Sub-band Spreading Technique for Adaptive Modulation in OFDM Systems

Bang Chul Jung, Jae Kyun Kwon, Hu Jin, and Dan Keun Sung

Abstract: **We propose a sub-band spreading technique for adaptive modulation (AM) in orthogonal frequency division multiplexing (OFDM) systems in order to reduce signaling overheads and to average frequency selective fading channels causing different signal-to-noise ratio (SNR) values for subcarriers in each sub-band. The conventional sub-band based AM schemes can also reduce signaling overheads and complexity for allocating a resource per sub-band at a time. However, they may suffer from the channel variation in a sub-band when the sub-band size is larger than the channel coherence bandwidth (BW). The sub-band spreading at the transmitter enables the received symbols in each sub-band to have an identical reliability even in a frequency selective fading channel. We rigorously analyze the averaged SNR value at the receiver of the sub-band spreading system and the analyzed average SNR in a sub-band is used for an adaptation criterion. The proposed AM scheme outperforms the conventional sub-band based OFDM scheme without spreading, and it can yield better throughput performance than the conventional subcarrier based AM schemes when we consider the signaling overheads.**

Index Terms: **Adaptive modulation (AM), orthogonal frequency division multiplexing (OFDM), sub-band spreading.**

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is one of the most promising techniques for high-speed data transmission over frequency selective fading channels [1]. This OFDM technique is widely used in broadband wireless access (BWA) systems [2]. It is also being considered as a physical layer technique for Evolved-UTRA [3]. Since parallel transmissions over a frequency selective fading channel yield a longer effective symbol duration than the delay spread, each subcarrier experiences a flat fading channel. However, a different fading characteristic for each subcarrier causes frequency-varying signal-to-noise ratios (SNR) values at the receiver. In this situation, the overall BER performance is limited by deep-faded subcarriers [4]. Various techniques have been used to compensate for the frequency selectivity of the channel.

Data symbol spreading techniques can be used for improving the performance of OFDM systems. We proposed a full-band spreading technique for averaging the frequency selective fading channels [5]. A combined scheme for a power control technique for each subcarrier and a data symbol spreading (full-band) has been proposed for improving the BER performance in OFDM systems [6]. These schemes utilize a full-band spreading, which spreads a data symbol onto whole subcarriers, to maximize the frequency diversity gain. However, the diversity gain becomes saturated as the number of independent paths increases, and the complexity due to the data spreading process increases as the number of multiplexed symbols increases. Therefore, a trade-off between the complexity and the BER performance should be taken into account. In addition, a variable spreading factor-orthogonal frequency and code division multiplexing (VSF-OFCDM) technique [7], [8] is a promising technique for next generation wireless communication systems, which also utilizes a data symbol spreading technique at the transmitter. It changes spreading factor (SF) according to cell structure (multi-cell or isolated cell environments) and radio link conditions (delay spread).

Another approach for overcoming frequency selective characteristics is to use an adaptive modulation (AM) algorithm [9]. The basic idea of the AM is to adaptively change the modulation schemes according to varying channel transfer functions. This AM scheme can be extended by adapting the transmit power for each subcarrier as well as the modulation mode. A water-filling (WF) scheme is theoretically optimum when we assume that the transmitter knows the channel transfer function [10]. Greedy algorithms have been proposed to implement WF practically in multicarrier systems [11], [12]. The greedy algorithms require a large amount of computations for finding an appropriate power level and modulation mode for each carrier. Several schemes have been proposed in order to reduce the complexity of greedy algorithms [13]–[15].

Signaling information including feed-back or feed-forward information must be transmitted in AM schemes. The feed-back information from the receiver indicates the wireless channel characteristics and the feed-forward information from the transmitter indicates which modulation is used for each subcarrier. If we apply a different modulation scheme for each subcarrier, the signaling information which indicates the modulation modes for each subcarrier may be required. Due to the time-varying characteristics of wireless channel, the signaling information should be sent at least every coherence time. Furthermore, when we consider that the number of subcarriers is more than $1,000$ in the BWA system [2] or Evolved-UTRA system [3], the signaling overhead problem is very severe. Hardware complexity also increases at the transmitter for selection of the appropriate modulation mode per subcarrier.

In order to solve these problems, the sub-band based AM

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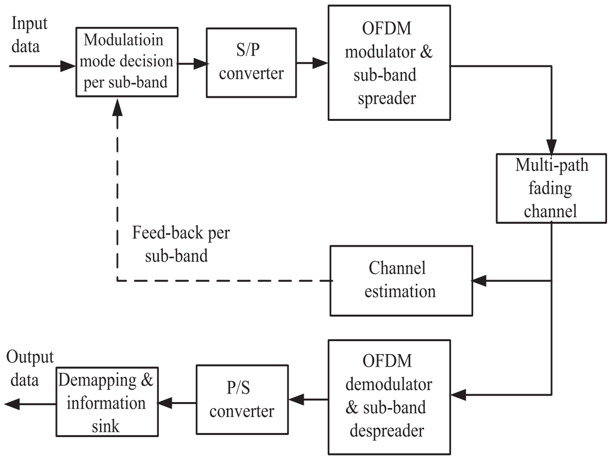

Fig. 1. Block diagram of a sub-band spreading based AM scheme.

