Anti-Jamming Partially Regular LDPC Codes for Follower Jamming with Rayleigh Block Fading in Frequency Hopping Spread Spectrum

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***Abstract*—Frequency hopping spread spectrum is widely used for military communication. Anti-jamming scheme for the system has been one of the main topics for a long time. This paper introduces follower jamming model with random dwell time and block fading environment with M-ary frequency shift keying (MFSK) modulation. For coding perspective, new low density parity check (LDPC) codes against follower jamming are proposed. To optimize codes over jamming environment, the partially regular structure and the corresponding density evolution are used. Simulation results show that the proposed codes outperform those of IEEE 802.16e standard in the presence of follower noise jamming.**

***Index Terms*—Frequency hopping, military communication, spread spectrum system, Rayleigh block fading, low density parity check (LDPC) codes, follower jamming**

I. Introduction

The spread spectrum system for military communication [1] is widely used for specific environment. Frequency hopping spread spectrum (FHSS) selects one of frequency band using pseudorandom sequence, which can make it hard to know the frequency hopping pattern and thus the system can obtain anti-jamming capability. Therefore, jammer attempts to send jamming signal in partial band randomly, called partial band jamming. Prior works to mitigate jamming use inter-hop interleaving, called bit interleaving coded modulation and iterative decoding (BICM-ID) [2] and Reed-Solomon (RS) concatenated coding [3] that can correct burst error caused by jamming. The prior techniques have high anti-jamming effects but they can increase computational complexity by decoding process.

However, there are more efficient jamming strategies one of which is a follower jamming. In follower jamming scenario, jammer scans the occupied frequency bands and send the jamming signal in the band found. To this end, jammer uses the frequency scanner called determinator [4] or communication electronic support measure (CESM) [5] that can guarantee certain level of the scanning probability. Slow frequency hopping (SFH) can be vulnerable to follower jamming environment. SFH is required to lengthen the hop period or decrease hopping speed, both of which are inevitable for high data rate communication.

In this paper, Rayleigh block fading environment with noncoherent M-ary frequency shift keying (NC-MFSK) modulation is considered. In block fading, gain attenuation values of the symbol are only dependent on the hop used. MFSK is usually adopted for military communication due to poor channel environment. Furthermore, the jamming scenario is the follower noise jamming (FNJ) with constant scan speed of the jammer. In this scenario, the interval and initial moment that the jammer scans frequency depend on the scan speed of the jammer and the dwell time is considered as random variable with probability distribution.

Low density parity check (LDPC) codes are the capacity-approaching codes. Constructions of the codes are highly diverse so that the codes are set for special environment such as block fading [6]. Partially regular LDPC (PR-LDPC) codes are the codes which have small irregularity of degree distribution and is designed for unequal error protection (UEP) [7]. PR-LDPC can also be used to anti-jamming communication systems. Simplified erasure-based channel environment and the corresponding density evolution (DE) are proposed for construction of PR-LDPC codes.

Sections II and III explain the system model and construction method of PR-LDPC codes for anti-jamming. The last two sections explain the simulation results and conclusions. Simulation is done for the same codelength as LDPC codes of the IEEE 802.16e standards. The result shows that the proposed codes have superior performance than the standard for all the symbol sizes and jamming environments.

II. System Model

A. NC-MFSK Modulation Model with Jamming

In this subsection, the modulation schemes and fading environments for frequency hopping are introduced. For block Rayleigh fading channel, we consider an i-th symbol in the k-th hops, where $0 \leq i \leq I-1$ and $0 \leq k \leq K-1$. Suppose that

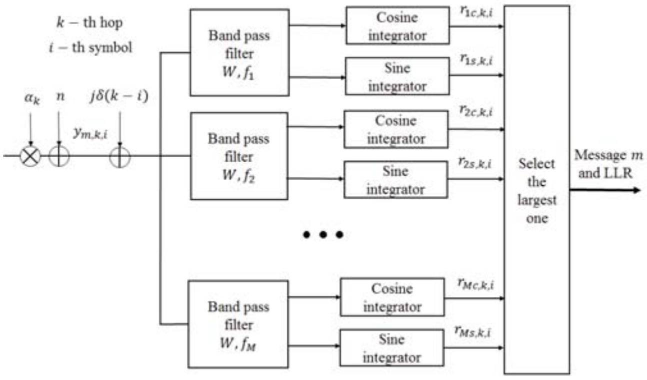


Fig. 1. The demodulator of NC-MFSK.

