Multiband Faster Than Nyquist Techniques in Multipath Channel for Spectrum Efficiency

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***Abstract* —**For improving bandwidth efficiency, FTN (Faster-Than Nyquist) method which transmits faster than the Nyquist rate is applied in wireless communications. However, performance degrade arising from ISI(Inter-Symbol Interference) induced by increasing the interference rate. To overcome this problem, we propose the multiband OFDM(Orthogonal Frequency Division Multiplexing)-FTN method which is uniformly dividing and allocating the encoded bits into multiband, and transmits the encoded bits using the frequency allocated to each band by applying the FTN transmission method to each band. Through simulation results by setting the interference ratio to 25%, we show that the performance of the proposed multiband FTN method is improved about 0.3 dB ~ 0.5 dB than that of single band FTN method. In multipath channels, only multiband FTN method was vulnerable to multipath whereas the multiband OFTM-FTN method was efficient for multipath. In addition, we confirmed that the performance improved as the subcarrier number of the proposed multiband OFDM-FTN method increased.

***Index Terms*—**FTN, Inter-symbol interference, Multiband, OFDM, Multiband OFDM-FTN

I. Introduction

Next-generation wireless and/or satellite communications require high transmission efficiency and high reliability to provide various services with subscribers. 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. Research on applying high order modulation and high-speed channel encoder/decoder to meet the high data rate is already saturated. Thus, research interest has been focused more on transmission methods. Recently FTN (Faster-Than Nyquist) method [1]-[3], which transmits faster than the throughput of Nyquist, is emerging as the standard for the next generation DVB-S3 (Digital Video Broadcasting-Satellite Third Generation) and FOBTV (Future of Broadcast Television) [4], [5]. It is possible to transmit signals faster than the Nyquist rate and maximize throughput with the same channel bandwidth. However, FTN method has a limitation in maximizing transmission efficiency due to performance degradation arising from ISI(Inter-Symbol Interference).

The other attempt is MIMO(Multiple Input Multiple Output)-FTN transmission method [6]-[8], 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.

In [6], there are two kinds of proposed MIMO-FTN system and presented how to remove ISI from each transmit antenna. First one is using the STTC (Space-Time Trellis Codes), the other one is using W-ZF (Weighted Zero Forcing) algorithm to distinguish symbols of each transmit antenna. In receiver side, BCJR algorithm [9] is used for canceling interference in order to improve error performance by increasing number of iterations [10].

MIMO-FTN method requires accurate channel estimation for each channel, yet does not improve performance compared to the SISO (Single Input Single Output)–FTN method. Furthermore, there is no improvement in terms of transmission efficiency due to the application of a space-time coding method.

Therefore, in this paper, we first propose a multiband FTN transmission method in which an FTN method is combined with a multiband method that is efficient in a selective-frequency fading channel by using multiple bands [11], [12]. The multiband FTN transmission method uniformly divided and allocated the encoded bits into multiband, and transmits the encoded bits using the frequency allocated to each band by applying the FTN transmission method to each band. In addition, it can improve performance through the effect of noise averaging by increasing the number of samples per bit in each band to reduce interference between adjacent channels.

Lastly, we propose an OFDM(Orthogonal Frequency Division Multiplexing) based FTN application method to apply the FTN transmission method in multipath channels as in massive mobile communication networks such as 5G.

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The OFDM method [13], [14] divides data into multiple carrier signals, and multiplexes and transmits them by adding orthogonality to minimize the interval between divided carrier signals. Since OFDM with high spectrum efficiency is efficient in a frequency selective fading channel environment and a multipath channel environment, it can maximize the band efficiency by applying the FTN method and also guarantee the performance in multipath channels. Therefore, in this paper, by using LDPC(Low Density Parity Check) codes [15,16] with a length of 64,800 bits applied to satellite and terrestrial broadcasting standards, we comparatively analyzed the performance of the existing method and the proposed methods, and also the performance of the multiband FTN transmission method and the OFDM-FTN transmission method in a multipath channel environment.

II. FTN Transmission Methods

FTN signaling is a technique of transmitting information at a rate higher than the allowed Nyquist limit. In order to improve the transmission efficiency by applying the FTN method, according to increasing the interference rate. However, performance degrade arising from ISI.