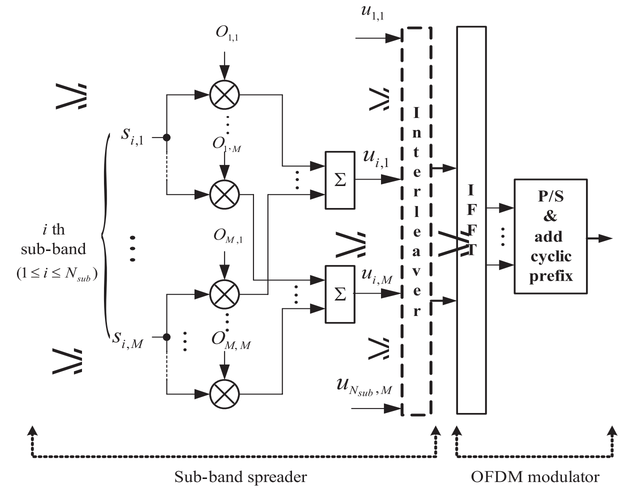

Fig. 2. Sub-band spreader and OFDM modulator.

scheme can be used. Either the lowest value among the channel gains [9] or the average value of channel gains [16] in each sub-band can be selected as a criterion to determine the modulation mode after grouping subcarriers into multiple sub-bands. In the former case, the BER performance can be assured, but the throughput is much less than for the subcarrier-by-subcarrier AM (SC-AM) scheme. In the latter case, if the channel coherence bandwidth (BW) is smaller than the BW of each sub-band, the scheme may not satisfy a given BER requirement. If we use the sub-band based AM scheme, the receiver may feedback an SNR value not for each subcarrier but for each sub-band and, thus, the feedback information can be reduced.

We propose a sub-band spreading technique for AM in OFDM systems in order to reduce signaling overheads and to average frequency selective fading channels causing different SNR values for subcarriers in each sub-band. The sub-band spreading at the transmitter enables the received symbols in each sub-band to have an identical reliability even in a frequency selective fading channel. The proposed scheme also reduces the signaling overheads because it operates based on the sub-band. The performance of the proposed AM scheme is compared with that of the conventional sub-band based AM schemes and the subcarrier based AM schemes. This paper is organized as follows: Section II proposes the sub-band based AM schemes and analyzes the average SNR at the receiver of the proposed OFDM system. The performance of the sub-band spreading system is evaluated in terms of BER and throughput by computer simulations in Section III, and conclusions are presented in Section IV.

II. SUB-BAND SPREADING BASED AM SCHEME

Fig. 1 shows the block diagram of a sub-band spreading based AM schemes. The whole frequency band is divided into multiple sub-bands and a spreading technique is applied to each sub-band for averaging the frequency selective fading channels in each sub-band. If the sub-band spreading technique is applied to an OFDM system, the symbols in a sub-band have identical reliability. Radio resources are allocated to each sub-band and the same modulation scheme is applied in each sub-band but the different modulations can be used for different sub-bands according to varying channel transfer function. The receiver estimates the channel transfer function and feedbacks the information about channel gain for each sub-band.

Fig. 2 shows the sub-band spreading processing using orthogonal codes (OCs). When the entire frequency band is divided into a number of sub-bands, the number of sub-bands (N_{sub}) can be selected flexibly according to the wireless channel environment such as channel delay profile ($1 \leq N_{sub} \leq N$, where N is the number of data subcarriers). Basically, when the sub-band size becomes small, the throughput performance is improved, but the signaling overhead becomes large. Thus, we need to consider these factors for deciding the sub-band structure together. On the other hand, once the sub-band structure is decided at the transmitter, the information on the structure should be transmitted to the receiver because the receiver needs this information for the de-spreading process. However, this information may be slowly varying, compared to information on the modulation scheme of each sub-band, and the signaling overhead informing the sub-band structure is negligible.

A distinct orthogonal codeword with the same length as the number of subcarriers in a sub-band is assigned to each symbol. In other words, M ($M = N/N_{sub}$) symbols are multiplexed ($\mathbf{u}$) using M distinct OCs ($\mathbb{O}$) for OFDM transmission over subcarriers in a sub-band. M denotes the *sub-band size*. The multiplexed symbols in ith sub-band by orthogonal codes can be expressed as:

$$\mathbf{u}_i = \mathbb{O}^{\mathbb{T}} \cdot \mathbf{s}_i \tag{1}$$

where $\mathbf{u}_i = [\mathbf{u}_{i,1}\mathbf{u}_{i,2}\cdots\mathbf{u}_{i,M}]^T$ and $\mathbf{s}_i = [\mathbf{s}_{i,1}\mathbf{s}_{i,2}\cdots\mathbf{s}_{i,M}]^T$. The orthogonal code set are defined as:

$$\mathbb{O} = \begin{bmatrix} O_{1,1} & O_{1,2} & \cdots & O_{1,M} \\ O_{2,1} & \ddots & \cdots & O_{2,M} \\ \vdots & \vdots & \ddots & \vdots \\ O_{M,1} & O_{M,2} & \cdots & O_{M,M} \end{bmatrix}. \tag{2}$$

The interleaver in Fig. 2 is only used for simulation for Fig. 3. The interleaver is represented using a dotted line block for this reason. Thus, each sub-band consists of the consecutive subcarriers in frequency domain.

