IEICE TRANS. FUNDAMENTALS, VOL.E90–A, NO.7 JULY 2007

PAPER *Special Section on Multi-dimensional Mobile Information Networks*

Collision Recovery for OFDM System over Wireless Channel

Yafei HOU[†] *and* **Masanori HAMAMURA**[††a)], ***Members***

SUMMARY We present an effective method of collision recovery for orthogonal frequency division multiplexing (OFDM)-based communications. For the OFDM system, the modulated message data can be demodulated using the partial time-domain OFDM signal. Therefore, the partial time-domain signal can be adopted to reconstruct the whole OFDM time-domain signal with estimated channel information. This property can be utilized to recover packets from the collisions. Since most collisions are cases in which a long packet collides with a short packet, the collided part is assumed to be short. The simulated results show that the method can recover the two collided packets with a certain probability and can be developed to solve the problem of hidden terminals. This method will dramatically benefit the protocol design of wireless networks, including ad hoc and sensor networks.

key words: *OFDM, collision recovery, capture effect, multipacket reception, hidden terminals, ad hoc networks*

1. Introduction

The transmission performance of the wireless networks is dominated by two main factors: the quality of the wireless link and collisions between packets. For the wireless multipath fading channel that causes intersymbol interference (ISI), the performance of the system, such as bit-error rate (BER), is rapidly deteriorated. Therefore, many techniques and systems are utilized to ensure a small BER. Orthogonal frequency division multiplexing (OFDM) is a well-known multicarrier transmission system that has been attracting attention because of its high tolerance to ISI. The OFDM system, therefore, has been selected as the standard for digital video broadcasting (DVB), digital audio broadcasting (DAB), WLAN (802.11a/g) and WiMAX (802.16a). It achieves high bandwidth efficiency for applications including wireless internet access, fourth-generation (4G) mobile communication systems, next-generation networks (NGNs) and power-line communication systems [1].

Packet collisions occur when two or more packets from different transmitters are simultaneously transmitted and interfere with each other over the common medium. It is often assumed that, except for the spread spectrum system, collided packets are discarded and must be retransmitted. Such a retransmission decreases the system throughput and increases the transmission delay. The performance of wireless communications and networks in distributed random multiple access is influenced by this restriction [2]. Thus, there have been many attempts to recover collided packets, such as by making use of the capture effect and multiuser detection (MUD). Furthermore, the error correction coding (ECC) [3] and diversity reception [4] enhance the capture effect and result in high probability that the collided packets are recovered.

However, with the capture effect [5], only the packet that has the highest signal-to-interference-plus-noise ratio (SINR) can be recovered from the collisions and other corrupted packets are discarded. The receiver can utilize the technique of multipacket reception (MPR) by which multiple packets can be retrieved from the collision [6]. However, such a technique requires all packets to adopt different power levels to ensure that the different SINRs are above the designed thresholds. In distributed random multiple access, nodes transmit packets in an uncoordinated fashion, so it is difficult to realize the above requirement [7]. MUD is a technique by which we can recover all packets at the expense of complexity of the receiver [8]. Since MUD requires user information (signatures), it is often utilized in code division multiple access (CDMA) systems.

On the other hand, most collisions occur when one user starts to build a connection or sends a response with a short packet, such as RTS (request-to-send), CTS (clear-to-send) or ACK (acknowledgement), to one node while a principal user is transmitting a long packet including data to an identical destination. Therefore, the collided part is not as long as the principal long packet. For example, the long packet of IEEE 802.11a (64 subcarriers) can convey 8184 bits (payloads) without preamble and control bits, but the length of ACK, RTS or CTS is no longer than 300 bits which can be carried by only six BPSK-modulated OFDM signals or three QPSK-modulated OFDM signals [9]. Undoubtedly, for the long packet, if such collided parts can be recovered, the system performance, such as throughput and delay, will be dramatically improved [6]. On the other hand, it will also benefit the protocol design of wireless networks because short packets often contain much important information, such as positions and power levels [10]–[12].

In this paper, we propose a method of collision recovery for OFDM-based packet communications. We will present the property that, for the OFDM system, the mod-

Manuscript received October 30, 2006.
Manuscript revised January 15, 2007.
Final manuscript received March 5, 2007.

[†]The author is with the Graduate School of Engineering, Kochi University of Technology, Kochi-ken, 782-8502 Japan and Dept. of Computing and Information Technology, Fudan University, P.R. China.
[††]The author is with the Dept. of Information Systems Engineering, Kochi University of Technology, Kochi-ken, 782-8502 Japan.
a) E-mail: hamamura.masanori@kochi-tech.ac.jp

DOI: 10.1093/ietfec/e90–a.7.1312

ulated message data can be demodulated using the partial time-domain OFDM signal. Therefore, the partial signal can be adopted to reconstruct the whole OFDM signal with estimated channel information. Utilizing this advantageous property, an effective method of collision recovery, which is somewhat similar to the scheme of successive interference cancellation (SIC) [13], can be realized. We simulated the recovery performance using different modulations for two users with identical SNR, and weak near-far effect, and showed that the method gives promising results and can be developed to solve the problem of hidden terminals.

Compared with other methods, the most important point is that our proposed method can recover both long and short packets from the collision, which can be utilized in ad hoc networks based on OFDM. For example, the short packets such as RTS often contain much important information of wireless nodes, such as their positions and desired transmission duration. If the nodes which have sent the RTS have not obtained the responses, they will retransmit the short packets (RTS) after a random delay and such a process will result in another collision. By utilizing our proposed method, the receiver can separate the short packets from the long packet when they are collided with the long packet. So in the next step, the receiver can send the responses according to the scheduling strategies to all nodes which have sent the RTS packets. On the other hand, in the near-far situation, our method can achieve better recovery performance in the weak near-far condition which is more realistic in the wireless LAN. Therefore, the proposed method can be utilized to solve the hidden terminal or exposed terminal problems and improve the performance of ad-hoc networks that are based on wireless LAN using OFDM techniques.

The paper is organized as follows. A basic model of the OFDM system with partial signals and its performance using BPSK and QPSK modulations over a multipath fading channel are described in Sect. 2. Then the method of collision recovery is presented in Sect. 3. We discuss some factors that influence the performance of recovery in Sect. 4. The performance of the proposed method is simulated in Sect. 5. We further discuss the performance of the OFDM system with partial signals using 8-QAM and 16-QAM modulations in Sect. 6 and the paper ends with conclusions presented in Sect. 7.

2. OFDM System with Partial Signal

2.1 Model of OFDM System with Partial Signal

For simplicity, the time-domain OFDM signal is expressed in complex base-band notation as

$$y(t) = \sum_{n=0}^{N-1} x(n) e^{j2\pi n f_0 t}, \quad t \in [0, T] \tag{1}$$

with $f_0 = 1/T$, T being the symbol duration of OFDM, $j = \sqrt{-1}$. $x(n)$ is the information-bearing message symbol that modulates the nth subcarrier ($n = 0, \ldots, N-1$),

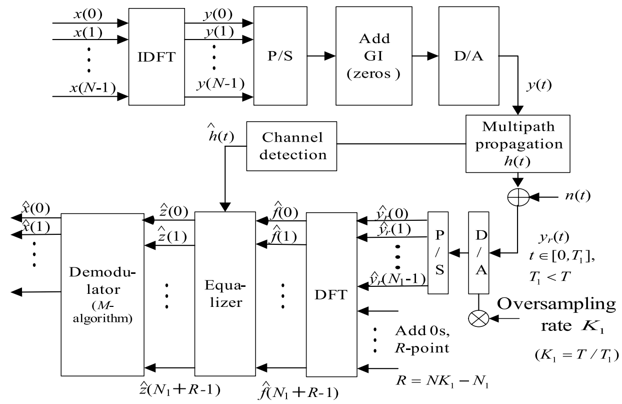


Fig. 1 Transmitter and receiver for OFDM system with partial signal.

and N is the number of subcarriers. Since the minimum frequency spacing f_0 between adjacent subcarriers is $1/T$, the normalized symbol duration of the OFDM signal is equal to or larger (with additional guard interval T_g) than one. Usually, the OFDM receiver utilizes the whole duration (f_0T=1) of the OFDM signal, except the guard interval (GI), to recover the message symbols. It has been shown that for some types of high-compaction multicarrier modulation (HC-MCM) [14]–[17], we can recover the message symbols even when only a partial duration of the OFDM signal can be utilized at the receiver.