Therefore, this chapter we propose a multiband FTN method to minimize interference due to the application of a single band FTN method. The multiband FTN transmission method uniformly divided and allocated the encoded bits into multiband, and transmits the encoded bits using the frequency allocated to each band by applying the FTN transmission method to each band. In addition, it can improve performance through the effect of noise averaging by increasing the number of samples per bit in each band to reduce interference between adjacent channels.

A. Single band FTN Method

Fig. 1 shows the single band FTN system structure based on turbo equalization.

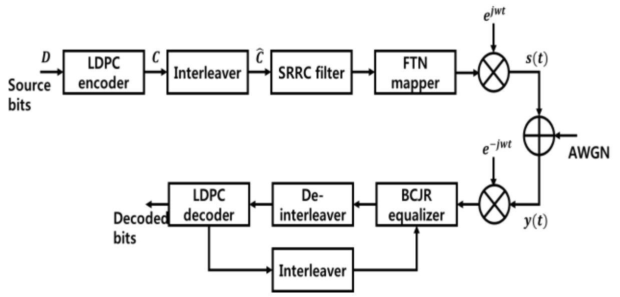

Fig. 1. The structure of single band FTN model

The source bits to be transmitted bit-stream $\boldsymbol{D}$ is given by

$$\boldsymbol{D} = \{d_1, d_2, \ldots, d_K\} \tag{1}$$

where K denotes a length of $\boldsymbol{D}$. First, $\boldsymbol{D}$ is encoded by the $(\boldsymbol{N}, \boldsymbol{K})$ outer codes. Coded bit stream $\boldsymbol{C}$ is given by

$$\boldsymbol{C} = \{\boldsymbol{c_1}, \boldsymbol{c_2}, \ldots, \boldsymbol{c_N}\}. \tag{2}$$

The encoded bits passed through the encoder transform burst error into random error via the interleaver. The interleaved output is canceled a posteriori from the proceeding received signal. The interleaving function helps the receiver convergence.

$\hat{\boldsymbol{C}}$ means the encoded bits has passed through the interleaver.

$$\hat{\boldsymbol{C}} = \{\hat{\boldsymbol{c}}_1, \hat{\boldsymbol{c}}_2, \ldots, \hat{\boldsymbol{c}}_N\}. \tag{3}$$

FTN signaling is a technique of transmitting information at a rate higher than the allowed Nyquist limit. Consequently, ISI necessarily occurred.

Interference transmission signal $\boldsymbol{s(t)}$ is given

$$\boldsymbol{s}(\boldsymbol{t}) = \sum_{n=1}^{N} \hat{\boldsymbol{C}}_n \boldsymbol{h}(\boldsymbol{t} - \boldsymbol{n\tau T}) \boldsymbol{e}^{jwt}, \quad \boldsymbol{\tau} < \boldsymbol{1}. \tag{4}$$

where $\hat{\boldsymbol{C}}_n$ are encoded bit stream after interleaving, $\boldsymbol{h(t - n\tau T)}$ is a unit-energy baseband pulse, $\boldsymbol{\tau}$ is interference time, $\boldsymbol{T}$ is symbol duration.

The received signal is given by

$$\boldsymbol{y}(\boldsymbol{t}) = \sum_{n=1}^{N} \hat{\boldsymbol{C}}_n \boldsymbol{p}\big((\boldsymbol{n} - \boldsymbol{t})\boldsymbol{\tau T}\big) + \boldsymbol{\eta}(\boldsymbol{t}). \tag{5}$$

where $\boldsymbol{p}\big((\boldsymbol{n} - \boldsymbol{t})\boldsymbol{\tau T}\big)$ is matched filter output, $\boldsymbol{\eta}(\boldsymbol{t})$ is Gaussian Noise at time of $\boldsymbol{t}$.

Received signal after the demodulation process and the matched filter operation, received signals are input to the BCJR equalizer to remove ISI. The output values of the BCJR equalizer are input to the LDPC decoder after passing through the de-interleaver.

B. Multiband FTN Method

In order to improve the transmission efficiency by applying the FTN method according to increasing the interference rate. However, performance degrade arising from ISI. To overcome this problem, we propose the multiband FTN method which is uniformly dividing and allocating the encoded bits into multiband, and transmits the encoded bits using the frequency allocated to each band by applying the FTN transmission method to each band. In addition, it can improve performance through the effect of noise averaging by increasing the number of samples per bit in each band to reduce interference between adjacent channels.

Fig. 2 shows the structure of transceiver for multiband FTN system.

