's packet error sequence using an Mth order Markov queue-based channel (QBC). In other words, the QBC is used to model the discrete channel at the packet level. Modeling accuracy is evaluated by comparing the simulated probability of codeword error (PCE) for the discrete channel with the numerically evaluated PCE for the QBC. Modeling results identify accurate low-order QBCs for a wide range of fading conditions and reveal that modeling the discrete channel at the packet level is an efficient tool for non-binary coding performance evaluation over channels with memory.

1. INTRODUCTION

Reed-Solomon (RS) codes are non-binary burst-error correcting codes of considerable importance in transmission systems operating over fading channels [1,2]. Due to their symbol (an element of the Galois field GF(2^b)) orientation, RS codes are well suited to an environment where errors occur in bursts.

This work considers the transmission of RS codes over a hard-decision binary frequency-shift keying demodulated flat time-correlated fading channel with hard-decision demodulation. The binary communication channel from the input of the modulator to the output to the demodulator is referred to as the binary *discrete channel* (DC) model.

We construct a binary packet error process for the DC model, where the packet (or symbol) length is equal to b (the length of the binary representation of the RS field element). Hereafter, we refer to a packet as a binary sequence of length b. In this case, the kth packet error bit is equal to 0 whenever the kth RS symbol is successfully transmitted across the DC model. Otherwise, the packet error bit is equal to 1. We then approximate the binary packet error process of the DC model using a recently introduced [3] queue-based channel (QBC) model which is a stationary Mth order additive Markov noise channel with only four parameters. The QBC at the packet level (i.e., at the symbol level) generates a binary sequence indicating whether or not an RS symbol is transmitted successfully across the DC model and captures the correlation among consecutive RS symbols.

The development of an accurate QBC for the DC model allows analytical coding performance evaluation with arbitrary fading rates and hence provides the tools for the construction of powerful coding techniques that effectively exploit the channel statistical memory as opposed to ignoring it via interleaving. Indeed, codes designed taking into account the channel memory can considerably outperform the traditional codes designed for the equivalent memoryless channel (realized via perfect interleaving) [4–6]. This is information theoretically justified as it is known that for a wide class of information stable channels (e.g., channels with additive stationary ergodic noise), memory increases capacity (e.g., see [3]).

Under bounded distance decoding, the probability of codeword error for RS codes is obtained from the probability of m symbol (packets) errors in a block of length n symbols, $P(m,n)$ [7]. It is worth mentioning that the expressions for $P(m,n)$ developed in the literature to study the performance of binary block codes over finite-state channel (FSC) models at the bit level [8,9] can be readily applied to study the performance of RS codes over FSC at the packet level. In this later case, the code's field size is a parameter of the model and is not considered in the $P(m,n)$ calculation. Thus, the development of FSC models at the packet level, such as the QBC modeling studied in this paper, can significantly simplify the performance analysis of RS codes over channels with memory.

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We generalize the results obtained in [10] by developing an expression for the probability distribution of the packet error process of the DC model with Rician fading under the assumption of constant (quasi-static) fading within a packet in order to parameterize higher-order Markovian QBC models in slow fading environments. Modeling results identify the QBC parameters for several fading conditions and reveal that low-order QBCs ($M \leq 4$) provide a good fit for the packet error process of the DC model, as opposed to higher-order QBC models required to model the DC error process at the bit level for slow fading [11]. Thus, the derivation of QBC models at the packet level facilitates both the modeling and the RS coding performance analysis.

2. COMMUNICATION SYSTEM

We consider an (n, k) RS coded communication system with RS symbols over the Galois field GF(2^b) whose codewords are of length $n = 2^b - 1$ symbols and contain k information symbols. The code can correct up to $t = \lfloor (n-k)/2 \rfloor$ symbols (under bounded distance decoding), where $\lfloor x \rfloor$ is the greatest integer less than or equal to x. Each symbol in GF(2^b) is mapped to a binary b-tuple (the vector space representation of the corresponding field element) and transmitted across a binary discrete (binary-input, binary-output) communication channel.