The transmitted multiplexed symbols $\{u_{i,k}\}$ arrive at the receiver through a frequency selective fading channel. After guard interval removal and an FFT process at the receiver, the received symbols in the ith sub-band is given as:

$$\mathbf{r}_i = \mathbb{H}_i \cdot \mathbf{u}_i + \mathbf{n}_i = [\mathbf{r}_{i,1}\mathbf{r}_{i,2}\cdots\mathbf{r}_{i,M}]^T \tag{3}$$

where $M \times M$ diagonal matrix $\mathbb{H}_i$ represents the fading on the M subcarriers in the ith sub-band and the vector $\mathbf{n}_i = [\mathbf{n}_{i,1}\mathbf{n}_{i,2}\cdots\mathbf{n}_{i,M}]^T$ denotes the noise on the M subcarriers. The diagonal term of $\mathbb{H}_i$ consists of M fading coefficients, $\{\alpha_{i,1}, \alpha_{i,2}, \cdots, \alpha_{i,M}\}$. Thus, the kth output of the ith sub-band, $\{r_{i,k}\}$ can be expressed as:

$$\begin{aligned} r_{i,k} &= \alpha_{i,k}u_{i,k} + n_{i,k} \\ &= \alpha_{i,k}\left(O_{1,k}s_{i,1} + O_{2,k}s_{i,2} + \cdots + O_{M,k}s_{i,M}\right) + n_{i,k} \end{aligned} \tag{4}$$

where $\alpha_{i,k}$ and $n_{i,k}$ represent the fading coefficient and the zero-mean AWGN value for the kth subcarrier in the ith sub-band, respectively. Applying a zero-forcing (ZF) criterion for one-tap equalization, we calculate $y_{i,j}$ as an estimate of $s_{i,j}$.

$$\begin{aligned} y_{i,j}^{\mathrm{ZF}} &= \frac{r_{i,1}}{\alpha_{i,1}}O_{j,1}^* + \frac{r_{i,2}}{\alpha_{i,2}}O_{j,2}^* + \cdots + \frac{r_{i,M}}{\alpha_{i,M}}O_{j,M}^* \\ &= s_{i,j} + \frac{O_{j,1}^*}{\alpha_{i,1}}n_{i,1} + \frac{O_{j,2}^*}{\alpha_{i,2}}n_{i,2} + \cdots + \frac{O_{j,M}^*}{\alpha_{i,M}}n_{i,M}. \end{aligned} \tag{5}$$

Each $n_{i,k}$ $(1 \le k \le M)$ has the same statistical characteristic and each chip of an orthogonal codeword has a power eqaul to $\frac{1}{M}$. Let n be a Gaussian random variable with a zero mean and the same variance as $n_{i,k}$. Then, (5) can be expressed as:

$$\begin{aligned} y_{i,j}^{\mathrm{ZF}} &= s_{i,j} + n\sqrt{\left(\frac{|O_{j,1}|}{|\alpha_{i,1}|}\right)^2 + \left(\frac{|O_{j,2}|}{|\alpha_{i,2}|}\right)^2 + \cdots + \left(\frac{|O_{j,M}|}{|\alpha_{i,M}|}\right)^2} \\ &= s_{i,j} + n\sqrt{\frac{1}{M}\left(\frac{1}{|\alpha_{i,1}|^2} + \frac{1}{|\alpha_{i,2}|^2} + \cdots + \frac{1}{|\alpha_{i,M}|^2}\right)}. \end{aligned} \tag{6}$$

From (6), the SNR for the estimate $y_{i,j}^{\mathrm{ZF}}$ is as follows:

$$\begin{aligned} \mathrm{SNR}_{y_{i,j}}^{\mathrm{ZF}} &= \frac{\mathrm{SNR}_{\mathrm{AWGN}}}{\frac{1}{M}\left(\frac{1}{|\alpha_{i,1}|^2} + \frac{1}{|\alpha_{i,2}|^2} + \cdots + \frac{1}{|\alpha_{i,M}|^2}\right)}, \\ \frac{1}{\mathrm{SNR}_{y_{i,j}}^{\mathrm{ZF}}} &= \frac{1}{M}\left(\frac{1}{\mathrm{SNR}_{r_{i,1}}} + \frac{1}{\mathrm{SNR}_{r_{i,2}}} + \cdots + \frac{1}{\mathrm{SNR}_{r_{i,M}}}\right) \end{aligned} \tag{7}$$

where $\mathrm{SNR}_{\mathrm{AWGN}}$ is the received SNR through AWGN channels and $\mathrm{SNR}_{r_{i,k}}$ is the received SNR through the kth subcarrier of the ith sub-band. Equation (7) shows that the SNR of each modulated symbol is obtained as the *harmonic mean* of the received SNRs through all subcarriers in a sub-band. Using the spreading technique, the received symbols with different OCs in each sub-band have an almost equalized reliability at the receiver, which can be expressed as:

$$\mathrm{SNR}_{y_{i,1}} \simeq \mathrm{SNR}_{y_{i,2}} \simeq \cdots \simeq \mathrm{SNR}_{y_{i,M}}. \tag{8}$$

The minimum mean squared error (MMSE) criterion can also be used for a one-tap equalization process. The tap coefficient of MMSE equalizer of the kth subcarrier output in the ith sub-band is given as [17]:

$$\omega_{i,k} = \frac{\alpha_{i,k}^*}{|\alpha_{i,k}|^2 + \sigma^2/E_s} \tag{9}$$

where x^* indicates complex conjugate of x, σ^2 indicates the noise variance at the receiver, and E_s indicates the transmitted symbol energy. Through (9), we estimate $u_{i,k}$. We assume that the transmitted symbol energy for each subcarrier within a sub-band is the same.