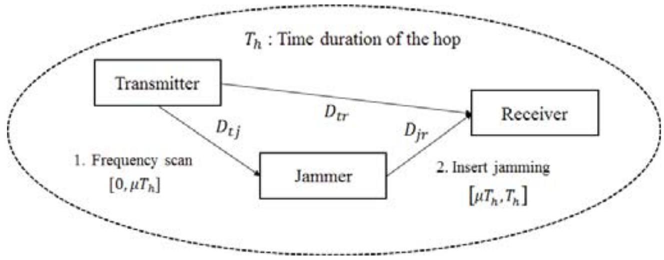


Fig. 2. Follower jamming environment.

the messages are sent on the $\bar{m}$-th tone of M-ary FSK, Then the received symbol without jamming $y_{\bar{m},k,i}$ is expressed as.

$$y_{\bar{m},k,i} = \alpha_k \sqrt{\mathcal{E}_{k,i}} + n \tag{1}$$

where $\mathcal{E}_{k,i}$ is the energy value of the symbol, n is an additive white Gaussian noise with zero mean and variance $\frac{N_0}{2}$ and α_k is normalized Rayleigh fading factor with $E[{\alpha_k}^2] = 1$ and density function $p(a) = 2\alpha_k e^{-{\alpha_k}^2}$. Note that α_k depends on the hop in block fading. For MFSK demodulation aspects, cosine and sine integrator detect phase ϕ with uniformly distribution over $[-\pi, \pi]$. The power, occurrence, and interval of jamming rely on the category of jamming, which will be discussed in the next subsection. In short, jamming signal is expressed as

$$\delta(k,i) = \begin{cases} 1, & \text{If jamming occurred in } y_{m,k,i} \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

Then, the received signal is expressed as

$$r_{mc,k,i} = \begin{cases} \alpha_k \sqrt{\mathcal{E}_{k,i}} \text{cos}\phi + j\delta(k,i) + n, & m = \bar{m} \\ j\delta(k,i) + n, & \text{otherwise} \end{cases} \tag{3}$$

$$r_{ms,k,i} = \begin{cases} \alpha_k \sqrt{\mathcal{E}_{k,i}} \text{sin}\phi + j\delta(k,i) + n, & m = \bar{m} \\ j\delta(k,i) + n, & \text{otherwise.} \end{cases} \tag{4}$$

Demodulator calculates the squared values and selects the largest one as demodulated message as

$$m'_{k,i} = \text{argmax}_m (r_{m,k,i}) \tag{5}$$

where $r_{m,k,i} = \sqrt{r_{mc,k,i}^2 + r_{ms,k,i}^2}$.

In the decoding procedure, one of the crucial parameter is binary log likelihood ratio (LLR). Binary LLR value in the decoder can be different by existence of side information, but α_k or statistics of j is difficult to know. Here, the decoder uses LLR considering only statistics of n, which is expressed as

$$\Lambda(r_{k,i}) = \log \frac{\sum_{G(m,i)=0} I_0 \left(\frac{\sqrt{(\mathcal{E}_{k,i}) r_{m,k,i}^2}}{\frac{N_0}{2}} \right)}{\sum_{G(m,i)=1} I_0 \left(\frac{\sqrt{(\mathcal{E}_{k,i}) r_{m,k,i}^2}}{\frac{N_0}{2}} \right)} \tag{6}$$

where $G(m,i)$ is a function that returns 0 when i-th bit mapped from message m is 0 and otherwise 1.