Figure 1 shows the transmitter and receiver for the OFDM system with a partial signal. $x(n)(n = 0, ..., N-1)$ is a message-bearing subcarrier symbol that takes a complex value to modulate a corresponding subcarrier. After the inverse discrete Fourier transform (IDFT) and parallel-to-serial (P/S) conversion process, several zeros are padded as the postfix GI to alleviate the influence of multipath fading. The duration of zero postfix (ZP) is T_g. The reason we choose ZP as GI is that such a method simplifies the demodulation and equalization of the receiver [18]. After digital-to-analog (D/A) conversion, the whole OFDM signal $y(t)$ ($t \in [0, T + T_g]$) is transmitted into the channel.

Suppose that the impulse response $h(t)$ of the fading channel is

$$h(t) = \sum_{i=1}^{L_P} A_i e^{j\theta_i} \delta(t - \tau_i) \quad t \in [0, T + T_g], \tag{2}$$

where L_P means the number of paths and each path has the relative path delay $\tau_i(\tau_1 \leq \tau_2 \leq \ldots \leq \tau_{L_P} < T_g)$. $A_i = A_i(t)$ and $\theta_i = \theta_i(t)$ are the slowly Rayleigh-fading amplitude attenuation and phase rotation of each path. We assume A_i and θ_i are constant during each OFDM symbol duration.

Suppose that only a portion of the OFDM signal, $y_r(t)$ ($t \in [0, T_1](T_1 \leq T)$), can be utilized in the receiver. $y_r(t)$ can be represented as

$$\begin{aligned} y_r(t) &= h(t) \otimes y(t) + n(t) \\ &= \sum_{i=1}^{L_P} A_i e^{j\theta_i} y(t - \tau_i) + n(t) \quad t \in [0, T_1], \end{aligned} \tag{3}$$

where $n(t)$ is the additive white Gaussian noise (AWGN).

The receiver generates N_1 discrete-time samples, $\hat{y}_r(m)$ ($m = 0, \ldots, N_1 - 1$), from the received signal $y_r(t)$ after analog-to-digital (A/D) conversion with oversampling rate K_1. We assume $K_1 = T/T_1$. Since the receiver utilizes the partial time-domain OFDM signal to demodulate the modulated data, we assume $T_1 \le T$. Therefore, the receiver needs not to implement the process of removing the GI. The N_1 received samples, $\hat{y}_r(m)$, followed by R zeros yield $\hat{f}(n)$ ($n = 0, \ldots, N_1 + R - 1$) by DFT, as shown in Fig. 1 ($R = K_1 N - N_1$, where R is the number of samples corresponding to the vanished period of the entire OFDM signal). It should be pointed out that the relation $K_1 = T/T_1$ is not necessary and we can set arbitrary integers for K_1 and R such that the relations $N_1/(R + N_1) = T_1/T$ and $N \le N_1$ hold. Then the DFT outputs $\hat{f}(n)(n = 0, \ldots, N_1 + R - 1)$ are equalized with the estimation $\hat{h}(t)$ of the channel impulse response $h(t)$. The goal of equalization is to reduce the multipath interference and we adopt the zero-forcing equalizer as described below.

Suppose each path delay τ_i corresponds to the duration of $N_{\tau_i}(i = 1, \ldots, L_P)$ samples after A/D conversion. At the receiver front, discrete-time samples $\hat{y}_r(m)(m = 0, \ldots, N_1 - 1)$ of the received signal $y_r(t)$ are

$$\begin{aligned}\hat{y}_r(m) &= \sum_{i=1}^{L_P} A_i e^{j\theta_i} \sum_{k=0}^{N-1} x(k) e^{j\frac{2\pi k(m-N_{\tau_i})}{N_1+R}} \\ &\quad \times [u(m - N_{\tau_i}) - u(m - N_1 + 1)] + n(m),\end{aligned} \tag{4}$$

where $n(m)$ is the discrete-time sample of $n(t)$ and $u(m)$ is the unit step function. Therefore, after DFT operation, as shown in Fig. 1, the receiver output $\hat{f}(n)(n = 0, \ldots, N_1 + R - 1)$ can be expressed as

$$\begin{aligned}\hat{f}(n) &= \frac{1}{N_1 + R}\left(\sum_{i=1}^{L_P} A_i e^{j\theta_i} \sum_{k=0}^{N-1} x(k) e^{-j\frac{2\pi n N_{\tau_i}}{N_1+R}}\right. \\ &\quad \left. \times \sum_{m=0}^{N_1-N_{\tau_i}-1} e^{j\frac{2\pi m(k-n)}{N_1+R}} + n'(n)\right),\end{aligned} \tag{5}$$

where $n'(n)$ is the DFT output of $n(m)$.

Suppose that $H(f)$ is the frequency response of channel $h(t)$ and its discrete representation is $H(n)(n = 0, \ldots, N_1 + R - 1)$, where $H(n) = H(f)|_{f=nf_0}$. Then the zero-forcing equalizer can be defined as

$$H_{ZF}(n) = \frac{1}{H(n)} = \left(\frac{1}{N_1 + R}\sum_{i=1}^{L_P} A_i e^{j\theta_i} e^{-j\frac{2\pi n\tau_i}{T}}\right)^{-1}. \tag{6}$$

After being passed through the equalizer, the received signal $\hat{f}(n)$ will be changed to $\hat{z}(n)$. $\hat{z}(n)(n = 0, \ldots, N_1 + R - 1)$ can be expressed as

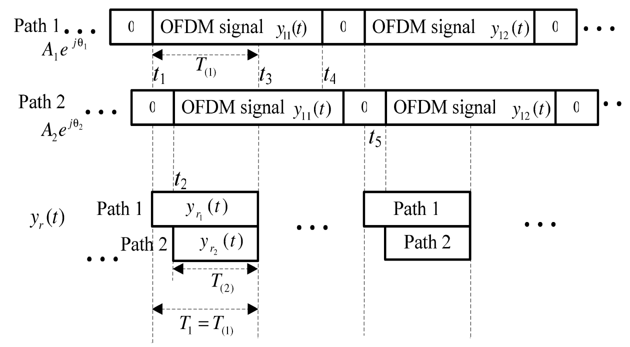


Fig. 2 Two-path fading channel.

$$\begin{aligned}\hat{z}(n) &= \hat{f}(n) \times H_{ZF}(n) \\ &= \frac{\sum_{i=1}^{L_P} A_i e^{j\theta_i} \sum_{k=0}^{N-1} x(k) e^{-j\frac{2\pi n\tau_i}{T}} \sum_{m=0}^{N_1-N_{\tau_i}-1} e^{j\frac{2\pi m(k-n)}{N_1+R}} + n'(n)}{\sum_{i=1}^{L_P} A_i e^{j\theta_i} e^{-j\frac{2\pi n\tau_i}{T}}}.\end{aligned} \tag{7}$$

For a multipath fading channel, the transmitted OFDM signals will be superposed by L_P signals. Figure 2 illustrates the received signals over a two-path fading channel (the complex amplitude of each path is $A_1 e^{j\theta_1}$ and $A_2 e^{j\theta_2}$ in Fig. 2). Suppose that one OFDM time-domain signal $y_{11}(t)(t \in [t_1, t_4])$ is transmitted over this channel and the receiver uses a partial signal $y_r(t)$ ($t \in [t_1, t_3], T_1 = (t_3 - t_1)$) to demodulate message symbols. From Fig. 2, $y_r(t)$ ($t \in [t_1, t_3]$) is the sum of the first-path partial signal $y_{r_1}(t)(t \in [t_1, t_3])$ and the second-path partial signal $y_{r_2}(t)(t \in [t_2, t_3])$. We use $T_{(i)}$ to represent the partial duration for the ith partial signal in a multipath channel. Therefore, $f_0 T_{(1)} = (t_3 - t_1)/(t_4 - t_1)$ and $f_0 T_{(2)} = (t_3 - t_2)/(t_4 - t_1) = f_0 T_{(1)} - \tau_1/(t_4 - t_1)$), where $\tau_1 = t_2 - t_1$ is the relative delay. Then, $y_r(t)$ ($t \in [t_1, t_3]$) can be represented as

$$y_r(t) = y_{11}(t) A_1 e^{j\theta_1} + y_{11}(t - \tau) A_2 e^{j\theta_2}. \tag{8}$$

