Optimal Time-Frequency Block Size and Mode-Switching Level for Adaptive OFDM System

Kil-Ho Shin
Wibro Technology Lab
Telecommunication R&D Center, Samsung Electronics
Suwon, Republic of Korea

Hyung-Myung Kim
Dept of EECS
Korea Advanced Institute of Science and Technology
Daejeon, Republic of Korea

***Abstract*— In this paper, an optimal determination method of the time-frequency block size and mode-switching level is proposed for adaptive OFDM system in frequency-selective time-varying channels. Considering the signaling overhead caused by the mode change information, frequency selectivity, and user's mobility, the optimization problem is formulated in the maximum spectral efficiency sense satisfying the target BER. Assuming that time-frequency block size is given, the mode-switching level is first optimized so that the spectral efficiency can be maximized satisfying the target BER. The time-frequency block size among candidates is then determined, which maximizes the spectral efficiency. Simulation results show that the proposed scheme outperforms conventional schemes, in terms of the spectral efficiency and the BER.**

Keywords- OFDM; spectral efficiency; time-frequency block size; mode-switching level; mode change information; Doppler frequency; rms delay spread

I. INTRODUCTION

In recent wireless communication systems, the need for high data rate services increases. However, high data rate communications are limited by the intersymbol interference (ISI) caused by multipath environments. In order to overcome multipath fading, orthogonal frequency division multiplexing (OFDM) systems adopting multicarriers are considered as potential solutions [1]. An approach for improving the spectral efficiency of OFDM systems in fading channels is to use the adaptive modulation. Based on the channel state information estimated at the receiver, the modulation mode applied to each subcarrier can be changed. The channel state information is usually an instantaneous Signal-to-Noise Ratio (SNR). Instantaneous SNR is fed back to the transmitter through feedback channel and it can be used as the essential information for determining the modulation mode at the transmitter [2].

Generally, in mode-switching-assisted adaptive modulation scenario, the mode-switching level is important parameter to improve the performances, in terms of the throughput and the BER. Up to now, various methods to find suitable mode-switching level have been attempted. Webb and Steele proposed the adaptive QAM with constant symbol rate in additive white Gaussian noise (AWGN) channel, where the mode-switching level was determined according to the SNR satisfying the target BER [3]. Goldsmith determined the suboptimal mode-switching level using the approximated BER of M-QAM [4]. Choi and Hanzo derived the optimum mode-switching level for constant-power adaptive modulation schemes in a flat fading channel using the exact closed-form expression for the average BER of M-QAM [5].

In adaptive OFDM systems, mode change information for all subcarriers should be sent to the receiver, which may increase the signaling overhead and reduce the throughput (bit/symbol) or spectral efficiency (bit/sec/Hertz). In order to reduce the signaling overhead, blockwise adaptive modulations were proposed in [6], [7]. In these schemes, subcarriers are clustered in a frequency block defined as a subband. However, adaptive modulations are performed with fixed mode-switching levels regardless of the block size [3]-[5].

In this paper, we consider the time-frequency block-based adaptive modulation with the variable mode-switching level, which is adaptively determined according to time-frequency block size, i.e., the number of adjacent symbols and subcarriers using the same modulation mode in time-frequency domain. In the proposed scheme, time block size is determined according to user's mobility, i.e., Doppler frequency and frequency block size according to frequency selectivity, i.e., rms delay spread. As the time-frequency block size increases, the signaling overhead decreases. However, the increase of average BER due to the variation of the channel gain within one time-frequency block may lead to fail in satisfying minimum target BER. In order to satisfy the target BER, the mode-switching level should increase. However, as the result, the spectral efficiency will decrease. Some trade-off exist between the time-frequency block size and the mode-switching level. The optimization problem is formulated in a sense of maximizing the spectral efficiency satisfying the target BER. After the mode-switching level is optimized, the time-frequency block size is determined.

