# Performance of $M$-ary Turbo Coded Synchronous FHSS Multiple Access Networks with Noncoherent MFSK under Rayleigh Fading Channels

Sungnam Hong, Kyungwhoon Cheun, Hyuntack Lim, and Sunghye Cho

***Abstract:*** **The performance of $M$-ary turbo coded synchronous, fast frequency-hopping spread spectrum multiple-access (FHSS-MA) networks with $M$-ary frequency shift keying (MFSK) and noncoherent detection is analyzed under Rayleigh fading. Results indicate that $M$-ary turbo codes dramatically enhance the performance of FHSS-MA networks using MFSK compared to binary turbo codes.**

***Index Terms:*** **Frequency-hopping, frequency shift keying, interference, multiple-access, noncoherent detection, Rayleigh fading.**

## I. INTRODUCTION

Frequency-hopping spread spectrum (FHSS) system was originally developed for military networks due to its low probability of intercept and anti-jamming capabilities, and papers regarding this aspect of FHSS systems are still retaining interest [1]–[2]. Moreover, synchronous, fast frequency-hopping spread spectrum multiple-access (FHSS-MA) systems considered in this paper are similar to frequency-hopping orthogonal frequency division multiple-access (FH-OFDMA) systems which are extensively used in commercial applications include worldwide interoperability for microwave access (WiMAX) (diversity mode) [3], 3rd generation partnership project (3GPP) long term evolution (LTE) (virtual resource blocks of distributed type) [4].

In a previous work [5], we analyzed the performance of binary coded, synchronous, fast FHSS-MA networks using $M$-ary frequency shift keying (MFSK) and noncoherent detection in Rayleigh fading channels. The joint probability density function (pdf) of the absolute values of the correlator outputs was derived which was used to compute the bit-interleaved coded modulation (BICM) channel capacity [6] and the soft decision decoding performance of 3GPP turbo and binary convolutional codes [7]. The results indicated that soft decision decoding based on the derived pdf drastically outperforms the legacy decoder based on the Gaussian approximation of the effect of the multiple access interference (MAI) on the correlator outputs.

On the other hand, results in [8] and [9] reveal that, with MFSK, the coded modulation (CM) channel capacity is significantly larger than the BICM channel capacity under the additive white Gaussian noise (AWGN) and Rayleigh fading channels. Moreover, the discrepancy between the BICM and the CM channel capacity increases with increasing $M$. For example, at a code rate of $1/3$, the CM channel capacity is superior to the BICM channel capacity by approximately $0.5$ dB with 4-FSK under the AWGN and Rayleigh fading channels. This difference increases to approximately 1.9 dB with 64-FSK [8],[9]. These results drive us to analyze the performance of fast FHSS-MA networks with MFSK and $M$-ary coding rather than binary coding.

In this paper, we analyze the performance of $M$-ary turbo coded, synchronous, fast FHSS-MA networks with MFSK and noncoherent detection under the AWGN and Rayleigh fading channels based on the joint pdf of the absolute values of the correlator outputs derived in [5]. We consider the case when the channel state information (CSI) is available at the receiver where CSI is defined as the magnitude of the channel response. The CM channel capacity along with the associated normalized network throughput are computed and the frame error rate (FER) performance of $M$-ary turbo codes designed in [9] is evaluated. Numerical results show that $M$-ary coded FHSS-MA networks dramatically outperform binary coded FHSS-MA networks, resulting in excess of 80% increase in the network capacity.

## II. SYSTEM MODEL

The system model considered in this paper is identical to that described in [5], other than the fact that $M$-ary turbo codes are used in place of binary turbo codes. Thus, in this section, we only give a sketchy description of the system model and the readers are referred to [5] for a more detailed description. We consider a synchronous fast FHSS-MA network with $K$, identical active users (transmitter-receiver pairs) in the network operating under independent Rayleigh fading channels. Each user transmits one MFSK modulated symbol per hop in one of the $q$ available frequency hopping slots and independently chooses a hopping slot for each symbol with equal probability. With synchronous hopping, the $M$ complex correlator outputs at the reference receiver can be written as follows given that the hop is