Therefore, for an L_P-path multipath channel, received signal $y_r(t)$ in Fig. 2 will be superposed with L_P partial signals, and $f_0 T_{(1)} \ge f_0 T_{(2)} \ge \ldots \ge f_0 T_{(L_P)} (f_0 T_1 = f T_{(1)})$. The differences between $f_0 T_{(i)}$ and τ_i/T can be decreased by increasing T. From (7), if the values of $\tau_i/T (= N_{\tau_i}/(N_1 + R))$ for $i = 1, \ldots, L_P$ are approximately identical, the multipath interference can almost completely be removed. Suppose that τ_i/T in (7) can be approximated as $\tau_i/T << 1$ and $N_{\tau_1}/(N_1 + R) \approx N_{\tau_2}/(N_1 + R) \approx \ldots \approx N_{\tau_{L_P}}/(N_1 + R)$. In this case, (7) is reduced to

$$\begin{aligned}\hat{z}(n) &= \sum_{m=0}^{N_1-N_{\tau_1}-1} \sum_{k=0}^{N-1} x(k) e^{j\frac{2\pi m(k-n)}{N_1+R}} + n''(n) \\ &= \sum_{k=0}^{N-1} x(k) \frac{1 - e^{j\frac{2\pi(N_1-N_{\tau_1})(k-n)}{N_1+R}}}{1 - e^{j\frac{2\pi(k-n)}{N_1+R}}} + n''(n)\end{aligned} \tag{9}$$

$$= \sum_{k=0}^{N-1} x(k) \frac{1 - e^{j2\pi(k-n)\frac{T_1-\tau_1}{T}}}{1 - e^{j\frac{2\pi(k-n)}{N_1}\frac{T_1-\tau_1}{T}}} + n''(n), \quad (10)$$

where $n''(n) = n'(n)/(\sum_{i=1}^{L_P} A_i e^{j\theta_i} e^{-j\frac{2\pi n \tau_i}{T}})$.

Finally, the estimates $\hat{x}(n)(n = 0, \ldots, N-1)$ of the message symbols $x(n)$ are recovered through the demodulation stage with the samples $\hat{z}(n)(n = 0, \ldots, N_1 + R - 1)$. Due to intercarrier interference (ICI), which is evident in (10), a reasonable approach for attaining a good demodulation performance will be the maximum likelihood sequence estimation (MLSE). However, the demodulation complexity (C_p) of MLSE increases exponentially with the number of subcarriers N and modulation type P(BPSK: $P = 2$; QPSK: $P = 4, \ldots$), that is, $C_p = P^N$, which is impractical for the demodulation for large N. But for large N, a demodulation method using the M-algorithm, in which the calculation complexity preserves a linear increase with N, has been proposed [17]. In this study, we adopt the M-algorithm to demodulate the message symbols.

2.2 M-Algorithm for OFDM System with Partial Signal

We briefly introduce the M-algorithm to demodulate the partial OFDM signal. Readers can find the detailed process and performance in [17].

Step 1: Generate partial message vectors $\mathbf{X}_u^{(1)} = [x(0), \ldots, x(U-1), \ldots, 0]$ $(u = 0, \ldots, P^U - 1;\ U \leq N;\ P = 2$ for BPSK, $P = 4$ for QPSK) of length N. Utilizing $\mathbf{X}_u^{(1)}$, produce P^U kinds of replica vectors $\mathbf{Z}_u^{(1)} = [z(0), \ldots, z(N_1 + R - 1)]$ by the same operation as shown in Fig. 1 without noise and fading. Therefore, the elements $z(l)(l = 0, \ldots, N_1 + R - 1)$ of $\mathbf{Z}_u^{(1)}$ can be expressed as

$$z(l) = \sum_{k=0}^{U-1} x(k) \frac{1 - e^{j2\pi(k-l)\frac{T_1}{T}}}{1 - e^{j\frac{2\pi(k-l)}{N_1}\frac{T_1}{T}}}. \quad (11)$$

Euclidian distances $d_u^{(1)}(u = 0, \ldots, P^U - 1)$ between $\mathbf{Z}_u^{(1)}$ and $\hat{\mathbf{Z}}$ are first evaluated using their elements partially as

$$d_u^{(1)} = \left(\sum_{l=0}^{U-1} |z(l) - \hat{z}(l)|^2 + \sum_{l=N}^{N_1+R-1} |z(l) - \hat{z}(l)|^2 \right)^{1/2}. \quad (12)$$

Then $M(M < P^U)$ kinds of $\mathbf{Z}_u^{(1)}$, which indicate small Euclidean distances, are chosen as $\mathbf{Z}^{(1)(r)}(r = 0, ..., M-1)$ from among P^U kinds of $\mathbf{Z}_u^{(1)}$, and vectors $\mathbf{X}_u^{(1)}$ which produce $\mathbf{Z}^{(1)(r)}$ are stored as $\mathbf{X}^{(1)(r)}$ $(r = 0, \ldots, M-1)$. The elements of vectors $\mathbf{X}^{(1)(r)}$ become candidates for the partial message symbols $\hat{x}(0), \ldots, \hat{x}(U-1)$.

Step 2: Redefine partial message vectors $\mathbf{X}_w^{(2)}(w = 0, \ldots, MP-1)$ of length N as $\mathbf{X}_w^{(2)} = [\mathbf{X}^{(1)(r)}, x(U), 0, \ldots, 0]$. Therefore, MP kinds of replica vectors $\mathbf{Z}_w^{(2)} = [z(0)...z(N_1 + R - 1)]$ are produced. Euclidian distances $d_w^{(2)}(w = 0, \ldots, MP-1)$ between $\mathbf{Z}_w^{(2)}$ and $\hat{\mathbf{Z}}$ are evaluated by

$$d_w^{(2)} = \left(\sum_{l=0}^{U} |z(l) - \hat{z}(l)|^2 + \sum_{l=N}^{N_1+R-1} |z(l) - \hat{z}(l)|^2 \right)^{1/2}. \quad (13)$$

Then, M kinds of $\mathbf{Z}_w^{(2)}$, which indicate small Euclidian distances, are chosen as $\mathbf{Z}_w^{(2)(r)}(r = 0, \ldots, M-1)$ from among MP kinds of $\mathbf{Z}_w^{(2)}$, and vectors $\mathbf{X}_w^{(2)}$ which produce $\mathbf{Z}_w^{(2)(r)}$ are stored as $\mathbf{X}^{(2)(r)}(r = 0, \ldots, M-1)$. The elements of vectors $\mathbf{X}^{(2)(r)}$ become new candidates for the partial message symbols $\hat{x}(0), \ldots, \hat{x}(U)$. Thus, $\hat{x}(U)$ is added to the candidates obtained in Step 1.

Step 3: MP kinds of $\mathbf{Z}_w^{(N-U+1)}$ are obtained by repeating Step 2 $N - U$ times. Finally, vector $\mathbf{X}^{(N-U+1)}$, which produces the minimum Euclidian distance, contains all the message symbols $\hat{x}(0), \ldots, \hat{x}(N-1)$.

From three steps, we can find that the M-algorithm can keep demodulation complexity as $C_p = P^U + (N - U)MP$ and C_p preserves a linear increase with N. The M-algorithm produces the replica vectors $\mathbf{Z}_u^{(i)}$ for each iteration according to (11). It should be pointed out that the HC-MCM system in [15] has the same $f_0 T_{(i)}$ $(i = 1, \ldots, L_P)$ since the transmitter of HC-MCM utilizes the partial signal with ZP-GI to transmit message symbols $x(n)$. However in this study, only the receiver adopts the partial signal to demodulate $x(n)$. This causes different values for $f_0 T_{(i)}(i = 1, \ldots, L_P)$ over the multipath channel. Nevertheless the algorithm can achieve an acceptable performance if relative values of τ_i/T are small enough to make $f_0 T_{(i)}$ $(i = 1, \ldots, L_P)$ almost the same over all the paths of the channel. Note that τ_i/T can be decreased with the increase of T (or equivalently, N).

