An Efficient Receiver Structure for Faster-than-Nyquist Signal in MIMO System

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Abstract —Next-generation wireless and/or satellite communications require high transmission efficiency and high reliability to provide various services with subscribers. To satisfied these requirements, incorporated MIMO (multiple-input-multiple-output) system with FTN (faster-than-Nyquist) techniques are considered in the paper. To improve performance and throughput, two kinds of MIMO turbo equalization techniques such as STTC (space-time trellis codes) and W-ZF(Weighted-Zero Forcing) are employed. They can yield significantly increased data rates and improved link reliability without additional bandwidth. In receiver side, BCJR algorithm is used for eliminating interferences induced by FTN transmission. Through the simulation results, based on MIMO-FTN transmission method, we compared the performance of layered space time codes with weighted zero forcing according to interference rate of FTN.

Index Terms—MIMO (Multiple-Input-Multiple-Output), FTN (Faster-than-Nyquist), W-ZF (Weighted-Zero Forcing), STTC (Space-time-trellis-code), BCJR, Turbo codes

I. Introduction

Recently, many methods for increase of throughput is being researched, as the next satellite broadcast / communication and the 5G based mobile communication demand for throughput is increasing, whilst the bandwidth is limited. However, it is very difficult to improve both throughput and performance, because the two are in a trade-off relationship. Therefore, it is the most important to develop methods which can maintain the performance to the maximum, whilst increasing the throughput.

At present, MIMO (Multiple-Input-Multiple-Output) technologies are being researched [1], which shows fast transmission efficiency whilst increasing the efficiency of the spectrum, as well as getting the benefits of diversity and encoding, among the solutions for improvement of the throughput of the DVB-S2 based satellite communication, the most representative method, improving the throughput via improving the decoding speed, research about which has already been saturated. As a result, a solution with the FTN (Faster-Than-Nyquist) method [2]-[4], which transmits faster than the throughput of Nyquist, is emerging as the standard for the next generation DVB-S3 [5]-[7].

The MIMO-FTN [8], [9] transmission method, which combines the MIMO and FTN methods to improve throughput, can maximize the improvement of throughput, however its decoding method and removal of interference is difficult, the research about which is under developed yet. However, in this study, we proposed a decoding method based on the MIMO-FTN techniques. Focus on how to remove ISI (Inter-Symbol Interference) from each transmit antennas, two kinds of proposed MIMO-FTN system are presented. Fixed on turbo codes as an outer codes, first one is using STTC (Space-Time Trellis Codes) [10], [11] as an inner code, and second one is using W-ZF (Weighted -Zero Forcing) algorithm to distinguish symbols of each transmit antenna. In receiver side, BCJR algorithm [13] is used for canceling interference in order to improve error performance by increasing number of iterations. Turbo decoder and BCJR decoder are connected through interleaving and de-interleaving that updates each other's information repeatedly. The performance was analyzed by simulation to compare MIMO-FTN based on layered space time codes and weighted zero forcing for verification of the MIMO-FTN turbo equalization scheme.

II. FTN Signal Modelling

FTN signaling is a technique of transmitting information at a rate higher than the allowed Nyquist limit. For example, when 10^4 data can be transmitted in accordance with the speed of Nyquist for a certain time, if FTN method is used reducing to 50%, 2×10^4 data can be transmitted in the same length of time. Consequently, ISI necessarily occurred. Interference transmission signal $x(t)$ is given

$$x(t)=\sqrt{E_s}\sum_n b(n)h(t-n\tau T),\ \tau<1 \tag{1}$$

where $b(n)$ are encoded bit stream, E_s is the average symbol energy, and $h(t)$ is a unit-energy baseband pulse, which for this paper we will assume is orthogonal to shifts by T, τ is interference time. Interference rate τ' is given by

$$\tau'(\%)=100\times(1-\tau) \tag{2}$$

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If interference ratio is defined differently, it means increasing the throughput as τ'.