The DC model is composed of a binary frequency-shift keying (BFSK) modulator, a time-correlated flat Rician fading channel with additive white Gaussian noise, and a hard quantized demodulator. The complex envelope of the fading process, $\tilde{G}(t)$, is a complex wide-sense stationary Gaussian process with normalized second moment, i.e., $\mathbf{E}[|\tilde{G}(t)|^2] = 1$ (where $\mathbf{E}[\cdot]$ denotes expectation), and covariance function given by Clarke's model $C(\tau) = 1/(1 + K_R)J_0(2\pi f_D \tau)$ where $J_0(x)$ is the zero-order Bessel function of the first kind, f_D is the maximum Doppler frequency, and K_R is the Rician factor. We define a binary error process $\{E_k\}_{k=1}^{\infty}$, where $E_k = 0$ indicates no bit error at the kth signaling interval of length T, and $E_k = 1$ indicates a bit error. The probability of an error sequence of length n at the bit level for the DC model, $e^n = e_1 e_2 \dots e_n$ is given in [12, Eq. 3] and is denoted here as $P_{\text{DC}}(e^n)$.

To construct the binary success/failure process $\{\beta_k\}_{k=1}^{\infty}$ of the transmitted packets (sequences of b bits) of the DC model, the binary error process $\{E_k\}_{k=1}^{\infty}$ is divided into packets of length b. The event $\beta_k = 0$ indicates the successful transmission of the kth packet, i.e., the sequence $E_{(k-1)b+1} \cdots E_{kb}$ is an all-zero sequence (denoted by 0^b), and $\beta_k = 1$ indicates a packet error (at least one bit in this packet is incorrectly decoded). Thus each binary random variable β_k is a function of the sequence $E_{(k-1)b+1} \cdots E_{kb}$ and it is the binary packet error process $\{\beta_k\}_{k=1}^{\infty}$ that the QBC model will herein attempt to emulate. Thus the sequence $\{\beta_k\}_{k=1}^{\infty}$ specifies the DC model at the packet level.

2.1. The QBC Model

The QBC generates a binary Mth-order stationary Markov noise process $\{Z_k\}_{k=1}^{\infty}$ using a finite queue [3]. The model is defined in terms of four parameters: the size of the queue, M, the bit error rate (BER), $p = \Pr(Z_k = 1)$, and correlation parameters ε and α, where $0 \leq \varepsilon < 1$, $\alpha \geq 0$. The state process of the QBC $\{S_k\}_{k=1}^{\infty}$, where $S_k \triangleq (Z_k, Z_{k-1}, \cdots, Z_{k-M+1})$, is a first-order Markov process with $2^M \times 2^M$ transition probability matrix $\mathbf{P} = [p_{ij}]$ given by [3, Eq.(4)] and state stationary distribution column vector $\mathbf{\Pi} = [\pi_i]$ given by [3, Eq.(5)].

We define two $2^M \times 2^M$ matrices $\mathbf{P}(0)$ and $\mathbf{P}(1)$, $\mathbf{P}(0) + \mathbf{P}(1) = \mathbf{P}$, where the (i, j)th entry of the matrix $\mathbf{P}(z)$ is the probability the model generates an error bit z when the QBC state process transitions from state i to j. For the QBC, the first 2^{M-1} columns of $\mathbf{P}(0)$ are exactly the same as those of $\mathbf{P}$, while the remaining 2^{M-1} columns are zeros. Similarly, the first 2^{M-1} columns of $\mathbf{P}(1)$ are all zeros, while the remaining 2^{M-1} columns are exactly the same as those of $\mathbf{P}$. The binary additive (first-order) Markov noise channel (BAMNC) with non-negative correlation coefficient is a special case of the QBC with $M = \alpha = 1$ and correlation coefficient ε. The autocorrelation function (ACF) of the QBC, $R_{\text{QBC}}[m] = \mathbf{E}[Z_i Z_{i+m}]$, satisfies a recursion given in [3, p.2821]. The correlation coefficient, Cor_{QBC}, for the QBC is a non-negative quantity given by

$$\text{Cor}_{\text{QBC}} = \frac{\frac{\varepsilon}{M-1+\alpha}}{1 - (M-2+\alpha)\frac{\varepsilon}{M-1+\alpha}}. \qquad (1)$$

