

Application of Wavelet Packet Modulation to Mobile Communication

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SUMMARY Wavelet packet modulation (WPM) using the discrete wavelet transform is a multiplexing transmission method in which data is assigned to wavelet subbands having different time and frequency resolutions. The WPM keeps data transmission throughput even in tone and impulse interference environments that cannot be achieved with conventional multiplexing methods such as TDM (Time division multiplexing) or OFDM (Orthogonal frequency division multiplexing). In this paper, we propose an effective multicarrier transmission method of WPM for wireless mobile communications. First, the transmission characteristics of WPM in fading environments are minutely investigated. Then, taking the advantage of the WPM and the OFDM that has an equalizing technique in multipath fading environments, we propose a multimode transmission method using them. The adaptive transmission in those fading and interference environments is achieved by using the multimode transmission. Their transmission performances are evaluated by computer simulations.

key words: *wavelet packet modulation, OFDM, multipath fading, multimode transmission*

1. Introduction

In mobile communications, a higher-rate data transmission is required because of the rapid progress of multimedia applications. However, the quality of transmission link often becomes lower due to the fading or interference in wireless transmission, and the measures for the degradation is necessary. OFDM is one of the multicarrier transmission methods to solve the problem and achieve the higher-rate wireless transmission. In OFDM, each subcarrier has lower-rate data and the transmission signal is combined by the use of FFT (fast Fourier transform) that enables the orthogonal multiplexing. Since the each subcarrier has lower data rate, the effect of multipath fading can be relatively suppressed. Moreover, using the guard interval (GI) technique, the degradation of multipath delay is effectively removed in OFDM. Therefore, the OFDM has widely been applied in many wireless systems.

On the other hand, in indoor wireless communications, Wireless LAN (WLAN) is a major access system used in office and home networks. The demands for an indoor mobile communication using such as PDAs (personal digital assistant) or wearable devices also grow recently. However,

when using the microwave-band, several other systems such as Bluetooth or microwave oven often cause interference to WLAN and the throughput becomes low. In addition, on the indoor wireless communication a complicated multipath fading occurs because of wall, ceiling or desk reflections, and the fading pitch becomes faster as the mobile terminal velocity increases. This multipath fading also degrades the communication quality and the throughput. Therefore, some methods are necessary for higher-speed indoor communications.

Wavelet packet modulation (WPM) is one of the multicarrier modulation methods using discrete wavelet transform (DWT) [1]–[3]. The WPM has the time and frequency resolution in transmission packets, so multiplexing of data can be carried out in both the time and the frequency domain. When tone and impulse interference is added into a transmission packet, all data are degraded in TDM and OFDM packets, while these interferences can be separable in WPM packets so that the throughput of transmission is kept with WPM even in these severe interference environments. The advantage of WPM would continue in the mobile communication. However, the performance of WPM in the mobile communication was not investigated in detail.

In this paper, we consider the application of WPM to the mobile communications. First, the transmission characteristics of WPM in fading environments are investigated. Then, we propose a multimode transmission method [4] using WPM and OFDM that enables the efficient transmission in both multipath and tone- and impulse-interference environments for the systems in such indoor communication. In this method, the WPM packet is selected for transmission in the interference environment, and the OFDM packet is selected in the multipath fading environment. The effectiveness of the method will be evaluated through computer simulations.

In the following, the WPM is briefly described in Sect. 2, and the transmission performances in fading environments are analyzed in Sect. 3. The multimode system configuration and simulation results are shown in Sect. 4, and the conclusion is remarked in Sect. 5.

2. Construction of Wavelet Packet Modulation

WPM was proposed by Lindsey [2]. The WPM is one of the multicarrier transmission methods where the time-frequency division multiplexing is carried out. These wavelet time-frequency subbands are orthogonal as well

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as the frequency subbands (subcarriers) of OFDM. In the OFDM, the FFT is used for the composition from subband signals to baseband signals and also the decomposition, while the discrete wavelet transform is used in WPM. Therefore, the division law of subbands is different between OFDM and WPM. Figure 1 shows an example of WPM, OFDM, and TDM packets. The WPM has the time-frequency-division subbands. As shown in Fig. 1, if there is pulse-wise (impulse in time axis) and tone-wise (impulse in frequency axis) interference in transmission air, all subband symbols are degraded in OFDM (b) and TDM (c) packets. The tone-wise interference is separable in OFDM but pulse-wise is not. Similarly, the pulse-wise interference is separable in TDM but tone-wise is not. By contrast, both interferences are separable in WPM packets because of the time and frequency resolution, and many subbands can be kept away from interference whenever the subbands are adequately arranged [2].