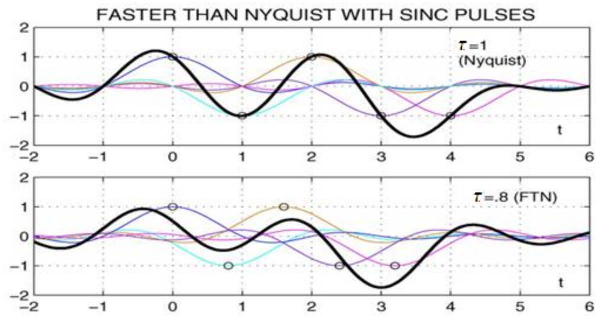

Fig. 1. FTN signaling with unit T sinc pulses and $\tau = 1$, $\tau = 0.8$.

Fig. 1 shows an example of sinc pulse FTN with orthogonal symbol time $\tau = 1$ and $\tau = 0.8$.

In the Fig. 1, we learn that there is no ISI generated as the transmission is run at the Nyquist rate when $\tau = 1$. However, when $\tau = 0.8$, the adjacent symbols affect each other due to FTN, and, as a result at each decision point of data, the parts labeled with circle are added to the raw data and affect them, and so we know that there is a change in the waveform due to the interference. Although the signal's waveform gets distorted due to ISI, if this issue is overcome, it can be see that the throughput improves by 25 % at the same time.

III. MIMO-FTN Turbo Equalization Model

A. Layered STTC Model

Consider an $N \times M$ MIMO communication system equipped with N-transmit antennas and M-receive antennas. The individual data streams of each transmitter are symbol aligned and are sent simultaneously. The data streams of each transmitter consist of successive data packages. Fig. 2 shows the proposed $N \times M$ MIMO-FTN system structure based on turbo equalization. Candidate of inner codes are STBC (Space-Time Block Codes) and STTC. This system is obtained diversity or spatial multiplexing effect. The maximum likelihood detection is optimal and fully exploits the available diversity. However, STBC for MIMO turbo equalization can't obtain coding gain even if increasing number of iteration. This is the reason that the outputs of STBC are not soft type symbols. The types of input symbols and output symbols must be soft symbols in order to improve performance by increasing number of iterations. Therefore, proposed MIMO-FTN system employs STTC techniques that have both diversity gain and encoding gain with 32 states proposed by Blum [10] as an inner code and employs turbo codes as an outer code. The information to be transmitted was encoded by a rate of 1/3 turbo codes with identical recursive encoders having the duo-binary generator polynomial with 16 states [14]. The source bits are encoded by turbo encoder and interleaved and STTC encoder, then mapping to QPSK symbols. Finally the bit stream is transmitted after distorted by FTN. Transmitted signals have been received by the receive antenna arrays, then significant performance improvement iterative turbo equalization BCJR algorithm for STTC decoder, de-interleaving and turbo decoding are performed.

The source bits to be transmitted bit-stream **D** is given by

$$\mathbf{D} = \{d_1, d_2, \cdots, d_k\} \tag{3}$$

where k is the size of **D**, First, **D** is encoded by the (N, K) outer codes. Coded bit stream **C** is given by

$$\mathbf{C} = \{c_1, c_2, \cdots, c_N\} \tag{4}$$

N is a length of the encoded bits. C is input to the STTC by two bits. Modulated signal after FTN method from the each transmission antenna is given by

$$\mathbf{B} = \{b_1, b_2, \cdots, b_l\} \tag{5}$$

l means the size of modulation output, and its sizes are different according to what kinds of modulation schemes are used. If modulation is QPSK, l equals to N/2.

