2016 International Symposium on Nonlinear Theory and Its Applications,
NOLTA2016, Yugawara, Japan, November 27th-30th, 2016

Packet Splitting and Adaptive Modulation Based on Time Domain CSI for Cooperative OFDM Systems

Yuta Ida†, Takahiro Matsumoto, and Shinya Matsufuji

Graduate School of Sciences and Technology for Innovation, Yamaguchi University
2–16–1 Tokiwadai, Ube-shi, Yamaguchi, 755-8611 Japan
Email: y.ida@yamaguchi-u.ac.jp†

Abstract—Cooperative communications obtain the transmission and channel diversity gains by using the relay node. However, since the redundancy signal is transmitted to obtain the transmission diversity gain, the transmission rate is degraded. Moreover, since cooperative communications include the interference in the relay node, the gain is degraded. The packet splitting has been proposed based on the channel state information (CSI) of the time domain to obtain the good system performance. In this paper, we propose the combination method with the packet splitting and the adaptive modulation based on the CSI of the time domain to improve the bit error rate (BER) and throughput performances for cooperative orthogonal frequency division multiplexing (OFDM) systems.

1. Introduction

The diversity gain technique is very important to improve the system performance and has been proposed in many fields [1], [2]. In multiple-input multiple-output (MIMO) systems, the transmission and channel diversity gains are obtained by using several transmitted antennas [1]. Similarly, cooperative communications obtain also these diversity gains by using the relay node since there are three links between the source and relay (SR), source and destination (SD), and relay and destination (RD) nodes [2]. On the other hand, cooperative communications degrade the system performance compared with MIMO systems since they include the interference in the relay node. Therefore, in cooperative communications, the relay method is important. In [2], the relay method has been proposed and this paper adapts the decode-and-forward (DF) which is detected the received signal in the relay node and is transmitted to the destination node.

To obtain the transmission diversity gain, the conventional cooperative communications transmit the same signal to the SD and SR links. On the other hand, since this operation degrades the transmission rate, the packet splitting has been proposed [3]-[5]. The packet splitting divides a packet based on the channel state information (CSI) and obtains the good channel diversity gain and prevents a burst error. [4] and [5] have proposed the packet splitting for cooperative communications, but [5] requires many feedback information (FBI) since it needs the CSI for each subcarrier channel. To overcome this problem, [4] have proposed the simple the packet splitting for cooperative communications which divides a packet based on the CSI of the time domain. Since the CSI of the time domain becomes a constant in the case of a small Doppler frequency, the number of FBI becomes only one. Moreover, the adaptive modulation has been proposed to improve the transmission rate and to keep the BER performance [5], [6]. The adaptive modulation changes the modulation level based on the CSI. However, [5] and [6] require also the CSI of each subcarrier channel and many FBI. Therefore, in this paper, we propose the combination method with the packet splitting and the adaptive modulation based on the CSI of the time domain for cooperative orthogonal frequency division multiplexing (OFDM) systems. This paper explains the cooperative OFDM systems in Section II. Then, the proposed packet splitting and adaptive modulation presented, and the computer simulation results are shown in Section III and IV. Finally, the conclusion is given in Section V.

2. Cooperative OFDM Systems

2.1. Channel Model

In the L discrete paths propagation channel with the different delay time, we assume the channel impulse response for the kth node as

$$h_k(\tau) = \sum_{l=0}^{L-1} h_{k,l}\delta(\tau - \tau_{k,l}), \tag{1}$$

where $h_{k,l}$ is the complex channel gain which satisfies $\sum_{l=0}^{L-1} E|h_{k,l}^2| = 1$, $E|\cdot|$ is the ensemble average operation, and $\tau_{k,l}$ is the delay time. After the fast Fourier transform (FFT) operation, the channel response is obtained as

$$\begin{aligned} H_k(f) &= \int_0^{\infty} h_k(\tau)\exp(-j2\pi f\tau)d\tau \\ &= \sum_{l=0}^{L-1} h_{k,l}\exp(-j2\pi f\tau_{k,l}). \end{aligned} \tag{2}$$

2.2. Cooperative OFDM Systems

Figure. 1(a) shows the structure of the source node. The binary data signal is generated, and the channel coding with

