Iterative Detection of *M*-FSK Signal on MIMO Frequency Selective Fading Channels

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Abstract— **In this paper, we have proposed the novel demodulation scheme of *M*-FSK (*M*-ary Frequency Shift Keying) signal on MIMO (Multiple Input Multiple Output) frequency selective channels. As for this demodulation scheme, there exists almost no investigation except a few reports. The proposed scheme uses FDE (Frequency Domain Equalization) and ISI (Inter-Symbol Interference) canceller plus MLD (Maximum Likelihood Detection). We further reduced the BER by using iterative feedback of detected results. The novelty in this paper is the integration of those techniques for detecting MIMO *M*-FSK signal. Through computer simulation, we have verified that the proposed scheme using FDE and ISI canceller plus MLD with iterative feedback exhibits the excellent BER characteristics compared with previously reported FDE detector.**

Keywords-MIMO, M-FSK, ISI, IAI, MLD, FDE, Multipath channel

I. INTRODUCTION

M-FSK signal has the constant envelope property and is appropriate to be amplified by nonlinear amplifier with high power efficiency. However, as *M*-FSK is a nonlinear modulation scheme, the equalization at the receiver side has been difficult when it is subjected to frequency selective channels. On the other side, due to the increasing demand of high data rate and reliable data transmission, MIMO schemes with multiple transmit and receive antennas become quite popular recently. The conventional MIMO scheme processes the received signals using linear matrix processing. However it has been difficult to apply the linear processing to the nonlinear modulation such as MIMO *M*-FSK, and accordingly there was almost no research on MIMO *M*-FSK signaling. So, we aimed to develop the MIMO *M*-FSK transmission scheme and examine its BER.

TABLE I LIST of PARAMETERS

M : Number of modulation level of FSK
n_T : Number of transmit antenna
n_R : Number of receive antenna
T_s : Symbol duration
KT_s : Maximum symbol delay time of multipath waves
$T_n = nT_s$: Block length for a FFT block
Δt : Sampling interval; $\Delta t = T_s / c$
c : Number of samples per a symbol
$N = cn$: Number of FFT samples
k : Time index of desired symbol time to be detected
$T_{CP} (= c_{CP} \Delta t)$: Cyclic Plefix length
I : Number of iterative feedbacks of block decision result
L : Number of delay paths

We had already shown that the FDE (Frequency Domain Equalization) scheme using CP (Cyclic Prefix) [1] is applicable to the signal separation and equalization of MIMO *M*-FSK signals [2]-[4], where the FDE is done before the demodulation process of *M*-FSK signal. This method was originally developed for SISO (Single Input Single Output) FSK signals [5]. In [6], we developed the detection scheme using ISI canceller and MLD to further improve the BER. In that scheme, the ISI's caused by the past symbols already detected were cancelled by ISI canceller, but the ISI cancellation caused by the future symbols and the separation of spatially multiplexed signals of MIMO transmission were achieved by MLD. This leads to the complexity of MLD of M^{Kn_T} where M is the modulation level (number of symbols) of *M*-FSK, KT_s the maximum symbol delay time of multipath waves, T_s the symbol duration and n_T the number of transmit antennas. As the complexity of MLD grows exponentially with the increase of K and n_T, the realization of this detector looks quite difficult even though using M-algorithm instead of MLD [6]. In this paper, in order to improve the BER characteristics of the FDE detector [2]-[4] and reduce the complexity of the detector in [6], we propose the novel demodulator structure in which the FDE is firstly done to obtain the tentative decision results. Using the tentative decision results, the ISI replicas due to the transmit symbols other than the desired symbol are cancelled form the receive signal. If the cancellation is perfect, we can obtain the receive signal as if only the desired symbol is transmitted. Then the MLD is applied to the receive signal to separate the IAI (Inter-Antenna Interference) of MIMO transmission. At this stage the output of MLD is regarded as the decision results of 0-th iteration. Then the 0-th decision results are fed back to the ISI canceller and again used as the tentative decision results for ISI cancellation. The ISI cancelled receive signal is then fed to the MLD again. This iterative processing is repeated and results in the better BER convergence. The basic structure of the above iteration receiver was developed in [7],[8] for the linear SC (Single Carrier)-FDE signals. In the proposed MIMO *M*-FSK demodulator, the complexity of MLD is proportional to M^{n_T} which does not depend on the ISI symbol length of K and this greatly reduces the complexity of detector enabling the detector for actual implementation.