If we use the MMSE criterion for a one-tap equalization, the equalized symbol, $y_{i,j}$, as an estimate of $s_{i,j}$ is expressed as:

$$\begin{aligned} y_{i,j}^{\mathrm{MMSE}} &= \sum_{k=1}^{M}\omega_{i,k}r_{i,k}O_{j,k}^* \\ &= \sum_{k=1}^{M}\omega_{i,k}\alpha_{i,k}\left(\sum_{l=1}^{M}O_{l,k}s_{i,l}\right)O_{j,k}^* \\ &\quad + \sum_{k=1}^{M}\omega_{i,k}O_{j,k}^*n_{i,k} \\ &= \sum_{k=1}^{M}\frac{|\alpha_{i,k}|^2}{|\alpha_{i,k}|^2 + \sigma^2/E_s}\left(\sum_{l=1}^{M}O_{l,k}O_{j,k}^*s_{i,l}\right) \\ &\quad + \sum_{k=1}^{M}\frac{\alpha_{i,k}^*O_{j,k}^*}{|\alpha_{i,k}|^2 + \sigma^2/E_s}n_{i,k} \\ &= s_{i,j} - \sum_{l=1}^{M}s_{i,l}\left(\sum_{k=1}^{M}O_{l,k}O_{j,k}^*\frac{\sigma^2/E_s}{|\alpha_{i,k}|^2 + \sigma^2/E_s}\right) \\ &\quad + \sum_{k=1}^{M}\frac{\alpha_{i,k}^*O_{j,k}^*}{|\alpha_{i,k}|^2 + \sigma^2/E_s}n_{i,k} \\ &= s_{i,j} - \zeta + \eta \end{aligned} \tag{10}$$

where ζ and η represent the self interference and filtered gaussian noise, respectively. From (10), the SNR for the estimate $y_{i,j}^{\mathrm{MMSE}}$ is as follows:

$$\mathrm{SNR}_{y_{i,j}}^{\mathrm{MMSE}} = \frac{E_s}{Var(\zeta) + Var(\eta)} \tag{11}$$

where $Var(x)$ indicates the variance of random variable x. $Var(\zeta)$ can be expressed as:

$$\begin{aligned} Var(\zeta) &= \sum_{l=1}^{M}Var(s_{i,l})\left|\sum_{k=1}^{M}O_{l,k}O_{j,k}^*\frac{\sigma^2/E_s}{|\alpha_{i,k}|^2 + \sigma^2/E_s}\right|^2 \\ &= E_s\sum_{l=1}^{M}\left|\sum_{k=1}^{M}O_{l,k}O_{j,k}^*\frac{\sigma^2/E_s}{|\alpha_{i,k}|^2 + \sigma^2/E_s}\right|^2 \end{aligned}$$

$$= E_s \sum_{l=1}^{M} \left(\sum_{k=1}^{M} O_{l,k} O_{j,k}^{*} \frac{\sigma^2/E_s}{|\alpha_{i,k}|^2 + \sigma^2/E_s} \right) \left(\sum_{h=1}^{M} O_{l,h} O_{j,h}^{*} \frac{\sigma^2/E_s}{|\alpha_{i,h}|^2 + \sigma^2/E_s} \right)^{*}$$
$$= E_s \sum_{l=1}^{M} \sum_{k=1}^{M} \sum_{h=1}^{M} \left(\frac{\sigma^2/E_s}{|\alpha_{i,k}|^2 + \sigma^2/E_s} \frac{\sigma^2/E_s}{|\alpha_{i,h}|^2 + \sigma^2/E_s} O_{l,k} O_{j,k}^{*} O_{l,h}^{*} O_{j,h} \right)$$
$$= E_s \sum_{k=1}^{M} \sum_{h=1}^{M} \left(\frac{\sigma^2/E_s}{|\alpha_{i,k}|^2 + \sigma^2/E_s} \frac{\sigma^2/E_s}{|\alpha_{i,h}|^2 + \sigma^2/E_s} O_{j,k}^{*} O_{j,h} \left(\sum_{l=1}^{M} O_{l,k} O_{l,h}^{*} \right) \right), \quad (12)$$

since the value of $\sum_{l=1}^{M} O_{l,k} O_{l,h}^{*}$ is equal to 1 when $k = h$ and is equal to 0 when $k \neq h$,

$$\begin{aligned} Var(\zeta) &= E_s \sum_{k=1}^{M} \left(\frac{\sigma^2/E_s}{|\alpha_{i,k}|^2 + \sigma^2/E_s} \frac{\sigma^2/E_s}{|\alpha_{i,k}|^2 + \sigma^2/E_s} O_{j,k}^{*} O_{j,k} \right) \\ &= E_s \sum_{k=1}^{M} \left(\left(\frac{\sigma^2/E_s}{|\alpha_{i,k}|^2 + \sigma^2/E_s} \right)^2 |O_{j,k}|^2 \right) \\ &= \frac{E_s}{M} \sum_{k=1}^{M} \left(\frac{\sigma^2/E_s}{|\alpha_{i,k}|^2 + \sigma^2/E_s} \right)^2 \end{aligned} \quad (13)$$

where we used the fact that $|O_{j,k}|^2 = 1/M$.