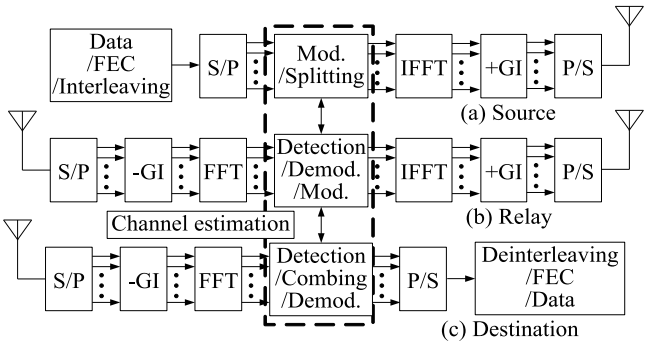

Figure 1: The block diagram of the proposed system.

the interleaving is performed. After the serial-to-parallel (S/P) conversion, the coded signal is modulated by the adaptive modulation which will be explain in Section 3. The time domain transmitted signal matrix is given by using the inverse FFT (IFFT) operation as

$$\mathbf{x}_k = \sum_{i=0}^{N_k-1} \sqrt{\frac{2S}{N_c}} \mathbf{X}_i \mathbf{w}^{-1}, k = \begin{cases} 0 & \text{for } SD \\ 1, 2, \cdots, K & \text{for } SR, \end{cases} \quad (3)$$

where S is the average transmission power, N_c is the number of subcarriers, $\mathbf{X}_i$ is the frequency transmitted signal matrix for the ith symbol after the adaptive modulation, $\mathbf{w}$ is the FFT matrix, $(\cdot)^{-1}$ is the inverse operation, and K is the number of relay nodes. N_k is the number of symbols after the packet splitting which will also be explain in Section 3. After the guard interval (GI) insertion and the parallel-to-serial (P/S) conversion, the time domain signal $\mathbf{x}_k$ is transmitted to the relay and destination nodes.

Fig. 1(b) shows the structure of the relay node. The time domain received signal matrix for the kth relay node is given by

$$\mathbf{y}_k = \mathbf{h}_k \mathbf{x}_k + \mathbf{z}_k, \quad (4)$$

where $\mathbf{h}_k$ is the matrix form of the channel impulse response $h_k(\tau)$ and $\mathbf{z}_k$ is the additive white Gaussian noise (AWGN) matrix for a single sided power spectral density of $\mathcal{N}_0$. After the S/P conversion and the GI elimination, the frequency domain received signal matrix is given by the FFT operation as

$$\mathbf{Y}_{k,i} = \sqrt{\frac{2S}{N_c}} \mathbf{y}_k \mathbf{w} = \sqrt{\frac{2S}{N_c}} \mathbf{H}_{k,i} \mathbf{X}_{k,i} + \mathbf{Z}_{k,i}, \quad (5)$$

where $\mathbf{H}_{k,i}$ is the matrix form of the channel response $H_k(f)$, $\mathbf{Z}_{k,i}$ is the AWGN matrix for zero-mean and variance of $2\mathcal{N}_0/T_s$, and T_s is the effective symbol length. In this paper, since the relay method adapts the decode-and-forward (DF), the frequency domain received signal matrix $\mathbf{Y}_{k,i}$ is equalized by using the zero-forcing (ZF) as

$$\tilde{\mathbf{X}}_{k,i} = \mathbf{H}_{k,i}^{-1} \mathbf{Y}_{k,i}. \quad (6)$$

The equalized signal matrix $\tilde{\mathbf{X}}_{k,i}$ is converted to the time domain signal matrix $\tilde{\mathbf{x}}_k$ as shown in Eq. (3) and is transmitted to the destination node.

Fig. 1(c) shows the structure of the destination node and its time domain received signal matrix is given by

$$\mathbf{y} = \mathbf{h}_0 \mathbf{x}_0 + \sum_{k=1}^{K} \mathbf{h}_k \tilde{\mathbf{x}}_k + \mathbf{z} = \sum_{k=0}^{K} \mathbf{h}_k \mathbf{x}_k + \tilde{\mathbf{z}}, \quad (7)$$

where $\tilde{\mathbf{z}}$ and $\mathbf{z}$ are the AWGN matrices with and without the detection error of the relay node, respectively. The time domain received signal $\mathbf{y}$ is processed as shown in Eqs. (5) and (6) as