The data that passes through the interleaver of Equation (3) is divided and distributed uniformly into $\boldsymbol{N_B}$ bands through S/P (Serial to Parallel) as shown in Equation (6).

$$\hat{\boldsymbol{C}}_b = \{\hat{\boldsymbol{c}}_1, \hat{\boldsymbol{c}}_2, \ldots, \hat{\boldsymbol{c}}_{N/N_B}\}, \quad (\boldsymbol{b} = \boldsymbol{1}, \boldsymbol{2}, \cdots, \boldsymbol{N_B}). \tag{3}$$

The uniformly divided data is transmitted by passing through a SRRC (Square Root Raised Cosine) filter and applying the FTN method.

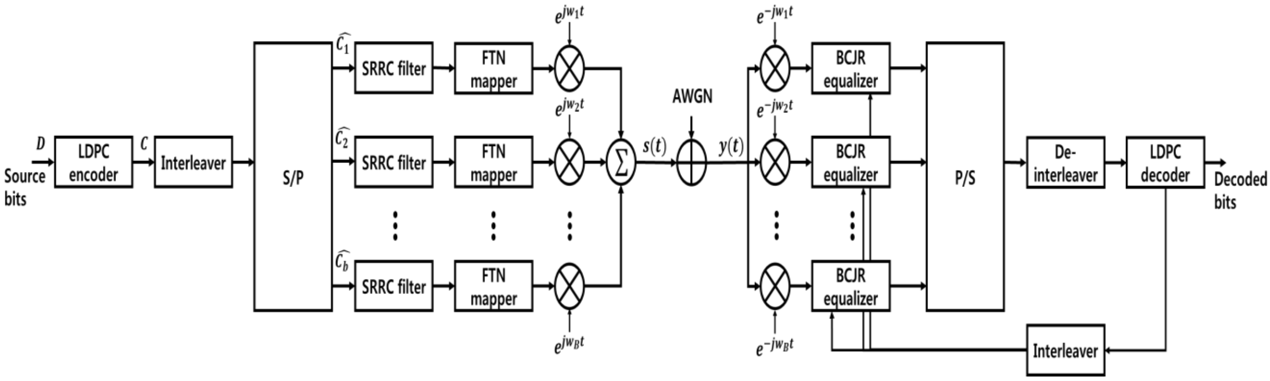

Fig. 2. The structure of multi band FTN model

Transmission signals given by

$$s(t)=\sum_{b=1}^{N_s}\sum_{n=1}^{N/N_b}\hat{C}_b(n)h\left(t-n\tau T_{N_B}\right)e^{jw_bt},\quad \tau<1. \quad (7)$$

Eq.(7) means the transmit data of multiband FTN method.

$h\left(t-n\tau T_{N_B}\right)$ is a unit-energy baseband pulse, T_{N_B} is symbol duration for each band.

In order to reduce ISI, the multiband FTN transmission method minimizes interference by increasing the number of samples per bit depending on the number of band, N_B. The frequency domain of the signals transmitted in each band is shown in Fig. 3. Let the bandwidth of a single band be B, then the bandwidth of each of the multiband is B / N_B.

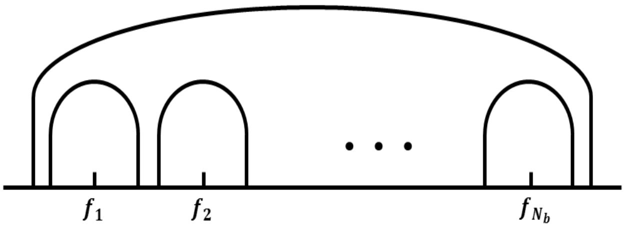

Fig. 3. Frequency domain of multiband

Received signal given by

$$\begin{aligned} y(t)&=s(t)+\eta(t)\\ &=\sum_{b=1}^{N_B}\sum_{n=1}^{N/N_b}\hat{C}_b(n)\,p_b\left((n-t)\tau T_{N_B}\right)e^{jw_bt}+\eta(t) \end{aligned}. \quad (8)$$

Let the output of each band passing through the matched filter be $z_b(t)$, then $z_b(t)$ is expressed as in Equation (9).

$$z_b(t)=\left(y(t)e^{-jw_bt}\right)*p_b(t),\quad \left(b=1,2,\cdots,N_b\right). \quad (9)$$

By separating the signal of each band after the demodulation process and the matched filter operation, received signals are input to the BCJR equalizer to remove ISI. The output values of the BCJR equalizer are input to the LDPC decoder after passing through P/S(Parallel to Serial) and the de-interleaver.