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This paper is organized as follows. In Section II, the FDE receiver for MIMO *M*-FSK is described and simulated. In Section III, the proposed detector with FDE and ISI canceller plus MLD is introduced. In Section IV, the BER results of proposed demodulator through computer simulation are shown. In Section V, the complexity of detector is described. The paper concludes with Section VI.

II. MIMO *M*-FSK DETECTION USING FDE

In Fig.1 we show the transmitter and receiver block diagram for MIMO *M*-FSK when using the FDE at the receiver. At the transmitter, the data bits are *M*-FSK modulated and CP is added to the transmit symbol block like Fig.2 with the block length of $T_n = nT_s$ where n is the number of symbols in a block and T_s is the symbol duration. From each antenna, the symbol block is transmitted. At the receiver, after the removal of CP, the received baseband I and Q signals are sampled at the sampling frequency of $f_s = 1/\Delta t$ where Δt is the sampling interval, $T_s = c\Delta t$ and c is the integer number. The value of c is taken large enough to satisfy the sampling theorem and not to make aliasing for the received analog I and Q signals.

The power spectral densities of continuous phase *M*-FSK signals are shown in Fig.3.

As a block length $T_n = nT_s$ contains cn samples, the number of FFT points becomes $N = cn$. The sampled complex discrete time signals $(I_p + jQ_p),\ p = 1,\cdots,N$ are then FFT-transformed and the FDE based on MMSE criterion is performed at each frequency point. As the result of FDE, the ISI compensation and the signal separation of spatially multiplexed signals are made simultaneously. Then the frequency domain samples are IFFT-transformed and the time domain discrete samples are obtained.

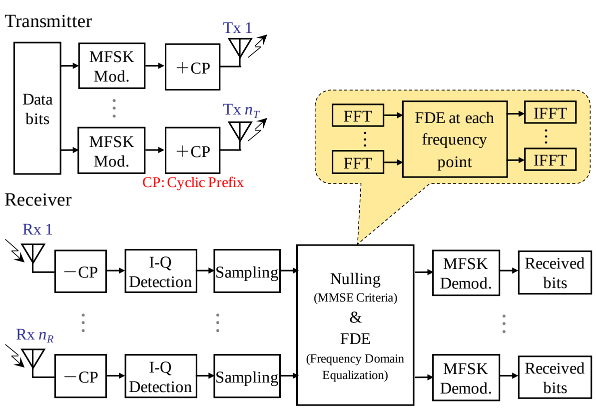

Figure 1. Block diagram of transmit and receive system of MIMO *M*-FSK using FDE at receiver on frequency selective MIMO channel

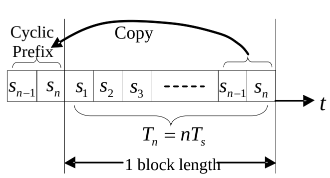

Figure 2. Insertion of CP at the transmitter

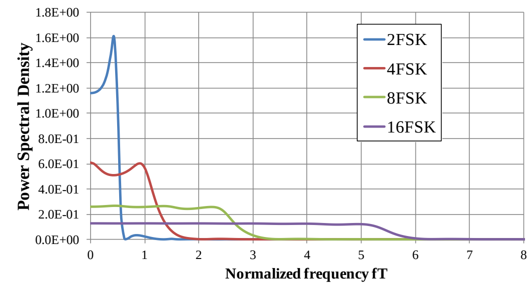

Figure 3. One-sided power spectral densities of *M*-FSK signals for modulation index *h*=0.7

These samples are equivalent to analogue *M*-FSK signals, because the sampling interval of Δt is taken small enough. The time domain samples are fed to the ordinary *M*-FSK detector. In this study, we employed a non-coherent energy detector as the *M*-FSK detector, because it is easy to implement and it does not need the phase synchronization [9]. In the energy detection of *M*-FSK signals, total *M* energy detectors are used, i.e., each energy detector for each frequency. The energy detectors for *M*-FSK are shown in Fig.4.