B. Follower Noise Jamming with Fixed Scan Speed

FNJ, also called as repeater-back jamming, is based on the assumption that the jammer can scan the occupied frequency. Generally, it is more power-efficient strategy than partial band jamming in that the jammer can succeed to interrupt the desired signal by jamming with high probability. Whereas, the jamming interval has the fundamental limitation by geometry of the transmitter, receiver, and jammer, which is explained in [8]. This relation is expressed as

$$T_p + T_j \le T_h \tag{7}$$

where $T_p = \frac{D_{tj} + D_{jr} - D_{tr}}{c}$, T_j is the processing time of the jammer, and T_h is the interval of one hop.

There is the time interval that the jamming does not exist for the fixed geometry, which is called jamming eclipse. There are two parameters describing FNJ such that ρ and μ. ρ is the probability that the jamming can be actually interrupted in a hop and μ is the ratio that the jamming exists in a hop.

Variable jamming interval scenario was suggested in [9]. This paper also uses variable interval by the processing time T_j, which depends on the scan time. The jammer wants to find the occupied frequency as quick as possible whereas it has to scan randomly due to the lack of information for frequency hopping pattern. Then, the timing that frequency is detected by the jammer is different at each hop. Furthermore, we assume that the jammer has the fixed scan speed v. Then the processing time T_j can be expressed as

$$T_j = T^* + T_{scan} \tag{8}$$

$$T_{scan} = \min \left(\frac{N_{fr}}{v}, (1-\mu) T_h \right). \tag{9}$$

In the adove, μ has to be divided into two terms. One is the earliest initial point of the jamming denoted by μ_a and the other is the latest initial point denoted by μ_b. Then, we have

$$\mu_a = \frac{T_p + T^*}{T_h} \tag{10}$$

$$\mu_b = \mu_a + \frac{N_{fr}}{vT_h}. \tag{11}$$

The initial point of jamming at each hop may differ by above assumption, which can be expressed as μ_k and ρ, $k \in [K]$. Then, we have

$$\mu_k \sim u[\mu_a, \min(\mu_b, 1)] \tag{12}$$

$$\rho = \frac{1-\mu_a}{\mu_b - \mu_a} \tag{13}$$

where u is random variable with uniform distribution. For convenience, we assume $T^* = 0$. By using geometry and certain v and T_h, jamming parameters are evaluated. $\delta(k,i)$ of received signal can be defined as

$$\delta(k,i) = \begin{cases} 1 & \frac{i}{K} \geq \mu_k \\ 0 & \text{otherwise.} \end{cases} \tag{14}$$

Regarding the power of jamming, the follower jamming is energy efficient in that the jammer only can interrupt jamming in valid frequency band. For general case, the jammer can select the tones of message in MFSK modulation or insert jamming all the tones regardless of the size into M. The difference is that the jammer should divide total power as the size of M increases, which weakens the jamming effect. For latter case, the average jamming statistics is expressed as

$$j \sim N\left(0, \frac{N_j}{2M\left(1 - \frac{\mu_a + \min(\mu_b,1)}{2}\right)}\right). \tag{15}$$

In this paper, only follower noise jamming with sufficiently high power is considered because the power of jamming is not a parameter that can be controlled.

III. Anti-Jamming PR-LDPC Codes for Follower Noise Jamming

PR-LDPC codes are firstly introduced in [7], which is proposed for UEP. Modified version of PR-LDPC codes for anti-jamming (AJ-PR-LDPC) codes are defined as below.

Definition 1 (($\boldsymbol{\lambda}, d_c, \boldsymbol{d}_v$) AJ-PR-LDPC codes)**.** *For an positive location vector $\boldsymbol{\lambda} = [\lambda_1, ..., \lambda_K]$, $\sum \lambda_i = 1$ and the corresponding variable node degree $\boldsymbol{d}_v = [d_{v,1}, ..., d_{v,K}]$ with $r(\boldsymbol{\lambda} \cdot \boldsymbol{d}_v) = d_c$, AJ-PR-LDPC codes have parity check matrix H that is constant weight d_c on the each row and each v_j, j-th column of H that has block size B, has to satisfy*

$$wt(v_j) = d_{c,k}, j' \in \left[B\sum_{i=1}^{k-1}\lambda_i, B\sum_{i=1}^{k}\lambda_i\right] \tag{16}$$

where j' is the value of j after modular-B operation. The parity check matrix structure of the AJ-PR-LDPC is expressed in Fig. 3.