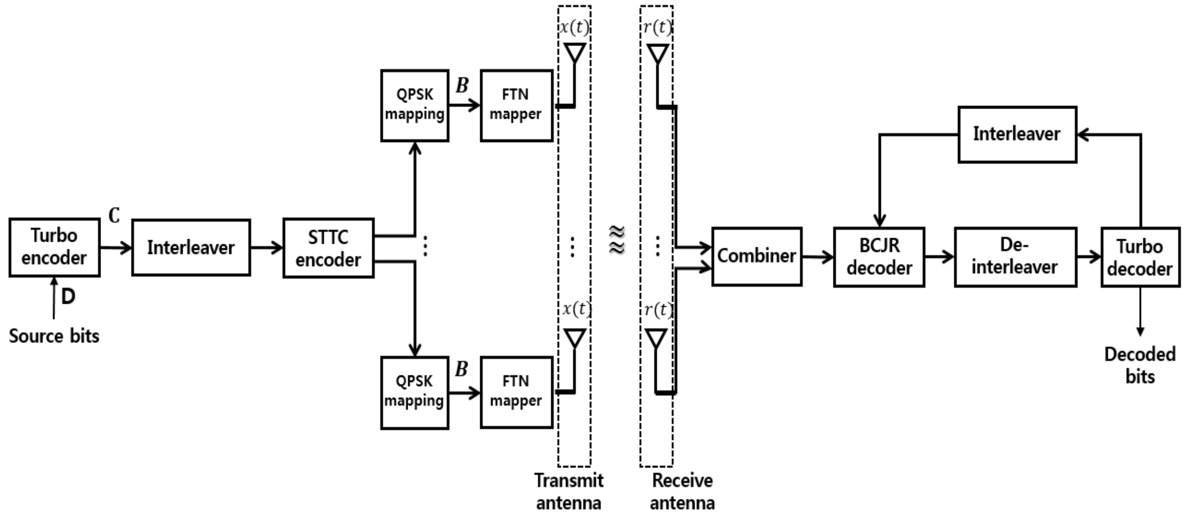

Fig. 2. Structure of turbo equalization model for MIMO-FTN

32 states encoding equations can be expressed by (6) and Fig. 3.

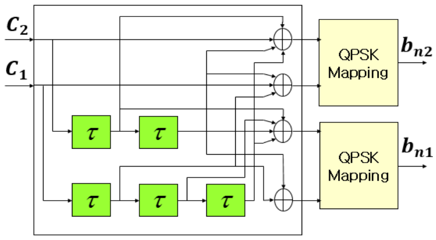

Fig. 3. The structure of STTC based on 32-state

$$\begin{aligned} b_{n1} &= 2\times(c_2(n-\hat{\tau})\oplus c_1(n-2\hat{\tau})\oplus c_2(n-2\hat{\tau})\oplus c_1(n-3\hat{\tau})) \\ &\quad +(c_2(n-2\hat{\tau})\oplus c_1(n-\hat{\tau})) \\ b_{n2} &= 2\times(c_2(n)\oplus c_2(n-\hat{\tau})\oplus c_2(n-2\hat{\tau})\oplus c_1(n-3\hat{\tau})) \\ &\quad +(c_2(n-2\hat{\tau})\oplus c_1(n-\hat{\tau})\oplus c_1(n)) \end{aligned} \qquad (6)$$

where b_{n1} , b_{n2} means the output values of two transmitting antenna as the output value, b_n at the time of n in the (6). $c_1(n)$,$c_2(n)$ means the input bit of the STTC encoder at the time of n . $c_i(n-\tau')$is a signal which is a delayed as much as the $\tau'$of the $i-th$ input signal.

Expanding SISO model shown in (1) to MIMO FTN system, the transmitted signal x_i at $i-th$ antenna is expressed as (6).

$$x_i(t)=\sqrt{E_s}\sum_n b_i(n)h(t-n\tau T),\ \tau<1,\ (i=1,2,\cdots,N) \qquad (7)$$

The received signal r_j at j-th receive antenna is given by

$$r_j(t)=\sum_{t=0}^{N-1} h_{ij}(t)*x_j(t)+n_j(t),\quad (j=1,2,\cdots,M) \qquad (8)$$

where n_j is Gaussian noise of receive antenna, h_{ij} is channel impulse response in the path between ith transmit antenna and jth receive antenna. MIMO-FTN with STTC as explained obtain low bit error rate, however it can't guarantee throughput efficiency induced by using coding technique. Therefore we present MIMO-FTN with W-ZF without throughput loss.

B. The W−ZF Receiver for MIMO-FTN Systems

Fig. 4 shows the proposed N×M MIMO-FTN system structure based on W-ZF.