The structure of WPM subband can be changed according to MRA(multiresolution analysis)-based general wavelet decomposition relation. The WPM packet construction as shown in Fig. 2 where the time-frequency resolution changes stepwise is called as MSM (multi-scale modulation). In MSM, the baseband signal $\{c_k^{(0)}\}$, i.e., wavelet composed signal, is obtained from wavelet reconstruction algorithm as [5]

$$c_k^{(j)} = (1/\sqrt{2}) \sum_l [p_{k-2l}c_l^{(j-1)} + q_{k-2l}d_l^{(j-1)}] \quad (1)$$

where $\{c_k^{(j)}\}$ and $\{d_k^{(j)}\}$ are the j -th subband k -th symbols, $\{p_k\}$ and $\{q_k\}$ are the two-scale sequence of wavelet. If we use the Haar wavelet,

$$\begin{aligned} p_0 = p_1 = q_0 = -q_1 = 1, \\ p_k = q_k = 0 \text{ (others)}. \end{aligned} \quad (2)$$

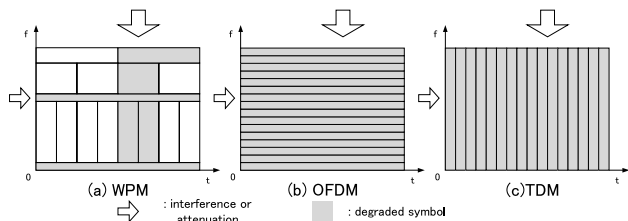


Fig. 1 Packet structures of WPM, OFDM, and TDM.

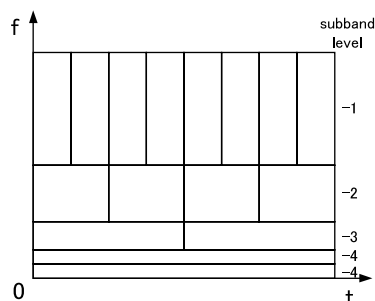


Fig. 2 Packet structure of MSM.

The transmitted baseband signals are again transformed into subband signals using wavelet decomposition algorithm as

$$c_k^{(j-1)} = (1/\sqrt{2}) \sum_l \gamma_{2k-l}c_l^{(j)} \quad (3)$$

$$d_k^{(j-1)} = (1/\sqrt{2}) \sum_l \eta_{2k-l}c_l^{(j)} \quad (4)$$

where $\{\gamma_k\}$ and $\{\eta_k\}$ are the decomposition sequence of wavelet. In the case of Haar wavelet,

$$\begin{aligned} \gamma_{-1} = \gamma_0 = -\eta_{-1} = \eta_0 = 1, \\ \gamma_k = \eta_k = 0 \text{ (others)}. \end{aligned} \quad (5)$$

$c^{(j)}$ and $d^{(j)}$ are sorts of wavelet filter banks, and the partition figure of wavelet packet is changed by the law of applying transmitting data to $c^{(j)}$ and $d^{(j)}$. In the following, we only consider the MSM as a basic type of WPM for simplicity, but the discussion is straightforwardly applicable to WPM.

3. WPM Transmission in Fading Environments

In this section, we investigate the bit error rate (BER) performances of WPM in fading environments to obtain potentials of WPM. Figure 3 shows the baseband block diagram of simulation system. To achieve the higher data rate, we consider the 16-QAM transmission in the system, but other cases such as BPSK or QPSK modulation can be treated as well. In the transmitter, data are mapped into the 16-QAM signal constellation and assigned into subbands of WPM through the serial to parallel conversion. Then, the signals are composed using inverse discrete wavelet transform (IDWT) and transmitted through the parallel to serial conversion. In the receiver, the received data are obtained by the operation in the reverse direction of the transmitter using discrete wavelet transform (DWT). The pilot symbol insertion and the fading estimation will be described below. First, the performance of WPM in the multipath fading environment is calculated. Figure 4 shows the two-path static fading model. The energy of direct and second paths are