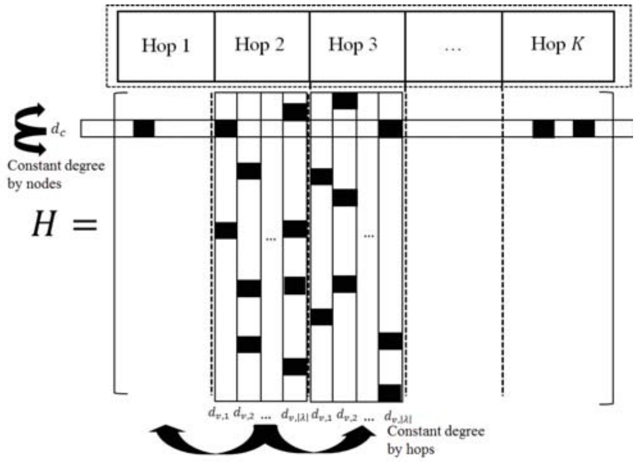


Fig. 3. The parity check matrix of AJ-PR-LDPC codes.

A. Simplified Channel Model and the Corresponding Density Evolution

For density evolution, channel model should be determined. Fig. 4(a) shows the model of error distribution of hop under follower jamming. The hop is divided into 3 intervals by the symbol error rate (SER). The leftmost interval is called as jamming eclipse. In the middle interval, jamming may probably exist and error rate grows linearly. In the last interval, the jamming always exists. Note that P_a and P_b are vary at each hop due to the existence of block fading.

It is challenging to formulate density evolution of above channel environment, since it has many parameters to be considered. Instead, simplified channel model is proposed in Fig. 4(b). In the simplified model, channels with errors are replaced by erasure and the middle interval with linear growth is changed to a series of $|\boldsymbol{\lambda}|-2$ staircase intervals. The corresponding density evolution of the simplified model is derived as

$$\epsilon_i = (\epsilon_b - \epsilon_a)\frac{i-1}{|\boldsymbol{\lambda}|-1} + \epsilon_a, i \in [1, |\lambda|] \tag{17}$$

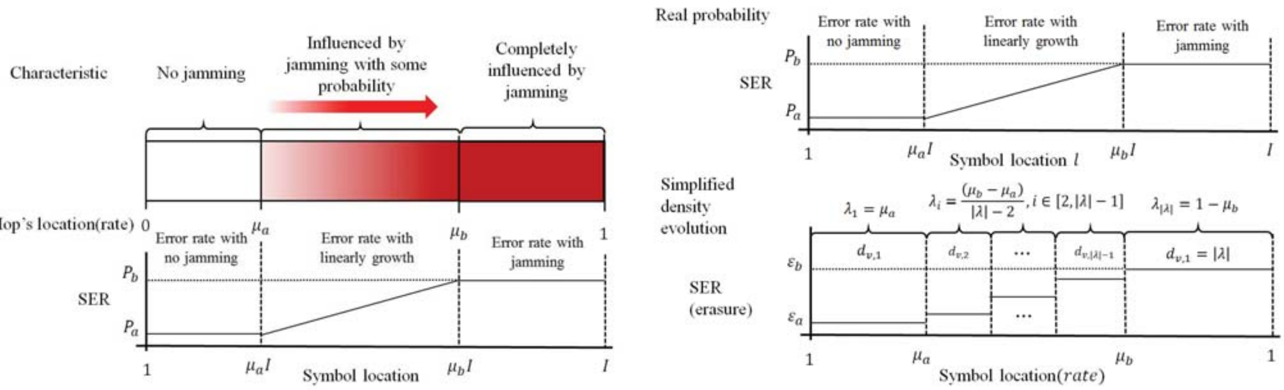
$$p_{l+1,i} = \epsilon_i q_{l+1}^{d_{v,i}-1} \tag{18}$$

$$q_{l+1} = 1 - \left(1 - \sum_{i=1}^{|\boldsymbol{\lambda}|} \lambda_i p_{l,i}\right)^{d_c - 1}. \tag{19}$$

The initial values ϵ_a, ϵ_b, and $\boldsymbol{\lambda}$ have to be determined. However, they cannot be given from the real space. Rather, they are evaluated heuristic way when constructing AJ-PR-LDPC codes.