$$\begin{aligned} \mathbf{Y}_i &= \sqrt{\frac{2S}{N_c}} \mathbf{y}\mathbf{w} = \sqrt{\frac{2S}{N_c}} \sum_{k=0}^{K} \mathbf{H}_{k,i} \mathbf{X}_{k,i} + \tilde{\mathbf{Z}}_i \\ &= \sqrt{\frac{2S}{N_c}} \mathbf{H}_i \mathbf{X}_i + \tilde{\mathbf{Z}}_i \end{aligned} \quad (8)$$

and

$$\hat{\mathbf{X}}_i = \mathbf{H}_i^{-1} \mathbf{Y}_i, \quad (9)$$

where $\tilde{\mathbf{Z}}_i$ is the AWGN matrix. After the demodulation and the P/S conversion, the detected signal $\hat{\mathbf{X}}_i$ is returned to the binary data signal.

3. Proposed Packet Splitting and Adaptive Modulation

3.1. Packet Splitting

For the case of a small Doppler frequency, the power for the CSI of time domain becomes a constant. By using this characteristic, we define its power for SD, SR, and RD links as λ_{SD}, $\lambda_{k,SR}$, and $\lambda_{k,RD}$. Firstly, the proposed method combines $\lambda_{k,SR}$ and $\lambda_{k,RD}$ to consider simply as

$$\lambda_k = (1-\alpha)\lambda_{k,SR} + \alpha\lambda_{k,RD}, \quad (10)$$

where α is the weight between SR and RD links. Next, the proposed method decides the number of symbols N_k for Eq. (3). The proposed method gives the number of symbols for SD link as

$$N_0 = \sum_{e=1}^{K} N \left\lfloor \frac{\omega\lambda_{SD}}{\lambda_{SD} + \lambda_e} \right\rfloor, \quad (11)$$

where N is the total number of symbols as $\sum_{k=0}^{K} N_k$ and ω is the weight between SD and SR to RD links, and $\lfloor\zeta\rfloor$ stands for the integer lower and closer to ζ. Moreover, the number of symbols for kth SR and RD links is given by

$$N_k = \sum_{e2=0}^{K2} \sum_{e1=1}^{K} (N - N_{e2}) \left\lfloor \frac{\lambda_k}{\lambda_{e1}} \right\rfloor, \quad (12)$$

where $K2$ is the number of decided symbols.

3.2. Adaptive Modulation

In this paper, the adaptive modulation for the proposed method consists of a quadrature phase shit keying (QPSK),

a 8 phase shit keying (8PSK), and a 16 quadrature amplitude modulation (16QAM). Moreover, since it is achieved by using the same CSI for the packet splitting, the additional FBI is not required. For the SD link, the proposed method decides the modulation level of the frequency transmitted signal matrix $\mathbf{X}_i$ for Eq. (3) as

$$\mathbf{X}_i = \begin{cases} \mathbf{X}_{i,4bit} & \text{for } Th_1 \geq \lambda_{SD} \\ \mathbf{X}_{i,3bit} & \text{for } Th_2 \leq \lambda_{SD} < Th_1 \\ \mathbf{X}_{i,2bit} & \text{otherwise,} \end{cases} \tag{13}$$

where Th_1 and Th_2 are the thresholds between a 16QAM and a 8PSK, a 8PSK and a QPSK, respectively, and $\mathbf{X}_{i,4bit}$, $\mathbf{X}_{i,3bit}$, and $\mathbf{X}_{i,2bit}$ are the modulated signal matrices for a 16QAM, a 8PSK, and a QPSK, respectively. Similarly, the adaptive modulated signal matrix for the SR link is also given by

$$\mathbf{X}_i = \begin{cases} \mathbf{X}_{i,4bit} & \text{for } Th_1 \geq \lambda_k \\ \mathbf{X}_{i,3bit} & \text{for } Th_2 \leq \lambda_k < Th_1 \\ \mathbf{X}_{i,2bit} & \text{otherwise.} \end{cases} \tag{14}$$