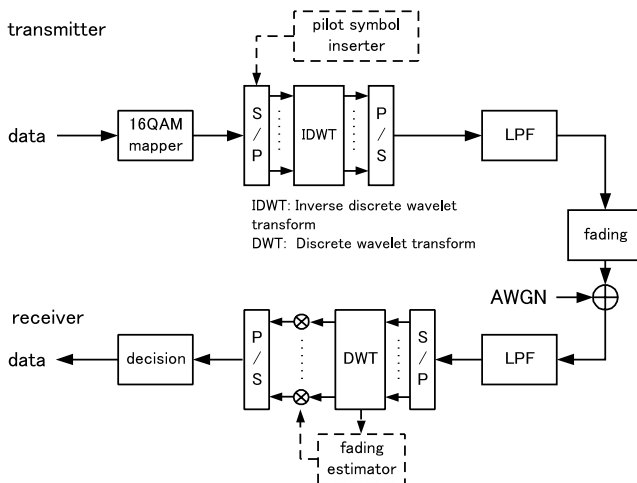


Fig. 3 System block diagram of WPM transmission.

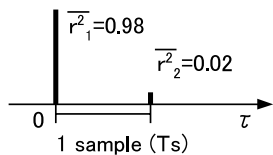


Fig. 4 Two-path delay profile model1.

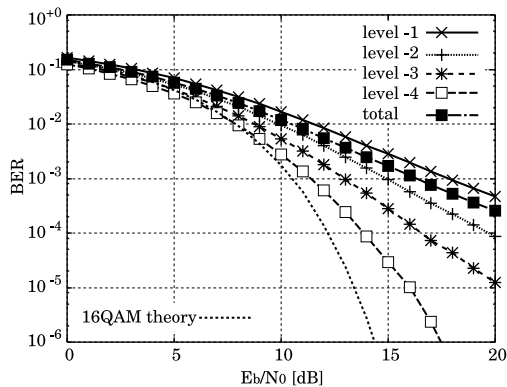


Fig. 5 BER performance of WPM in multipath fading environment.

Table 1 Simulation parameters of WPM.

signal constellation	Gray-assigned 16-QAM
wavelet function	Haar
packet structure	MSM
subband level	-1 to -4
number of subbands	16
samples per packet	16

assumed as 0.98 and 0.02, respectively, and the delay time is fixed as one sample (T_s) of MSM packet. The number of samples per one packet depends on the subband level. In the MSM, a packet consists of 2^n samples when the maximum subband level is $-n$. Figure 5 shows the BER of each level where the level j means the wavelet subbands of $d_k^{(j)}$. The packet structure is as same as in Fig. 2, and the simulation parameters of modulation and wavelet are listed on Table 1. It is obviously shown the performance of lower level is better than that of upper level, and its difference from level -4 to -1 is about 6.5 dB at BER= 10^{-3} . Naturally it comes from the difference of the relative length of one subband in the time domain. Since the lower subband has a longer time span for one subband, the performance becomes better in the multipath fading environment. Therefore, in that environment, we should arrange the WPM frame with subbands that have a longer time span.

Next, using the system in Fig. 3 the BER in a flat fading environment is calculated. To transmit the WPM in the flat fading environment, some compensation method is necessary. Pilot-symbol assisted modulation (PSAM) [6]–[8] is one of the compensation methods that estimates the fading from received pilot symbols inserted periodically at a transmitter, and compensates it. We use it for the WPM.

Figure 6 shows the frame structure. Known pilot symbols are inserted into each subband at every two frames. The

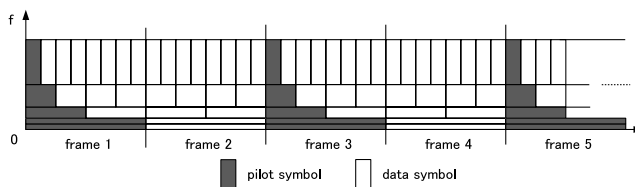


Fig. 6 Pilot-symbol structure in a WPM frame.

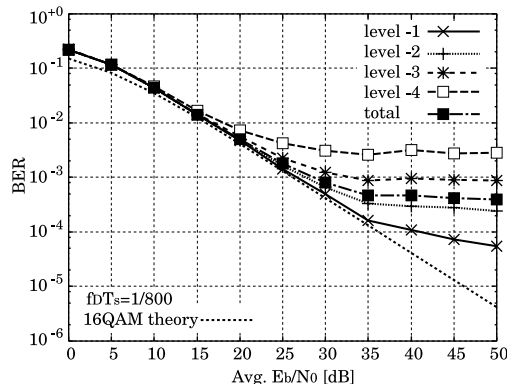


Fig. 7 BER performance of WPM in Rayleigh fading environment.