III. OFDM-FTN APPLICATIONS

We confirmed that the multiband FTN transmission method presented in Chapter 2 was superior to the single band FTN transmission method in the AWGN channel by increasing the number of samples per bit in each band using multiple bands. The multiband FTN transmission method based on the OFDM method uses multiple bands by assigning a frequency to each band. However, in terms of spectrum efficiency, the multiband FTN transmission method is as same as the existing single band. Therefore, we propose an OFDM-FTN transmission method by applying the FTN method to the OFDM method which shows excellent performance in a multipath channel environment and has high spectrum efficiency by using multiple subcarriers.

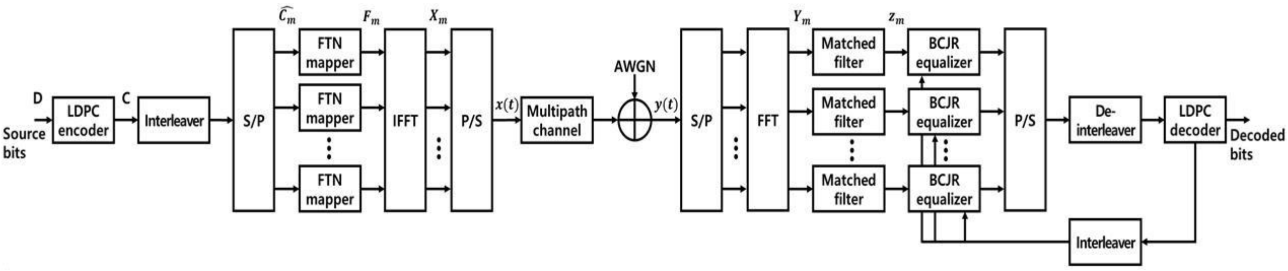

Fig. 4. The structure of OFDM-FTN model

Fig. 4 shows the structure of OFDM-FTN system. The original signal bit sequence $\boldsymbol{D}$ to be transmitted and the encoded data $\boldsymbol{C}$ passed through the encoder are expressed as in Equation (1) and Equation (2), respectively. After passing through the interleaver, the encoded data is divided into the subcarrier number by S/P and expressed as $\hat{\boldsymbol{C}}_{\boldsymbol{m}}$ as shown in the following Equation (10).

$$\hat{C}_m = \left\{ \hat{c}_1, \hat{c}_2, \cdots, \hat{c}_{N/M} \right\}. \tag{10}$$

where $\boldsymbol{M}$ is the number of sub-carriers. $\hat{\boldsymbol{C}}_{\boldsymbol{m}}$ passes through the FTN mapper and $\boldsymbol{F_m}$ is the signal generated by applying the interference ratio that is set for each FTN mapper. $\boldsymbol{F_m}$ passes through the IFFT(Inverse Fast Fourier Transform) and the transmitted signal is expressed as in the following Equation (11).

$$x(t) = \sum_{m=0}^{M-1} X_m(t) e^{j2\pi tm/M}. \tag{11}$$

where $X_m(t)$ are the OFDM symbols of m^{th} band. The transmission signal passed through the multipath channel and the AWGN channel.

Received signal as given by

$$y(t) = \sum_{l=0}^{L-1} x(t-l) h_l(t) + \eta(t). \tag{12}$$

where $\boldsymbol{L}$ denotes the total number of multipath and $\boldsymbol{l}$ means the l^{th} path of all multipath. $h_l(t)$ refers to the channel response coefficient on the lth path. The received signal $y(t)$ is divided into $\boldsymbol{M}$ by S/P and passes through the FFT(Fast Fourier Transform).

After FFT, $Y_m(t)$ is given by

$$y_m(t) = \sum_{n=0}^{N/M-1} y(t) e^{-j2\pi nm/M}. \tag{13}$$

After FFT, $Y_m(t)$ passes through the matched filter, and the signal after $z_m(t)$ passing through the matched filter is expressed as in Equation (14)

$$z_m(t) = Y_m(t) * h_m(t). \tag{14}$$

$h_m(t)$ refers to the response of each matched filter. P/S is performed for $z_m(t)$ after it passes through BCJR equalizer. For the signal for which de-interleaver is performed, the decoded data is obtained through the LDPC decoder.