4. Computer Simulation Results

In this section, we evaluate the system performance of the proposed method by using the computer simulation. In this simulation, the system model and the parameter are shown in Figure 1 and Table 1. In the source node, the original bit data is generated and is coded by the convolutional code (rate $R = 1/2$ and constrain length $\mathcal{K} = 7$) with the interleaving. After the S/P conversion, the parallel signal is modulated. The proposed method adapts the adaptive modulation which consists of a QPSK, a 8PSK, and a 16QAM based on Eqs. (13) and (14). The modulated signal converts the time domain signal by the IFFT operation, and its signal inserts the GI and converts the P/S mode. Here, the proposed method adapts also the packet splitting based on Eqs. (11) and (12). From [4], we define the weights α and ω as $(\alpha, \omega) = (0.3, 1)$. The time domain signal after the packet splitting is transmitted to the two relay and one destination nodes via a propagation channel with a 7 paths Rayleigh fading. In the relay node, the received signal is transmitted to the destination node by the DF whose equalization is the ZF. In the destination node, the received signal converts the S/P mode and eliminates the GI. The time domain received signal which combines the divided signal for the packet splitting is converted to the frequency domain signal by the FFT operation and is detected by the ZF. The detected signal is demodulated based on the adaptive modulation and converts the P/S mode. After the deinterleaving, its signal is decoded by the Viterbi decoding algorithm and the bit signal is output.

The throughput is defined as

$$T_{tp} = \frac{N_c CR}{T}(1 - P_{per}), \tag{15}$$

where C is the modulation level, T is the symbol duration, and P_{per} is the packet error rate (PER). From Eq. (15) and Tab. 1, the maximum throughput for a QPSK, a 8PSK, and a 16QAM is 16, 24, 32 Mbps, respectively. Tab. 2 shows the relation of the throughput between Th_1 dB and Th_2 dB in $E_b/N_0 = 25$ dB. The value of Tab. 2 is derived by using the computer simulation. This means that the value of the throughput is changed by selecting the different threshold. This paper adapts the threshold as $(Th_1, Th_2) = (0, -5)$ and $(30, 0)$. $(Th_1, Th_2) = (30, 0)$ means the middle value of the maximum throughput between a QPSK and a 8PSK, and $(Th_1, Th_2) = (0, -5)$ means also the middle value of the maximum throughput between a 8PSK and a 16QAM.

Fig. 2 shows the throughput versus E_b/N_0 for the packet splitting and the proposed method. The QPSK, 8PSK, and 16QAM with the packet splitting show the good throughput performance in $E_b/N_0 < 14$, $14 \leq E_b/N_0 < 17$, and $E_b/N_0 \geq 17$, respectively. The proposed method for $(Th_1, Th_2) = (30, 0)$ and $(0, -5)$ shows the middle throughput performance between the QPSK and the 8PSK, the 8PSK and the 16QAM, respectively. This is because the proposed method selects the middle value of the throughput from Tab. 2. For the maximum throughput, the proposed

Table 1: Simulation parameters.

Data modulation	QPSK, 8PSK, 16QAM
Data detection	ZF
Symbol duration	$4\,\mu s$
Nuber of data symbols	80
Number of subcarriers	64
Number of relay nodes	2
FFT size	64
Guard interval	16 sample times
Path model	7 paths Rayleigh fading
Channel estimation	Perfect
FEC	Convolutional code ($R = 1/2, \mathcal{K} = 7$)
Weight	$(\alpha, \omega) = (0.3, 1)$

Table 2: The relation of the throughput between Th_1 dB and Th_2 dB in $E_b/N_0 = 25$ dB.

$Th_1 \backslash Th_2$	-10	-5	0	5
-10	31.81	–	–	–
-5	31.44	31.05	–	–
0	28.60	28.19	25.28	–
5	24.10	23.72	20.78	16.33
10	23.87	23.49	20.66	16.15
15	23.86	23.48	20.64	16.14
20	23.86	23.48	20.63	16.13
25	23.86	23.48	20.62	16.13
30	23.86	23.48	20.62	16.13

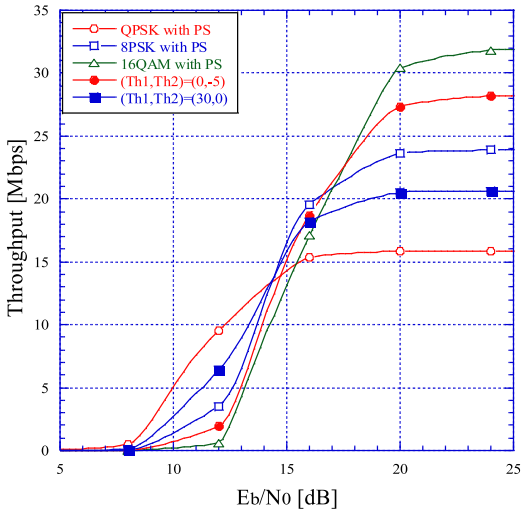

Figure 2: The throughput versus E_b/N_0 for the packet splitting and the proposed method.

