Throughput Maximization by Adaptive Switching with Modulation Coding Scheme and Frequency Symbol Spreading

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***Abstract*—This paper proposes a novel adaptive control method that maximizes throughput by optimally switching adaptive modulation and coding (AMC) and frequency symbol spreading (FSS). AMC has been extensively studied and is widely adopted as a method for optimizing throughput in fluctuating channels caused by shadowing, multipath fading and mobility. By applying AMC, communication performance can be effectively improved for varying channels. Forward error correction (FEC) is also used as communication quality improvement method. FEC is effective to improve throughput performance especially in a low SNR region. However, it has sacrificed the maximum throughput in the case of the good channel situation. FSS has been proposed as a method for suppressing the influence of frequency selective fading without degrading the maximum throughput by dispersing subcarrier symbol to all frequency components. FSS can obtain large frequency diversity gain by its diffusibility. From the simulation results, we confirm the effectiveness of the proposed method from the viewpoint of maximizing throughput.**

***Index Terms*—Adaptive modulation and coding, Frequency symbol spreading.**

I. Introduction

DUE to the spread of smart phones and tablets in the general tier and technological innovation such as IoT, the use of the Internet is increasing, and the demand for data communication is steadily increasing [1][2]. In wireless communication systems, the channel fluctuates under the influence of shadowing, multipath fading and mobility. The main factor that degrades communication performance is this channel fluctuation [3][4]. Furthermore, due to such fluctuation, wireless channel capacity cannot be utilized at the maximum efficiency and transmission efficiency deteriorates significantly. To solve this problem, adaptive modulation and coding (AMC) scheme attract a lot of attention since it can achieve maximum transmission efficiency [5]–[8]. In AMC, parameters such as the modulation scheme and the coding rate are adaptively determined depending on the channel conditions [9]–[11]. The merit of AMC is to track channel fluctuations and maximize throughput performance under the given link conditions. Thanks to adaptively controlling modulation level and coding rates, it can be confirmed that AMC is a very effective technique for improving throughput [12]–[14]. Meanwhile, it has a trade-off relationship between the spectral efficiency and bit error rate (BER) depending on influence of channel fluctuation. Setting higher modulation order increases information bits to be transmitted raising spectral efficiency but it may occur frequent communication error. Forward error correction (FEC) can compensate such error bits by using additional redundant bits. An error correction capability can be controlled via its redundancy, i.e. coding rate. In this case, the maximum throughput deteriorates in inverse proportion to the coding rate. AMC has features that compensate for these drawbacks and adapt to spectral efficiency according to channel condition. In the case of a poor channel situation, we select a low modulation level and a low coding rate to suppress deterioration of communication performance. Conversely, when the channel state is good, a high modulation level and a high coding rate are chosen to maximize the throughput performance. Orthogonal frequency devision multiplexing (OFDM) using FEC should allow slight reduction of potentially achievable throughput even at highest coding rate in an excellent channel condition. In order to address the above issue and acquire better communication performance, frequency symbol spreading (FSS) has been proposed for OFDM systems. FSS is a method creatively inspired by a multicarrier code division multiple access (MC-CDMA). The major difference of FSS with MC-CDMA is that modulated symbols are diffused to all frequency band (i.e. all subcarriers) via orthogonal spreading codes and are then superimposed [15][16]. FSS can reduce the influence of frequency selective fading by obtaining the frequency diversity. This feature of FSS brings improved BER performance even without FEC and thus it can achieve maximized throughput by the transmission with less redundancy. In addition, FSS has also feature that the power density of the detection signal becomes equal for each subcarrier. Therefore, FSS unnecessitates sophisticated AMC per subcarrier and hence it can significantly reduce the amount of feedback information (FBI) which includes signal-to-noise power ratio (SNR) information or channel state information (CSI) to implement AMC [17]–[21]. It is also possible to reduce the influence of feedback delay contributing to improving the communication performance. Because of the above characteristics, there is high

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communicational affinity between FSS and AMC.

Focusing on the high affinity of FSS and AMC, this paper proposes the adaptive control method that maximizes throughput by optimally switching AMC and FSS [22]. Since FEC acquires the error correction capability with redundant bits, the maximum spectrum efficiency will be limited as this error correction capability becomes larger. In other words, when FEC is used, a trade-off relationship arises between error correction capability and throughput. Furthermore, FBI as overhead becomes enormous since the precise adaption control needs detailed FBI, e.g. optimizing per subcarrier. Therefore, by applying FSS, it is possible to resolve these problems and to achieve a higher throughput without redundancy. Of course, the method using FEC is very effective especially in a low SNR region. Thus, proposed system contains the hybrid transmission scheme so as to switch from conventional AMC to the system using FSS. In the conventional method, such a transmission structure is not switched, and the modulation scheme and coding rate are controlled [23]–[27]. Compared with the conventional method, the proposed method can acquire better throughput in any link conditions. In addition, the transmission with less redundancy can realize an efficient communication such as the reducing the influence of feedback delay and complexity. This paper expands its contribution originated in our conference paper [22] by introducing various levels of modulation orders up to 256QAM. Effectiveness of the proposal also validated in more stringent mobility condition.