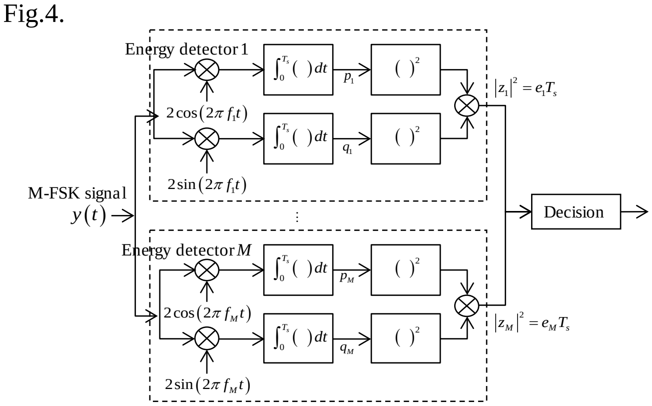

Figure 4. Energy detectors for *M*-FSK signal

The FDE weight with MMSE criterion is expressed as

$$\boldsymbol{D}(f) = E\{\boldsymbol{a}\boldsymbol{a}^H\}\boldsymbol{H}^H\left[\boldsymbol{H}E\{\boldsymbol{a}\boldsymbol{a}^H\}\boldsymbol{H}^H + \sigma^2\boldsymbol{I}_{n_R}\right]^{-1} \quad (1)$$

where $\boldsymbol{a} = \boldsymbol{a}(f)$ is the transmit signal vector at frequency point f, $\boldsymbol{H} = \boldsymbol{H}(f)$ the channel matrix, σ^2 the receive noise power, $E\{\ \}$ the ensemble average, $(\ )^H$ the Hermitian transpose, n_R the number of receive antenna, $\boldsymbol{I}_{n_R}$ the identity matrix. When $\boldsymbol{S}(f)$ denotes the power spectral density matrix of *M*-FSK signals, we have

$$E\{\boldsymbol{a}(f)\boldsymbol{a}^H(f)\} = \{\boldsymbol{S}(f)\Delta f\}\boldsymbol{I}_{n_T} = \{\boldsymbol{S}(f)[c/(NT_s)]\}\boldsymbol{I}_{n_T} \quad (2)$$

where n_T is the number of transmit antennas. By substituting (2) into (1), we obtain

$$\boldsymbol{D}(f) = \boldsymbol{H}^H\left[\boldsymbol{H}\boldsymbol{H}^H + \sigma^2 NT_s/\{c\boldsymbol{S}(f)\}\boldsymbol{I}_{n_R}\right]^{-1} \quad (3)$$

Using the FDE weight of (3), MIMO *M*-FSK signal is equalized and demodulated. The BER characteristics of FDE receiver for MIMO or SISO *M*-FSK with *M*=2, 4, 8 and 16 are examined through computer simulation. The computer simulation condition is shown in Table I. The delay profile between each transmit and receive antenna is illustrated in Fig.5. The BER results are shown in Fig.6.

From Fig.6, we observe that the BER characteristics are

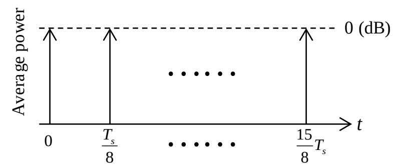

Figure 5. Power delay profile between each transmit and receive antenna

TABLE II SIMULATION CONDITION FOR MIMO *M*-FSK SIGNAL WITH FDE

Modulation	2 , 4 , 8 16 FSK
Modulation index	h=0.7
Number of Tx & Rx antennas	1×1 , 2×2 , 4×4
Channel model between each Tx and Rx antenna	Quasi-static 16 delay paths Rayleigh fading with equal power
Signal equalization and separation	FDE (MMSE criterion)
Symbol duration	T_s
Number of sample points in a symbol duration c	c=8,16,32,64 (2,4,8,16FSK) $T_s = c\Delta t$
Interval of delay paths	$T_s/8$
Maximum delay time	$15T_s/8$
Length of Cyclic Prefix	$2T_s$
Block length nT_s	$16T_s$
Number of FFT points (nc)	128, 256, 512, 1024

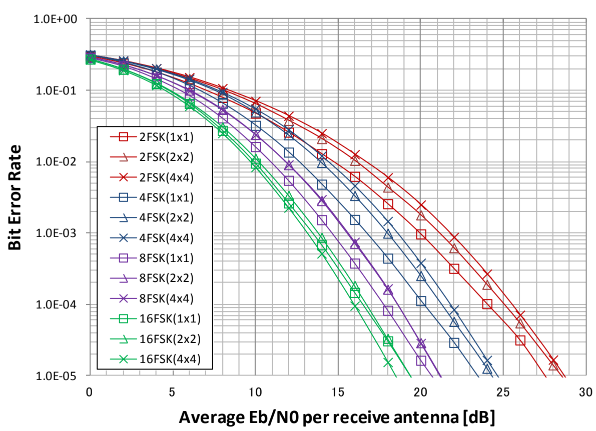

Figure 6. BER characteristics of MIMO *M*-FSK with FDE and energy detector

improved as the value of *M* increases from 2FSK, 4FSK, 8FSK to 16FSK. This improvement is due to the bandwidth expansion of *M*-FSK signal with larger *M* value. Due to the FDE, the diversity order, i.e., the gradient of BER curve, is the same among 1×1, 2×2 and 4×4. This is also observed in MIMO OFDM with FDE. Accordingly, we can say that the multi-stream MIMO transmission is available for *M*-FSK through the FDE receiver.