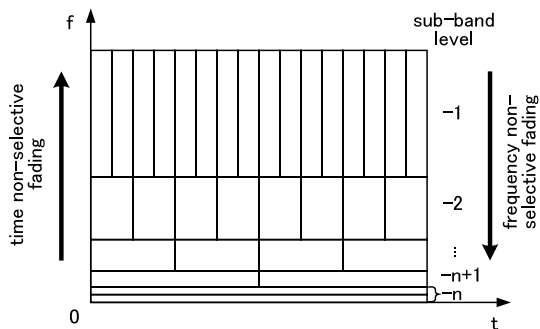


Fig. 8 Fading influence for MSM frame.

outermost point (3, 3) of 16-QAM constellation is used as the pilot symbol. In the receiver, the fading is estimated in the time direction from these pilot symbols at each subband respectively and independently, and then, it is compensated. Thus, the pilot symbol interval is different at each subband as shown in Fig. 6, where more points are interpolated at the upper level subbands. We calculated the BER of the transmission system in Fig. 3 in dynamic Rayleigh fading environment where the normalized fading pitch $f_d T_s$ is 1/800. It should be noted that the fading pitch is normalized by the sample period T_s , not by the packet period. The result in Fig. 7 shows, on the contrary to pilot symbol interval, the BER of the upper level becomes better. It is because the relative time span of one subband on the upper level is short and the fading can be treated as time-invariant during one symbol. Thus, it is effectively compensated at the upper subbands. On the lower level, the fading changes during one subband, and then the estimation accuracy decreases.

Consequently, it is confirmed as shown in Fig. 8, the shorter time-span subband is desirable for flat fading and the

longer time-span subband is desirable for multipath fading when using the WPM.

4. Multimode Transmission Method Using WPM and OFDM

A multimode transmission is one of the adaptive communication methods that change some system components such as transmission rate and modulation, corresponding to the status of a transmitter, a receiver, data, or transmission environments. It enables the increase of transmission throughput and quality. Since the transmission environments change frequently and significantly in wireless mobile communications, the multimode transmission is effective for wideband communications by means of the efficient use of resources such as a signal power and a spectrum bandwidth. For the wireless communication such as indoor and mobile transmission, the performance in the severe multipath and interference environments must be improved. As one of the solution, we propose a multimode transmission method using WPM and OFDM. As shown in Fig. 9, WPM and OFDM have different symbol assignment in a packet. This difference appears as the difference of transmission performance in fading or interference environments. That is, the degradation of transmission in time-impulse noise and tone jammer

environment can be suppressed by use of WPM, and that in multipath fading environments can be suppressed by use of OFDM. Therefore, if we construct a multimode system with WPM and OFDM, both advantages will be obtained. For example, in the case of indoor wireless transmission using ISM (Industrial scientific and medical) band, the radio waves used in other systems such as microwave oven may be jammers. In addition, deep multipath fading occurs when the mobile terminal is moving. In such case, the multimode transmission that switches WPM and OFDM corresponding to the transmission environments is effective, and the degradation could be suppressed.

4.1 Configuration of Multimode Transmission

Figure 10 shows the block diagram of multimode transmission with WPM and OFDM. In the transmitter, some modes including OFDM and WPMs where each mode has a different wavelet partition law are prepared, and data are transmitted in one mode corresponding to the transmission environment. In the receiver, the mode is detected, the data are decoded, and some information about the transmission feeds back to the transmitter. Thus, in order to follow the transmission environments, any feedback line is necessary and a proper mode must be selected. Then, the increase of