The rest of the paper is organized as follows. In section II, the target adaptive OFDM-FDD system is introduced. Section III describes how to determine the optimal time-frequency block size and the mode-switching level in the proposed adaptive OFDM-FDD system and section IV presents the simulation results and performance comparisons. Finally, section V concludes this paper.

II. SYSTEM MODEL

We consider a single user downlink OFDM-FDD system in a single cell-based time-varying frequency-selective channel with L multipaths. It is assumed that equal power is distributed to all subcarriers, and that mode change information is error-

TABLE I. FIVE-MODE ADAPTIVE MODULATION PARAMETER

i	0	1	2	3	4
b_i	0	1	2	4	6
Mode	No Tx	BPSK	QPSK	16QAM	64QAM

free, and that the estimation of Doppler frequency and rms delay spread is perfect. One time-frequency block consists of blocks of N_T adjacent symbols and N_F adjacent subcarriers respectively. At the beginning of the time block, the inclusion of N_p preambles is made. One pilot symbol is inserted in every frequency block during one time block. The time-frequency block size is pairwisely denoted by (N_T , N_F). The same modulation mode is used within one time-frequency block so that the mode change information is sent to the receiver once every time-frequency block via the data channel. The modulation mode is determined based on the SNR of the first pilot symbol within one time-frequency block.

III. OPTIMAL TIME-FREQUENCY BLOCK SIZE AND MODE-SWITCHING LEVEL

A. Problem Formulation

We formulate an optimization problem to determine time-frequency block size and mode-switching level to maximize the spectral efficiency satisfying the target BER. Assuming that the five-mode adaptive modulation is used as shown in TABLE I, the cost function is given by

$$\max_{N_T,N_F,\mathbf{S}(N_T,N_F)} SE(N_T,N_F,\mathbf{S}(N_T,N_F)) \quad \text{subject to } B_{ave} \le B_{tar} \quad (1)$$

where $SE(N_T,N_F,\mathbf{S}(N_T,N_F))$ is the spectral efficiency (bit/sec/Hertz), N_T time block size, N_F frequency block size, $\mathbf{S}(N_T,N_F)$ mode-switching level set, B_{ave} average BER, and B_{tar} target BER. In order to satisfy the BER requirement, the mode-switching level should be changed according to time-frequency block size. Hence, the mode-switching level set is defined as

$$\mathbf{S}(N_T,N_F) = \{s_1(N_T,N_F), s_2(N_T,N_F), s_3(N_T,N_F), s_4(N_T,N_F)\}. \quad (2)$$

The spectral efficiency and the average BER can also be formulated as

$$SE(N_T,N_F,\mathbf{S}(N_T,N_F)) = \frac{(N_T-N_p)(N_F-1)(N/N_F)\sum_{i=0}^{4} b_i \int_{s_i(N_T,N_F)}^{s_{i+1}(N_T,N_F)} f(\gamma)d\gamma - N/N_F(\lceil \log_2 5 \rceil)}{N_T T_s N\Delta f}, \quad (3)$$

$$B_{ave} = \frac{(N/N_F)\sum_{i=0}^{4} b_i \int_{s_i(N_T,N_F)}^{s_{i+1}(N_T,N_F)} \overline{p}_{m_i}(\gamma) f(\gamma)d\gamma}{(N_T-N_p)(N_F-1)(N/N_F)\sum_{i=0}^{4} b_i \int_{s_i(N_T,N_F)}^{s_{i+1}(N_T,N_F)} f(\gamma)d\gamma} \le B_{tar}, \quad (4)$$

where N denotes the total number of subcarriers, N_p the number of preamble symbol, T_s a symbol time, Δf a subcarrier spacing, $s_i(N_T,N_F)$ the mode-switching level needed to transmit a symbol at mode *i*, $(N/N_F)(\lceil \log_2 5 \rceil)$ the total mode change information bit needed to represent five transmission modes, where $\lceil x \rceil$ is the least integer greater than or equal to x , b_i the bit per symbol in mode *i*, and $f(\gamma) = 1/\bar{\gamma}\exp(-\gamma/\bar{\gamma})$ the pdf of the instantaneous channel SNR, γ, in a Rayleigh fading channel with the average channel SNR, $\bar{\gamma}$. Let us define $\overline{p}_{m_i}(\gamma)$ as the sum of the average BER within one time-frequency block when the modulation mode *i* is applied.