The variance of $Var(\eta)$ can be expressed as

$$Var(\eta) = \frac{\sigma^2}{M} \sum_{k=1}^{M} \left(\frac{|\alpha_{i,k}|}{|\alpha_{i,k}|^2 + \sigma^2/E_s} \right)^2. \quad (14)$$

As the SNR increases, $Var(\zeta)$ becomes zero and $Var(\eta)$ becomes

$$\frac{\sigma^2}{M} \sum_{k=1}^{M} \left(\frac{1}{|\alpha_{i,k}|^2} \right). \quad (15)$$

Thus, the MMSE criterion exhibits similar characteristics to that of the ZF criterion for high SNR values from (13) and (14). In this case, the equalized SNR of each sub-band is also approximately equal to the harmonic mean of the received SNRs.

The system complexity of the sub-band spreading based system can be approximated by the number of multiplications at the transmitter. As shown in Fig. 2, M^2 multiplications are needed per sub-band block and there exist N_{sub} sub-bands. Thus, the overall number of multiplications at the transmitter is expressed as:

$$\begin{aligned} N_{mul} &= M^2 N_{sub} = M^2 \left(\frac{N}{M} \right) \\ &= MN. \end{aligned} \quad (16)$$

The number of multiplications increases as the sub-band size M increases. As the sub-band size increases, the performance is improved since the diversity effect increases. However, the complexity at the transmitter also increases as the sub-band size increases as noted above. Furthermore, the diversity effect becomes saturated as the sub-band size increases. Hence, the sub-band size (M) is needed to be selected considering both performance and complexity.

If the sub-band spreading technique is applied to an OFDM system, the symbols in a sub-band have identical reliability at the receiver. Therefore, each sub-band has a *constant SNR* and the sub-band spreading scheme at the transmitter assures the BER performance at the receiver even if the coherence BW of the channel is smaller than the BW of the sub-band. The harmonic mean of the SNR values of the subcarriers in each sub-band is computed at the receiver when a ZF criterion is used, and the receiver sends the computed harmonic mean of the SNR values in the sub-band to the transmitter through the feed-back channel. When we use an MMSE criterion at the receiver, the averaged SNR in (11) is transmitted through the feed-back channel. The corresponding modulation mode for each sub-band is determined from a pre-computed table at the transmitter.

In the sub-band spreading based AM scheme, *feed-back information* about the channel transfer function from the receiver, and *feed-forward information* informing the modulation mode utilized at the transmitter are not required for each subcarrier, but they are required for each sub-band and, thus, the required signaling overhead is reduced. The throughput increases if the size of each sub-band decreases, but the complexity and signaling overhead increase. Especially, when we use a greedy algorithm for allocating radio resources per subcarrier at the transmitter, a large computational load is required.

If we use a sub-band based adaptation technique without spreading at the transmitter, the *adaptation criterion* should be carefully chosen because the channel coherence bandwidth varies according to varying communication environments. In the subcarrier-by-subcarrier AM (SC-AM) scheme, the received SNR value of each subcarrier becomes an adaptation criterion. In the sub-band based adaptation systems, if we select a received SNR value of the specific subcarrier as an adaptation criterion, the bit error performance may not be assured because of the subcarriers with lower SNR values than the criterion. The phenomenon becomes worse as the size of each sub-band increases. Hence, it may be reasonable to select the subcarrier with the worst SNR value in the sub-band as an adaptation criterion as shown in [9]. However, the BER performance is assured in the proposed AM scheme with a sub-band spreading technique even when the coherence bandwidth of the wireless channel is smaller than the BW of each sub-band.

III. SIMULATION RESULTS AND DISCUSSIONS

Two simulation models are considered for the proposed AM scheme with a sub-band spreading technique. In *the first case*, the channel is assumed to be static and the signaling overhead may be negligible. In *the second case*, the channel varies quickly and signaling information regarding the modulation mode used at the transmitter is required for each transmission.

In the second case, we assume that the channel coherence time is shorter than an OFDM symbol duration. However, the channel transfer function is assumed to be known at the transmitter from the reliable feed-back information in both cases. Hence, the signaling overhead includes only feed-forward information in this simulation. The effective throughput is defined as the throughput of user data excluding the signaling overhead of the OFDM symbols. When the channel varies very quickly, a channel mismatch between the channel estimation and data transmission degrades the performance of AM schemes. However, in this paper, we focus on the signaling overhead due to the time-varying characteristics of wireless channel. Therefore, in *the second case*, the performance degradation due to the channel mismatch is not considered. The exact channel transfer function is assumed to be known to the transmitter through the reliable feedback channel just prior to transmission.