III. ITERATIVE DETECTION OF MIMO *M*-FSK USING FDE AND ISI CANCELLER PLUS MLD

By using the equalization and signal separation with FDE and energy detector, the demodulation of MIMO *M*-FSK signal can be achieved. However, the BER characteristic of FDE receiver is not enough and we aim to obtain further BER improvement. In order to do this, we consider the decision results from FDE as the tentative decision results. Using the tentative decision results, the ISI replica at the receiver is generated and is subtracted from the receive signal. If the tentative decision results from FDE are correct, we can cancel the ISI and obtain the receive signal as if only transmit symbols at desired time k are transmitted from n_T transmit antennas. For this receive signal, the separation of spatially multiplexing is done using MLD. Then we consider the outputs of MLD as the reliability enhanced decision results and use them as the evolved tentative decision results. Using the evolved results, the new ISI replicas are generated and again subtracted from the receive signal to cancel the ISI. After this ISI cancellation, the MLD is again employed to separate the spatial multiplex. This iterative processing is repeated to improve the BER for each iteration. The above iterative procedure algorithm was originally reported in [7] for MIMO SC-FDE receiver.

In Fig.7, the transmitter and receiver block diagram is shown for this iterative demodulator. At the transmitter, *M*-FSK symbols with the block length of nT_s are generated and the CP with the length of $c_{CP}\Delta t$ is added at the head of the block. Each block with CP is transmitted from each antenna. At the receiver, after removing the CP, the equalization and signal separation are firstly done through FDE and the tentative decision results are obtained. Those tentative decision results are fed to the ISI canceller and the replica for ISI cancellation is generated. The replicas are made in order to cancel the ISI's caused by the total $2K$ transmit symbols before and after the desired symbol at time k. Accordingly, in making the ISI replica, the transmit symbol at time k in the tentative decision results is set to zero. By subtracting the ISI replica from the receive signal, the ISI components due to the transmit symbols before and after the transmit symbol at time k are cancelled. If the tentative decision results are correct, we can get the receive signal as if the symbols at time k are only transmitted from antenna $1 \sim n_T$ with spatially multiplex. Then in order to separate the spatial multiplex, the MLD is applied to the ISI cancelled receive signal and the decision results at time k are obtained. The new decision results at time k are sequentially fed back to the ISI canceller and the decision time is evolved from k to $(k+1)$. After obtaining all the decision results for n symbols, those decision results for n symbols are replaced

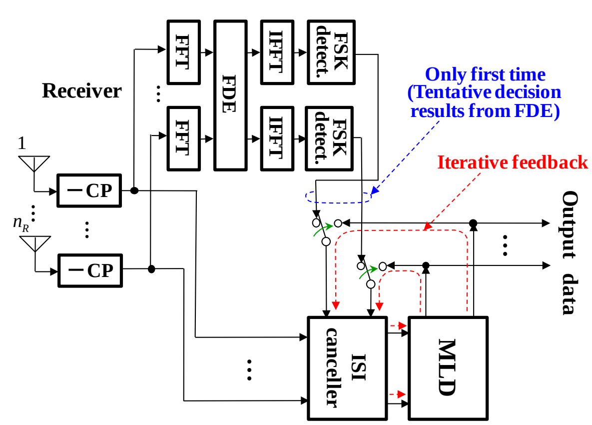

Figure 7. Iterative demodulation scheme of MIMO *M*-FSK using FDE and ISI canceller plus MLD (Transmitter is the same as Fig.1.)

as the new tentative decision results of a block. The above procedure for a FDE block with n symbols is repeated I times to obtain the final decision results.