$$\overline{p}_{m_i}(\gamma) = \begin{cases} 2\sum_{n=N_p}^{N_T}\sum_{k=1}^{N_F/2-1}\int_0^\infty BER_{m_i}(y) f_{Y(n,k)}(y|\gamma)dy \\ +\sum_{n=N_p}^{N_T}\int_0^\infty BER_{m_i}(y) f_{Y(n,N_F/2)}(y|\gamma)dy & (N_F \ne 2) \\ \sum_{n=N_p}^{N_T}\int_0^\infty BER_{m_i}(y) f_{Y(n,1)}(y|\gamma)dy & (N_F = 2), \end{cases} \quad (5)$$

where $BER_{m_i}(y)$ is a bit error probability (BER) of mode *i* in AWGN channel [3] and $f_{Y(n,k)}(y|\gamma)$ is the conditional pdf of an instantaneous channel SNR, *y*, for *n* symbols away from pilot symbol and *k* subcarriers away from pilot subcarrier when instantaneous SNR of pilot symbol is given by γ .

$$f_{Y(n,k)}(y|\gamma) = \frac{1}{\bar{\gamma}(1-|r_H(n,k)|^2)}\exp\left(-\frac{\frac{y}{\bar{\gamma}} + |r_H(n,k)|^2\frac{\gamma}{\bar{\gamma}}}{1-|r_H(n,k)|^2}\right) I_0\left(\frac{2|r_H(n,k)|\sqrt{\frac{\gamma}{\bar{\gamma}}}}{1-|r_H(n,k)|^2}\sqrt{\frac{y}{\bar{\gamma}}}\right) \quad (6)$$

where $r_H(n,k)$ is the channel correlation function for *n* symbols away from pilot symbol and *k* subcarriers away from pilot subcarrier. $r_H(n,k)$ is given by

$$r_H(n,k) = J_0(2\pi f_d n T_s)\sum_{l=1}^{L}\sigma_l^2 e^{-j2\pi k\Delta f\tau_l} \quad (7)$$

where L , σ_l^2 , f_d , and τ_l are the number of multipath, the power of the *l*th path channel gain, Doppler frequency, and the delay spread of the *l*th path, respectively [8]. The following property is used for the derivation of (6).

Property; In a frequency domain, if the Rayleigh fading channel gain of the the *m*th subcarrier at time *t* in OFDM system is known, the channel gain of the (*m*+*k*)th subcarreir at time $t+nT_s$ has Rician distribution.

The spectral efficiency depends on the mode-switching level and the time-frequency block size. Hence, deriving the joint optimal pair of the time-frequency block size and the mode-switching level is mathematically intractable because the mode-switching level also depends on time-frequency block size. We propose another approach as shown in Fig. 1. First, assuming that time-frequency block size is given, the mode-switching level is optimized in order to maximize the spectral efficiency satisfying the target BER. Second, time-frequency block size among candidates is determined, which maximizes the spectral efficiency.