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hit by $0 \leq K' \leq K$ users [5] :

$$\Omega_l = H_1 \delta_{m_1,l} + Z_l^{K'}, \;\; l = 0, 1, \ldots, M-1 \quad (1)$$

where $Z_l^{K'} \triangleq \sum_{k=2}^{K'+1} H_k \delta_{m_k,l} + \mu_l$ is the combined contribution of the MAI and the AWGN on $\Omega_l$. Note that, for notational convenience, the users are indexed such that the reference user has index 1. Here, $\{H_1, H_2, \cdots, H_{K'+1}\}$ are zero-mean, independent and identically distributed (i.i.d.), proper complex Gaussian RVs with $E\{H_j{}^* H_k\} = \delta_{j,k}$ where $\delta_{j,k} = 1$ if $j = k$ and zero, otherwise and $x^*$ denotes the complex conjugate of $x$. Also, $m_k$ is the symbol transmitted by the $k$th user that is assumed to be independent between users and uniformly distributed on $\{0, 1, \ldots, M-1\}$. Finally, $\{\mu_0, \mu_1, \cdots, \mu_{M-1}\}$ are zero-mean, i.i.d., proper complex Gaussian RVs with $E\{\mu_j{}^* \mu_k\} = \delta_{j,k}/\gamma$ and $\gamma \triangleq \bar{E}_s/N_0$ where $\bar{E}_s$ is the average signal energy received from the paired transmitter and $N_0/2$ is the two-sided power spectral density of the AWGN.

Let $B_l \triangleq \sum_{k=2}^{K'+1} \delta_{m_k,l}$, then, conditioned on the variables $B_l$, $m_1$, and $|H_1|$, the envelope of the correlator outputs, $R_l \triangleq |\Omega_l|$ follow the Ricean distribution given by [8]

$$f_{R_l}\left(r_l | B_l, m_1, |H_1|\right) = \frac{2r_l}{B_l + 1/\gamma} \exp\left(-\frac{r_l^2 + |H_1|^2 \delta_{m_1,l}}{B_l + 1/\gamma}\right) \times I_0\left(\frac{2r_l |H_1| \delta_{m_1,l}}{B_l + 1/\gamma}\right), r_l \geq 0 \quad (2)$$

where $I_0(\cdot)$ is the zeroth-order modified Bessel function of the first kind [10]. As in [5], we assume that the number of frequency hopping slots, $q$ is sufficiently large so that $B_l$'s approximately i.i.d. with $\Pr(B_l = d) = \binom{K-1}{d} p_{h,M}^d \left(1 - p_{h,M}\right)^{K-1-d}$ and $p_{h,M} = 1/(qM)$, which results in the correlator outputs being statistically independent. It was demonstrated in [5] that this assumption is valid for all practical purposes. Denoting the envelope of the correlator outputs under this assumption as $\widehat{\mathbf{R}} \triangleq \left(\widehat{R}_0 \; \widehat{R}_1 \cdots \widehat{R}_{M-1}\right)$, the joint pdf of $\widehat{\mathbf{R}}$ conditioned on $K$, $m_1$ and $|H_1|$ is given by [5]

$$f_{\widehat{\mathbf{R}}}\left(\mathbf{r} | K, m_1, |H_1|\right) = \prod_{l=0}^{M-1} f_{\widehat{R}_l}\left(r_l | K, m_1, |H_1|\right) \quad (3)$$

where

$$f_{\widehat{R}_l}\left(r_l | K, m_1, |H_1|\right) = \sum_{k=0}^{K-1} \binom{K-1}{k} p_{h,M}^k \left(1 - p_{h,M}\right)^{K-1-k} \times f_{R_l}\left(r_l | B_l = k, m_1, |H_1|\right). \quad (4)$$

The corresponding log-likelihood ratio vector is then given by [11], $\widehat{\mathbf{L}}\left(m_1 | K, \mathbf{r}, |\mathbf{H_1}|\right) = \left(0 \; \widehat{L}^1 \; \widehat{L}^2 \cdots \widehat{L}^{M-1}\right)$ where

$$\widehat{L}^k \triangleq \ln\left\{\frac{f_{\widehat{\mathbf{R}}}\left(\mathbf{r} | K, m_1 = k, |H_1|\right)}{f_{\widehat{\mathbf{R}}}\left(\mathbf{r} | K, m_1 = 0, |H_1|\right)}\right\}, k = 1, 2, \cdots, M-1. \quad (5)$$