IV. Simulation Results

We analyzed the performance of the multiband FTN method and the OFDM-FTN method presented in this paper through computer simulations. In order to compare the performance of the FTN transmission method in the existing single band, we comparatively analyzed the performance depending on the increase of N_B for the same interference ratio. Simulation parameters are listed in Table I. As shown in Fig. 2 and Fig. 5, LDPC decoder and 4-states BCJR equalizer are connected through interleaving and de-interleaving, which allows the decoders to repeatedly update each other's information. With respect to the BCJR equalizer, the output values can be used as extrinsic information for the LDPC decoder to improve its performance via iteration. Therefore, in this simulation, LDPC inner iteration was set to 60 and the outer iteration was set to 5

TABLE I. Simulation Parameters

Total number of data	10^6
Channel coding	LDPC
Coding rate	1/2
Modulation	BPSK
Number BCJR states	4
Number of band (N_B)	1 - 6
Number of subcarriers (M)	4, 8, 16, 32
Roll off factor	0.35
Samples per bit (N_s)	single band : 8 multiband : $8 \times N_B$
Interference ratio (τ')	25%
LDPC inner iteration	60
Outer iteration	5

In Table I. interference ratio τ' is given by

$$\tau'(\%) = 100 \times (1-\tau) \tag{15}$$

A. Performance Analysis of Multiband FTN

We considered an environment where only the general AWGN channel is present for the simulation of the performance analysis of the multiband FTN. In order to compare the performance of the FTN transmission method in the single band, we compared the performance by setting the interference ratio to 25%. The performance depending on the increase of N_B is shown in Table II.

TABLE II. Performance of Multiband FTN According to N_B

	N_B					
SNR_R	1	2	3	4	5	6
-0.8	$10^{-1.33}$	$10^{-1.88}$	$10^{-2.24}$	$10^{-2.70}$	$10^{-3.00}$	$10^{-3.40}$
-0.7	$10^{-1.38}$	$10^{-1.99}$	$10^{-2.41}$	$10^{-3.84}$	0	0
-0.6	$10^{-1.42}$	$10^{-2.21}$	$10^{-3.92}$	0	-	-
-0.5	$10^{-1.48}$	0	0	-	-	-
-0.4	$10^{-1.56}$	-	-	-	-	-
-0.3	$10^{-2.11}$	-	-	-	-	-
-0.2	0	-	-	-	-	-

In Table II, SNR_R is expressed by the received signal strength σ^2_{s+n} and the noise strength σ^2_n as in Equation (16),

$$SNR_R = \frac{\sigma^2_{s+n} - \sigma^2_n}{\sigma^2_n} \quad (16)$$

As shown in Table II, $N_B = 1$ means the single band FTN transmission method and $N_B > 1$ means the multiband FTN transmission method. Although the number of samples per bit N_s increases in proportional to the number of bands N_B, the bandwidth of the transmitted signal is the same. For the single band, we increased proportionally whenever N_B increased based on $N_s = 8$. We could confirm that the performance improved as the number of $N_B = 1$ increased compared to $N_B = 1$. The performance was improved by approximately 0.5dB when $N_B = 5,6$ compared with the single band FTN transmission method with $N_B = 1$, and the performance kept improving as the value of N_B was continuously increased. However, it was confirmed that the performance improvement became reduced when $N_B = 5$ or more.