We consider the ISI replica generation at the receiver for the first symbol ($k=1$) in a block with the length of nT_s. When the MLD is done 0 times, the ISI cancellation replica $\boldsymbol{y}'^{(0)}_{1,ij}$ for the 1st symbol in a block from transmit antenna j to receive antenna i is given by

$$\boldsymbol{y}'^{(0)}_{1,ij} = \begin{pmatrix} y^{(0)}_{1,ij}(c-1+c_{CP}) \\ \vdots \\ y^{(0)}_{1,ij}(0) \end{pmatrix}$$

$$= \begin{pmatrix} h_{ij}(0) & \cdots & h_{ij}(c_{CP}) & 0 & \cdots & 0 \\ 0 & \ddots & & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & & \ddots & 0 \\ 0 & \cdots & 0 & h_{ij}(0) & \cdots & h_{ij}(c_{CP}) \end{pmatrix} \begin{pmatrix} \left.\begin{matrix} x^{(0)}_j(c-1+c_{CP}) \\ \vdots \\ x^{(0)}_j(c) \end{matrix}\right\} c_{CP} \\ \left.\begin{matrix} 0 \\ \vdots \\ 0 \end{matrix}\right\} c \\ \left.\begin{matrix} x^{(0)}_j(-1) \\ \vdots \\ x^{(0)}_j(-c_{CP}) \end{matrix}\right\} c_{CP} \end{pmatrix} \quad (4)$$

where the number of samples in a symbol T_s is c （$T_s = c\Delta t$ ） , the CP length $c_{CP}\Delta t$, the sample of transmit signal $x^{(0)}_j(p)$ at $t = p\Delta t$ (p: integer number), the complex gain of l-th ($l = 0,1,\cdots,c_{CP}-1$) delay path $h_{ij}(l)$. Also the subscript “1” in $\boldsymbol{y}'^{(0)}_{1,ij}$ means the 1st symbol and the superscript “(0)” the execution times of MLD. In (4), the sample values at sample time $t = 0,\cdots,(c-1)\Delta t$ of the 1st symbol in a transmit block is set to zero. Also in (4), $x^{(0)}_j(-c_{CP}),\cdots,x^{(0)}_j(-1)$ and $x^{(0)}_j(c),\cdots,x^{(0)}_j(c-1+c_{CP})$ show the c_{CP} samples before and after the symbol at time $k=1$ respectively. As shown in Fig.8, the first part with the length of $T_{CP}(=c_{CP}\Delta t)$ and the last part of T_{CP} in a FFT block are circularly copied after the tail and before the head of a block respectively. This is because the FDE for obtaining the tentative decision results is based on the circular convolution in a time domain, i.e., we have to consider the ISI components falling in the first part T_{CP} in a FFT block and the ones falling in the subsequent part T_{CP} after the tail of a block.

The receive replica $\boldsymbol{y}''^{(0)}_{1,ij}$ for MLD of the 1st symbol in a block is given by

$$\boldsymbol{y}''^{(0)}_{1,ij} = \begin{pmatrix} y''^{(0)}_{1,ij}(c-1+c_{CP}) \\ \vdots \\ y''^{(0)}_{1,ij}(0) \end{pmatrix}$$

$$= \begin{pmatrix} h_{ij}(0) & \cdots & h_{ij}(c_{CP}) & 0 & \cdots & 0 \\ 0 & \ddots & & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & & \ddots & 0 \\ 0 & \cdots & 0 & h_{ij}(0) & \cdots & h_{ij}(c_{CP}) \end{pmatrix} \begin{pmatrix} \left.\begin{matrix} 0 \\ \vdots \\ 0 \end{matrix}\right\} c_{CP} \\ x^{(0)}_j(c-1) \\ \vdots \\ x^{(0)}_j(0) \\ \left.\begin{matrix} 0 \\ \vdots \\ 0 \end{matrix}\right\} c_{CP} \end{pmatrix} \quad (5)$$

$\boldsymbol{y}''^{(0)}_{1,ij}$ in (5) is the output from the channel when only the

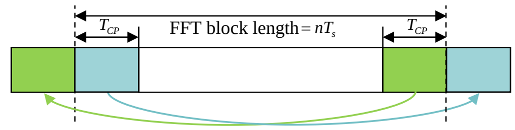

Figure 8. Termination processing in a FFT block for ISI cancellation

1st transmit symbol T_s is transmitted. In generating MLD replica, all the transmit symbols other than at time k are set to zero. Those two replicas in (4) and (5) have to be generated so as to satisfy the phase continuity of FSK, because we are assuming the continuous phase *M*-FSK.