The received signal vector **r** is modeled by

$$\mathbf{r}=\mathbf{Hs}+\mathbf{n} \qquad (9)$$

where **s** is transmit data symbol vector from the N_{th} transmit antennas, **n** is additive white Gaussian noise. Then the complete $N\times M$ channel matrix **H** can be presented as

$$\mathbf{H}=\begin{bmatrix} h_{11} & h_{21} & \dots & h_{N1} \\ h_{12} & h_{22} & & h_{N2} \\ \vdots & & \ddots & \vdots \\ h_{1M} & h_{2M} & \cdots & h_{NM} \end{bmatrix}. \qquad (10)$$

If we assume the CSI(Channel State Information) is perfect, the zero forcing estimate of the transmitted data symbol vector can be written as

$$\tilde{\mathbf{r}}=\mathbf{G}(\mathbf{Hs}+\mathbf{n})=\mathbf{s}+\mathbf{Gn} \qquad (11)$$

where $\mathbf{G}=\mathbf{H}^{\dagger}=(\mathbf{H}^{\mathrm{H}}\mathbf{H})^{-1}\mathbf{H}^{\mathrm{H}}$, † denotes the pseudo-inverse operation. From (11), the received signal $\tilde{\mathbf{r}}$ composed of the sum of the transmit data symbol **s** and the noise part of **Gn**. **Gn** term makes performance degraded because unit of G matrix are not greater than 1. In order to solve these problems, to reduce effect of **Gn** term, we try to multiply weighting value as shown in (12) to the zero forcing output. This is called W-ZF algorithm.

$$\alpha_i=\frac{1}{\sum_{j=1}^{M}|\acute{h}_{ij}|^2} \qquad (i=1,2,\cdots,N) \qquad (12)$$

where $\acute{h}_{ij}$ is unit of matrix $\mathbf{H}^{-1}$.

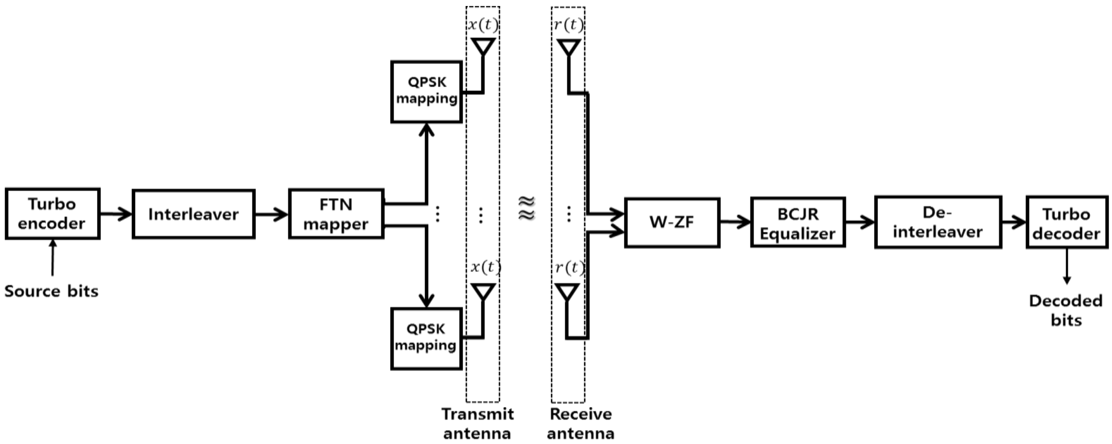

Fig. 4. The structure of W-ZF model for MIMO-FTN system.

C. Inner Codes and Its Decoding Scheme

In this regard, in this study, the BCJR decoding method, which can do soft decision the output of the Viterbi decoder, to the space-time trellis encoding method and eliminate ISI of W-ZF model. The trellis, which shows the change as well as the output value in accordance with the input value, was used for calculated the value of BM (Branch-Matric), FSM (Forward-State-Matric) and BSM (Backward-State-Matric.