B. Construction of AJ-PR-LDPC Codes Based on DE

The proposed codes are described in Algorithm 1. For constructing PR-LDPC codes, the following initial values $\epsilon_a, \epsilon_b, \boldsymbol{\lambda}, s_a, s_b$, and code rate r should be determined, where s_a, s_b are incremental factor related to the symbol erasure probability. Then, the maximum degree values of variable



(a) Exact model.

(b) Simplified model.

Fig. 4. SER by the location of the hop in FNJ model with fixed scan speed.

nodes $\boldsymbol{d}_{v,max} = [d_{v,1,max}, ..., d_{v,K,max}]$ and the check nodes $d_{c,max}$ are needed. The parameters can be evaluated intuitively but large $\boldsymbol{\lambda}, d_{c,max}$ and small s_a, s_b can make the algorithm time-consuming.

Algorithm 1 Selection of degree pairs of AJ-PR-LDPC codes

Input: $\epsilon_a, \epsilon_b, s_a, s_b, \boldsymbol{\lambda}, \boldsymbol{d}_{v,max}, d_{c,max}$, and r.

Generate all the degree pairs D of $(\boldsymbol{d_v}, d_c)$ which satisfy $\boldsymbol{d}_v \leq \boldsymbol{d}_{v,max}$, $d_c \leq d_{c,max}$.

while There exist the degree pairs more than one **do**

Set D_n as the degree pairs that are not converged to 0 for each element of D by the proposed density evolution.

$D \leftarrow D \setminus D_n$

$\epsilon_a \leftarrow \epsilon_a + s_a$, $\epsilon_b \leftarrow \epsilon_b + s_b$.

end while

Select the remaining degree pairs of D

Use partially regular PEG to generate H by the selected degree pair.

Output: the parity check matrix H.

The resulting degree pair does not guarantee convergence in the channel but has better than other pairs. Partially regular progressive edge growth (PEG) can be implemented with modification of regular PEG or permutation of columns from the irregular PEG. In this paper, the specific construction of PR-LDPC code is introduced and compared to LDPC code defined in IEEE 802.16e in the next section.

IV. Simulation Result

The simulation is done for SFH systems of NC-MFSK with follower jamming and Rayleigh block fading. The symbol sizes $M = 2, 4, 8, 16$ are used and the jamming environment is considered as in the following 3 cases; no jamming, the jamming with fast scan speed, and slow scan speed cases. Hopping size is 192 bits for all M and the scan speed is defined as proportional values of N_{fr} and T_h. The scan speed of fast speed case is $v = \frac{2N_{fr}}{T_h}$ and the scan speed of slow case is $v = \frac{N_{fr}}{2T_h}$. The parameter representing jamming power $\frac{E_b}{N_j}$ is -50[dB] if the jamming exists. The jamming overwhelms the message signal regardless of μ or M. Table I summarizes the channel parameters.

