LTE-Advanced에서 프리코딩에 의한 효율적인 상향링크 적응 방식

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Efficient Link Adaptation Scheme using Precoding for LTE-Advanced Uplink MIMO

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요 약

LTE-Advanced 시스템은 최대 15bps/Hz의 주파수 효율을 달성하기 위해 상향링크 다중 안테나 전송을 지원해야 한다. 본 논문은 LTE-Advanced 상향링크 MIMO 시스템 구조를 제안하고 프리코딩에 의한 링크 적응방식을 고려하여 단말당 오류율을 줄이고 시스템 용량을 향상시키는데 기여할 수 있다. 특히, 2x4 MIMO 시스템에서 최적의 프리코딩 행렬을 선택하여 랭크를 결정하는 방식을 제안하고 MMSE(minimum mean squared error) 수신기에 대한 SINR(signal-to-interference and noise ratio)을 유도한다. 제안 방식의 성능 검증을 위해 실질적인 MIMO 채널 모델에서 BLER(BLock Error Rate) 시뮬레이션을 수행한다. 제안 방식이 full-rank로 고정해서 보내는 경우보다 더 좋은 성능을 발휘하며 MCS가 낮거나 고속 이동시에 더 큰 이득을 얻을 수 있다.

Key Words : LTE-Advanced, DFT-Spread-OFDMA, MIMO, Precoding, Rank

ABSTRACT

LTE-Advanced system requires uplink multi-antenna transmission in order to achieve the peak spectral efficiency of 15bps/Hz. In this paper, the uplink MIMO system model for the LTE-Advanced is proposed and an efficient link adaptation shceme using precoding is considered providing error rate reduction and system capacity enhancement. In particular, the proposed scheme determines a transmission rank by selecting the optimal wideband precoding matrix, which is based on the derived signal-to-interference and noise ratio (SINR) for the minimum mean squared error (MMSE) receivers of 2x4 multiple input multiple output (MIMO). The proposed scheme is verified by simulation with a practical MIMO channel model. The simulation results of average block-error-rate(BLER) reflect that the gain due to the proposed rank adapted transmission over full-rank transmission is evident particularly in the case of lower modulation and coding scheme (MCS) and high mobility, which means the severe channel fading environment.

Ⅰ. Introduction

Further advancement of 3GPP Long-Term Evolution (LTE) is termed as LTE-Advanced, which is targeted to fulfill the requirements of IMT-Advanced.

The LTE-Advanced should reach a downlink peak data rate of 1Gbps and an uplink peak data rate of 500Mbps from a system requirement viewpoint[1]. The higher peak data rates can be

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fulfilled in wider bandwidth, which is supported by carrier aggregation up to 100MHz[2].

DFT-spread-OFDMA (DFT-SOFMA) is the transmission scheme for the LTE-Advanced uplink. There is only one DFT per component carrier even in the presence of multiple component carriers. Furthermore, both frequency contiguous and frequency-non-contiguous resource allocation is supported on each component carrier[3].

In addition, the LTE-Advanced should support multi-antenna transmission schemes such as spatial multiplexing and transmit diversity. In particular, the uplink spatial multiplexing is required to reach the peak spectral-efficiency target of 15bps/Hz. In the uplink single user spatial multiplexing, up to two transport blocks can be transmitted from a scheduled UE in a subframe per uplink component carrier.

The research goal is to derive SINRs and propose an efficient selection scheme of an optimal precoding matrix for the single user spatial multiplexing DFT-SOFDMA. The optimal precoding matrix can be selected using the derived SINR and channel quality measurements. Therefore, the number and amount of data streams to be transmitted can be adapted with minimizing error rates so that the channel capacity is maximized without implementation complexity[4].

To achieve the above goals, we assume that the UE shall support multi-antenna transmission and the eNodeB sahll select an optimal precoding matrix per UE in such a way of maximizing channel capacity.

Section II presents the system model of 2x4 MIMO DFT-SOFDMA for the LTE-Advanced uplink, and further Section III derives the SINR for MMSE receivers. Section IV proposes the precoding matrix selection scheme as well as the channel quality measurement scheme from sounding reference signals. Simulation results are discussed in Section V, and finally this paper is concluded in Section VI.

Ⅱ. DFT-SOFDMA System Model

DFT-SOFMA is the transmission scheme for the LTE-Advanced physical uplink shared channel (PUSCH). Fig. 1 shows a system model of a MIMO DFT-SOFDMA transmitter with two codewords and two transmit antennas. A codeword corresponds to a sequence of data stream. Each codeword is scrambled with a UE-specific scrambling sequence and then modulated resulting in a block of complex-valued symbols[5][6]. The complex-valued modulation symbol for each codeword is mapped onto the layers prior to layer shifting. If layer shifting is configured, precoding is applied after the layer shifting. Otherwise, precoding is applied after the layer mapping.