The number of decoding trellis states of BCJR are 32 states. Each state consists of previous state, present state and next state. Given $s' = \{s'_1, s'_2, \cdots, s'_{32}\}$ - the previous state, $s = \{s_1, s_2, \cdots, s_{32}\}$ - the present state, $x = \{x_1, x_2, \cdots, x_n\}$ - the transmitted code-word, $r = \{r_1, r_2, \cdots, r_n\}$ - the received code-word LLR (log-likelihood-ratio) of $x_j\,(j = 1, 2, \cdots, n)$ can be calculated as (13).

$$\begin{aligned} L(x_j) &= \max{}^*[\alpha_{j-1}(s') + \gamma_j(s', s) + \beta_j(s)](s', s) : x_j = 0 \\ &\quad - \max{}^*[\alpha_{j-1}(s') + \gamma_j(s', s) + \beta_j(s)](s', s) : x_j = 1 \end{aligned} \tag{13}$$

The FSM $\alpha_j(s)$, BSM $\beta_{j-1}(s')$, and BM $\gamma_j(s', s)$ are given by

$$\alpha_j(s) = \max{}^*[\alpha_{j-1}(s') + \gamma_j(s', s)]\ , \tag{14}$$

$$\beta_{j-1}(s') = \max{}^*[\beta_j(s) + \gamma_j(s', s)]\ , \tag{15}$$

$$\gamma_j(s', s) = \log \rho(s_j = s, r_j \mid s_{j-1} = s') = \log \rho(r_j \mid x_j)\rho(x_j)\ . \tag{16}$$

The Euclidean distance of branch metrics between possible transitions at each node is calculated in Fig. 5.

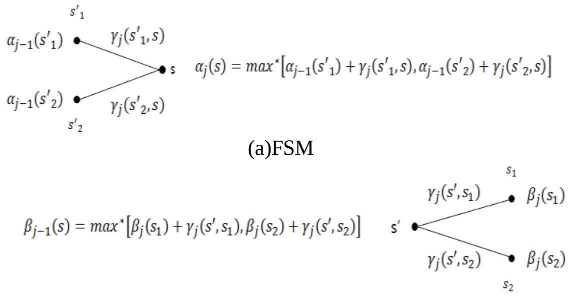

Fig. 5. Trellis structure and metric calculation

where, max* - operator is defined as

$$\max{}^*(x, y) = \max(x, y) + \log(1 + e^{|x-y|})\ . \tag{17}$$

D. Turbo Decoding Scheme

The transmission structures shown in the Fig. 2 and Fig. 4 applies the interleaver to between the turbo codes and FTN mapper. The bit stream, having gone through the turbo encoding, is input into the STTC or FTN mapper after the interleaving, to which ISI, calculated by FTN, is added. The received signal, to which the transmitted signal restored via channel estimation is added, is input into the BCJR decoder.

The received signal which had been transmitted as FTN, compounds signals via code combine, in accordance with the number of receiving antennas. The LLR value is output as much as the received bit stream size, via the BCJR decoder. At each state, the probability value of ‘00’, “01”, “10”, and “11” is output. Therefore, the LLR can be obtained at the timing *k* and each state *m*; the LLR value for four of two bits, *i*, *j* can be obtained with the following (18).

$$L(C_k^{i,j}) = \min\left\{\begin{matrix} \sum_m \lambda_k^{00}(m), \sum_m \lambda_k^{01}(m), \\ \sum_m \lambda_k^{10}(m), \sum_m \lambda_k^{11}(m) \end{matrix}\right\} \quad (k = 1, 2, \cdots, K)\ . \tag{18}$$

$\lambda_k^{00}(m), \lambda_k^{01}(m), \lambda_k^{10}(m)$, and $\lambda_k^{11}(m)$ denotes the LLR value for two input bits, i, j, each state, m. The decoding method of BCJR calculates the LLR value at each state in accordance with the input value of two bits. The estimated LLR value is relocated to the address used in prior to the interleaver of the transmitter, and then it is input into the turbo decoder. The turbo decoder output the LLR value which has the same form as the (18) via the FSM and BSM processes, because it decodes with the probability of two bits having received the LLR value of two bits. Therefore, after 2 certain repetition, the bit row is decoded like the (18).

IV. Simulation Results

Computer simulations are used to study the performance evaluation. The simulation was done on the only AWGN channel. For the comparison purpose, Table I listed parameters for simulation.