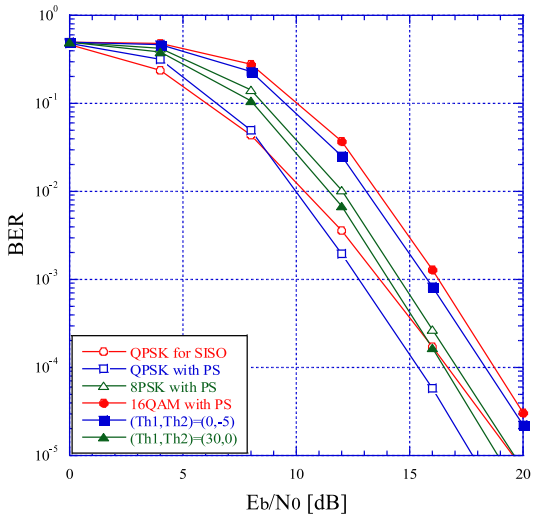

Figure 3: The BER versus E_b/N_0 for the QPSK (SISO), the packet splitting, and the proposed method.

method for $(Th_1, Th_2) = (30, 0)$ and $(0, -5)$ improves about 25 % compared with the QPSK and the 8PSK, respectively.

Fig. 3 shows the BER versus E_b/N_0 for the QPSK (SISO), the packet splitting, and the proposed method. The BER of the QPSK with the packet splitting shows about 2 dB gain compared with the QPSK for SISO since the packet splitting obtains the good channel diversity gain and prevents a burst error. The BER of the proposed method for $(Th_1, Th_2) = (30, 0)$ shows about 1 dB gain compared with the QPSK for SISO and the 8PSK with the packet splitting. This is because the proposed method for $(Th_1, Th_2) = (30, 0)$ has the effect of the QPSK with the packet splitting strongly. Similarly, the BER of the proposed method for $(Th_1, Th_2) = (0, -5)$ shows also about 1 dB gain compared with the 16QAM with the packet splitting since it has the effect of the 8PSK with the packet splitting strongly.

5. Conclusion

In this paper, we have proposed the combination method with the packet splitting and the adaptive modulation based on the CSI of the time domain for cooperative OFDM systems. The proposed method achieves the packet splitting to improve the BER performance and the adaptive modulation to improve the transmission rate based on the same CSI. From the computer simulation results, the proposed method has shown the good BER and throughput performances by adjusting the threshold Th_1 and Th_2.

Acknowledgments

This work was supported by the Mazda Foundation.

References

[1] A. Zelst, R. Nee, and G.A. Awater, "Space division multiplexing (SDM) for OFDM systems," *Proc. of VTC2000-Spring*, pp. 1070-1074, May 2000.

[2] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Trans. on Info. Theory*, vol. 50, no. 12, pp. 3062-3080, Dec. 2004.

[3] S. Sun, T. Hunziker, J. Cheng, M. Taromaru, and T. Ohira, "Optimal frame splitting for downlink MIMO channels with distributed antenna arrays," *IEEE Trans. on Vehi. Tech.*, vol. 57, no. 6, pp. 3848-3854, Nov. 2008.

[4] Y. Ida, C. Ahn, T. Kamio, H. Fujisaka, and K. Haeiwa, "Variable packet splitting transmission in multi-relay cooperative communications with DF and DAF for SC-FDMA," *EURASIP J. on Wirel. Commun. and Net.*, vol. 2013, no. 64, pp. 1-8, Mar. 2013.

[5] Y. Ida, E. Nishikuma, C. Ahn, T. Matsumoto, and S. Matsufuji, "Achievement of packet splitting and adaptive modulation based on same feedback information for DF cooprative communications," *IEICE Tech. Rep.*, CS2014-108, pp. 91-94, Feb. 2015.

[6] M. Kitakata, C. Ahn, T. Omori, and K. Hashimoto, "Throughput performance enhancement applying adaptive modulation for single symbol decodable QO-STBC with full diversity," *Proc. of APCC2013*, pp. 58-62, Aug. 2013.