2.3 Simulated Performance of OFDM System with Partial Signal over Multipath Fading Channel

We choose the fading channel model of JTC' 94 (indoor residential B) [19] to simulate the performance of our system. The duration of each OFDM signal is T_S $(T_S = T + T_g)$. The receiver utilizes the partial signals with durations $f_0 T_1 = 0.5$ and 0.625 to demodulate all symbols $x(n)$ $(n = 0, ..., N-1)$ by the M-algorithm. The common specifications of simulations are listed in Table 1.

Table 1 Specifications of simulations.

System Item	Parameter
Subcarrier modulation	BPSK, QPSK
Synchronization	Complete
Channel type	JTC' 94 (indoor residential B) (L_P=8)
Equalization	zero-forcing equalization
Supported symbol rate (OFDM symbol/second)	250k ($T + T_g = 4\,\mu$s), N=32; 125k ($T + T_g = 8\,\mu$s), N=64; 62.5k ($T + T_g = 16\,\mu$s), N=128
Relative delay for each path (ns)	0, 50, 100, 150 200, 250, 300, 350
Relative power attenuation for each path (dB)	0, −2.9, −5.8, −8.7, −11.6, −14.5, −17.4, −20.3
Maximum Doppler frequency shift f_D (Hz)	20
Duration of zero guard signal	T_g=0.25T
$f_0 T_1$	0.4, 0.5, 0.625, 1
Noise	additive white Gaussian noise
Values U, M for M-algorithm	BPSK U=4, M = 16; QPSK U=2, M = 16

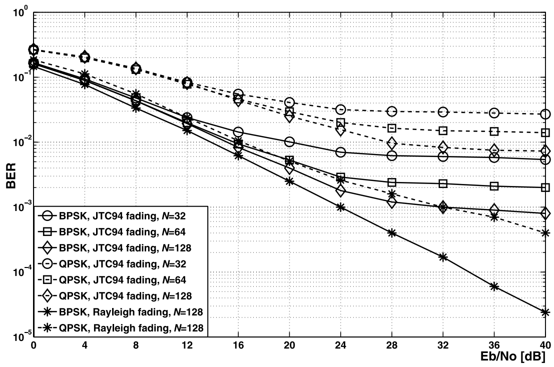


Fig. 3 BER of OFDM system with partial signal, f_0T_1=0.5.

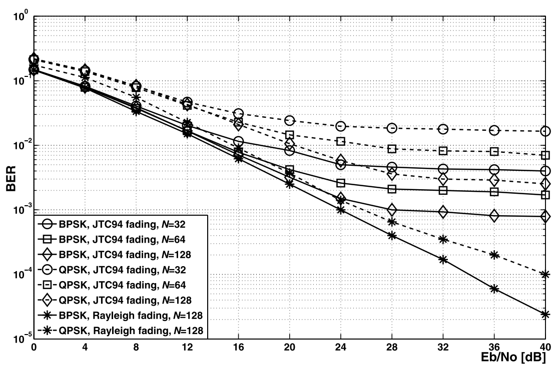


Fig. 4 BER of OFDM system with partial signal, f_0T_1=0.625.

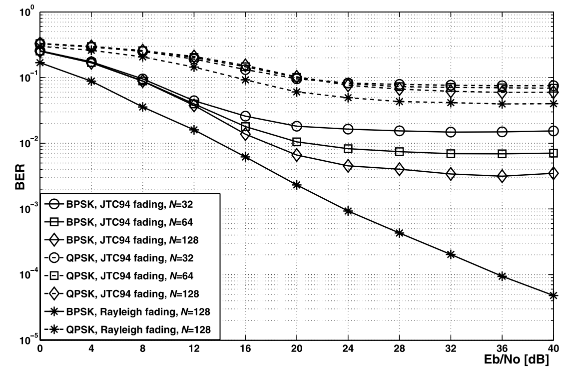


Fig. 5 BER of OFDM system with partial signal, f_0T_1=0.4.

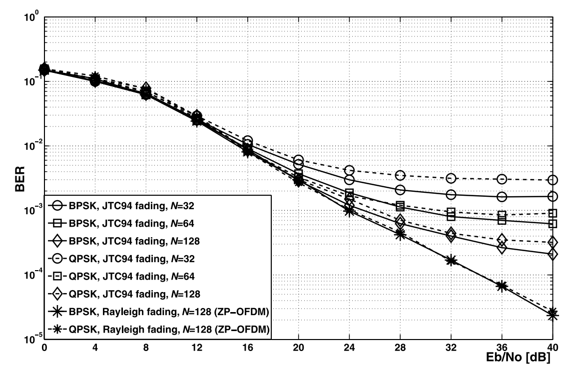


Fig. 6 BER of OFDM system with partial signal, f_0T_1=1.

Figure 3 shows the BER performance for $f_0T_1 = 0.5$, which means half the OFDM signal for the first path, which results in $f_0T_{(i)} < 0.5$ for $i \in [2, \ldots, L_P]$. We assume that the receiver knows the channel information and carries out the zero-forcing equalization. From Fig. 3, we confirm that the partial signal can be used to demodulate all symbols $x(n)$ ($n = 0, 1, ..., N-1$) with the M-algorithm. Particularly for BPSK, we can achieve a better BER performance. We also can confirm that the performance is improved with increasing N. The reason is that τ_i/T and the differences between $f_0T_{(1)}$ and $f_0T_{(L_P)}$ are decreased. On the other hand, from (7), due to the effect of different τ_i/T, the equalizer cannot totally remove ISI of the multipath channel. Therefore, an error floor appears for large SNR. Such an influence is severer for QPSK than that for BPSK.

Figure 4 shows the BER performance for $f_0T_1 = 0.625$. Compared with the results in Fig. 3, the performance is improved, particularly for QPSK-modulated OFDM. We also give the simulated performance of the system over a one-path Rayleigh-fading channel (N=128), which can be regarded as the performance of the system over the multipath fading channel with N increasing to infinity. The results also prove that we can improve the system performance by increasing N.

We assume that the system utilizes the partial OFDM signal to demodulate the data and reconstruct the whole OFDM signal. To achieve better recovery performance, the parameter f_0T_1 should be adopted appropriately when collision happens. For system design that the proposed method achieves better recovery performance, the value of f_0T_1 must be in [0.5, 0.625] or similar values which will be described in the following sections. To further evaluate the effectiveness and performance limit of the system that utilizes the partial OFDM signal, we simulate the BER performance of OFDM system with partial signal using BPSK and QPSK for f_0T_1=0.4 in Fig. 5 and for f_0T_1=1 in Fig. 6, respectively. The BER performance degrades severely for QPSK modulation with $f_0T_1 = 0.4$, even over a one-path Rayleigh-fading channel (N=128). The reason is that ICI is dramatically increased by smaller value of f_0T_1 and intensify the error propagation during the each iteration of M-algorithm. It should be mentioned that for $f_0T_1 = 1$, the error floor will still appear because $f_0T_1 = 1$ means the intact OFDM signal for the first path, but $f_0T_{(i)} < 1$ for $i \in [2, \ldots, L_P]$, which causes the different τ_i/T. Therefore, the equalizer cannot totally remove ISI due to the multipath channel. On the other hand, we also give the simulated BER performance of the system with $f_0T_1 = 1$ over a one-path Rayleigh-fading channel (N=128). It can be regarded as the performance of the system over the multipath fading channel with N increasing to infinity. For $f_0T_1 = 1$, the system over a one-path Rayleigh-fading channel can also be treated as the ZP-OFDM [18] system over a one-path Rayleigh-fading. The simulated results also confirm that performance degradation always appears for the different τ_i/T and smaller f_0T_1.

To further evaluate the system performance, we simu-

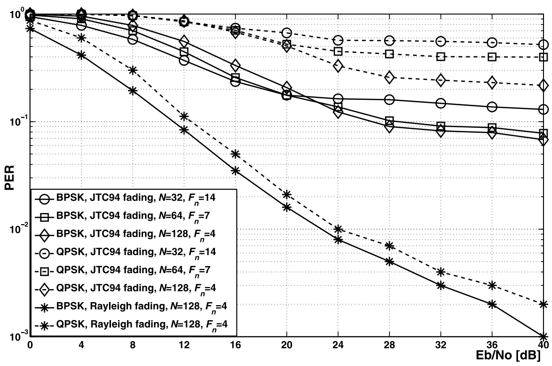


Fig. 7 PER of OFDM system with partial signal, f_0T_1=0.625.