TABLE I: SIMULATION PARAMETER

Inner channel coding	Turbo codes with 16 states
MIMO-FTN turbo equalization model	STTC with 32 states model W-ZF model
Number of transceiver antennas	N=2, M=2
Channel	AWGN + Rayleigh Fading
Coding rate	1 / 3 (K = 984)
τ'	0%, 10%, 20% , 30%, 40%
Modulation	QPSK
Iteration	3

Fig. 7 shows bit error performance of MIMO FTN system based on Fig. 2.

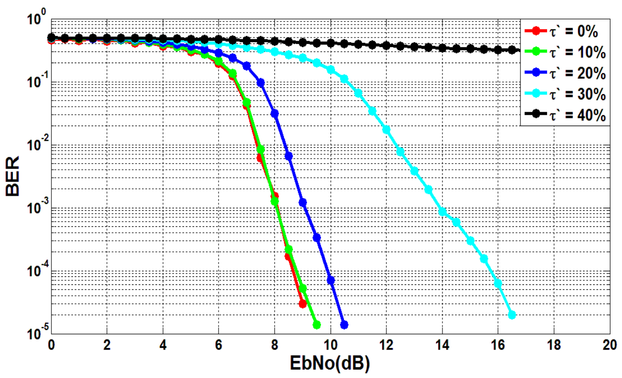

Fig. 7. Performance of MIMO-FTN system according to τ' (N=2, M=2).

Increasing FTN interference rate τ', to maintain $BER = 10^{-5}$, the performances are degraded. However, over the τ' =40%, error floors are occurred due to excessive ISI.

Fig. 8 shows the BER performance of MIMO-FTN system based on Fig. 4.

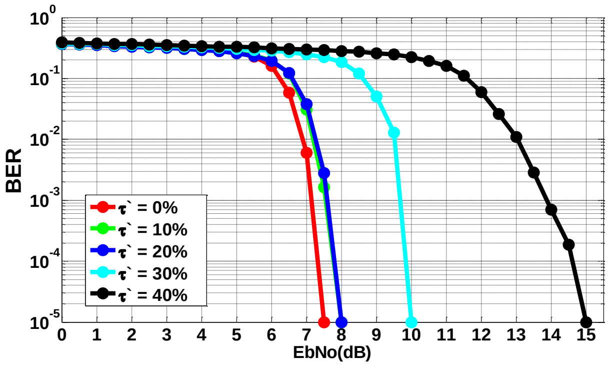

Fig. 8. Performance of MIMO-FTN system based on zero forcing according to τ' (N=2, M=2).

When τ' is 0%, 10%, 20%, the gains are achieved by 1.5[Db]~2.5[Db] compared to Fig. 7 at a BER of 10^{-5}. 7[Db] gains are achieved in the case of τ'=30%.

In the MIMO-FTN system based on layered space time codes, error floor occurred when τ'=40%, however the MIMO-FTN system based on W-ZF did not occur error floor. Based on Fig. 7 and Fig. 8, as increasing τ', the performance gaps are larger between MIMO-FTN with W-ZF method and STTC method.

Based on BER graph of Fig. 7 and Fig. 8, we confirmed that MIMO-FTN with W-ZF method is more efficient than STTC method in aspect to performance and throughput efficiency.

V. Conclusions

Many methods for increase of throughput is being researched, as the next satellite broadcast/communication and the 5G based mobile communication's demand for throughput is increasing. However, the bandwidth is limited, so many ways to increase throughput come to the fore.

In this paper, we proposed two types of MIMO-FTN system model, associating with the FTN technique and the MIMO having high efficiency of transmission. The first one employs STTC as an inner code, and the outer codes are turbo codes. In receiver side, BCJR algorithm is used for STTC decoder. Even if its scheme obtain low bit error rate, it can't guarantee throughput efficiency induced by using coding technique. Therefore we proposed second type of MIMO-FTN with W-ZF without throughput loss.

In simulation results, MIMO-FTN with W-ZF method is obtain coding gain of 1.5[dB] ~7[dB] compared to STTC method in according to various interference rate τ'. Therefore we confirmed that MIMO-FTN with W-ZF method is more efficient than STTC method in aspect to performance and throughput efficiency.

Accordingly, as the MIMO-FTN system based on the STTC and W-ZF, efficient transmission and performance of up to τ'=30%~40% are expected, which can be applied to the next generation wireless communication.

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