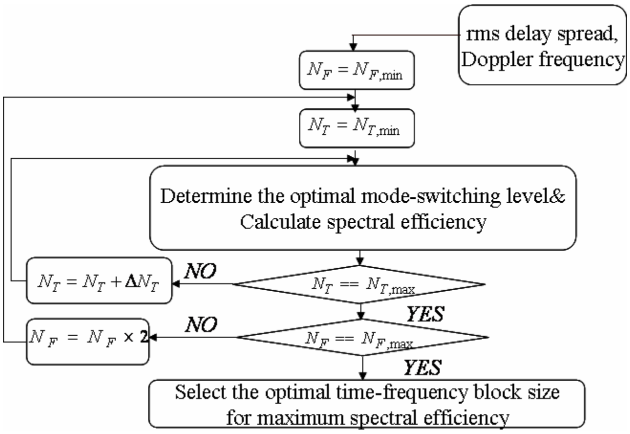

Fig. 1. The proposed adaptive modulation scheme

B. *Decision of Optimal Mode-Switching Level*

When the particular time-frequency block size is given in the channel with fixed Doppler frequency and rms delay spread, we can derive the mode-switching level that maximizes the spectral efficiency satisfying the target BER. We can use the Lagrangian multiplier to solve the optimization problem (1). The modified cost function is rewritten as

$$Z = SE(N_T, N_F, \mathbf{S}(N_T, N_F)) + \lambda \left\{ \begin{array}{l} (N/N_F)\sum_{i=0}^{4} b_i \int_{s_i(N_T,N_F)}^{s_{i+1}(N_T,N_F)} \overline{p}_{m_i}(\gamma) f(\gamma) d\gamma - \\ B_{tar}(N_T - N_p)(N_F - 1)(N/N_F)\sum_{i=0}^{4} b_i \int_{s_i(N_T,N_F)}^{s_{i+1}(N_T,N_F)} f(\gamma) d\gamma \end{array} \right\} \quad (8)$$

To find the optimal mode-switching level, the following conditions should be satisfied.

$$\frac{\partial Z}{\partial s_i(N_T, N_F)} = 0 \quad (9)$$

$$\frac{\partial Z}{\partial \lambda} = 0 \quad (10)$$

Rearranging (10), we can obtain

$$\begin{aligned} &\frac{\partial Z}{\partial s_i(N_T, N_F)} \\ &= \frac{(N_T - N_p)(N_F - 1)/N_F(b_{i-1} - b_i) f(s_i(N_T, N_F))}{N_T T_s \Delta f} \\ &+ \lambda \left\{ \begin{array}{l} -\, b_i \overline{p}_{m_i}(s_i(N_T, N_F)) \\ + b_{i-1} \overline{p}_{m_{i-1}}(s_i(N_T, N_F)) \end{array} \right\} f(s_i(N_T, N_F)) \\ &- \lambda B_{tar}(N_T - N_p)(N_F - 1)\,(b_{i-1} - b_i) f(s_i(N_T, N_F)) = 0. \end{aligned} \quad (11)$$

From (11), we can also obtain

$$f(s_i(N_T, N_F)) \left[\begin{array}{l} (N_T - N_p)(N_F - 1)(b_{i-1} - b_i) \\ \left(\frac{1}{N_T N_F T_s \Delta f} - \lambda B_{tar}\right) \\ + \lambda \left\{ \begin{array}{l} -\, b_i \overline{p}_{m_i}(s_i(N_T, N_F)) \\ + b_{i-1} \overline{p}_{m_{i-1}}(s_i(N_T, N_F)) \end{array} \right\} \end{array} \right] = 0 \quad (12)$$

In (12), the trivial solution, $f(s_i(N_T, N_F)) = 0$, is not considered. After rearranging (12) in the case of i=1 and eliminating the Lagrangian multiplier, λ , (12) is rewritten as

$$\overline{p}_{m_1}(s_1(N_T, N_F)) = \frac{b_i \overline{p}_{m_i}(s_i(N_T, N_F)) - b_{i-1}\overline{p}_{m_{i-1}}(s_i(N_T, N_F))}{b_i - b_{i-1}}. \quad (13)$$

If we newly define the left hand side and right hand side of (13) as $Y_1(s_1(N_T, N_F))$ and $Y_2(s_2(N_T, N_F))$, respectively, then we have

$$Y_1(s_1(N_T, N_F)) = Y_i(s_i(N_T, N_F)) \quad \text{for i = 2,3,4}, \quad (14).$$

If $Y_i(s_i(N_T, N_F))$ has the monotonous property, there exists the inverse of $Y_i(s_i(N_T, N_F))$ and then we can determine a unique $s_i(N_T, N_F)$ from $Y_1(s_1(N_T, N_F))$. Hence, it is necessary to show the existence of the inverse of $Y_i(s_i(N_T, N_F))$.