3. DERIVATION OF PACKET ERROR STATISTICS

The bit error rate of the packet error process of the DC model, denoted as BER_β, is given by

$$\text{BER}_\beta = \Pr(\beta_i = 1) = 1 - P_{\text{DC}}(0^b). \qquad (2)$$

We express the ACF of a binary stationary process as

$$R[m] = \Pr(1\Omega^{m-1}1) = 1 + \Pr(0\Omega^{m-1}0) - 2\Pr(0) \quad (3)$$

where Ω^{m-1} is the set of all binary sequences of length $m - 1$. For the packet error process of the DC model, $\Pr(0) = \Pr(\beta_k = 0) = P_{\text{DC}}(0^b)$, and $\Pr(0\Omega^{m-1}0) = \Pr(\beta_k = 0, \beta_{k+m} = 0)$ is obtained from $P_{\text{DC}}(0^{2b})$ with the (i, j)th entry of the $2b \times 2b$ normalized covariance matrix modified to $J_0(2\pi f_D |i_1 - j_1| T)$ where

$$j_1 = \begin{cases} j + (m-1)b, & \text{if } j \geq b+1 \\ j, & \text{if } j < b+1. \end{cases} \qquad (4)$$

A similar definition holds for i_1. We denote $P'_{\text{DC}}(0^{2b}) \triangleq \Pr(\beta_k = 0, \beta_{k+m} = 0)$. Thus, the ACF for the packet error process of the DC model is expressed from (3) as

$$R_\beta[m] = 1 + P'_{\text{DC}}(0^{2b}) - 2P_{\text{DC}}(0^b). \qquad (5)$$

The correlation coefficient of the packet error process of the DC model, denoted by Cor_β, is expressed as

$$\mathrm{Cor}_\beta = \frac{P_{\text{DC}}(0^{2b}) - P^2_{\text{DC}}(0^b)}{P_{\text{DC}}(0^b)(1 - P_{\text{DC}}(0^b))}. \qquad (6)$$

3.1. Probability of the Packet Error Sequence under Slow-Fading Conditions

An approximation for $\Pr(\beta_k = 1)$ and $R[m]$ for the packet error process of the DC model with Rayleigh fading was derived in [10] under the assumption that the fading process is constant within a packet, but varying from packet to packet according to Clarke's model. We herein generalize the results obtained in [10] by developing an expression for the probability of a packet error sequence of length n for the DC model with Rician fading under the same assumptions in order to parameterize higher-order QBC models as may be required in a slow fading environment.

Let $A_k = |\tilde{G}(kT)|$ be a constant fading amplitude within a packet. For a packet of length b, using the binomial theorem, the conditional packet error probability can be written as [10]

$$\Pr(\beta_1 = \ell_1 \mid a_1) = \sum_{k=\ell_1}^{b} (-1)^{k+\ell_1} \binom{b}{k} [\Pr(E_1 = 1 \mid a_1)]^k.$$

The conditional probability of a packet error sequence is written as

$$\Pr(\beta_1 = \ell_1, \beta_2 = \ell_2, \cdots, \beta_n = \ell_n \mid a_1, a_{1+b}, \cdots, a_{1+(n-1)b}) = \sum_{k_1=\ell_1}^{b} \cdots \sum_{k_n=\ell_n}^{b} \prod_{i=1}^{n} (-1)^{k_i+\ell_i} \binom{b}{k_i} [\Pr(E_{1+(i-1)b} = 1 \mid a_{1+(i-1)b})]^{k_i}.$$

For BFSK modulation with non-coherent demodulation

$$[\Pr(e_{1+(i-1)b} = 1 \mid a_{1+(i-1)b})]^{k_i} = \left(\frac{1}{2}\right)^{k_i} e^{-\frac{E_s}{N_0}\frac{k_i}{2} a^2_{1+(i-1)b}}.$$

We then write the probability of the packet error sequence for the DC model as

$$\begin{aligned} &\Pr(\beta_1 = \ell_1, \beta_2 = \ell_2, \cdots, \beta_n = \ell_n) = \\ &\sum_{k_1=\ell_1}^{b} \cdots \sum_{k_n=\ell_n}^{b} \prod_{i=1}^{n} (-1)^{k_i+\ell_i} \tbinom{b}{k_i} \left(\tfrac{1}{2}\right)^{k_i} \mathbf{E}[e^{-\frac{E_s}{N_0}\frac{k_i}{2}\sum_{i=1}^{n} a^2_{1+(i-1)b}}] \\ &= \sum_{k_1=\ell_1}^{b} \cdots \sum_{k_n=\ell_n}^{b} \prod_{i=1}^{n} (-1)^{k_i+\ell_i} \tbinom{b}{k_i} \left(\tfrac{1}{2}\right)^{k_i} \times \\ &\frac{\exp\{-\frac{E_s}{N_0} K_R \mathbf{1}^T \mathbf{F}((K_R+1)\mathbf{I} + \frac{E_s}{N_0}\overline{\mathbf{C}}\mathbf{F})^{-1}\mathbf{1}\}}{\det(\mathbf{I} + \frac{E_s}{N_0}(1+K_R)^{-1}\overline{\mathbf{C}}\mathbf{F})} \end{aligned} \qquad (7)$$