The rest of this paper is organized as follows. System model based on FSS-OFDM is defined in Sections II. Section III describes the switching principle of AMC and FSS scheme in our proposal. Computer simulation results and discussions are presented in Section IV and V, respectively. Finally, conclusion is drawn in Section VI.

II. System Model based on FSS

Incorporating AMC scheme into FSS can realize more optimized throughput performance in given SNR. Here describes a system model of interest using FSS-OFDM.

A. Frequency Symbol Spreading (FSS)

Fig. 1 shows a concept of FSS. OFDM modulated signal at the m-th subcarrier ($m = 1, \ldots, N_c$) and the i-th symbol index ($i = 1, \ldots, 2N_p + N_d$), $d(m,i)$, is spread to N_{SF} subcarriers via the orthogonal spreading code. Here, N_c, N_d and N_p indicate the number of subcarriers, data symbols and pilot symbols, respectively. Energy of each symbol is divided by N_c/N_{SF} blocks. Each spread symbol experiences all channel components and thus the frequency diversity gain can be obtained after despreading at the receiver. It virtually equalizes channel gains of all subcarriers within a FSS block. The number of required FBI can be reduced to the same amount of FSS blocks, i.e. $N_c/N_{FS} < N_c$. As shown in Fig. 1(a), the transmission signal of conventional OFDM is affected by frequency selective fading. Therefore, the probability that the signals are correctly detected becomes lower as the influence of the fading becomes stronger. In this case, the information of each symbol need to perform AMC. On the other hand, in the case of using FSS, Fig. 1(b) shows that the power density of each subcarrier is equalized among FSS block. This means that all despread data symbols have the same SNR despite being affected by frequency selective fading. Thus, it is possible to control AMC with the same SNR information. For this reason, the system using FSS can drastically reduce FBI.

B. Transmitter Structure

The transmission time-domain signal by applying FSS is expressed as

$$\begin{aligned} s(t) = & \sum_{i=0}^{N_d+N_p-1} \sqrt{\frac{2P}{N_c}} \cdot l(t-iT) \\ & \cdot \left[\sum_{m=0}^{N_c-1} v(m,i) \cdot \exp\{-j2\pi m(t-iT)/T_s\} \right], \end{aligned} \tag{1}$$

$v(m,i)$ denotes the spread symbol of the m-th subcarrier and the i-th symbol index. N_c denotes the number of DFT points. P denotes the average transmission power. T is the symbol length of OFDM , and T_s is the effective OFDM symbol length excluding guard interval (GI). Here, assuming that GI length is T_g, $T = T_s + T_g$ is satisfied. The subcarrier spacing orthogonalized on the frequency axis is $1/T_s$. $l(t)$ indicates the pulse of transmission represented by

$$l(t) = \begin{cases} 1 & -T_g \leq t \leq T_s \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

Frequency spread symbols in frequency-domain, $v(m.i)$ can be expressed by using original OFDM modulated symbols $d(m,i)$ satisfying $E\left[|d(m,i)|\right] = 1$, as

$$\begin{aligned} v(m,i) = & \sum_{k=0}^{N_{SF}-1} c_k(m \bmod N_{SF}) \\ & \cdot d(\{m/N_{SF}\}N_{SF} + k, i), \end{aligned} \tag{3}$$

where N_{SF} denotes the FSS blocks number, $c_k(n)$ indicates the Hadamard code for applying FSS.

C. Receiver Structure

GI of the received signal is eliminated, and S/P conversion is performed. The time domain received signals experienced multipath fading channel can be expressed as,

$$r(t) = \int_{-\infty}^{\infty} h(\tau,t) s(t-\tau) d\tau + n(t), \tag{4}$$

where $h(\tau,t) = \sum_{j=0}^{J-1} \acute{h}_j(\tau_j)\delta(t-\tau_j)$ represents the channel impulse response composed of J taps. $\acute{h}_j$ denotes the complex gain which fluctuates based on Jakes' model. τ_j and δ indicate the discrete number of time delay of the propagation path and the Dirac's delta function respectively. $n(t)$ is the additive white Gaussian noise (AWGN) which has power spectral