Let us define $\beta_1(y)$ and $\beta_i(y)$ as

$$\beta_1(y) = BER_{m_1}(y) \quad (15)$$

$$\beta_i(y) = \frac{b_i BER_{m_i}(y) - b_{i-1} BER_{m_{i-1}}(y)}{b_i - b_{i-1}}. \quad (16)$$

Then, $Y_1(s_1(N_T, N_F))$ and $Y_2(s_2(N_T, N_F))$ can be rewritten as

$$Y_1(s_1(N_T, N_F)) = \left\{ \begin{array}{ll} \int_0^\infty \beta_1(y) \left[\sum_{n=N_p}^{N_T} \left(\begin{array}{l} 2\sum_{k=1}^{N_F/2-1} f_{Y(n,k)}(y|s_1(N_T, N_F)) \\ + f_{Y(n,N_F/2)}(y|s_1(N_T, N_F)) \end{array} \right) \right] dy & (N_F \neq 2) \\ \int_0^\infty \beta_1(y) \left[\sum_{n=N_p}^{N_T} f_{Y(n,1)}(y|s_1(N_T, N_F)) \right] dy & (N_F = 2), \end{array} \right. \quad (17)$$

$$Y_i(s_i(N_T, N_F)) = \left\{ \begin{array}{ll} \int_0^\infty \beta_i(y) \left[\sum_{n=N_p}^{N_T} \left(\begin{array}{l} 2\sum_{k=1}^{N_F/2-1} f_{Y(n,k)}(y|s_i(N_T, N_F)) \\ + f_{Y(n,N_T/2)}(y|s_i(N_T, N_F)) \end{array} \right) \right] dy & (N_F \neq 2) \\ \int_0^\infty \beta_i(y) \left[\sum_{n=N_p}^{N_T} f_{Y(1,n)}(y|s_i(N_T, N_F)) \right] dy & (N_F = 2). \end{array} \right. \quad (18)$$

Let us define the noncentrality parameter S and variance V as follows.

$$S = |r_H(n,k)| \sqrt{\frac{s_i(N_T, N_F)}{\overline{\gamma}}}. \quad (19)$$

$$V = \frac{1}{2}(1 - |r_H(n,k)|^2). \quad (20)$$

Let $F_{Y(n,k)}(t \mid s_i(N_T, N_F))$ be

$$F_{Y(n,k)}(t \mid s_i(N_T, N_F)) = \int_0^t f_{Y(n,k)}(y|s_i(N_T, N_F))dy, \quad t > 0 \quad (21)$$

When n,k are fixed, (21) is a monotonic decreasing function for $s_i(N_T, N_F)$ since $f_{Y(n,k)}(y|s_i(N_T, N_F))$ achieves its maximum value when y is S. $\beta_1(y)$ and $\beta_2(y)$ are the monotonic decreasing functions of y [5]. Both $Y_1(s_1(N_T, N_F))$ and $Y_2(s_1(N_T, N_F))$ are also monotonically decreasing as $s_1(N_T, N_F)$ and $s_2(N_T, N_F)$ increase, respectively. However, $\beta_3(y)$ and $\beta_4(y)$ are not monotonic decreasing [5]. Accordingly, $Y_3(s_3(N_T, N_F))$ and $Y_4(s_4(N_T, N_F))$ are not monotonic decreasing function of $s_3(N_T, N_F)$ and $s_4(N_T, N_F)$, respectively. Therefore, multiple roots satisfying (14) may exist. Note that low value of mode-switching level implies the high average channel SNR. In Webb's scheme [3] most frequently used in conventional adaptive modulation schemes, the typical value of $s_3(N_T, N_F)$ and $s_4(N_T, N_F)$ are 16.57dB and 22.95dB, respectively. If both $s_3(N_T, N_F)$ and $s_4(N_T, N_F)$ are less than -12.3dB and -0.4dB, respectively, such a case corresponds to the values of average channel SNR which is not in the range of our interests, i.e., 7-30dB. Therefore, it is reasonable that the values $s_3(N_T, N_F)$ and $s_4(N_T, N_F)$ should be larger than -12.3dB and -0.4dB, respectively. Hence, we can conclude that $Y_3(s_3(N_T, N_F))$ and $Y_4(s_4(N_T, N_F))$ are monotonically decreasing with respect to mode-switching level in the range of our interests. Hence, the mode-switching level set depend on $s_1(N_T, N_F)$ and it is given by