where $\mathbf{I}$ is the identity matrix of length n, E_s/N_0 is the signal-to-noise ratio, matrix $\mathbf{F} = \mathrm{diag}(k_1/2, \cdots, k_n/2)$, $\mathbf{1}$ is the all-one vector of size n, and the (i, j)th entry of $\overline{\mathbf{C}}$ is $J_0(2\pi f_D |i - j| bT)$, $1 \le i, j \le n$. The next section considers the problem of fitting the discretized Rayleigh and Rician DC model at the packet level using QBC models (including the BAMNC model).

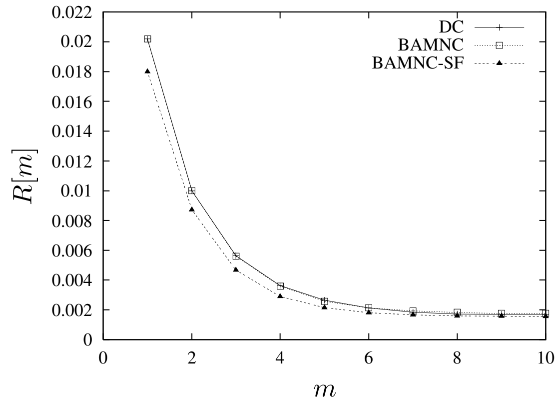

Fig. 1. Comparison of the ACFs of the Rayleigh DC model and the BAMNC models, for $E_s/N_0 = 20$ dB, $f_D T = 0.005$, $K_R = -\infty$ dB. Packets of length 8.

4. MODEL PARAMETERS ESTIMATION

Given a DC model with fixed E_s/N_0, $f_D T$, K_R, we first calculate $P_{\text{DC}}(0^b)$ and $P_{\text{DC}}(0^{2b})$ and the bit error rate BER_β and the correlation coefficient Cor_β using (2) and (6), respectively. The parameters of the BAMNC are obtained by setting $p = \mathrm{BER}_\beta$ and $\varepsilon = \mathrm{Cor}_\beta$. We denote by BAMNC-SF (BAMNC under slow fading) a BAMNC whose parameters p and ε are derived from (7).

Fig. 1 compares (at the packet level) the ACF of the DC model with the ACF of the BAMNC and BAMNC-SF models which are fitted to the DC model. The DC model has parameters $E_s/N_0 = 20$ dB, $f_D T = 0.005$ and $K_R = -\infty$ dB (Rayleigh fading). Packets are of length 8. We observe a good ACF agreement between the BAMNC and the DC when $f_D T$ is less than (curves not shown) or equal to 0.005. For $f_D T = 0.005$, the ACF curves for these two models coincide. The BAMNC-SF may be considered acceptable for $f_D T = 0.005$, but this will be further investigated in the next section. We also observe that when $f_D T = 0.001$ (curves not shown), the ACF curves for the BAMNC and BAMNC-SF are identical, but these curves exhibit greater discrepancies when compared to that of DC model, which indicates that higher-order QBC models are required for modeling DC models at the packet level with slowing-varying fading channels.