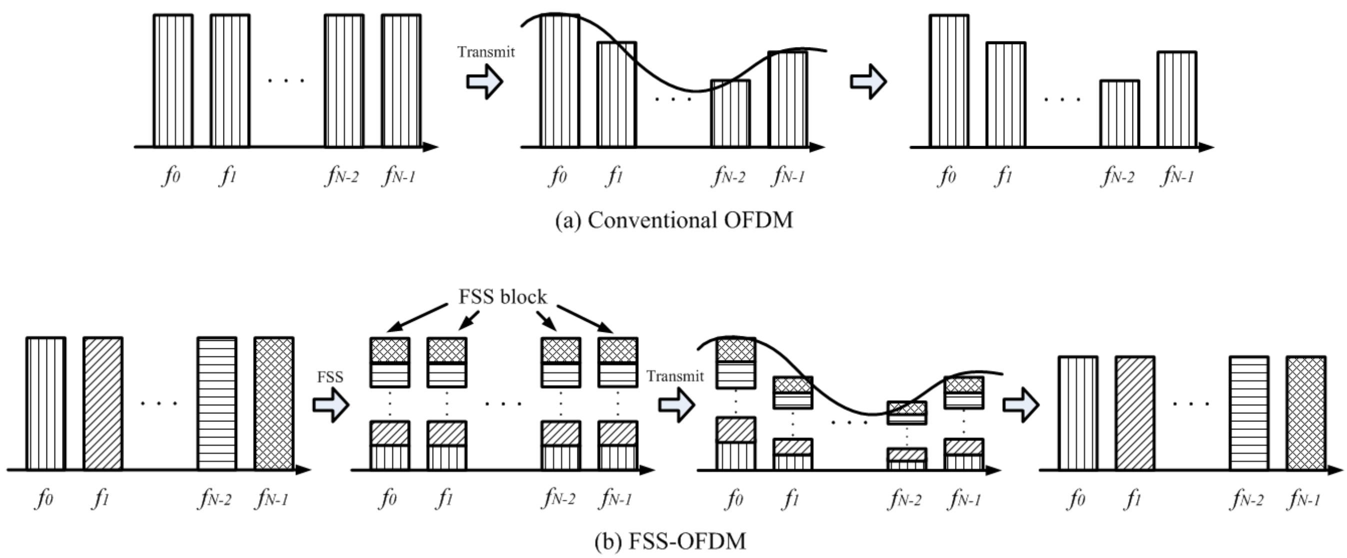

Fig. 1. A concept of FSS.

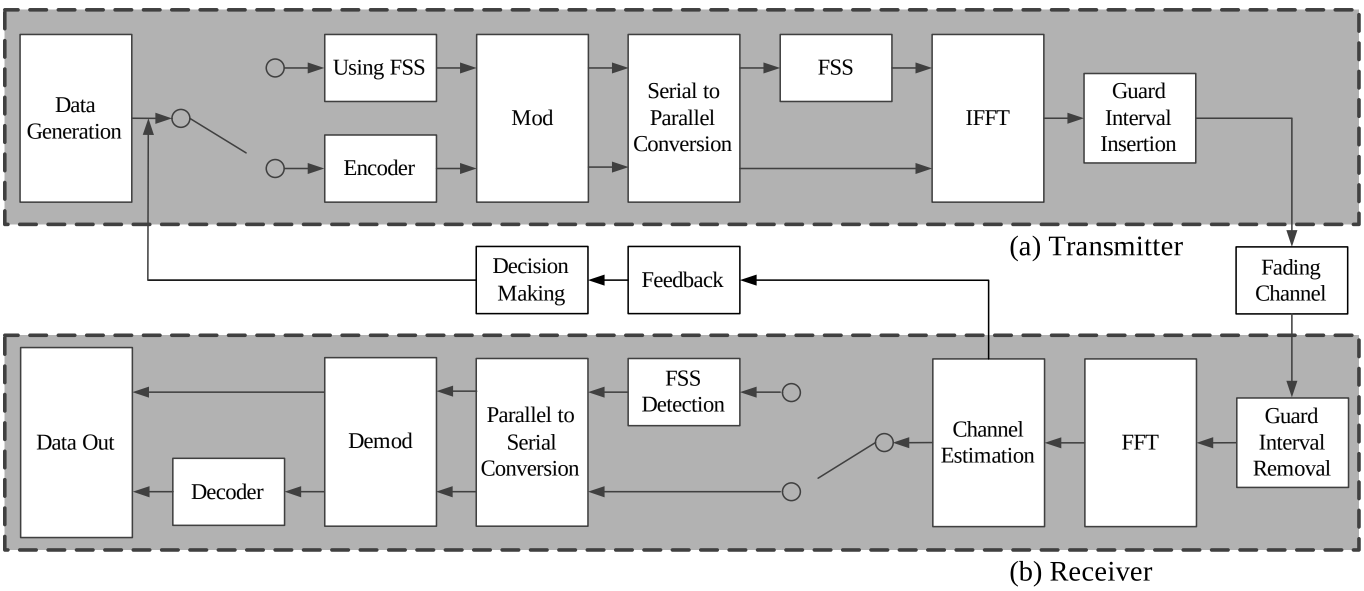

Fig. 2. Proposed transmitter and receiver structures.