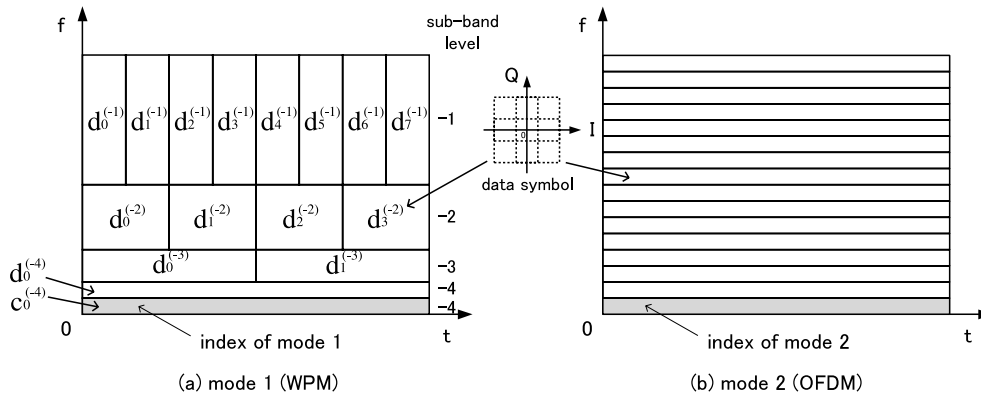


Fig. 9 WPM and OFDM packet structure.

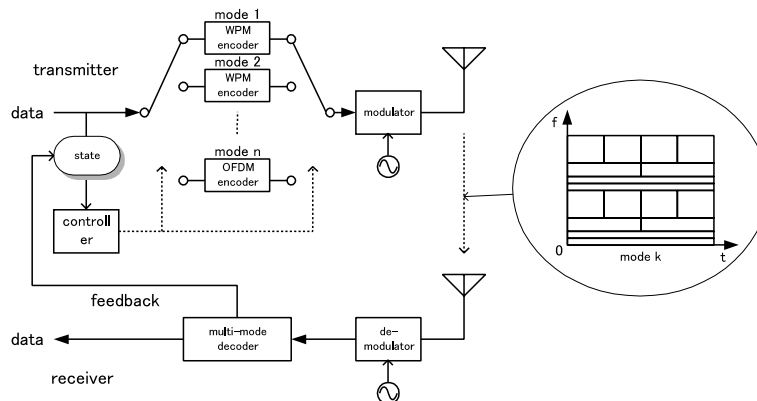


Fig. 10 WPM and OFDM multimode transmission system.

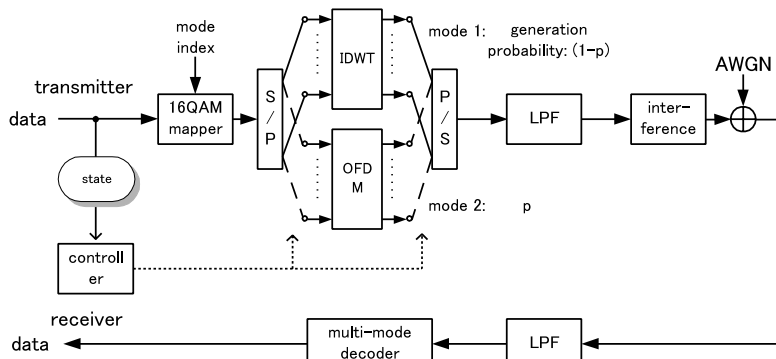


Fig. 11 One-way multimode transmission system.

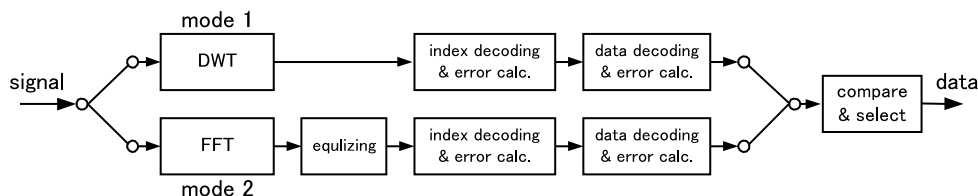


Fig. 12 Two-mode search decoding based on Euclidean distance.

throughput will be expected in those severe environments. The system complexity depends on the number of modes, and basically it increases linearly with the number for both the transmitter and receiver. For the mobile terminal, since the complexity should be lower due to a power consumption, the number of mode has to be determined by both facility and complexity. In this paper, however, to obtain the basic transmission characteristics of the multimode method of WPM and OFDM, we compose the simple two-mode one-way system as shown in Fig. 11 and carry out the computer simulations. In the figure, the mode is determined at only transmitter and the baseband signals are composed as MSM of WPM or OFDM packet. Even in the one-way multimode system, for example, the effective multimode transmission can be carried out on uplink from the mobile terminal to the base station, because the transmitter knows the status about a movement of terminal. Figure 9 also shows the frame structure of the two-mode packet where mode 1 is WPM and mode 2 is OFDM used in Fig. 11. In the transmitter, the mode is determined and the data are assigned into sub-domain of corresponding packet structure. Then, the frame is composed by using the inverse discrete wavelet transform (IDWT) or inverse fast Fourier transform (IFFT). In Fig. 9, the number of subbands on both modes are 16 so that the data transmission rate is equivalent, and the number of samples per packet is 16 on both modes.