Using those receive replicas, the squared Euclidian distance between the ISI subtracted signal from the receive signal $\boldsymbol{y}_{1,i}$ at receive antenna i and the MLD replica is calculated. The candidate $\boldsymbol{x}_1^{(0)}$ of transmit symbol vector for the 1st symbol in a FFT block is determined so as to minimize the distance metric as shown below.

$$\boldsymbol{x}_1^{(0)} = \arg\min_{\boldsymbol{x}_1^{(0)}} \left\{ \sum_{i=1}^{n_R} \left\| \left(\boldsymbol{y}_{1,i} - \sum_{j=1}^{n_T} \boldsymbol{y}'^{(0)}_{1,ij} \right) - \sum_{j=1}^{n_T} \boldsymbol{y}''^{(0)}_{1,ij} \right\|^2 \right\} \quad (6)$$

where

$$\boldsymbol{x}_1^{(0)} = \left[\boldsymbol{x}^{(0)}_{1,1} \ \cdots \ \boldsymbol{x}^{(0)}_{1,n_T} \right]^T, \quad \boldsymbol{x}^{(0)}_{1,j} = \left[x^{(0)}_{1,j}(0) \ \cdots \ x^{(0)}_{1,j}(c-1) \right]^T \quad (7)$$

$$\boldsymbol{y}_{1,i} = \begin{pmatrix} y_i(c-1+c_{CP}) \\ \vdots \\ y_i(0) \end{pmatrix}$$

$$= \sum_{j=1}^{n_T} \begin{pmatrix} h_{ij}(0) & \cdots & h_{ij}(c_{CP}) & 0 & \cdots & 0 \\ 0 & \ddots & & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & & \ddots & 0 \\ 0 & \cdots & 0 & h_{ij}(0) & \cdots & h_{ij}(c_{CP}) \end{pmatrix} \begin{pmatrix} x^{(0)}_j(c-1+c_{CP}) \\ \vdots \\ x^{(0)}_j(-c_{CP}) \end{pmatrix} \quad (8)$$

The decision result $\boldsymbol{x}_1^{(0)}$ of MLD in (6) is regarded as the new tentative decision result and is fed back to the ISI canceller to detect the 2nd symbol in a block at time $k=2$. Next, for the 2nd symbol, the ISI cancellation and MLD are executed and the decision result of $\boldsymbol{x}_2^{(0)}$ is obtained. Then $\boldsymbol{x}_2^{(0)}$ is regarded as the new tentative decision result and is fed back to the ISI canceller for determining the 3rd symbol $\boldsymbol{x}_3^{(0)}$. Those sequential feedback procedure is repeated up to the *n*-th symbol in a block. The obtained decision results for all the n symbols in a block are regarded as the block decision results, which is again fed back to the ISI canceller and the subsequent MLD processing is done. This feedback of block decision results is repeated I times and the final decision results are obtained.

IV. SIMULATION RESULTS OF ITERATIVE DETECTION RECEIVER FOR MIMO *M*-FSK

Computer simulations are made to verify the BER improvement of iterative receiver. The simulation condition is listed in Table III. The delay profile is the same as in Fig.5. The BER results are shown in Fig.9 to Fig.14.

From Fig.9~14, we observe that the BER characteristics of “FDE and ISI canceller plus MLD” receiver with iterative detection are better than “FDE” receiver. We also see the BER is improved as the number I of iterative feedbacks increases. $I=4$ (#4) is enough for the BER convergence, where the MLD is repeated five times for a block.

V. COMPARISON OF COMPLEXITY OF RECEIVER STRUCTURE

We compared the complexity between the receiver with "FDE" and the one with "FDE and ISI canceller plus MLD." The complexity is compared as the number of complex additions and multiplications required for detecting one symbol of FSK. The equations for calculating the complexity are given in Table IV, where we assume $I=1$, the maximum delay time of multipath wave is $(L-1)(2\Delta t)$ and $O\left(n_T^{\,2}\right)=n_T^{\,2}$. We also show the numerical results of complexity in Fig.15 and Fig.16. From those results, we know that the complexity of FDE receiver is far less than the "FDE and ISI canceller plus MLD" receiver. For the FDE receiver, the complexity gradually increases as the number of symbols n in a FFT block becomes large, but does not depend on the delay time parameter L of multipath. On the other hand, for the "FDE and ISI canceller plus MLD" receiver, we observe that the complexity increases as L becomes large, but does not depend on the number of symbols n in a block.