We consider a multipath fading channel with an exponential delay profile where each delay component is independently Rayleigh-distributed. The root-mean-square (RMS) value of the delay spread is 5 μs and the maximum delay spread is 25 μs. The OFDM parameters are set as follows: The center frequency is 1.9 GHz; the channel BW is 5 MHz; the number of subcarriers is 1024; the effective symbol duration is 204.8 μs, and the guard interval is 25.6 μs. These parameters are based on a wide-area cellular-like system with a target data rate of 10 to 20 Mbps [18]. Furthermore, in Fig. 3, we assume that the channels are time-invariant. We use an MMSE criterion for one-tap equalization process.

Fig. 3 shows the BER performance for varying the sub-band size. As noted before, the BER performance is improved as the sub-band size increase because the diversity gain is increased, but the diversity effect is saturated. The conventional system in Fig. 3 indicates the OFDM system without sub-band spreading technique at the transmitter. If we use a sub-band size of 32, the additionally required SNR for satisfying a BER of 10^{-4} is less than 2dB, compared with the SNR value of the full-band spreading scheme. In addition, the complexity of the full-band spreading scheme is 32 times larger than for the sub-band spreading scheme with a sub-band size of 32 as noted in (16). Hence, we utilize a sub-band spreading scheme with a sub-band size of 32 for the following simulations.

We first consider the fixed threshold adaptation scheme [9] which only adapts the modulation order according to channel transfer function and it does not change power level. Fig. 4 compares the effective throughput (bits per subcarrier, BPS) of the proposed AM scheme using sub-band spreading with the throughput of the conventional schemes including SC-AM scheme both with and without taking into account the signaling overhead. A target BER is set to 10^{-4} in order to compare the performance of the proposed system with Keller and Hanzo's result [9]. The sub-band size M is 32 and, thus, the whole frequency band consists of 32 sub-bands, i.e., $N_{sub} = 32$, in the proposed scheme. The transmitter only changes the modulation mode. The modulation modes used in the simulation are no transmission, BPSK, QPSK, and 16-QAM. Hence, the maximum BPS is 4. We utilize two criteria, ZF and MMSE, for one-tap equalization at the receiver and the harmonic mean of SNR values in a sub-band as the criterion of the adaptation in the proposed AM scheme.

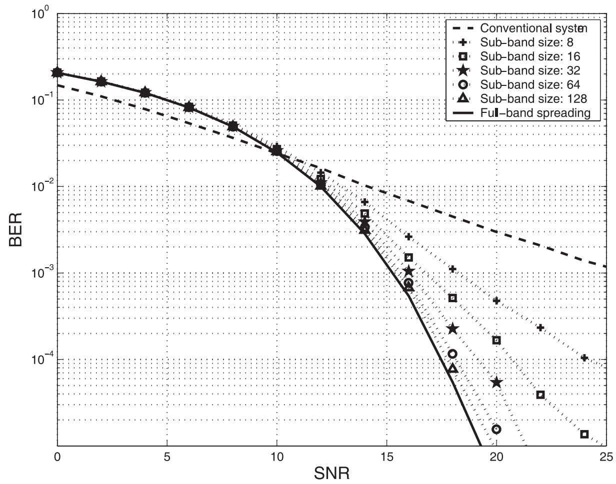

Fig. 3. BER performance for varying sub-band size.

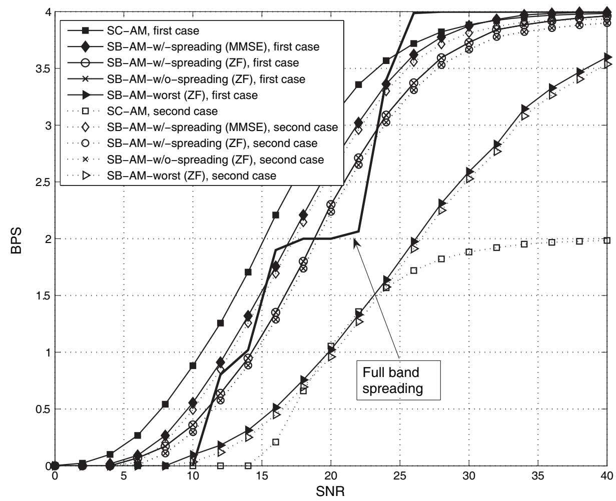

Fig. 4. Effective BPS of the proposed adaptive modulation scheme for satisfying a BER value of 10^{-4} when the fixed threshold adaptation scheme is applied.

The SC-AM scheme exhibits the best performance in terms of throughput in the first case. However, in the second case, 2048 bits are required for signaling information in the SC-AM scheme since the number of modulation modes is 4 and the number of subcarriers is 1024. However, only 64 bits are required for signaling in sub-band based adaptation schemes including the proposed scheme because the 32 subcarriers are grouped into a sub-band that uses a single modulation mode. The proposed scheme yields a better effective throughput than the SC-AM scheme in this case. The first and second channel environments yield the upper and lower bounds of throughput (BPS) in AM systems, respectively, considering the signaling overhead for the channel variation. The proposed scheme is robust to this channel variation and has a reduced complexity since the AM is applied to each sub-band and not to each subcarrier. The feed-back information for the proposed scheme also is reduced by a factor of $1/M$ and the proposed scheme has the same complexity and the signaling overhead as the sub-band adaptation scheme based on a subcarrier with the worst SNR,