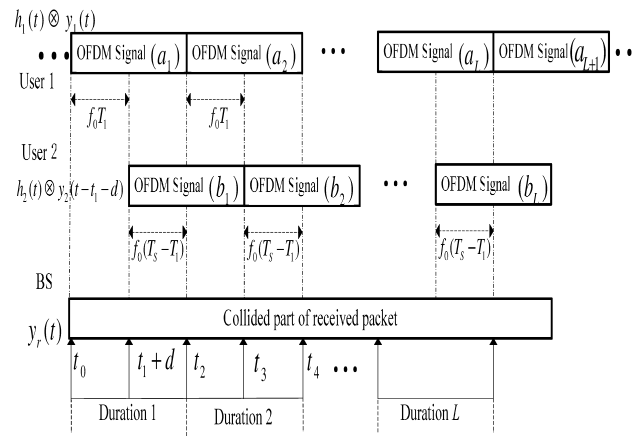


Fig. 8 Collisions of two packets.

late the packet error rate (PER). Let us use F_n to represent the number of OFDM signals in one packet. We assume that a packet error occurs if more than one of the transmitted data bits in one packet are missdetected. Figure 7 shows the PER performance for $f_0T_1 = 0.625$. The results show that although the BER under such a condition is large even when Eb/No is beyond 28 dB, bit errors will be concentrated in a small number of packets because of worse channel conditions. For example, for BPSK-modulated OFDM with $N = 128$ and $F_n = 4$ (each packet can transmit 512 bits), approximately 92% of packets can be correctly demodulated. For $N = 128$ and $F_n = 4$ in a QPSK-modulated OFDM system, approximately 81% of packets can be correctly demodulated. Such rates can be improved by increasing N.

3. Packet Recovery with Partial OFDM Signal

We have described that for OFDM systems, message symbols can be demodulated with the partial OFDM signal. We can utilize this property to recover two collided packets. This method is somewhat similar to the scheme of successive interference cancellation (SIC) [13] which is widely adopted in CDMA systems.

Figure 8 illustrates a scenario of the collision of two packets, $y_1(t)$ from user 1 and $y_2(t)$ from user 2. Both packets consist of several OFDM signals, each of which can be expressed by formula (1). The duration of each OFDM signal is T_S. We assume that user 1 is the principal user who is transmitting a long packet and user 2 is a hidden terminal who has just started to build a connection with a short packet at time t_1. Therefore, after the transmission over the respective channels $h_1(t)$ and $h_2(t)$, packet $y_1(t)$ collides with packet $y_2(t)$ at time $t_1 + d$, where d is the transmission delay of user 2. The relative delay of $y_2(t)$ from the first collided OFDM signal a_1 of user 1 is $t_1 + d - t_0 (t_1 \in [t_0, t_2])$. Therefore, the received signal $y_r(t)$ can be represented as

$$y_r(t) = h_1(t) \otimes y_1(t) + h_2(t) \otimes y_2(t - t_1 - d) + n(t). \quad (14)$$

$y_r(t)$ can also be represented over $t \in [t_0, t_2]$ as (see also Fig. 8)

$$y_r(t) = \begin{cases} h_1(t) \otimes y_1(t) + n(t) & t \in [t_0, t_1 + d] \\ h_1(t) \otimes y_1(t) + h_2(t) \otimes y_2(t - t_1 - d) + n(t) & \\ & t \in [t_1 + d, t_2]. \end{cases} \quad (15)$$

As can be seen from (15), there is no collision in $t \in [t_0, t_1 + d]$. Therefore, collided packets $y_1(t)$ and $y_2(t)$ can be recovered iteratively from $y_r(t)$ by the following steps.

(a) By the method described in Sect. 2, the receiver (BS) recovers the message symbols carried by OFDM signal a_1, using the partial signal of $y_r(t)$ $(t \in [t_0, t_1 + d])$.

(b) The receiver reconstructs $h_1(t) \otimes y_1(t) (t \in [t_0, t_2])$ with the recovered message symbols and channel information $h_1(t)$, and subtracts it from $y_r(t)$. By this, the receiver can obtain signal $y_r'(t)(t \in [t_1 + d, t_2])$, which is the received signal without OFDM signal a_1.

(c) The receiver recovers the message symbols carried by OFDM signal b_1 using the partial signal of $y_r'(t)$ $(t \in [t_1 + d, t_2])$.

(d) The receiver reconstructs $h_2(t) \otimes y_2(t - t_1 - d)(t \in [t_1 + d, t_3])$ with the recovered message symbols and channel information $h_2(t)$, and subtracts it from $y_r'(t)(t \in [t_1 + d, t_3])$. By this, the receiver can obtain received signal $y_r''(t)(t \in [t_2, t_3])$, which is the received signal without OFDM signal b_1 in $y_r'(t)(t \in [t_1 + d, t_3])$. The new $y_r''(t) = h_1(t) \otimes y_1(t) + n(t)(t \in [t_2, t_3])$ can be treated as $y_r(t)$ in the next duration to recover the message symbols of OFDM signal a_2.

The receiver repeats processes (a) to (d) until all the collided parts of the two packets are recovered (i.e., until OFDM signal a_{L+1} is recovered).

4. Some Factors which Influence Performance of Recovery

To achieve better recovery performance, f_0T_1 and $f_0(T_s - T_1)$ in Fig. 8 should be adopted appropriately. Such a requirement can be realized with the aid of time slots. We assume that all long packets are transmitted at the beginning of time slots, and the short packets are delayed in their transmissions by $t_1 - t_0$ from the beginning of time slots. On the basis of Fig. 8 and the above process of collision recovery, we can infer that the performance of recovery depends on the following factors.

4.1 Propagation Delay between Transmitters and Receiver

Propagation delay d cannot be a large value. For example, in Fig. 8, if $t_1 + d$ equals t_2, then $f_0(T_S - T_1) = 0$. Such a condition will invalidate the recovery method. The maximum delay depends on the allowable maximum transmission distance between BS and transmitters. For wireless LAN or the ad hoc network, the maximum transmission distance is often assumed to be 30 m to 60 m for an indoor situation and within 300 m to 600 m for the outdoor case. Thus d is 0.1 μs or 0.2 μs, at most, in the indoor case and 1 μs or 2 μs in the outdoor case. Compared with the duration of the OFDM signal, for example, 4 μs in Table 1, the delay changes $f_0 T_1$ and $f_0(T_S - T_1)$ only 2.5% to 5% in the indoor situation. Such values will not significantly decrease the performance of the recovery. Furthermore, the system can adopt a large T (or equivalently, N) to increase the duration of the OFDM signal. Therefore, if the maximum propagation distance is small, such an influence can be negligible.

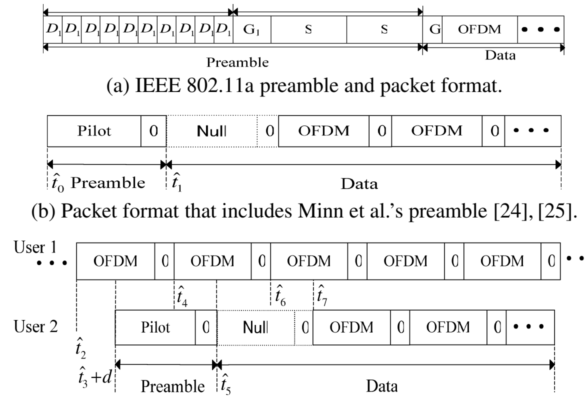
4.2 Detection of Collision Position

The receiver must detect the position of collision, which means the position of $t_1 + d$ in Fig. 8. On the basis of the recovery method and Fig. 8, BS can utilize partial duration $(t_1 - t_0)/T$ of OFDM signal a_1 of user 1 to remove it from $y_r(t)$. After that, BS can detect $t_1 + d$. Therefore, the first step of the detection of the collision position is equivalent to the detection of collision occurrence.