We next employ (7) to find the probability of all packet error sequences of length $M + 1$ and use these probabilities to parameterize the Mth-order QBC model ($M > 1$) at the packet level under slow fading conditions. We denote these models by M-QBC-SF. This is achieved using the methodology proposed in [11] which selects the QBC parameters that minimize the Kullback-Leibler divergence rate between the DC and QBC packet error process for identical packet error rate and correlation coefficient. We denote the bit error rate and the correlation coefficient obtained using the probabilities (7) by $\text{BER}_{\beta-\text{SF}}$ and $\text{Cor}_{\beta-\text{SF}}$, respectively. We then set $p = \text{BER}_{\beta-\text{SF}}$ and $\text{Cor}_{\text{QBC}} = \text{Cor}_{\beta-\text{SF}}$. The parameter α is then expressed from (1) as

$$\alpha = \frac{\varepsilon + \text{Cor}_{\beta-\text{SF}}(1-M) + (M-2)\varepsilon}{\text{Cor}_{\beta-\text{SF}}(1-\varepsilon)}. \tag{8}$$

For a fixed $\text{Cor}_{\beta-\text{SF}} > 0$ and M, the parameter α is a non-decreasing function of ε and is non-negative whenever ε is in the interval Δ given by

$$\Delta = \left[\frac{\text{Cor}(M-1)}{1+\text{Cor}(M-2)}, 1\right]. \tag{9}$$

The parameter $\varepsilon \in \Delta$ is selected to maximize [11]

$$\sum_{z^{M+1}} P_{\text{DC}}(z^M)[\log_2 P_{\text{QBC}}(z_{M+1} \mid z^M)] \tag{10}$$

where $P_{\text{QBC}}(z_{M+1} \mid z^M)$ is the QBC conditional probability of the noise symbol z_{M+1} given the previous M symbols. This is evaluated using the QBC noise block probability [3, Eq.(6),(7)].

5. NUMERICAL PCE RESULTS

This section presents PCE curves when an RS code is transmitted over the DC model and its QBC approximation at the packet level. For specific values of the DC model parameters (E_s/N_0, f_DT, K_R) we first calculate the QBC parameters according to the procedure described in Section 4 and then use an extension of the method proposed in [7] to numerically determine the PCE for the QBC model. In order to verify the effectiveness of a particular QBC model, PCE results for RS codes over the DC model are obtained by simulations (PCE simulations over the binary BFSK modulated hard-decision demodulated fading channels).

Fig. 2 presents PCE versus f_DT for the (255, 197) RS code ($b = 8$, $t = 29$ symbols) over the BAMNC and the M-QBC-SF, $M = 1, 2, 3$, that approximates the DC model with Rayleigh fading ($K_R = -\infty$ dB), for $E_s/N_0 = 20$ dB. Simulation results for the DC model are labeled as DC in the figures of this section. We observe that the BAMNC-SF is not adequate for modeling the DC models considered. The PCE curves of the DC model and the 2-QBC-SF and 3-QBC-SF match quite well when $f_DT \leq 0.002$. In particular, the PCE values of the DC model and the 3-QBC-SF are almost identical when $f_DT \leq 0.001$. The BAMNC is reasonably accurate for fast and medium fading rates, i.e., $f_DT \geq 0.01$. Surprisingly, the accuracy of the BAMNC indicated in Figure 1(b), for $f_DT = 0.005$ (according to the ACF criterion) is not validated in Fig. 2 (under the PCE criterion).

Fig. 3 shows PCE curves versus E_s/N_0 for the (255, 155) RS code ($b = 8$, $t = 50$ symbols) over the M-QBC-SF, $M = 2, 3$, for DC models with Rayleigh fading ($K_R = -\infty$ dB) for $f_DT = 0.001$. We clearly note that 3-QBC-SF is an accurate

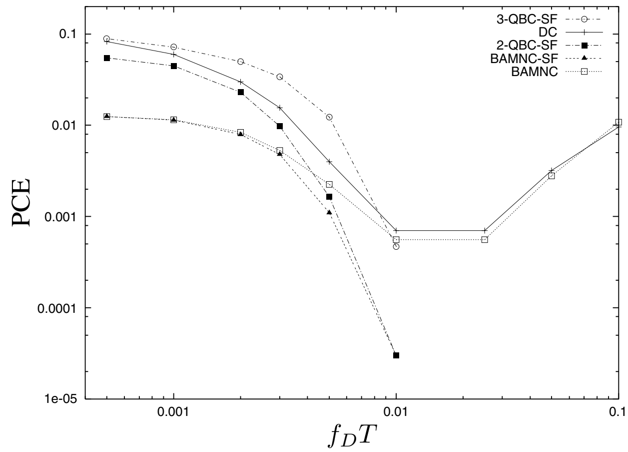

Fig. 2. PCE versus f_DT for the (255,197) RS code ($b = 8$, $t = 29$) over the BAMNC and the M-QBC-SF, $M = 1, 2, 3$. DC model with Rayleigh fading ($K_R = -\infty$ dB), $E_s/N_0 = 20$ dB.

model for Rayleigh DC model with $f_DT = 0.001$, for a broad range of E_s/N_0. We also observe (curves not shown) that the 4-QBC-SF provides accurate results in a slower varying fading channel with $f_DT = 0.0005$ over a broad range of E_s/N_0.