To improve the decoding mode error, a mode-index symbol is inserted into the packet as shown in Fig. 9. These mode-index symbols increase the Euclidean distance of inter-mode [4]. Since we use 16-QAM as modulation method, the outer diagonal points of (3, 3) and (-3, -3) are taken as the mode-index symbols for mode 1 and 2, respectively.

Table 2 Simulation parameters of two-mode system.

signal constellation	Gray-assigned 16-QAM
mode-index code	mode 1: (3, 3), mode 2: (-3, -3)
mode 1	MSM (4 subbands, 16 samples, Haar wavelet)
mode 2	OFDM (16 subbands)
decoding	two-mode search

Figure 12 shows a two-mode search decoding process. First, the received packet is decomposed by using DWT (mode 1) and FFT (mode 2) in the receiver. Next, after the equalization of the multipath fading is carried out in mode 2, the sums of the Euclidean distance on each mode are calculated. We assume the guard interval is used and the multipath equalizing is perfectly done for OFDM packet, but for simplicity we omitted the insertion of guard interval. Then, decoding is carried out on the mode which has the smaller sum. The distance of two modes is enlarged by the insertion of mode-index. Note that if the mode-index symbols are assigned at the same time-frequency sub domain like Fig. 9, the calculated results of DWT and FFT at the mode-index become identical. Therefore, a prior decoding of the mode-index can be carried out either by DWT or by FFT, if the step-decoding in which the mode and data are decoded stepwise is adopted. It simplifies the decoding process. However, in this decoding scheme, the mode error yields to the noise of mode-index symbol, and then the bit error rate (BER) performance becomes worse than that of two-mode search.

4.2 Numerical Results

To evaluate the performances, we carried out the computer simulations in severe transmission environments. Table 2

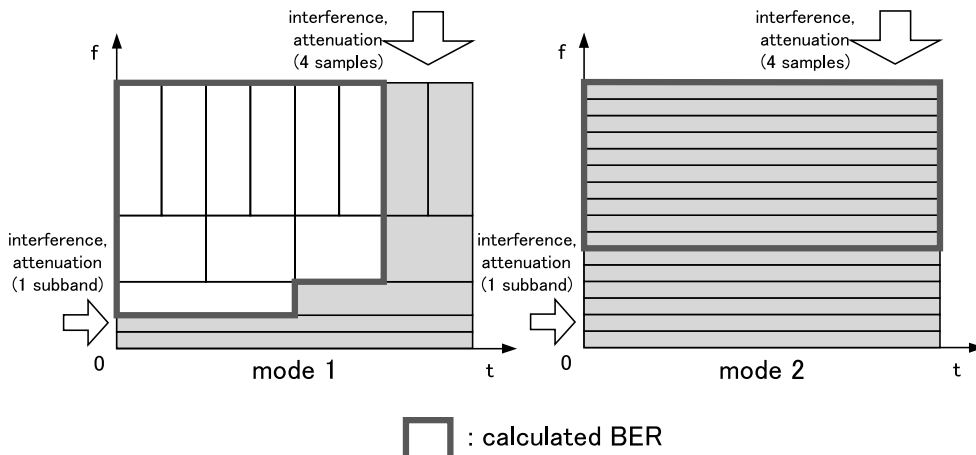


Fig. 13 Tone and impulse attenuation in each packet.

lists the parameters. The modes of every packet are assumed to be generated randomly with the mode 2 probability of p ($0 \leq p \leq 1$). Both modes have the same packet size of 16 samples per packet.

First we analyzed the performance in the tone-wise and pulse-wise interference environment as shown in Fig. 13. Here, the tone and pulse interference means the interference which is unevenly distributed in the time and frequency domains. It is assumed that every packet is interfered by the tone and periodical impulse interference on the baseband system. On both modes, the tone interference appears at every second subband on the frequency axis, in the meantime the periodical impulse interference appears at every last four samples on the time axis. Then, all subbands are degraded in the OFDM packet, while many subbands are unaffected in the WPM packet. To confirm it, the partial BER performance of packets (marked in Fig. 13) are compared where $p = 0.5$. Each BERs of WPM and OFDM, whose packets are randomly generated in the transmitter, are calculated separately. We assume the two cases of interference. One is that there is a tone and impulse attenuation where the interfered region indicated by arrows in Fig. 13 becomes zero, and the other is that there is a tone and impulse additive noise where the noise are added into the second frequency subband and the last four time samples independently. Each noise power is as same as packet signal and the phase is independently random. Figures 14 and 15 show the former and latter BERs, respectively, and Fig. 16 shows the decoding mode error rate performance of two cases. The performance of conventional single carrier 16-QAM in the same condition is also illustrated as ‘single’ in comparison.