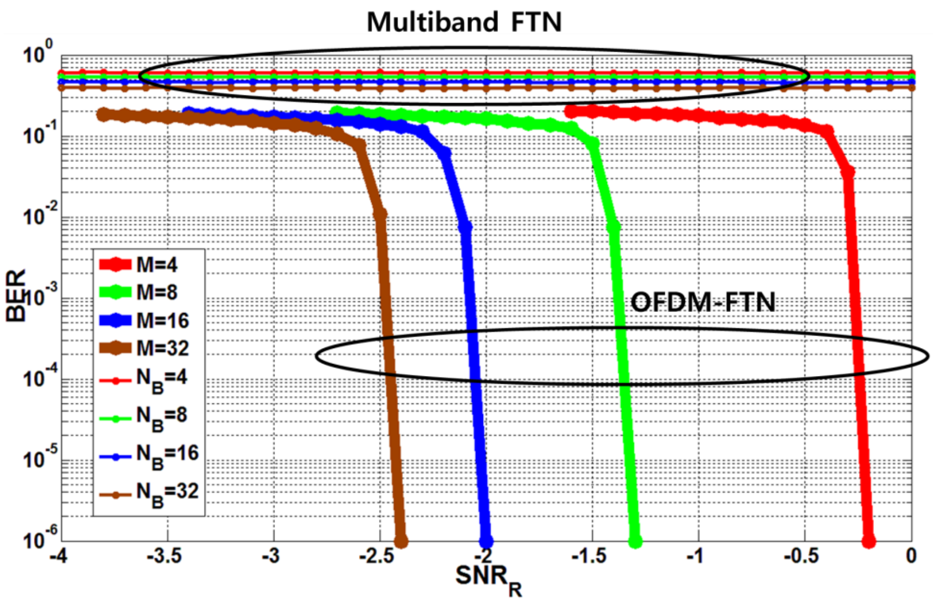

Fig. 5. Performance comparison between the multiband FTN and OFDM-FTN method in multipath channels.

B. *Performance Analysis of OFDM-FTN in Multipath Channel*

In section 4.1, we confirmed that the performance of multiband FTN is improved over a single band FTN. Simulation was conducted to compare the performance of the proposed OFDM-FTN with multiband FTN.

The simulation parameter was the same as Table 1. We considered the multipath environment. In order to compare the two methods in the same environment, N_B of the multiband FTN transmission method is set to 4, 8, 16, 32 and the subcarrier number, M, of the proposed OFDM-FTN transmission method is also set to 4, 8, 16, 32, that is, they were compared using the same number of frequencies with $N_B = M$.

The multipath channel environment is simulated by setting the multipath number L to 3 in Equation (12) and setting the channel response coefficients $h(0)$ to 0.8, $h(1)$ to 0.2, and $h(2)$ to 0.1.

For the single band FTN and multiband FTN transmission methods, it was confirmed that data could not be decoded in the multipath channel environment. This shows that the single band and multiband FTN transmission methods are vulnerable in the multipath channel environment. The performance of the proposed OFDM-FTN method that can address these issues is shown in Fig. 5. The performance of the proposed OFDM-FTN transmission method in the multipath channel environment was confirmed to be superior to that of the multiband FTN method. When verifying the performance of the proposed transmission method at $BER = 10^{-4}$, performance was improved by approximately 1.1dB if the subcarrier number $M = 4$ and $M = 8$.

Performance was improved by approximately 0.7dB if $M = 8$ and $M = 16$. It was improved by approximately 0.4dB if $M = 16$ and $M = 32$.

Through simulation results, we confirmed that the multiband FTN transmission method was vulnerable to multipath whereas the OFDM-FTN transmission method was efficient for multipath. In addition, we confirmed that the performance improved as the subcarrier number M of the proposed OFDM-FTN transmission method increased.

V. Conclusions

In this paper, we proposed the multiband FTN method which is uniformly dividing and allocating the encoded bits into multiband, and transmits the encoded bits using the frequency allocated to each band by applying the FTN transmission method to each band. In addition, it can improve performance through the effect of noise averaging by increasing the number of samples per bit in each band to reduce interference between adjacent channels. In simulation results by fixing the interference ratio to 25% in only AWGN channel, we show that the performance of the proposed multiband FTN method is improved about 0.3 dB ~ 0.5 dB than that of single band FTN method. That's why the effect of noise averaging by increasing the number of samples per bit in each band can be reduced interference between adjacent channels. However, in terms of spectrum efficiency, the multiband FTN transmission method is as same as the existing single band. It is also the single band and multiband FTN transmission methods are vulnerable in the multipath channel environment. In order to improve the bandwidth efficiency and performance simultaneously in multipath channels such as in massive mobile communication networks such as 5G, we proposed multiband OFDM-FTN transmission method by applying the multiband FTN method to the OFDM method which shows excellent performance in a multipath channel environment and has high spectrum efficiency by using multiple subcarriers. Through simulation results, multiband FTN methods, it was confirmed that data could not be decoded in the multipath channel environment. The performance of the proposed OFDM-FTN transmission method in the multipath channel environment was confirmed to be superior to that of the multiband FTN method. In addition, we confirmed that the performance was improved as the subcarrier number increased. Through the paper, to satisfy both bandwidth efficiency and performance improvement, we confirm multiband OFDM-FTN method is useful in wireless communications.

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