One simple detection method of collision occurrence is that BS checks the received signal power over the GI signal of user 1. Since a long packet utilizes the ZP-GI T_g, which is longer than τ_{L_P}, and the signals of late paths undergo high power attenuations, the received signal $y_r(t)$ will be only the noise component during the late period of the GI if there is no collision from user 2. Therefore, if the received power of $y_r(t)$ increases rapidly during the GI of user 1, BS can assume that collision has occurred and can carry out the recovery algorithm using partial duration $(t_1 - t_0)/T$ of the OFDM signal of user 1. Then BS removes user 1's signal during $t \in [t_0, t_2]$ and checks the propagation delay d of user 2. Such a simple detection can be used even in the situation with a weak near-far effect. We will describe a preamble-based method of obtaining d in the following subsection. Otherwise, if there is no distinct increase of power during the GI of user 1, the receiver can assume that no collision happens. Then the receiver utilizes the received signal including the guard interval to demodulate the data of user 1 using one-tap equalizer which is identical to the ZP-OFDM system [18].

4.3 Estimation of Channel Information $h_2(t)$ of User 2

Generally speaking, the packet utilizes preamble to obtain



(a) IEEE 802.11a preamble and packet format.

(b) Packet format that includes Minn et al.'s preamble [24], [25].

(c) Preamble recovery from the collision.

Fig. 9 Packet format and preamble recovery from the collision.

channel information; for example, IEEE 802.11a adopts the 16 μs preamble, which includes the duration of four OFDM signals, to estimate the channel information. Figure 9(a) illustrates the preamble structure specified in IEEE 802.11a [19]. The preamble consists of ten identical short training symbols (D_1), each of which is 0.8 μs, and two identical long training symbols (S), each of which is 3.2 μs plus a 1.6 μs prefix (G_1) which precedes the long training symbols. The short training symbols are used for timing, signal detection, automatic gain control (AGC) level setting, coarse timing synchronization and coarse carrier frequency offset correction by auto-correlation and cross-correlation methods [19]. The long training symbols are used for fine carrier frequency offset and channel estimation.

The preamble of IEEE 802.11a cannot be used for user 2 because the short training symbols that are utilized to achieve coarse frequency and timing synchronization are corrupted. Fortunately, there are many preamble designs for OFDM systems [20]–[23], particular, Minn et al. utilized one OFDM training symbol to estimate the channel information and to implement the frequency and timing synchronization [24], [25]. Figure 9(b) shows the packet format that is Minn et al.'s preamble and data part. This preamble uses one specifically designed training symbol having a steep rolloff timing metric trajectory. It can implement the frequency, timing synchronization and channel estimation iteratively and can be adopted in many types of time-varying multipath fading channels. The simulated performances of timing, frequency synchronization and channel estimation can be found in [24]. Minn et al.'s also presented a sliding-observation-vector-based maximum-likelihood combined timing and frequency synchronization and channel estimation method using a repetitive training OFDM signal [25].

We can utilize this preamble to estimate $h_2(t)$ and implement the timing and frequency synchronization. Figure 9(b) shows the packet format that includes one pilot OFDM signal as the preamble and several OFDM signals to transmit the data. To improve the performance of estimation, the first OFDM signal of the data part only transmits a null OFDM signal. This structure of the preamble also simplifies the detection of collision occurrence.

Suppose that BS knows the impulse response $h_1(t)$ and that user 2 starts the transmission of a short packet at $\hat{t}_3$. After propagation delay d, it collides with the long packet. The pilot training symbol can be obtained by the following process. Using the partial OFDM signals of user 1 during $[\hat{t}_2, \hat{t}_3]$ and $[\hat{t}_5, \hat{t}_6]$ ($\hat{t}_3$ is a known parameter for the BS and transmitters, and $\hat{t}_5 = \hat{t}_3 + d + T_S$ can be determined from the maximum propagation delay), BS can remove two OFDM signals (during $[\hat{t}_2, \hat{t}_6]$) of user 1. Then the preamble of user 2 (during $[\hat{t}_3 + d, \hat{t}_5]$) can be obtained. Utilizing the methods described in [24] and [25], BS can estimate channel information $h_2(t)$, implement the frequency and timing synchronization, and then obtain the timing of collision d.

5. Simulated Results of Collision Recovery

In this section, we present the simulated results of the collision recovery described in the above section. It is assumed that each user experiences independent multipath fading, and the fading model is JTC'94 (indoor residential B, delay spread=70 ns), which has been described in Table 1. The common specifications of simulations are identical to those listed in Table 1. The duration of time slots is an integer multiple of T_S, and the long packets include 250 OFDM signals which are transmitted at the beginning of time slots. User 2 delays short packet transmission by $0.5T_S$ from the beginning of time slots. The maximum transmission distance between BS and transmitters is 30 m. These conditions cause f_0T_1, $f_0T_2 = f_0(T_S - T_1)$ of Fig. 8 to be 0.625. Each user utilizes an identical duration T_S. We assume that BS implements timing and frequency synchronization and obtains $h_1(t)$ and $h_2(t)$ using Minn et al.'s preamble, the performance of which has been theoretically proved and simulated [24], [25]. Such a preamble can also be utilized to detect the occurrence of collision, as can be seen from Fig. 9(c).

5.1 Simulated Results of Two Users with Equal SNR and Identical Modulation

We give the simulated results for different N and SNR in the case where two users transmit data with BPSK in Fig. 10 and QPSK in Fig. 11, respectively. The simulated results show that, for different lengths of the short packet (without the length of preamble), the collided part can be recovered with a different successful recovery ratio (SRR) which is defined as the ratio of the times of successful recovery of collided parts of both packets to the times of all collisions. It is assumed that N is 32, 64 or 128. Due to the error floor of the demodulation, SNR has little influence on SRR when SNR varies from 30 dB to 40 dB. N=128 can yield the best performance in Fig. 10 and Fig. 11 because precise equalization can be achieved as described in Sect. 2.2.

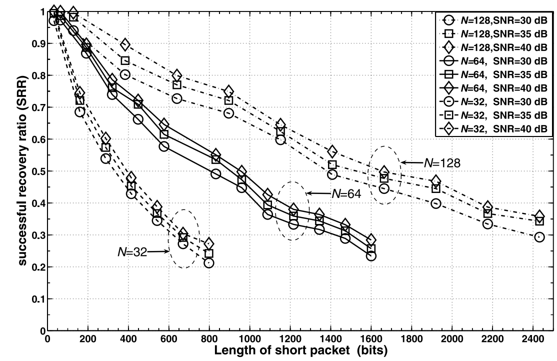


Fig. 10 Performance of collision recovery (user 1 and user 2 transmit packets with BPSK-modulated OFDM).

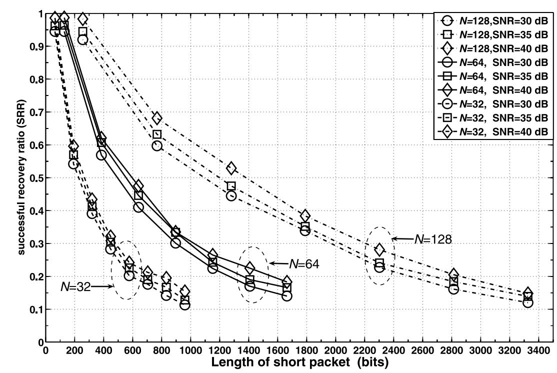


Fig. 11 Performance of collision recovery (user 1 and user 2 transmit packets with QPSK-modulated OFDM).

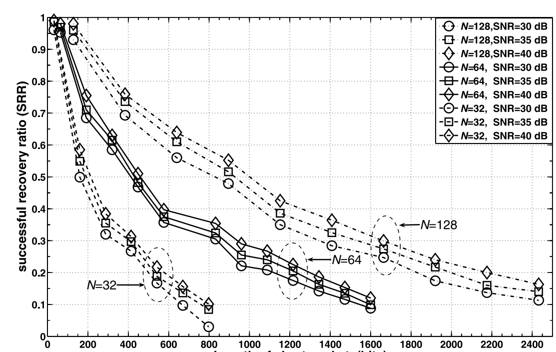


Fig. 12 Performance of collision recovery (user 1 transmits packet with QPSK-modulated OFDM, user 2 transmits short packet with BPSK-modulated OFDM).