The results in Figs. 14 and 15 show that the BER of WPM packet not affected by interference is almost as same as the theoretical curve of 16-QAM. This slight degradation comes from insertion of mode-index and is 0.28 dB. However, the BERs of OFDM and single carrier 16-QAM are severely degraded. From Fig. 16, we can see the decoding mode error is gradually decreasing for E_b/N_0 even in severe interference environments. It is the effect of the mode in-

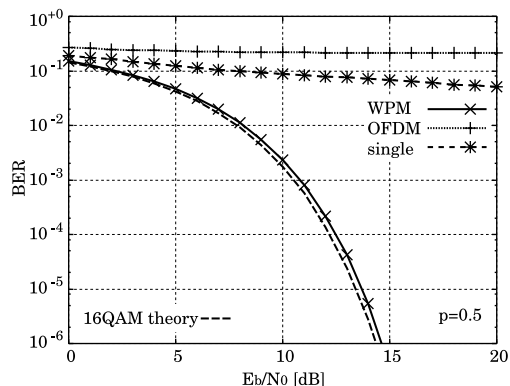


Fig. 14 Partial BER performance in attenuation environment.

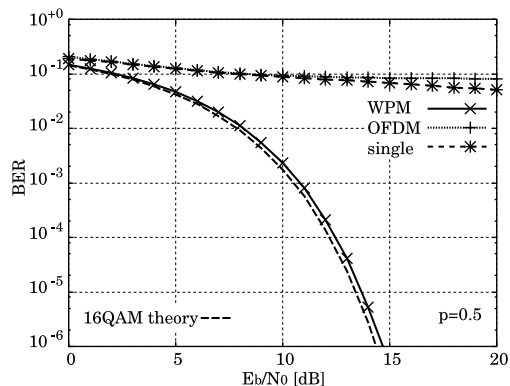


Fig. 15 Partial BER performance in interference environment.

dex. Considering the more practical use, the overall BER performance with FEC (forward error correction) was calculated. A BCH-(63,39,9) code is adopted for each packet of 64 bits and the error correction is carried out after the decision of multimode decoding. The number of data in one packet are 36 bits because the mode index takes four bits. It is assumed that no interleaver such with large memory size is applied to enable a fast mode change at every packet. The conventional method is the single carrier 16-QAM with

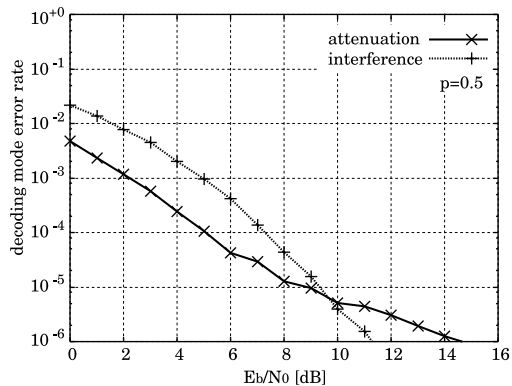


Fig. 16 Decoding mode error rate performance.

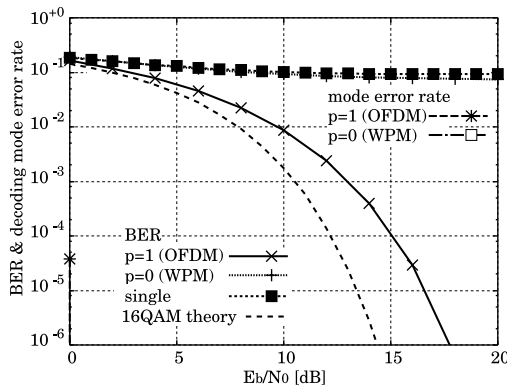


Fig. 19 BER and decoding mode error rate performance in multipath environment.