## III. CHANNEL CAPACITY AND NORMALIZED THROUGHPUT

In this section, we compute the CM channel capacity given $K$ denoted, $C^{\mathrm{CM}}(K)$ and the corresponding normalized throughput denoted, $W^{\mathrm{CM}}(K)$ for the synchronous fast FHSS-MA network under consideration. Since the $Z_l^{K'}$s in (1) are i.i.d. under the large $q$ assumption [5], the resulting channel is symmetric. Hence, for the case when the number of hopping slots, $q$ is sufficiently large, the CM channel capacity with noncoherent detection with CSI may well be approximated by [6]

$$\widehat{C}^{\mathrm{CM}}(K) = 1 - \frac{1}{\log_2 M} \times E_{|H_1|}\left[E_{\widehat{\mathbf{R}}||H_1|}\left\{\log_2\left(\frac{\sum_{k=0}^{M-1} f_{\widehat{\mathbf{R}}}\left(\widehat{\mathbf{R}} | K, m_1 = k, |H_1|\right)}{f_{\widehat{\mathbf{R}}}\left(\widehat{\mathbf{R}} | K, m_1 = 0, |H_1|\right)}\right) | K, m_1 = 0, |H_1|\right\}\right] \quad (6)$$

where the expectation operations may be evaluated using the Monte-Carlo integration technique [12]. The corresponding normalized network throughput, defined as the average number of successfully transmitted information bits per unit time per unit bandwidth assuming channel capacity achieving codes, is $\widehat{W}^{\mathrm{CM}}(K) \triangleq K\widehat{C}^{\mathrm{CM}}(K)/2q_{\mathrm{BFSK}}$ [13] where $q_{\mathrm{BFSK}}$ is the number of available frequency hopping slots assuming BFSK modulation, representing the normalized bandwidth.

## IV. NUMERICAL RESULTS

In this section, we present the CM channel capacity and the associated normalized network throughput results for the network under consideration along with the FER performance for rate-1/3, $M$-ary turbo codes designed in [9]. The corresponding results for the binary coding case, reproduced from [5], are also given for comparison purposes. In addition, the sensitivity of the maximum likelihood (ML) decoder performance to estimation errors in system parameters $K$ and $\gamma$ is presented. For all numerical results, the AWGN signal-to-noise ratio, $\bar{E}_b/N_0$ is set to 20 dB, unless otherwise specified, where $\bar{E}_b$ is the average received energy per information bit with $\bar{E}_b \triangleq \bar{E}_s/(\rho \log_2 M)$ where $\rho$ denotes the code rate. Also, the number of available frequency hopping slots assuming BFSK modulation, $q_{\mathrm{BFSK}}$, is assumed to be 128 and thus, the number of available frequency hopping slots with MFSK modulation is $q_{\mathrm{MFSK}} = 2\log_2 M \cdot q_{\mathrm{BFSK}}/M$.

Fig. 1 shows the plots of $K$ versus the channel capacity, where for a given channel capacity (code rate), the value of $K$ indicates the maximum number of allowed users in the network guaranteeing reliable communications. The CM channel capacity curves are computed from (6) and the BICM channel capacity curves are computed from (18) in [5]. The results show that the CM provides drastically improved performance compared to the BICM. For example, at a code rate of 1/3, the maximum number of active users that may be supported by the CM FHSS-MA network using 256-FSK increases approximately two-fold compared to that by the BICM FHSS-MA network using 8-FSK. Here, 8 and 256 are optimum modulation orders that maximize the value of $K$ for the BICM and the CM systems with a

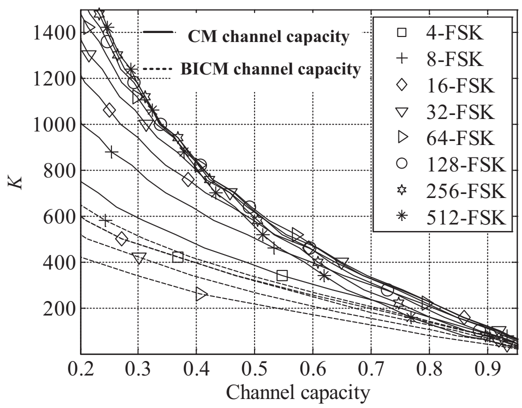


Fig. 1. The maximum number of active users supported versus channel capacity. Noncoherent detection with CSI. $\bar{E}_b/N_0 = 20$ dB, $q_{\mathrm{BFSK}} = 128$.