density of N_0. The received signal as a result of FFT (i.e. frequency domain expression) is expressed as

$$\begin{aligned}\tilde{r}(m,i) &= \frac{1}{T_s}\int_{iT}^{T_s+iT} r(t)\exp\{-j2\pi m(t-iT)/T_s\}dt \\ &= \sqrt{\frac{2P}{N_c}}\sum_{c=0}^{N_c-1} v(c,i)\cdot\frac{1}{T_s}\int_0^{T_s}\exp\{j2\pi(c-m) \\ &\quad \cdot t/T_s\}\cdot\left\{\int_{-\infty}^{\infty} h(\tau,t+iT)l(t-\tau)\right. \\ &\quad \cdot\exp(-j2\pi c\tau/T_s)d\tau\}\,dt + \hat{n}(m,i),\end{aligned} \tag{5}$$

$\hat{n}(m,i)$ is AWGN whose variance is $2N_0/T_s$ with zero-mean. Suppose the maximum value of τ is smaller than T_g, the integral with respect to τ can be expressed as

$$\begin{aligned}&\sum_{c=0}^{N_c-1}\left\{\int_{-\infty}^{\infty} h(\tau,t+iT)l(t-\tau)\exp(-j2\pi c\tau/T_s)d\tau\right\} \\ &\quad = \sum_{c=0}^{N_c-1}\int_0^{T_s} h(\tau,t+iT)\exp(-j2\pi c\tau/T_s)d\tau \\ &\quad = H(m/T_s,t+iT),\end{aligned} \tag{6}$$

Furthermore, under the assumption that the channel state remains almost flat within the symbol duration T,

$$H(m/T_s,t+iT) \approx H(m/T_s,iT) \quad \text{for } 0 \leqq t \leqq T \tag{7}$$

Therefore, Eq. (5) can be rewritten as follows.

$$\begin{aligned}\tilde{r}(m,i) &= \frac{1}{T_s}\sqrt{\frac{2P}{N_c}}\sum_{c=0}^{N_c-1} v(c,i)\cdot\int_0^{T_s}\exp\{j2\pi(c-m)t/T_s\}\\ &\cdot\left\{\int_{-\infty}^{\infty} h(\tau,t+iT)l(t-\tau)\cdot\exp(-j2\pi c\tau/T_s)d\tau\right\}dt\\ &+\hat{n}(m,i)\\ &\approx\sqrt{\frac{2P}{N_c}}H(m/T_s,iT)v(m,i)+\hat{n}(m,i),\end{aligned} \tag{8}$$

The received signal is despread by using the same spreading code to detect the original OFDM symbol. In this case, the orthogonality of spread symbols is broken by frequency selective fading. To compensate it, frequency equalization combing is required. Here, we apply a minimum mean square error combing (MMSEC). After performing channel estimation from the pilot signal, demodulated data signal to which frequency equalization combing is applied is given by

$$\begin{aligned}\tilde{d}(m,i) &= \sum_{b=0}^{N_{SF}-1} w(b,i)\cdot\tilde{r}(N_{SF}\cdot\lfloor m/N_{SF}\rfloor+b,i)\\ &\cdot c^*_{m \bmod \mathrm{N_{SF}}}(b),\end{aligned} \tag{9}$$

where $w(n)$ denotes the combing weight of FSS, and it is given by

$$w(n) = \frac{\sqrt{\frac{2P}{N_c}}\cdot\tilde{H}(n)}{\left|\sqrt{\frac{2P}{N_c}}\cdot\tilde{H}(n)\right|^2+2\tilde{\sigma}^2}. \tag{10}$$

$\tilde{H}(n)$ is the estimated channel of the n-th subcarrier, and $\tilde{\sigma}^2$ is the noise dispersion for each subcarrier.

D. System Assumptions

In this paper, we use the frame structure as shown in Fig. 3. The packet consists of $N_d = 30$ data symbols and $N_p = 2$ pilot symbols. Each OFDM symbol is composed of $N_c = 64$ subcarriers. The duration of guard interval is 0.8 μs and the effective symbol duration is 3.2 μs. The multipath channel is modeled as 15 Rayleigh fading paths with exponential decay and its interval is 50ns. The Doppler frequency is 10 Hz. Details of simulation parameters are shown in Table 1. The simulation parameters follows the fundamental OFDM systems and here assumes a rich multipath environment so as to be a pessimistic evaluation.

TABLE I
SIMULATION PARAMETERS

Transmission scheme	OFDM
Data Modulation	QPSK,16QAM, 64QAM, 256QAM
Number of subcarriers / FFT	64 / 64
Frame size	32 symbols (N_p=2,N_d=30)
GI length	16 sample times
Doppler frequency	10 Hz, 40 Hz
Fading	15 path Rayleigh fading
Channel estimation	Least square
FEC	Convolutional code (R = 1/2, 2/3, 3/4, 5/6)
Bandwidth	20 MHz

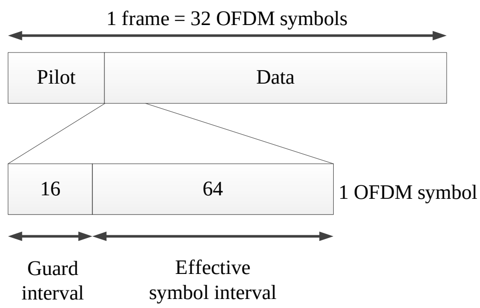

Fig. 3. Frame structure.