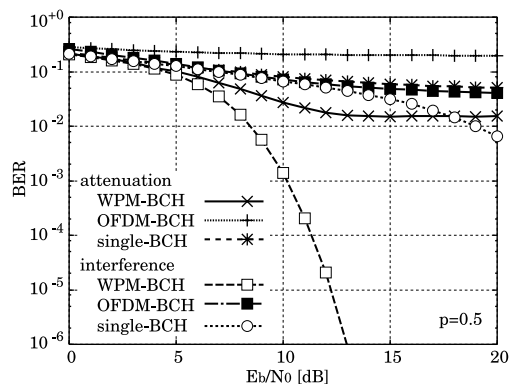


Fig. 17 Overall BER performance with BCH code.

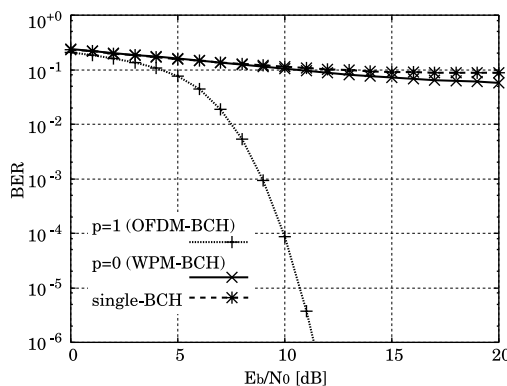


Fig. 20 BER performance of BCH code in multipath environment.

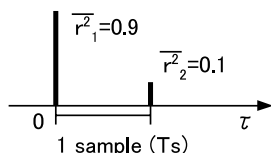


Fig. 18 Delay profile of two-path model.

an enhanced BCH-(64,39,10) code. The result in Fig. 17 shows the WPM outperforms in the both cases of attenuation and interference. Especially, in the additive noise case, it means the WPM with FEC can recover data under severe time-frequency crossing interference.

Next, the performance in a multipath environment is calculated. Figure 18 shows the static multipath model where the profile is two-path with one sample delay, and the powers of first and second paths are 0.9 and 0.1, respectively. Each path is assumed to be static and the equalizer using guard interval is carried out in mode 2. Figure 19 shows the BER versus E_b/N_0 and the decoding mode error rate where $p = 0$ and $p = 1$. The results show that the BER of OFDM is quite better than those of WPM and single carrier. It is because the equivalent length in time scale of one symbol is longer in OFDM than in WPM and single carrier. Therefore the OFDM packets have an advantage in multipath fading environments. In Fig. 19, the decoding mode error is almost zero except at $E_b/N_0 = 0$ dB with $p = 1.0$.

There is no white-squared line in Fig. 19 because the mode error didn't appear on WPM mode. The mode index is assigned at a longest time subband in a packet as shown in Fig. 9, so that the degradation caused by multipath fading is less and the mode selection in the receiver is correctly carried out. Figure 20 shows the BER with BCH code, where the result follows the bare performance in Fig. 19. When compared with single carrier transmission in Figs. 14, 15, 17, 19, and 20, either WPM or OFDM outperforms. Therefore, if the transmission line is supposed to have multipath and time-frequency interference environments, it is useful to compose a multimode with WPM and OFDM, not with single carrier.

Thus, it is shown that the better quality transmission is achieved by using the multimode method of WPM and OFDM even in interference and fading environments. To make the multimode method effective, an appropriate interference detection is still required. The two dimensional channel estimation of time and frequency domains such as blind [9] and pilot symbol aided [10] will enable it. The better performance can be obtained with WPM in the interference model and with OFDM in multipath model. For example, we may apply it to the mobile terminal where mode 1 is used in the interference environment such as microwave-band when the terminal is not moving, and mode 2 is used in multipath environments when the terminal is moving. The

efficient transmission is obtained by changing the modes adaptively. For more complicated environments, adding the adequate modes of WPM that have different partitions and the feedback loop, the system will follow the environments.

5. Conclusion

We considered the application of WPM to mobile communications. The transmission characteristics in fading environments were analyzed. The results showed the correlation between subband span in the time and frequency axes, and fading parameters. Then, we proposed the multimode transmission method using WPM and OFDM which can be applied to multiple transmission environments. Using the different transmission characteristics between WPM and OFDM in fading and interference environments, good performance may be possible in both environments with the adaptive switching of them. By using the feedback link, the adaptive multimode system can be composed which follows the many transmission environments, and the WPM will sufficiently be used in mobile communications.

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