$$\begin{aligned} \mathbf{S}(N_T, N_F) &= \mathbf{S}(s_1(N_T, N_F)) \\ &= \left\{ \begin{matrix} s_1(N_T, N_F), s_2(s_1(N_T, N_F)), \\ s_3(s_1(N_T, N_F)), s_4(s_1(N_T, N_F)) \end{matrix} \right\}. \end{aligned} \quad (22)$$

We should find the optimal $s_1(N_T, N_F)$ satisfying the target BER. After we multiply (4) by the denominator of left hand side of (4) and then moving the right hand side into its left hand side, we define $T(\mathbf{S}(s_1(N_T, N_F)))$ using $\mathbf{S}(s_1(N_T, N_F))$ as

$$\begin{aligned} &T(\mathbf{S}(s_1(N_T, N_F))) \\ &= E(\mathbf{S}(s_1(N_T, N_F))) - B_{tar} B(\mathbf{S}(s_1(N_T, N_F))) \end{aligned} \quad (23)$$

where

$$\begin{aligned} &E(\mathbf{S}(s_1(N_T, N_F))) \\ &= (N/N_F) \sum_{i=0}^{4} b_i \int_{s_i(N_T,N_F)}^{s_{i+1}(N_T,N_F)} \overline{p}_{m_i}(\gamma) f(\gamma) d\gamma \end{aligned} \quad (24)$$

$$\begin{aligned} &B(\mathbf{S}(s_1(N_T, N_F))) \\ &= (N_T - N_p)(N_F - 1)(N/N_F) \sum_{i=0}^{4} b_i \int_{s_i(N_T,N_F)}^{s_{i+1}(N_T,N_F)} f(\gamma) d\gamma. \end{aligned} \quad (25)$$

To satisfy the target BER requirement, the mode-switching level set should satisfy

$$T(\mathbf{S}(s_1(N_T, N_F))) \le 0. \quad (26)$$

TABLE II. CONVELTIONAL SCHEMES

	The mode decision method	The mode-switching levels used
Scheme 1	One pilot's SNR in a frequency block	Webb's scheme [3]
Scheme 2	Each subcarrier's SNR	Webb's scheme [3]
Scheme 3	One pilot's SNR in a frequency block	Choi's scheme [5]
Scheme 4	Each subcarrier's SNR	Choi's scheme [5]

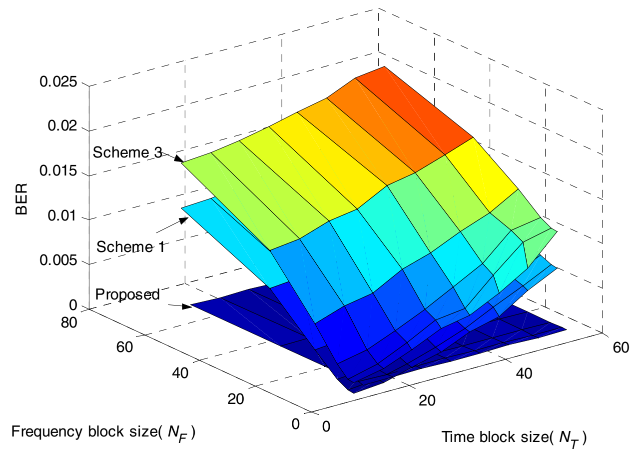

Fig. 2. BER versus time-frequency block size ($f_d = 50$Hz, $\tau_{rms} = 1260$nsec)