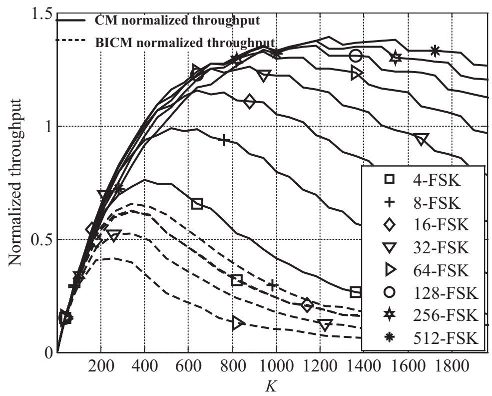


Fig. 2. Normalized throughput of synchronous fast FHSS-MA networks versus $K$. Noncoherent detection with CSI. $\bar{E}_b/N_0 = 20$ dB, $q_{\mathrm{BFSK}} = 128$.

code rate of 1/3, respectively. Similarly, the corresponding normalized throughput results shown in Fig. 2 also lead to similar conclusions.

Table 1 shows the maximum number of active users supported in the network guaranteeing the reliable communication for the BICM and the CM systems with code rates of 1/3, 1/2, and 2/3. These values are obtained by finding the values of $K$ satisfying that the BICM and the CM channel capacity conditioned on $K$ are equal to given code rates. We note that for the CM system at a given code rate, there is an optimum modulation order that maximizes the number of active users supported in the network, as with the BICM system. For example, at code rates of 1/3, 1/2, and 2/3, the optimum modulation orders of the CM systems are 256, 64, and 32, respectively, and that for the BICM systems are all 8. Also, in the aspects of the maximum normalized network throughput (Fig. 2), the optimum modulation order of the CM system is 256 that is a maximum modulation order satisfying integer $q_{\mathrm{MFSK}}$ for $q_{\mathrm{BFSK}} = 128$, while the optimum modulation order of the BICM system is 8.

Table 2 shows the maximum number of active users supported in the network guaranteeing the reliable communication for $\bar{E}_b/N_0 = 10$ dB, i.e., thermal noise dominated. Note that for $\bar{E}_b/N_0 = 10$ dB, the maximum number of active users supported in the network decreases compared to the case with $\bar{E}_b/N_0 = 20$ dB for both the BICM and the CM cases, as expected. However, the results clearly show that the CM still provides drastically improved performance compared to the BICM.

Table 1. The maximum number of active users supported in the network guaranteeing the reliable communication for code rates of 1/3, 1/2, and 2/3. Noncoherent detection with CSI, $\bar{E}_b/N_0 = 20$ dB, $q_{\mathrm{BFSK}} = 128$.

| $M$ | Code rate $= 1/3$ | | Code rate $= 1/2$ | | Code rate $= 2/3$ | |
|---|---|---|---|---|---|---|
| | CM | BICM | CM | BICM | CM | BICM |
| 4 | 550 | 440 | 385 | 315 | 250 | 210 |
| 8 | 720 | 465 | 500 | 330 | 325 | 215 |
| 16 | 850 | 440 | 575 | 310 | 360 | 200 |
| 32 | 940 | 380 | 615 | 265 | 375 | 165 |
| 64 | 990 | 300 | 625 | 210 | 365 | 130 |
| 128 | 1015 | 220 | 620 | 155 | 340 | 95 |
| 256 | 1025 | 155 | 590 | 105 | 305 | 65 |

We next turn our attention to the performance of practical $M$-ary turbo codes in synchronous fast FHSS-MA networks with MFSK. The codes considered are rate-1/3, $M$-ary turbo codes designed in [9]. Results are also provided for the binary 3GPP turbo code as specified in the 3GPP standard [7] for comparison purposes. The number of information bits carried in a code frame is taken to be 5,114 bits and the $M$-ary/binary turbo codes are decoded via the iterative log-maximum a posteriori (MAP) decoder [14] with 20 decoder iterations per frame.

Table 3 shows the maximum number of active users that may be supported at FERs of $10^{-1}$ and $10^{-2}$ with $M$-ary turbo codes designed in [9] and the binary 3GPP turbo code [7]. We first note that the synchronous fast FHSS-MA network with MFSK and practical $M$-ary and binary turbo codes perform quite close to the CM and the BICM theoretical limits for all modulation orders. Hence, $M$-ary turbo coded FHSS-MA networks drastically outperform binary turbo coded FHSS-MA networks as predicted by the theoretical results. For example, the number of active users that may be supported at an FER of $10^{-2}$ by the $M$-ary turbo coded system with 64-FSK shows close to 80% increase compared to that of the binary turbo coded system with 8-FSK as predicted by the channel capacity results[1].