Fig. 4 presents PCE versus f_DT for the (255, 197) RS code ($b = 8$, $t = 29$ symbols) over the BAMNC and the M-QBC-SF, $M = 2, 3, 4$, for the DC model with Rician fading, $K_R = 5$ dB, $E_s/N_0 = 15$ dB. The BAMNC is accurate in the same range of f_DT observed in the Rayleigh case ($f_DT > 0.01$), while the 4-QBC-SF is a good model when $f_DT < 0.001$.

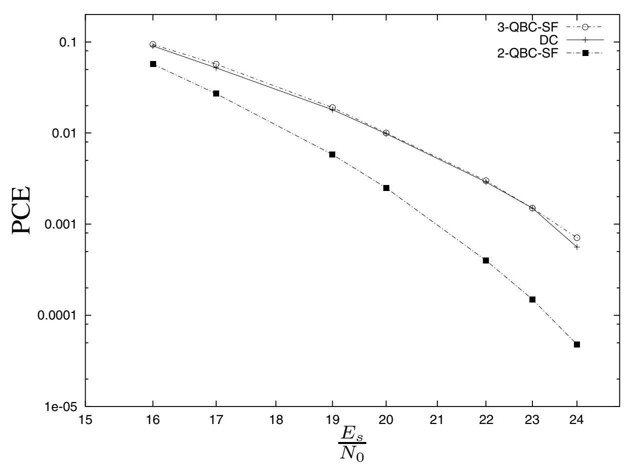

Fig. 3. PCE versus E_s/N_0 for the (255,155) RS code ($b = 8$, $t = 50$) over the M-QBC-SF, $M = 2, 3$. DC model with Rayleigh fading ($K_R = -\infty$ dB), $f_DT = 0.001$.

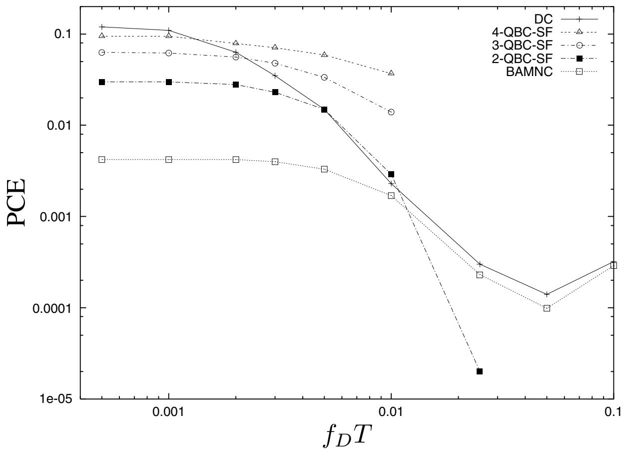

Fig. 4. PCE versus $f_D T$ for the (255,197) RS code ($b = 8$, $t = 29$) over the BAMNC and the M-QBC-SF, $M = 2, 3, 4$. DC model with Rician fading ($K_R = 5$ dB), $E_s/N_0 = 15$ dB.

6. CONCLUSIONS

We developed Mth order Markovian QBC models at the packet (symbol) level for an RS coded discrete channel representing a hard-decision demodulated Rician fading channel (called the DC model). Since one of the main goals of a model is to generate a PCE which is approximately the same as the PCE for the original channel, we evaluated the QBC models in terms of the PCE criterion. The comparison of the PCE obtained analytically (for the QBC model) and by simulations (for the DC model) revealed that the M-QBC-SF is a good approximation for the DC model when $f_D T \geq 0.001$. In particular, such QBC models with $M \leq 4$ were shown to approximate well the DC models with slow Rayleigh fading for a broad range of signal-to-noise ratios. Also, the 4-QBC-SF is adequate for Rician DC models with $f_D T = 0.001$. The QBC models developed in this work can be applied to derive powerful decoding strategies for RS codes that can exploit channel memory [4, 6, 13].

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