TABLE I
Jamming Environment of the Simulation

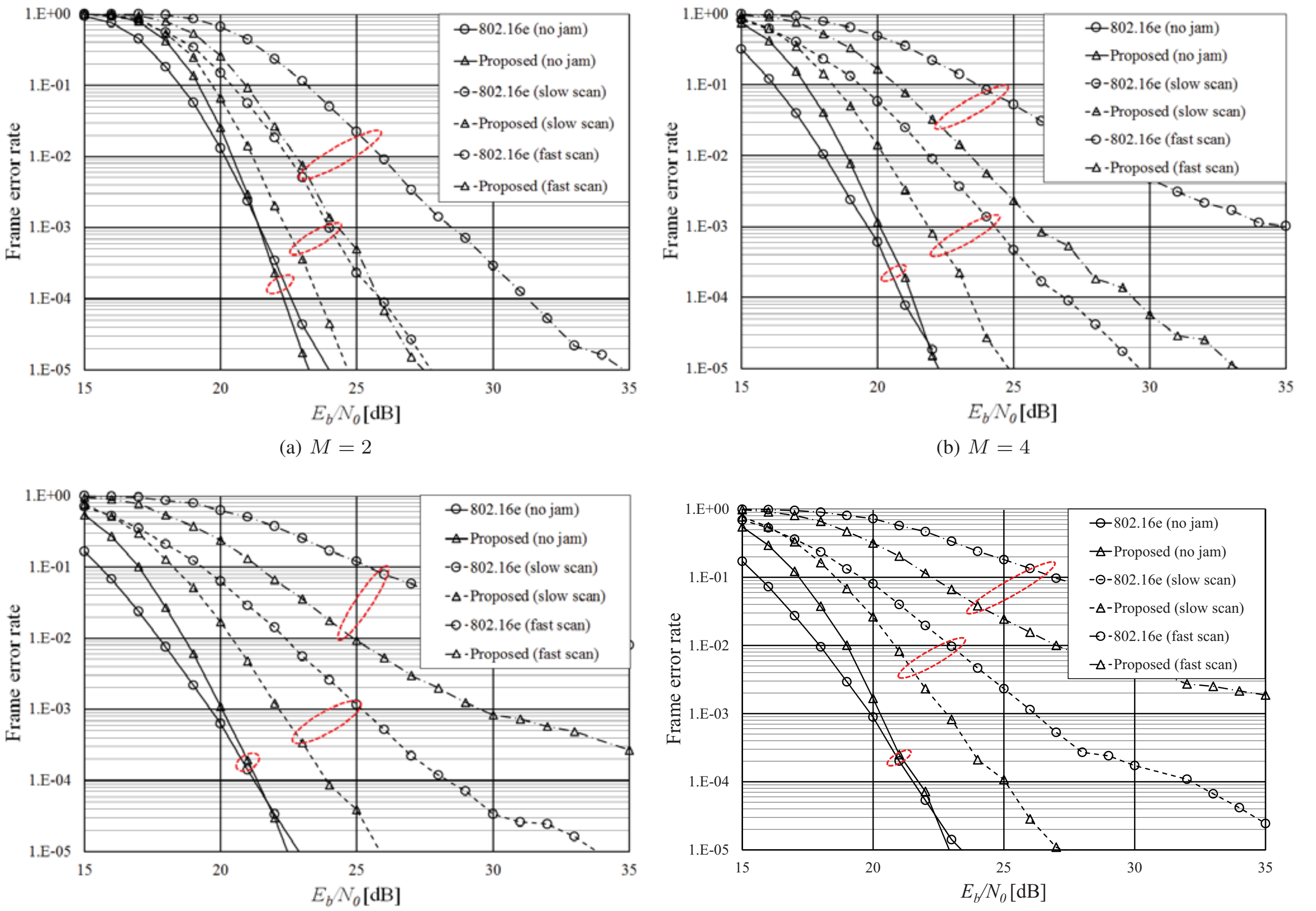
Cases	*Modulation*	μ_a	μ_b	ρ	E_b/N_j
No jamming	NC-MFSK	-			
Slow scan	with	3/8	11/8	5/8	-50
Fast scan	M=2,4,8,16	3/8	7/8	1	[dB]

The code has the codelength $N = 2304$ and code rate $r = \frac{1}{2}$, which are the same as those of IEEE 802.16e standards. LDPC codes with IEEE 802.16e standards has good performance with practical codelength in the simulation environment. In a code, there are 12 hops regardless of M. AJ-PR-LDPC codes in this simulation have initial values $\epsilon_a = 0.2, \epsilon_b = 0.9, s_a = s_b = 0.01, \boldsymbol{\lambda} = (\frac{3}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}), d_{c,max} = 8$, and $\boldsymbol{d}_{v,max} = (8, 8, 8, 16, 16, 20)$. $\boldsymbol{\lambda}$ is chosen according to the fast scan case. The resulting AJ-PR-LDPC codes have parameters $d_c = 5, \boldsymbol{\lambda} = (\frac{5}{8}, \frac{2}{8}, \frac{1}{8})$, and $\boldsymbol{d}_v = (2, 3, 4)$. Decoder uses belief propagation with LLR values of MFSK. The resulting frame error rate (FER) of the codes are shown in the Fig. 5.