In order to maximize the spectral efficiency, the smallest $s_1(N_T, N_F)$ satisfying (26) should be selected as an optimal mode-switching level, i.e., $s_{1,opt}(N_T, N_F)$. With $s_{1,opt}(N_T, N_F)$, we can determine the unique $s_{2,opt}(N_T, N_F)$, $s_{3,opt}(N_T, N_F)$, and $s_{4,opt}(N_T, N_F)$.

C. Decision of Optimal Time-Frequency Block Size

In subsection III-*B*, assuming that the time-frequency block size is given among the candidate set, we determined the mode-switching level that maximizes the spectral efficiency satisfying the BER requirement. Based on the determined mode-switching level set, we can calculate the spectral efficiency and determine the optimal time-frequency block size that maximizes the spectral efficiency among the candidate set as

$$(N_{T,opt}, N_{F,opt}) = \arg\max_{N_T, N_F} SE(N_T, N_F, \mathbf{S}_{opt}(N_T, N_F)) \quad (27)$$

where $\mathbf{S}_{opt}(N_T, N_F)$ is the optimal mode-switching level set given N_T and N_F.

IV. SIMULATION RESULTS

The simulation is performed in 2.3GHz OFDM-FDD system with N=1024, T_s=102.4μsec, $\Delta f = 9.765$kHz, $\bar{\gamma}$=20dB,

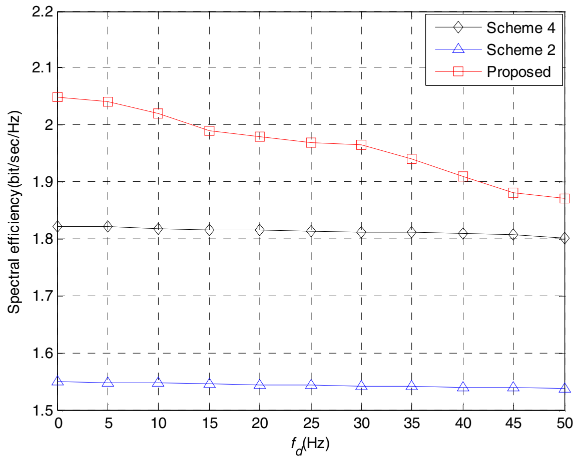

Fig. 3. The spectral efficiency versus Doppler frequency
($\tau_{rms} = 0n\sec, N_T = 24, N_F = 8$)

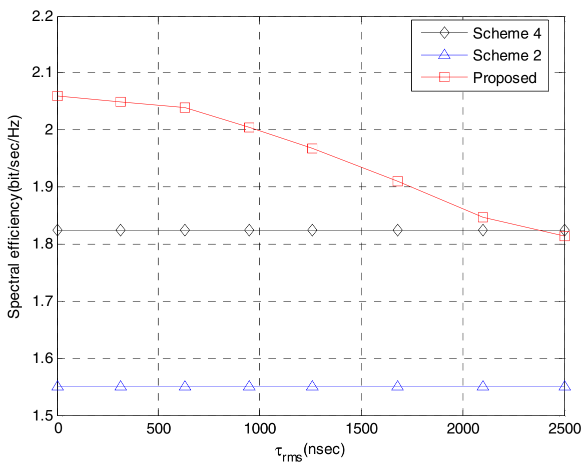

Fig. 4. The spectral efficiency versus rms delay spread
($f_d = 0\text{Hz}, N_T = 24, N_F = 8$)