Table 1. Comparison of performance signaling overhead for various adaptation schemes

AM schemes	feed-back overhead (bits)	feed-forward overhead (bits)	effective BPS (first/second)	BER
SC-AM	NQ	NP	high/low	satisfied
SB-AM-Worst	$N_{sub}Q$	$N_{sub}P$	low/low	satisfied
SB-AM-w/o-spreading	$N_{sub}Q$	$N_{sub}P$	high/high	not satisfied
SB-AM-w/-spreading	$N_{sub}Q$	$N_{sub}P$	**high/high**	**satisfied**

this is called the SB-AM-Worst scheme, in a sub-band as an adaptation criterion [9]. The proposed scheme yields better performance than the SB-AM-Worst scheme in both cases in terms of the effective throughput. The conventional sub-band based AM scheme without spreading uses the same adaptation criterion as the proposed AM scheme, which is the harmonic mean of SNR values of subcarriers in a sub-band. We call it the SB-AM-without (w/o)-spreading scheme. Thus, the SB-AM-w/o-spreading scheme yields the same effective throughput as the proposed scheme as shown in Fig. 4. We also show the throughput performance of the full band spreading scheme in which $N_{sub} = 1$ in the proposed scheme. In this case, the same modulation scheme is used for all subcarriers and the signaling overhead is equal to 4 bits. Table 2 summarizes and compares the five different AM schemes.

Fig. 5 shows the BER performance of the proposed AM scheme and the conventional AM schemes. The target BER is set to 10^{-4}. The SB-AM-Worst scheme satisfies the target BER sufficiently as expected. The SC-AM scheme and the proposed schemes meet the target BER tightly, which means these schemes fully utilize the channel resources. The BER fluctuation can occur since the modulation order increases as the SNR increases. If there are much more modulation levels, then BER performance is maintained on the target BER. Note that the SB-AM-w/o-spreading scheme does not satisfy the target BER, while the proposed AM scheme satisfies it. Hence, if we utilize the SB-AM-w/o-spreading, the adaptation criterion should be set to a lower value than a harmonic mean of SNR values of subcarriers in a sub-band for satisfying the target BER. Furthermore, in this case, the throughput performance is degraded compared with the proposed scheme with sub-band spreading. This phenomenon becomes more prominent as the target BER decreases. We here assume that the exact channel transfer function is known at the transmitter just before transmission.

Now we consider the adaptive power and bit loading for OFDM systems. In this case, we change the power level as well as the modulation mode for each subcarrier or sub-band. We use a greedy algorithm as a bit and power allocation algorithm, which is known as the optimum allocation scheme. In the original greedy algorithm, the transmitter searches the subcarrier which has the least incremental power when one additional bit is allocated to the subcarrier until the target data rate is reached or the transmit power is exhausted [11], [12]. Since the original greedy algorithm requires exhaustive sorting and adds one more bit at a time, the order of operations is expected to be $O(R_T N)$, where R_T and N denote the total number of loaded bits and the number of subcarriers, respectively. If we group multiple subcarriers into a sub-band with a sub-band size of $M(= N/N_{sub})$, we can allocate M bits at a time and need to

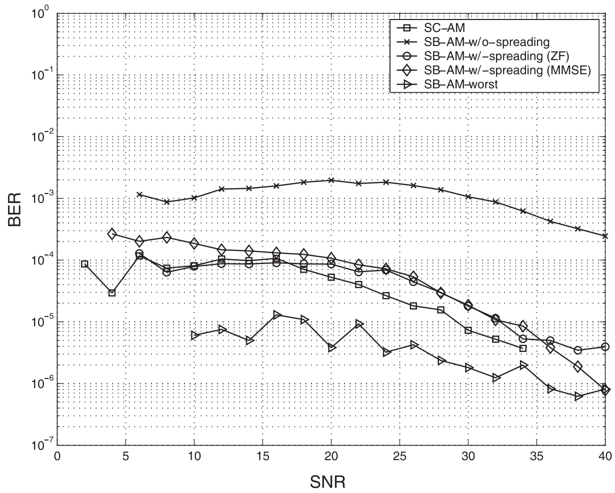

Fig. 5. BER performance comparison between the proposed scheme and the conventional schemes for a target BER value of 10^{-4} when the fixed threshold adaptation scheme is applied.

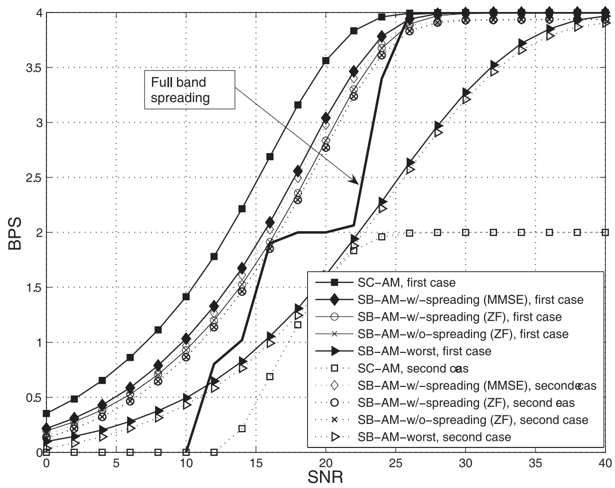

Fig. 6. Effective BPS of the proposed adaptive modulation scheme for satisfying a BER value of 10^{-4} when the greedy algorithm is applied.

search N_{sub} bands, not N subcarriers. Therefore, the proposed sub-band based AM scheme requires the order of operations of $O(\frac{R_T}{M} N_{sub}) = O(\frac{R_T N}{M^2})$. The sub-band based AM scheme significantly reduces the system complexity of the greedy algorithm.