Finally, we study the sensitivity of the ML decoder performance to estimation errors in $K$ and $\gamma$. Table 4 lists the maximum number of active users supported at an FER of $10^{-2}$ for a range of estimation errors in $K$ and $\gamma$ where $\hat{K}$ and $\hat{\gamma}$ denote the estimates of $K$ and $\gamma$ made at the receiver, respectively. Note that as with the binary case [5], the ML decoder performance for the $M$-ary turbo coded FHSS-MA network is quite immune to estimation errors in the received $\gamma$ and $K$, thus requiring only

[1] As shown in Table 1, 8 and 256 are optimum modulation orders of the BICM and the CM systems at a code rate of 1/3, respectively. However, due to the huge complexity of 128-ary and 256-ary turbo decoder, the performance of the $M$-ary turbo coded system using 64-FSK is compared with that of the binary turbo coded system using 8-FSK. By theoretical results in Table 1, it is expected that the performance of the $M$-ary turbo coded system using 64-FSK will be close to that with 256-FSK.

Table 2. The maximum number of active users supported in the network guaranteeing the reliable communication for $\bar{E}_b/N_0 = 20$ dB and $\bar{E}_b/N_0 = 10$ dB. Noncoherent detection with CSI, code rate $= 1/3$, $q_{\mathrm{BFSK}} = 128$.

| $M$ | $E_b/N_0 = 20$ dB | | $E_b/N_0 = 10$ dB | |
|---|---|---|---|---|
| | CM | BICM | CM | BICM |
| 4 | 550 | 440 | 255 | 190 |
| 8 | 720 | 465 | 375 | 195 |
| 16 | 850 | 440 | 450 | 155 |
| 32 | 940 | 380 | 495 | 120 |
| 64 | 990 | 300 | 510 | 90 |
| 128 | 1015 | 220 | 510 | 55 |
| 256 | 1025 | 155 | 500 | 35 |

Table 3. The maximum number of active users supported at FERs of $10^{-1}$ and $10^{-2}$. Noncoherent detection with CSI, $\bar{E}_b/N_0 = 20$ dB, $q_{\mathrm{BFSK}} = 128$, code rate $= 1/3$. Binary turbo code: 3GPP turbo codes [7]. $M$-ary turbo codes [9]. Frame length $= 5,114$ bits.

| $M$ | FER | CM theoretical limit | $M$-ary turbo codes | BICM theoretical limit [1] | Binary turbo codes |
|---|---|---|---|---|---|
| 4 | $10^{-1}$ | 550 | 500 | 440 | 398 |
| | $10^{-2}$ | | 491 | | 390 |
| 8 | $10^{-1}$ | 720 | 645 | 460 | 424 |
| | $10^{-2}$ | | 633 | | 413 |
| 16 | $10^{-1}$ | 850 | 729 | 440 | 394 |
| | $10^{-2}$ | | 713 | | 383 |
| 32 | $10^{-1}$ | 940 | 768 | 380 | 337 |
| | $10^{-2}$ | | 748 | | 326 |
| 64 | $10^{-1}$ | 990 | 775 | 267 | 337 |
| | $10^{-2}$ | | 758 | | 257 |

Table 4. The maximum number of active users supported at an FER of $10^{-2}$ as a function of the estimation errors in $K$ and $\gamma$. Noncoherent detection with CSI, $\bar{E}_b/N_0 = 20$ dB, $q_{\mathrm{BFSK}} = 128$, code rate $= 1/3$. $M$-ary turbo codes [9]. Frame length $= 5,114$ bits.

| $M$ | $\frac{\hat{K}-K}{K} \times 100\%$ | | | $10\log_{10}\frac{\hat{\gamma}}{\gamma}$ dB | | |
|---|---|---|---|---|---|---|
| | -80 | 0 | 80 | -3 | 0 | 3 |
| 4 | 461 | 491 | 471 | 478 | 491 | 475 |
| 8 | 582 | 633 | 605 | 615 | 633 | 610 |
| 16 | 645 | 713 | 680 | 691 | 713 | 685 |
| 32 | 667 | 748 | 713 | 722 | 748 | 713 |
| 64 | 665 | 758 | 718 | 719 | 758 | 716 |

a very crude estimates of these network parameters for ML decoding.

## V. CONCLUSIONS

In this paper, we analyze the performance of $M$-ary turbo coded, synchronous, fast FHSS-MA networks with MFSK and noncoherent detection under the AWGN and Rayleigh fading channels. The CM channel capacity along with the associated normalized network throughput are computed and the FER performance of $M$-ary turbo codes are evaluated. Numerical results show that $M$-ary coded FHSS-MA networks using $M$-ary FSK dramatically outperform binary coded FHSS-MA networks using $M$-ary FSK, resulting in excess of 80% increase in the network capacity.

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