TABLE III SIMULAION CONDITIONS FOR MIMO *M*-FSK WITH ITERATIVE DETECTION

Modulation	2 , 4 , 8 FSK
Modulation index	*h*=0.7
Number of Tx & Rx antennas	2×2 , 4×4
Channel model between each Tx and Rx antenna	Quasi-static 16 delay paths Rayleigh fading with equal power
Signal equalization and separation	FDE (MMSE criterion) & ISI canceller + MLD
Symbol duration	T_s
Number of sample points for symbol duration c	c=8,16,32 (2,4,8FSK) $T_s=c\Delta t$
Interval of delay paths	$T_s/8$
Maximum delay time	$15T_s/8$
Length of Cyclic Prefix	$2T_s$
Block length nT_s	$16T_s$
Number of FFT points (nc)	128, 256, 512
Number of block iteration I	#0, #1, #2, #3, #4

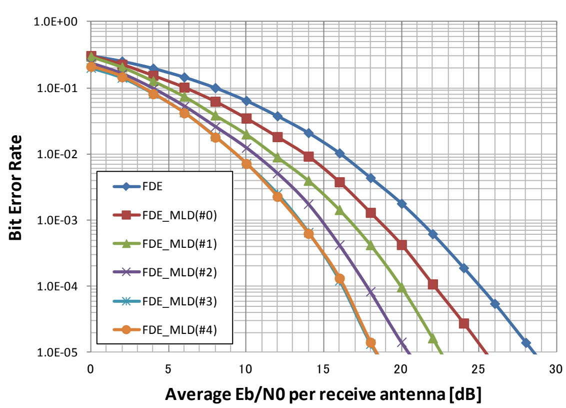

Figure 9. BER comparison between conventional FDE receiver and proposed iterative receiver (2FSK, 2×2)

VI. CONCLUSIONS

In this study, we have proposed the new receiver structure for *M*-FSK signal on frequency selective MIMO channels. In addition to the FDE receiver which was proposed previously, we demonstrated the novel receiver structure in which the ISI components are firstly cancelled by the tentative decision results obtained by FDE and then the MLD is employed to separate the spatial multiplexing.

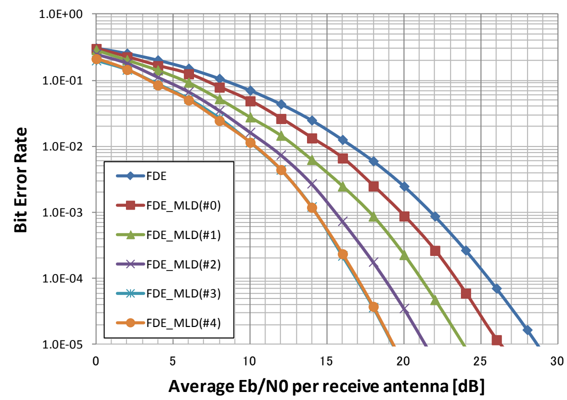

Figure 10. BER comparison between conventional FDE receiver and proposed iterative receiver (2FSK, 4×4)

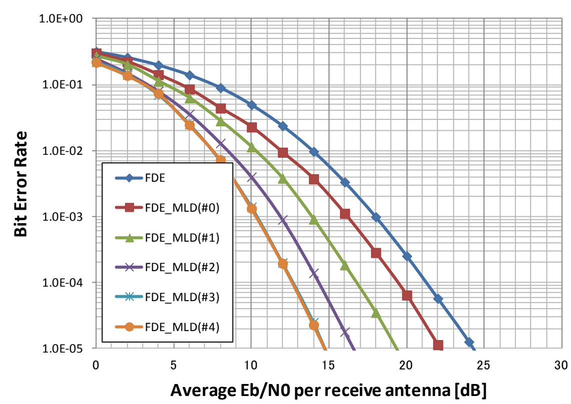

Figure 11. BER comparison between conventional FDE receiver and proposed iterative receiver (4FSK, 2×2)

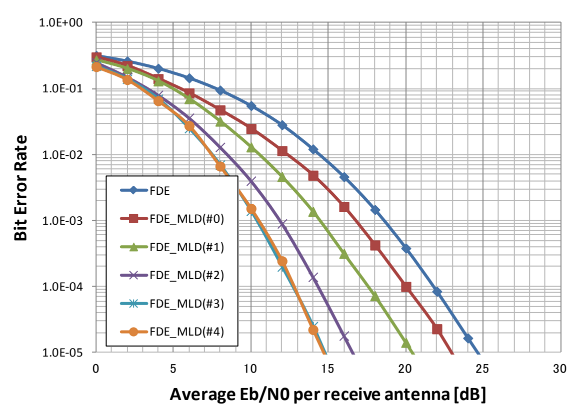

Figure 12. BER comparison between conventional FDE receiver and proposed iterative receiver (4FSK, 4×4)