III. PROPOSAL: AMC CONTROL FOR FSS-OFDM

Fig. 2 shows the block diagram of the proposed system. As shown in Fig. 2, the method using FSS on the upper side and the method using conventional AMC on the lower side are switched by the SNR threshold in the proposed method. The generated data is determined by using FBI of SNR, whether to use FSS or to use conventional AMC. After the decision, the data signal is modulated and transmitted. On the receiving side, after performing channel estimation, in case that using FSS, despreading is performed. On the other hand, if it is a signal using conventional AMC, decoding is performed and a signal is detected. We employ a convolutional code (CC) as FEC [28]–[31]. Since FEC generates redundant bits to acquire error correction capability, the maximum throughput deteriorates due to such redundant bits. There is a trade-off between error correction capability and achievable throughput. Adaptively controlling coding rate according to the channel condition is essential to ensure the communication quality. It is especially helpful to maintain the throughput performance in a lower SNR regime. On the other hand, the advantage of FSS is that error rate performance can be improved even without FEC in a higher SNR regime, i.e. throughput can be maximized due to exclusion of redundancy.

Focusing on the above features of AMC and FSS, we newly propose the adaptive modulation scheme that control coding rate according to the various channel state in a lower SNR regime and use only by FSS without CC in the case of a high SNR.

In this paper, modulation levels of QPSK, 16QAM, 64QAM and 256QAM are used for the AMC and FSS-OFDM system. Also available coding rates are 1/2, 2/3, 3/4 and 5/6 for CC. The BER performance of the various conventional OFDM are shown in Fig. 4. Here omits the lines showing almost the same performance, e.g. lines of 64QAM. The error correction capability increases because the redundant bits increase, so the BER performance is improved. At the higher order of modulation levels, the BER performance tends to be degraded. Fig. 5 shows the BER performance of FSS-OFDM system.

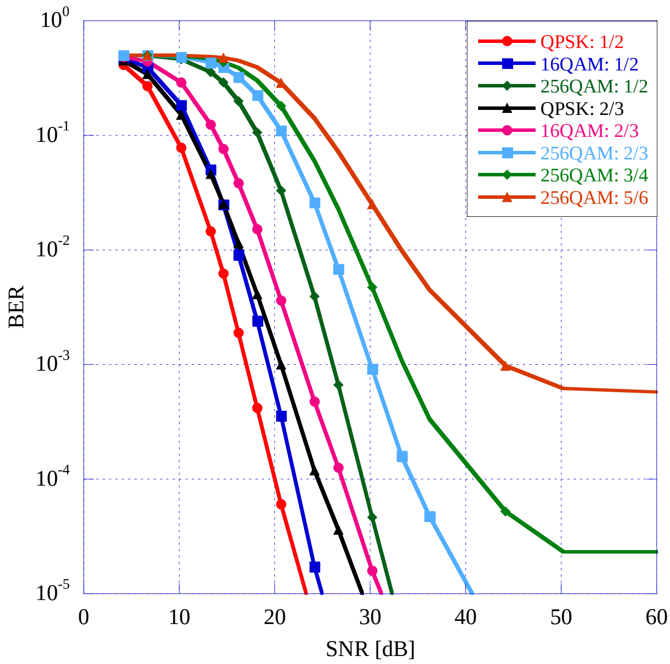

Fig. 4. BER performance of various coding rates.

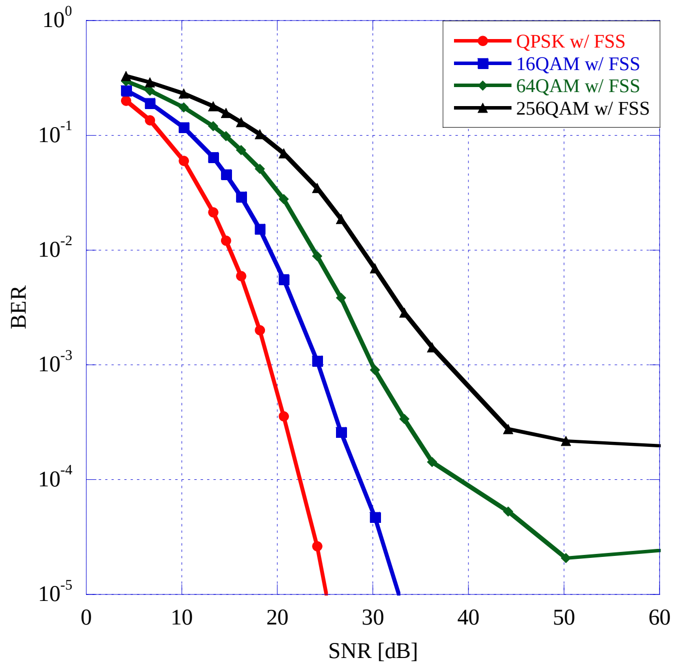

Fig. 5. BER performance of FSS.