N_p =2, $P_{th} = 10^{-3}$. The candidate set of time and frequency block size are {2,4,6,8,16,32,64} and {12,18,24,30, 36,42,48, 54} respectively. Note that the channel model is ITU-R pedestrian channel B. For the performance comparisons, we considered four conventional adaptive modulation schemes, which are illustrated in Table II. When target BER is 10^{-3} with average channel SNR 20dB, the mode-switching level set used in Choi's scheme is (4.05dB, 7.88dB, 14.52dB, 20.95dB) and the mode-switching level set used in Webb's scheme is (6.81dB, 9.82dB, 16.57dB, 22.95dB). Fig. 2 shows the BER performances for the proposed scheme and scheme 1 and 3. It is shown that scheme 1 and 3 do not satisfy the target BER as the time-frequency block size increases, while the proposed scheme satisfies the target BER regardless of the time-frequency size. In Fig. 3, the spectral efficiency in the proposed scheme is 4%($f_d = 50\text{Hz}$)- 20%($f_d = 0\text{Hz}$) higher than scheme 2 and about 23%($f_d = 50\text{Hz}$)-32%($f_d = 0\text{Hz}$) higher than scheme 4, respectively. Also, in Fig. 4, the spectral efficiency in the proposed scheme is about 29%($\tau_{rms} = 1000n\sec$)-32% ($\tau_{rms} = 0n\sec$) higher than scheme 2 and 12%($\tau_{rms} = 1000n\sec$)-20% ($\tau_{rms} = 0n\sec$) higher than scheme 4, respectively. The main reason of the gain in spectral efficiency of Fig. 3 and Fig. 4 is the reduced signaling overhead in the proposed scheme compared with that in the scheme 2 and scheme 4.

V. CONCLUSION

Optimal time-frequency block size and mode-switching level were derived for a single user downlink adaptive OFDM-FDD system. Applying the proposed scheme, we can reduce the signaling overhead so that the spectral efficiency can be maximized satisfying the target BER. The proposed scheme outperforms conventional schemes, which employ subcarrier-based and frequency block-based adaptive modulation with the fixed mode switching levels, in terms of the spectral efficiency and the BER. This proposed scheme can be directly extended to a single user uplink adaptive OFDM-FDD system. Therefore, it is believed that the time-frequency block size and the mode-switching level obtained in the proposed scheme can play an important role in designing the adaptive OFDM-FDD system.

REFERENCES

[1] J. A. C. Bingham, "Multicarrier modulation for data transmission: An idea whose time has come," *IEEE Commun. Mag.*, vol. 28, pp. 5–14, May 1990.

[2] L. Hanzo, W. Webb, and T. Keller, *Single and Multi–Carrier Quadrature Amplitude Modulation.* New York: Wiley; IEEE Press, 2000.

[3] W. T. Webb and R. Steele, "Variable rate QAM for mobile radio," *IEEE Trans. Commun.*, vol. 43, pp. 2223–2230, July 1995.

[4] S. T. Chung and A. J. Goldsmith, "Degrees of freedom in adaptive modulation: A unified view," *IEEE Trans. Commun.*, vol. 49, pp. 1561-1571, Sep. 2001.

[5] B. J. Choi and L. Hanzo, "Optimum mode-switching-assisted constant-power single- and multicarrier adaptive modulation," *IEEE Trans. Veh. Technol.*, vol. 52, pp. 536-560, May 2003.

[6] T. Keller and L. Hanzo, "Adaptive modulation techniques for duplex OFDM transmission," *IEEE Trans. Veh. Technol.*, vol. 49, pp. 1893-1906, Sep. 2000.

[7] R. Grunheid, E. Bolinth, and H. Rohling, "A blockwise loading algorithm for the adaptive modulation technique in OFDM systems," in *Proc. Veh. Technol. Conf. 2001 Fall*, vol. 2, pp. 948-951, Oct. 2001.

[8] Y. Li, L. J. Cimini Jr., and N. R. Sollenberger, "Robust channel estimation for OFDM Systems with rapid dispersive fading channels," *IEEE Trans. Commun.*, vol. 46, pp. 902-915, July 1998.