5.2 Simulated Results of Two Users with Equal SNR and Different Modulation

It is often assumed that the long packet transmits data with QPSK to achieve a higher transmission rate, and that a short packet, such as ACK, RTS or CTS, utilizes BPSK to send control signals. Figure 12 shows the simulated results of collision recovery versus length of short packet (without the length of preamble), it indicates the similar performance of

SRR shown in Figs. 10 and 11.

5.3 Simulated Results of Two Users with Weak Near-far Effect

Figures 13 and 14 show the simulated SRR in the presence of a weak near-far effect. N is assumed to be 128 in all simulations. We chose the values of SNR for user 1 to be 30, 35, or 40 dB and SINR for user 1 to be −10, −5, 5, or 10 dB in Fig. 13, which shows the recovery performance versus length of short packet (without the length of preamble). QPSK is assumed for both users. The results indicate that SRR with (SNR, SINR) = (40 dB, 10 dB) for user 1 is approximately identical to that with (SNR, SINR) = (30 dB, −10 dB) for user 2 with increasing length of the short packet. When the packet for user 2 is extremely short, for example, one OFDM signal (without the length of preamble), the different powers of $y_r(t)(t \in [\hat{t}_6, \hat{t}_7]$ in Fig. 9(c)) for SINR=10 dB and −10 dB make SRR different.

Figure 14 shows the SRR performance versus length of short packet (without the length of preamble) of the case that user 1 transmits a long packet by QPSK-modulated OFDM and user 2 transmits a short packet by BPSK-modulated OFDM. Because of the different modulations, SINR=10 dB and −10 dB for user 1 cannot yield the equal SRR when the length of the short packet increases. However, both Figs. 13 and 14 show that better SRR can be obtained under a weaker near-far condition.

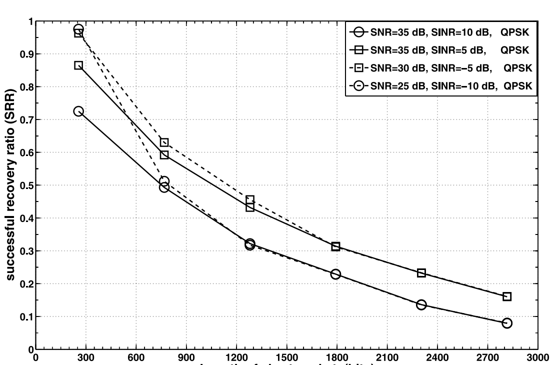


Fig. 13 Performance of collision recovery (both packets utilize QPSK-modulated OFDM; the values of SINR and SNR are those for user 1).

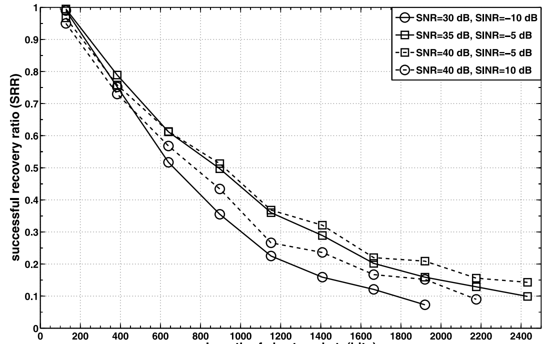


Fig. 14 Performance of collision recovery (user 1 transmits packet with QPSK-modulated OFDM but user 2 transmits a short packet with BPSK-modulated OFDM; the values of SINR and SNR are those for user 1).

6. Performance of OFDM System with Partial Signal Using 8- and 16-QAM over Multipath Channel

In the proposed method, we use the M-algorithm to reduce the complexity of MLSE when only a portion of transmitted signal is received. The M-algorithm can keep demodulation complexity (C_p) as $P^U + (N - U)MP$ for each partial OFDM signal, where P, U and M, are modulation type, depth of initial candidate path and number of survivors for each iteration, respectively.

The BER and PER performance for the system using BPSK and QPSK modulations is acceptable, but there will be large degradation of performance using the 16-QAM or 64-QAM modulation. The reason derives from the main factor: the acceptable demodulation complexity or the number of survivors for each iteration (parameter M) of the M-algorithm. Generally speaking, larger M will achieve better BER or PER performance but increase the demodulation complexity. When the system adopts 8-QAM (P=8) or 16-QAM (P=16) modulation, which increases the value of P, for the identical demodulation complexity to that of using BPSK modulation or QPSK modulation, the BER or PER performance will be dramatically degraded. Even when the M-algorithm moderately increases the value of M, the error propagation will still decrease the BER or PER performance for large N.

Figures 15 and 16 show the BER and PER performance of 8-QAM-modulated OFDM system with partial signal, respectively. The common specifications of simulations are identical to that listed in Table 1. The system chooses f_0T_1=0.625, 0.75 and N=64. For each value f_0T_1, we make M (the number of survivors for each iteration) be 16, 32 and 64, respectively, which enable to increase the BER performance of the system as can be seen from Figs. 15 and 16. However, compared with that using the BPSKor QPSK, there exists large degradation of performance. Even for the system over a Rayleigh fading channel

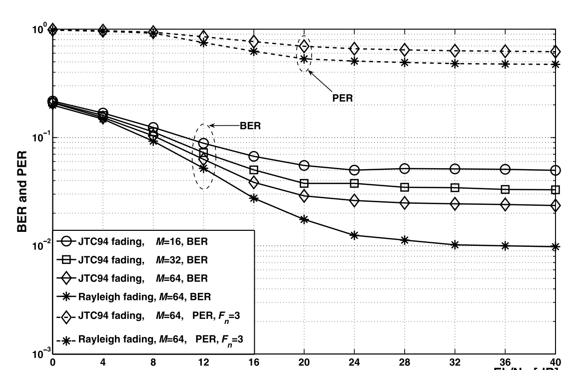


Fig. 15 BER and PER performance of 8-QAM-modulated OFDM system with partial signal, f_0T_1=0.625, U = 2, N=64.

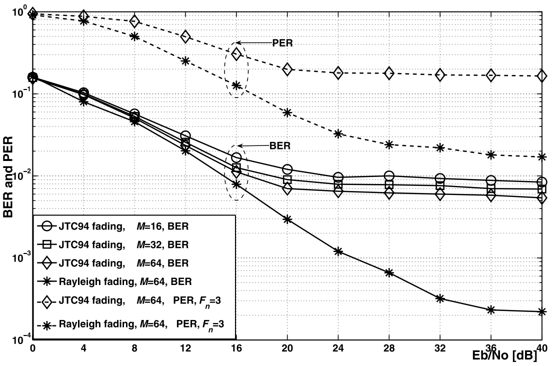


Fig. 16 BER and PER performance of 8-QAM-modulated OFDM system with partial signal, f_0T_1=0.75, U = 2, N=64.

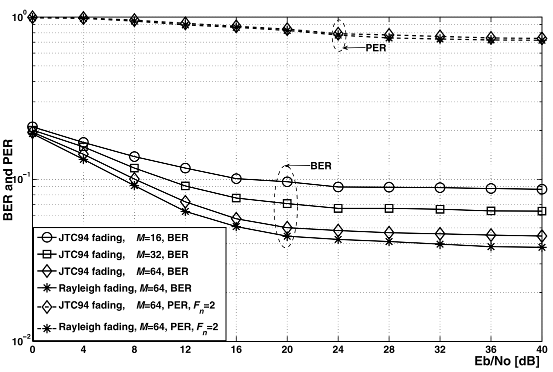


Fig. 17 BER and PER of 16-QAM-modulated OFDM system with partial signal, f_0T_1=0.75, U = 1, N=64.

(N=64), which can be regarded as the performance of the system over the multipath fading channel with N increasing to infinity, the system with f_0T_1=0.625 cannot dramatically improve the system performance by increasing N to infinity. But for f_0T_1=0.75, the BER and PER performance can be improved by increasing N and M. Therefore, the proposed method can be utilized in the syetem where the long packet is modulated by 8-QAM OFDM but the short packet adopts BPSK or QPSK OFDM (in such a case, we must choose $f_0T_1 = 0.75$ and $f_0(T_S - T_1) = 0.5$ in Fig. 8.) The simulated results in Fig. 17, which 16-QAM-modulated OFDM system chooses f_0T_1=0.75 and N=64, show that there exists large degradation of BER and PER performance. Therefore, it seems that the proposed method cannot be utilized for the QAM-modulated OFDM system using M-algorithm when the number of constellation $P \geq 16$. It is also a challenging topic in our future research.