Here "w/" in the legend represents "with". FSS takes better frequency diversity and hence good BER performance are obtained without CC. In this study, BER = 10^{-3} is set as the threshold to switch the scheme that can obtain sufficiently good performance from the viewpoint of BER. By comparing Figs. 4 and 5, it is possible to obtain SNR ranges for switching the modulation level and the coding rate from the intersection point with the determined BER threshold of 10^{-3}. What is important here is to optimize full use of spectrum efficiency by FSS. From figures, in the low SNR region smaller than 19.0 dB, it can be confirmed that QPSK and 16QAM with coding rate of 1/2 are effective. However, in the higher SNR regions, 16QAM, 64QAM and 256QAM with FSS should be applied from the view point of throughput performance. Therefore, resultant BER performance to switch AMC and FSS is shown in Fig. 6. From Fig. 6, QPSK with coding rate 1/2 should be applied for SNR < 19.0 dB. In the region of 19.0 dB $\leq$ SNR < 23.0 dB, 16QAM with coding rate 1/2 is the most suitable. When the SNR is between 23.0 dB and 24.5 dB, 16QAM with coding rate 2/3 can be applied. 16QAM for FSS without CC can be used in the case of 24.5 dB $\leq$ SNR < 30.0 dB. When 30.0 dB $\leq$ SNR 37.5 dB, 64QAM applying FSS is utilized. In regions higher than these SNR, 256QAM is available to achieve the highest throughput. Table 1 summarizes the SNR regions to switch AMC and FSS. In this system, AMC is executed for each OFDM frame.

IV. Throughput Performance Evaluation

Fig. 7 shows the throughput performance of convolutionally coded QPSK, 16QAM with coding rate of 1/2 and 2/3 (... w/ coding rate: 1/2 or 2/3) and uncoded 16QAM, 64QAM and 256QAM with FSS (... w/ FSS) when spreading code N_{SF} = 64 at Doppler frequency of 10 Hz. In the lower

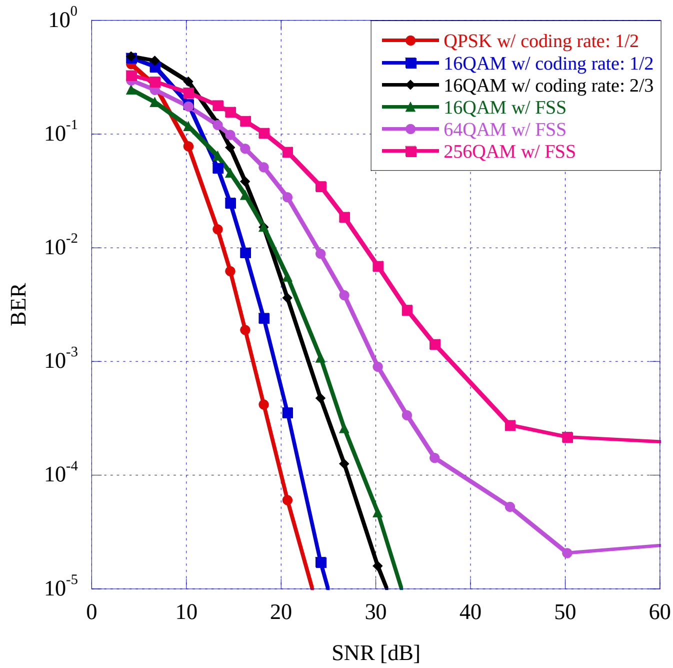

Fig. 6. BER performance of proposed switching AMC and FSS.

SNR region, coded QPSK and 16QAM is effective from the viewpoint of raising part of the throughput. For this reason, CC has the error correction capability by redundant bits according to the coding rate, and it can be confirmed that high performance can be exhibited even in a poor communication environment. On the other hand, FSS achieves the better maximum throughput performance than coded scheme in the larger SNR regime. As mentioned in Fig. 6, the method applying FSS

TABLE II
SWITCHING THRESHOLD PARAMETERS

Threshold	Modulation	Coding rate	bit/symbol
SNR < 19.0dB	QPSK	1/2	1
19.0dB ≤ SNR < 23.0dB	16QAM	1/2	2
23.0dB ≤ SNR < 24.5dB	16QAM	2/3	2.7
24.5dB ≤ SNR < 30.0dB	16QAM	–	4
30.0dB ≤ SNR < 37.5dB	64QAM	–	6
37.5dB ≤ SNR	256QAM	–	8