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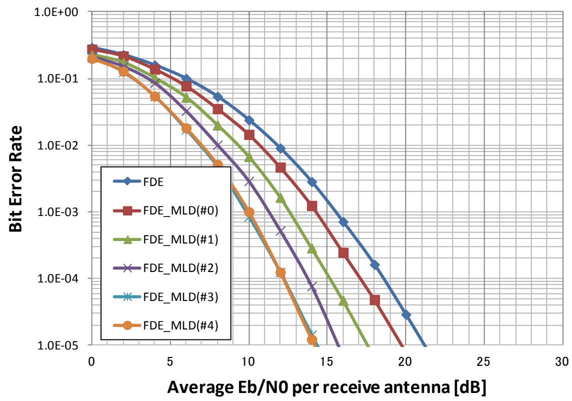

Figure 13. BER comparison between conventional FDE receiver and proposed iterative receiver (8FSK, 2×2)

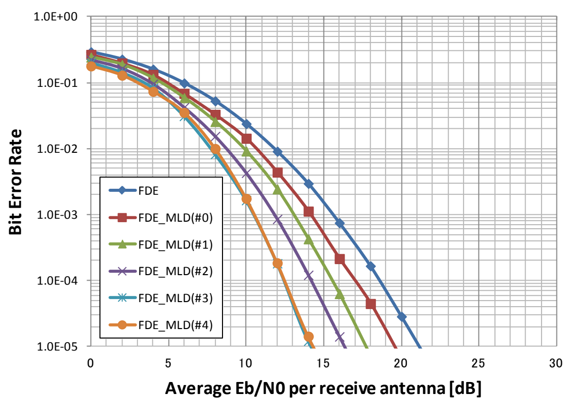

Figure 14. BER comparison between conventional FDE receiver and proposed iterative receiver (8FSK, 4×4)

TABLE IV NUMBER OF COMPLEX ADDITIONS AND MULTIPLICATIONS FOR DETECTING ONE *M*-FSK SYMBOL

FDE	$c\times\left[10\log_2(c\times n)+2\times O(n_T^{2})+2n_T-13\right]$
FDE & ISI canceller + MLD	$c\times\left[10\log_2(c\times n)+2\times O(n_T^{2})+2n_T-13\right]$ $+2\{c\times n_R\times(L\times n_T+1)\}\times(M^{n_T}+1)/n_T$

The proposed receiver improves the BER with the iterative feedback of decision results. The BER characteristics of proposed iterative receiver are improved very much when compared with the conventional FDE receiver. By using the tentative decision results obtained from the FDE, the complexity of MLD in the proposed iterative receiver does not depend on the transmit block length and becomes modest, while the high quality separation of spatially multiplexed signals that comes from MLD is maintained.

As future studies, instead of known channel state information (CSI) at the receiver, the measured CSI will be employed and the features of MIMO *M*-FSK comparing with existing linear modulations should be clarified.

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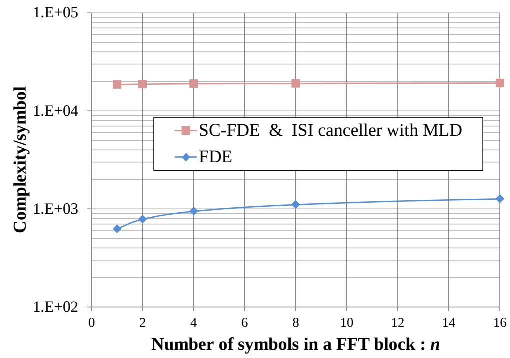

Figure 15. Complexity comparison of receivers for symbols n in a block

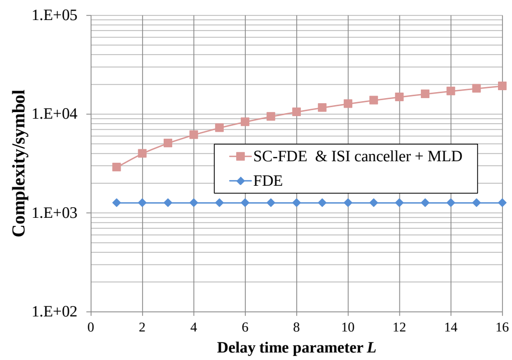

Figure 16. Complexity comparison of receivers for the maximum delay time of $(L-1)(2\Delta t)$

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