7. Conclusions

We have presented an effective method of collision recovery for OFDM-based communications. Because the modulated message data can be demodulated using the partial OFDM signal, the partial signal can be employed to reconstruct the whole OFDM signal using estimated channel information. We utilized this advantageous property to recover the collided parts of two OFDM packets. Since most collisions involve a long packet colliding with short packets, the collided parts are short and can be recovered by our method.

Generally speaking, the performance of recovery depends on many factors such as the conditions of channel fading, number of subcarriers, modulation and more importantly, f_0T_1. A larger number of subcarriers can lead to better recovery performance, as was revealed in all simulations. Therefore, the performance of our method can be improved by using a WiMAX (802.16a) system that can support a maximum of 2048 subcarriers [26].

It should be pointed out that almost all limitations of this proposed method are a result from demodulation. In this study, we chose the M-algorithm for demodulation because it is simple and has low complexity. However the performance of demodulation also limits the selections of many factors such as f_0T_1. For example, if the demodulation can recover all OFDM message data with a smaller T_1, it can recover the collision generated by more than two packets by a similar method. Thus we will further improve the performance of this method in the future. Performance improvement of our method using the ECC and diversity reception is also very important as a future research.

References

[1] T.S. Rappaport, A. Annamalai, R.M. Buehrer, and W.H. Tranter, "Wireless communications: Past events and a future perspective," IEEE Commun. Mag., vol.40, no.5, pp.148–161, May 2002.

[2] R. Ramanathan and J. Redi, "A brief overview of ad hoc networks: Challenges and directions," IEEE Commun. Mag., vol.30, no.5, pp.–, May 2002.

[3] S. Lin and D.J. Costello, Jr., Error Control Coding: Fundamentals and Applications, second ed., Prentice Hall, Englewood Cliffs, NJ, 2005.

[4] Y. Li, J.C. Chuang, and N.R. Sollenberger, "Transmitter diversity for OFDM systems and its impact on high-rate data wireless networks," IEEE J. Sel. Areas Commun., vol.17, no.7, pp.1233–1243, July 1999.

[5] A. Woo, K. Whitehouse, F. Jiang, J. Polastre, and D. Culler, "Exploiting the capture effect for collision detection and recovery," Proc. IEEE EmNetS-II, pp.45–52, Sydney, Australia, May 2005.

[6] S. Ghez, S. Verdu, and S. Schwartz, "Optimal decentralized control in the multipacket channel," IEEE Trans. Autom. Control, vol.34, no.11, pp.1153–1163, Nov. 1989.

[7] W. Luo and A. Ephremides, "Power levels and packet lengths in random multiple access with multi-packet reception capability," IEEE Trans. Inf. Theory, vol.52, no.2, pp.46–58, Feb. 2006.

[8] S. Verdu, Multi-user Detection, Cambridge University Press, 1998.

[9] G. Bianchi, "Performance analysis of the IEEE. 802.11 distributed coordination function," IEEE J. Sel. Areas Commun., vol.18, no.3, pp.535–547, March 2000.

[10] L. Tong, Q. Zhao, and G. Mergen, "Multipacket reception in random access wireless networks: From signal processing to optimal medium access control," IEEE Commun. Mag., vol.39, no.11, pp.108–112, Nov. 2001.

[11] Q. Zhao and L. Tong, "A multi-queue service room MAC protocol for wireless networks with multipacket reception," IEEE/ACM Trans. Netw., vol.11, no.1, pp.125–137, Feb. 2003.

[12] V. Naware, G. Mergen, and L. Tong, "Stability and delay of finite user slotted ALOHA with multipacket reception," IEEE Trans. Inf. Theory, vol.51, no.7, pp.2636–2656, July 2005.

[13] J.G. Andrews, "Interference cancellation for cellular systems: A

contemporary overview," IEEE Wireless Commun., vol.12, no.2, pp.19–29, April 2005.
[14] M. Hamamura and S. Tachikawa, "Bandwidth efficiency improvement for multi-carrier systems," Proc. IEEE PIMRC2004, pp.48–52, Barcelona, Spain, Sept. 2004.
[15] M. Hamamura and S. Tachikawa, "On high compaction FDM comunication systems," IEICE Technical Report, WBS2003-45, July 2003.
[16] Y. Hou and M. Hamamura, "Bandwidth efficiency of PC-OFDM systems with high compaction multi-carrier modulation," Proc. IEEE WCNM2005, pp.177–180, Wuhan, China, Sept. 2005.
[17] S. Takahashi, M. Hamamura, and S. Tachikawa, "A demodulation complexity reduction method using M-algorithm for high compaction multi-carrier modulation systems," Proc. IEEE ISWCS2004, pp.336–341, Mauritius, Sept. 2004.
[18] B. Muquet, Z. Wang, G.B. Giannakis, M. de Courville, and P. Duhamel, "Cyclic prefixing or zero padding for wireless multicarrier transmissions?," IEEE Trans. Commun., vol.50, no.12, pp.2136–2148, Dec. 2002.
[19] K. Halford and M. Webster, "Multipath Measurement in Wireless Lan," Intersil Application Note AN9895, Oct. 2001.
[20] L. Hanzo, M. Munster, B.J. Choi, and T. Keller, OFDM and MC-CDMA for Broadband Multi-user Communications, WLANs and Broadcasting, John Wiley, IEEE Press, Sept. 2003.
[21] T.M. Schmidl and D.C. Cox, "Robust frequency and timing synchronization for OFDM," IEEE Trans. Commun., vol.45, no.12, pp.1613–1621, Dec. 1997.
[22] H. Stefan and M. Weinfurtner, "Comparison of preamble structures for burst frequency synchronization," Proc. IEEE Globecom2000, pp.1488–1493, San Francisco, CA, Nov. 2000.
[23] H. Stefan and M. Weinfurtner, "Burst frame and frequency synchronization with a Sandwich preamble," Proc. IEEE Globecom2001, pp.1366–1370, San Antonio, Texas, Nov. 2001.
[24] H. Minn, V.K. Bhargava, and K.B. Letaief, "A robust timing and frequency synchronization for OFDM systems," IEEE Trans. Wirel. Commun., vol.2, no.4, pp.822–839, July 2003.
[25] H. Minn, V.K. Bhargava, and K.B. Letaief, "A combined timing and frequency synchronization and channel estimation for OFDM," IEEE Trans. Commun., vol.54, no.3, pp.416–422, March 2006.
[26] A. Ghosh, J.G. Andrews, R. Chen, and D.R. Wolter, "Broadband wireless access with WiMax/802.16: Current performance benchmarks and future potential," IEEE Commun. Mag., vol.43, no.2, pp.129–136, Feb. 2005.

Yafei Hou received his B.S. degree in Electronic Engineering from Anhui University of Technology and Science, China, in 1999 and M.S. degree in Computer Science from Wuhan University, China, in 2002. During 2002–2004, as a Ph.D. candidate he was at Department of Computing and Information Technology, Fudan University, China. He is now a Ph.D. candidate at Kochi University of Technology (KUT), Japan, as an international student of cooperation between KUT and Fudan University. His main areas of interest are communication systems, wireless networks, ad-hoc networks and signal processing.

Masanori Hamamura received his B.S., M.S. and Ph.D. degrees in electrical engineering from Nagaoka University of Technology, Nagaoka, Japan, in 1993, 1995 and 1998, respectively. From 1998 to 2000, he was a Research Fellow of the Japan Society for the Promotion of Science. Since 2000, he has been with the Department of Information Systems Engineering at Kochi University of Technology, Kochi, Japan, where he is now an Associate Professor. From 1998 to 1999, he was a visiting researcher at Centre for Telecommunications Research, King's College, London, United Kingdom, where he worked on adaptive signal processing for mobile systems. His current research interests are in the areas of spread spectrum systems, mobile communications and signal processing. Dr. Hamamura is a member of IEEE.