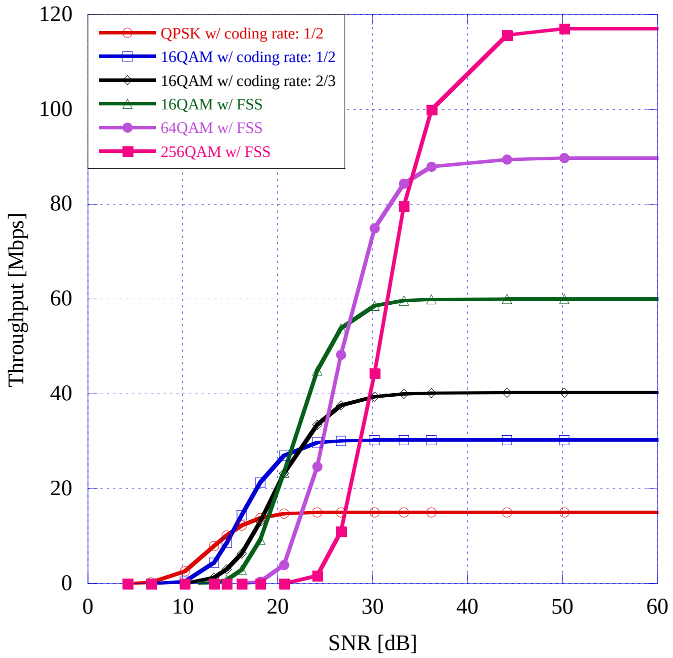

Fig. 7. Throughput performance at Doppler frequency of 10 Hz.

has the sufficiently good BER performance without using error correction. Therefore, the spectral efficiency can be maximized in comparison with the case without using FSS.

Fig. 8 presents the throughput performance of conventional AMC that utilize QPSK, 16QAM, 64QAM and 256QAM with coding rate 1/2, 2/3, 3/4 and 5/6 for CC and proposed AMC/FSS switching method when spreading code is N_{SF} = 64 at a Doppler frequency of 10Hz. The proposed system optimally switches the conventional OFDM with AMC in the lower SNR regime and FSS with AM in the higher SNR regime. From the viewpoint of BER performance, FSS can exhibit the comparable or superior performance depending on the conventional FEC scheme due to its frequency diversity. It can be observed by comparing the results of Figs. 4 and fig:BER2. Since FEC can flexibly set the coding rate, there is a region (especially in low SNR) where throughput can be maximized depending on the coding rate. In the higher SNR region, advantage of FSS excluding redundancy brings enhanced throughput performance. As a result, the achievable throughput can be improved by as much as 35%.

Figs. 9 and 10 represent the throughput performance at

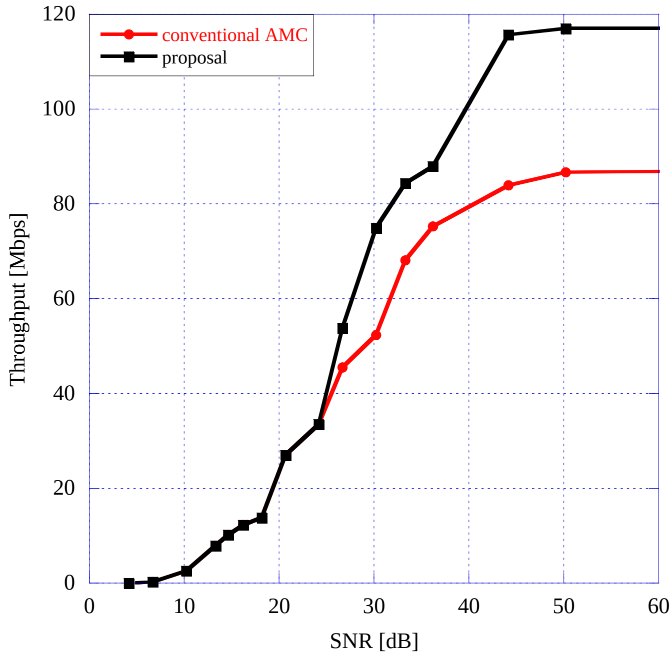

Fig. 8. Throughput performance of proposed system at Doppler frequency of 10 Hz.