In the greedy algorithm, the adaptation criterion should be also carefully chosen when we use the sub-band based AM scheme. The harmonic mean of SNR values of subcarriers in a sub-band is used for the adaptation criterion in the proposed algorithm. Fig. 6 shows the effective BPS of the proposed AM

Table 2. Different adaptation schemes

Notation	Adaptation unit	Spreading	Adaptation criterion	Equalizer
SC-AM	subcarrier	No	SNR of each subcarrier	ZF
SB-AM-w/-spreading (MMSE)	sub-band	Yes	averaged SNR in (11)	MMSE
SB-AM-w/-spreading (ZF)	sub-band	Yes	averaged SNR in (7)	ZF
SB-AM-w/o-spreading (ZF)	sub-band	No	averaged SNR in (7)	ZF
SB-AM-Worst (ZF)	sub-band	No	the worst SNR in a sub-band	ZF

scheme and those of the conventional AM schemes when we utilize the greedy algorithm at the transmitter. All schemes operate for satisfying a BER requirement of 10^{-4}. The SC-AM scheme yields the best performance in the first simulation case as expected, but it yields the worst performance in the second simulation case. It requires the SNR value of each subcarrier from receiver. When we consider the cellular downlink, the feedback information from each MS in the uplink should be reduced due to a lack of resources. Furthermore, the number of operations required to allocate resources of the SC-AM scheme is M^2 times larger than that of the sub-band based schemes. The SB-AM-w/o-spreading has the same throughput performance as the proposed scheme since it has the same adaptation criterion as that of the proposed scheme. The sub-band based AM schemes require much smaller signaling overhead than the SC-AM scheme.

Fig. 7 shows the BER performance of the four AM schemes. The SC-AM scheme, the proposed AM scheme, and the SB-AM-Worst scheme satisfy the target BER, but the SB-AM-w/o-spreading scheme does not meet the target BER, which has the same throughput performance as the proposed AM scheme. Therefore, the SB-AM-w/o-spreading scheme should reduce the adaptation threshold than the harmonic mean value for satisfying the target BER and it results in a decrease in the throughput.

Table 1 compares the performance and signaling overhead including feed-back and feed-forward signaling of the proposed AM scheme and the conventional schemes. Q indicates the number of bits for SNR quantization at the receiver and $P = \log_2 N_{mod}$, where N_{mod} indicates the number of modulation schemes. The effective BPS is *high* if the BPS is larger than 2.5 where the average SNR value is equal to 25 dB and it is *low*, otherwise. In the SB-AM-w/o-spreading in Table 1, the adaptation criterion is set to the harmonic mean of SNR values in a sub-band, which is the same as that of the SB-AM-w/-spreading.

IV. CONCLUSIONS

A sub-band spreading technique is applied to adaptive modulation in OFDM systems to reduce the complexity and signaling overhead. We consider a fixed threshold adaptation method which only changes the modulation mode with the fixed power and a greedy algorithm which changes the transmit power as well as the modulation mode. The proposed adaptive modulation scheme with sub-band spreading yields better effective throughput performance than the subcarrier-by-subcarrier adaptive modulation scheme when the channel varies quickly in both adaptation schemes. Furthermore, the proposed AM scheme with sub-band spreading satisfies the target BER, while the sub-band based AM scheme without sub-band spreading does not

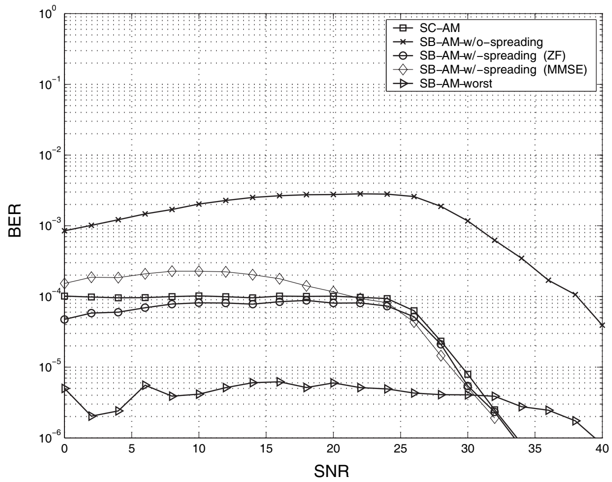

Fig. 7. BER performance comparison between the proposed scheme and the conventional schemes for a target BER value of 10^{-4} when greedy algorithm is applied.

satisfy it.

In this paper, when deriving SNR, the symbols within the same sub-band to be detected are considered separately. However, if those symbols modulated onto the same sub-band are jointly estimated, better performance may be achieved. We leave this topic for further study.

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