In Fig. 5, red circle represents the same jamming environment except the code used. The proposed one represents AJ-PR-LDPC codes. With the same M, LDPC codes of IEEE 802.16e have superior performance than the proposed one for all M with no jamming case. However the AJ-PR-LDPC codes have more coding gain in two jamming cases, which shows the anti-jamming effect. The largest coding gain is obtained in slow scan case. It is shown that the larger M results in better performance in low $\frac{E_b}{N_0}$ as M is larger, but worse in high $\frac{E_b}{N_0}$.

V. Conclusion

In this paper, it is assumed that the SFH and MFSK with Rayleigh block fading channel with follower jamming to simulate tactical environment. Furthermore, the new model for follower jamming with fixed scan speed in FHSS environment



(a) $M = 2$ (b) $M = 4$ (c) $M = 8$ (d) $M = 16$

Fig. 5. Performance comparison of the proposed codes and the codes of IEEE 802.16e in SFH with jamming and Rayleigh block fading for $M = 2, 4, 8,$ and 16.

is proposed. The model of probabilistic hop error distribution can be simplified with erasure stair-form model and it is used for density evolution design of AJ-PR-LDPC codes. The proposed algorithm is used to derive the degree pair with ordinal excellence and PR-PEG is used to generate actual H. The simulation result shows that the proposed codes have excellent performance in the presence of jamming than those of IEEE 802.16e standards which originally outperforms the proposed one in the channel with no jamming cases.

Acknowledgment

The authors gratefully acknowledge the support from Electronic Warfare Research Center at Gwangju Institute of Science and Technology (GIST), originally funded by Defense Acquisition Program Administration (DAPA) and Agency for Defense Development.

References

[1] M. K. Simon, J. K. Omura, R. A. Scholtz, and B. K. Levitt, *Spread Spectrum Communications Handbook*, Revised ed. New York, NY, USA: McGraw-Hill, 1994.

[2] J. Dai, D. Guo, and B. Zhang, "A BICM-MD-ID scheme in FFH system for combatting partial-band interference," *Wireless Communications and Signal Processing (WCSP)*. pp. 1-4, Oct. 2010.

[3] C. Frank and M. Pursley, "Concatenated coding for frequency-hop spread-spectrum with partial-band interference," *IEEE Trans. Commun.*, vol. 44, pp. 377-387, Mar. 1996.

[4] E. Felstead, "Follower jammer considerations for frequency hopped spread spectrum," *IEEE MILCOM.*, vol.2, 1998.

[5] A. D. Martino, *Introduction to Modern EW Systems*, Norwood, MA, USA: Artech House, 2012.

[6] J. J. Boutros, A. G. Fbregas, E. Biglieri, and G. Zemor, "Low-density parity-check codes for nonergodic block-fading channels," *IEEE Trans. Inf. Theory*, vol. 56, pp. 4286-4300, Sep. 2010.

[7] N. Rahnavard, H. Pishro-Nik, and F. Fekri, "Unequal error protection using partially regular LDPC code," *IEEE Trans. on Commmun.*, vol. 55, pp 387-391, March 2007.

[8] D. J. Torrieri, "Fundamental limitations on repeater jamming of frequency-hopping communications," *IEEE Journal on Selected Areas in Communications*, vol. 7. pp. 569-575, May 1989.

[9] A. Hansson, J. N. Senior, and K. Wiklundh, "Performance analysis of frequency-hopping ad hoc networks with random dwell-time under follower jamming," *IEEE MILCOM.*, pp. 848 - 853, 2015.