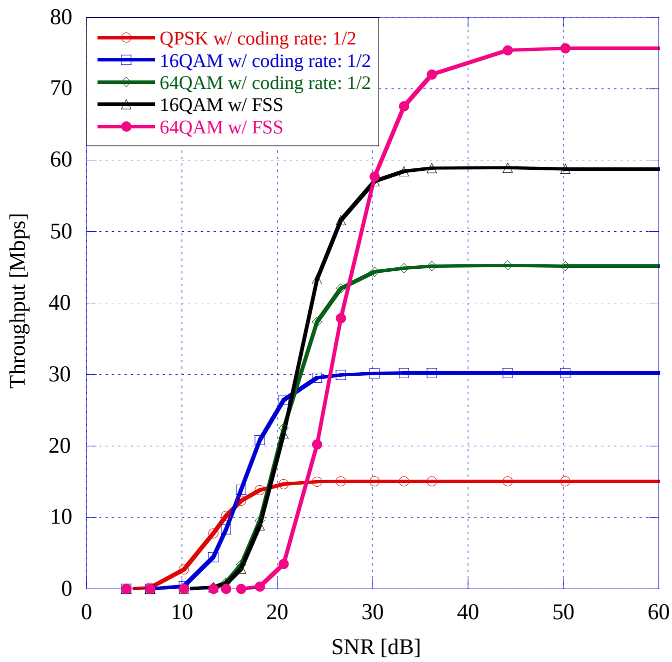

Fig. 9. Throughput performance at Doppler frequency of 40 Hz.

Doppler frequency is 40 Hz. Here, since performance of 256QAM use is severely affected by Doppler frequency and is deteriorated, it is excluded for switching. From Fig. 10, the maximum throughput of proposed system is improved by 31% compared to the conventional system.

In the conventional 256QAM, as shown in Fig. 4, BER performances of 256QAM with coding rates of 3/4 and 5/6 cause the error floor because the bits widely distributed on the spectrum are greatly affected by influence of channel

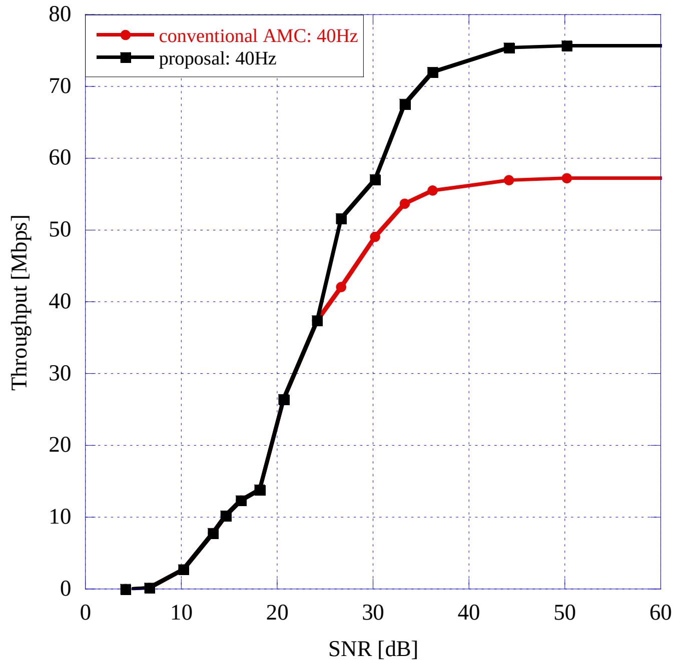

Fig. 10. Throughput performance of proposed system at Doppler frequency of 40 Hz.

fluctuation according to Doppler frequency. On the other hand, the FSS keeps error floor to a minimum. FSS has also better tolerance to Doppler shift effect due to its diffusibility. Phase fluctuation due to Doppler shift is considered to be dispersed thanks to FSS, so that error rate performance can be improved. Therefore, the maximum throughput of FSS can outperform compared to the conventional AMC. In general, the SNR regime in which parameters are switched varies depending on various conditions such as link status, user mobility, and packet size in throughput calculation. Nevertheless, the above results confirmed that it is effective to use AMC in the low SNR regime and use FSS in the high SNR regime. Our proposal can be the valuable solution to fully maximize the throughput performance for better supporting drastic increase of traffic demands.

V. Discussion: Computation Complexity

In proposed method, the computational complexity is increased because FSS performs matrix multiplication using orthogonal spreading code. At the transmitter, it requires N_c^2 multiplications per OFDM symbol as shown in (3). At the receiver, in addition to the matrix operation for despreading, MMSEC is applied to compensate for collapse of orthogonality due to frequency selective fading, and it requires $2 \times N_c$ multiplications according to (9) and (10). Thus computational complexity by FSS totally increases by $2N_c(N_c+1)$ per OFDM symbol. The increment of these computational amounts depends on the number of subcarriers and FSS blocks. It could be acceptable for practical implementation.

VI. Conclusion

This paper proposed the adaptive switching strategy on AMC and FSS for OFDM system. FSS not only has the feature of maximizing achievable throughput performance, but also has the frequency diversity effect to improve the BER without FEC. FSS has strong tolerance to Doppler frequency caused by multipath, thanks to its diffusibility. Therefore this paper aimed to improve the throughput performance by hybrid use of FSS and conventional AMC. From simulation results, it can be confirmed that the proposed system can improve throughput performance especially in higher SNR regions and its improvement is maximally 35% compared to the conventional AMC.

Acknowledgement

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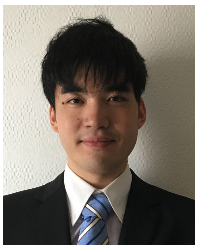

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