The layer mapping and shifting generates a block of vectors, $D = \left[D^{(0)} D^{(1)} \cdots D^{(L-1)}\right]$ and L is the total number of data streams. The block of complex-valued symbols for the lth stream is mapped onto antenna port p and is denoted as a

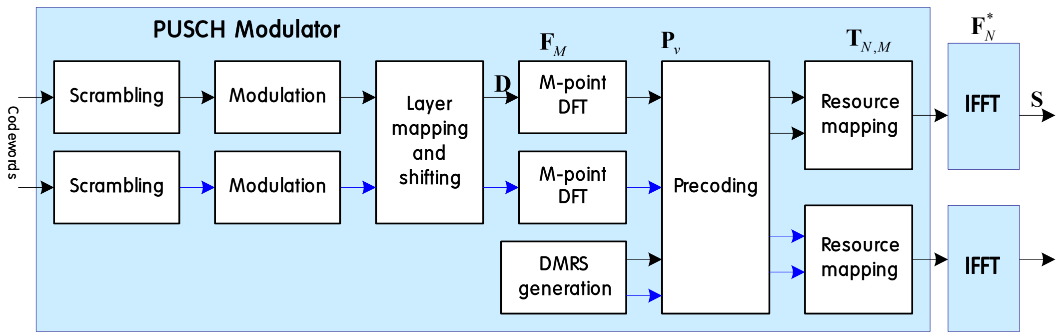

Fig. 1. MIMO DFT-SOFDMA transmitter for LTE-Advanced

vector of M elements.

$$\mathbf{D}^{(l)} = \left[d_0 \quad d_1 \quad \cdots \quad d_{M-1} \right]^T \tag{1}$$

The transmit signal vector without cyclic prefix(CP) is denoted as $S = \left[S^{(0)} S^{(1)} \cdots S^{(P-1)} \right]$ and given as following.

$$\mathbf{S} = \mathbf{F}_N^* \mathbf{T}_{N,M} \mathbf{P}_v \mathbf{F}_M \mathbf{D} \tag{2}$$

where P is the total number of transmit antennas, F_M is the M-point DFT, P_v is the precoding matrix, $T_{N,M}$ is the resource mapping matrix and F_N^* is the N-point IFFT. Each IFFT generates complex-valued time-domain DFT-SOFDMA signal for each antenna port.

After the N-point FFT in the receiving side, the received signal vector in the frequency domain is given as

$$\mathbf{R} = \mathbf{H}\mathbf{T}_{N,M} \mathbf{P}_v \mathbf{F}_M \mathbf{D} + \mathbf{Z} \tag{3}$$

where H is the frequency domain channel response and Z is the received noise. In case of two transmit antennas and J receive antennas, the channel matrix at kth subcarrier is represented as

$$\mathbf{H}_k = \begin{bmatrix} H_k^{00} & H_k^{10} \\ H_k^{01} & H_k^{11} \\ \vdots & \vdots \\ H_k^{0(J-1)} & H_k^{1(J-1)} \end{bmatrix} \tag{4}$$

where H_k^{pj} represents the frequency domain channel response at the kth subcarrier from the pth transmit antenna to the jth receive antenna.

If we denote the frequency domain equalization as G, the decision signal after IDFT is given as

$$\hat{\mathbf{D}} = \mathbf{F}_M^\dagger \mathbf{T}_{N,M}^\dagger \mathbf{G}(\mathbf{H}\mathbf{T}_{N,M} \mathbf{P}_v \mathbf{F}_M \mathbf{D} + \mathbf{Z}) \tag{5}$$

where $H_v = HP_v$.

Ⅲ. SINR Derivation

In [7], the post detection SINR for DFT-SOFDMA is derived for SISO when MMSE equalizer is adopted. In [8], the closed-loop precoding multirank transmission was evaluated for LTE-Advanced uplink based on simplified effective SNR.

However, we need to derive the exact post detection SINR for MIMO DFT-SOFDMA with multi-stream in order to realize efficient link adaptation in the future LTE-Advanced uplink.

The post-detection SINR for MIMO DFT-SOFDMA with MMSE equalizer can be more precisely analyzed according to the number of data streams when one or two data streams can be transmitted using spatial multiplexing with two transmit antennas. Most of all, the number of data streams determines the dimension of precoding matrix. The SINR for the MIMO receiver is usually impaired by multi-stream interference, channel fading and noise[9],[10].

3.1 Single stream transmission

First, denote the precoding matrix as $P_v = \left[v_0 \ v_1 \right]^T$ in case of single data stream (L=1). Therefore, the precoded channel matrix is simplified to the SIMO case as derived in equation (6).

$$\mathbf{H}_v = \begin{bmatrix} H_{v,k}^0 \\ H_{v,k}^1 \\ \vdots \\ H_{v,k}^{J-1} \end{bmatrix} = \begin{bmatrix} v_0 H_k^{00} + v_1 H_k^{10} \\ v_0 H_k^{01} + v_1 H_k^{11} \\ \vdots \\ v_0 H_k^{0(J-1)} + v_1 H_k^{1(J-1)} \end{bmatrix} \tag{6}$$

The frequency-domain MMSE equalization for the jth receive antenna, G_k^j is derived in (7).

$$G_k^j = \frac{H_{v,k}^{j*}}{\sum_{j=0}^{J-1} \left| H_{v,k}^j \right|^2 + \sigma^2}, \quad j = 0,1,..,J-1 \tag{7}$$

Using equation (6) and (7), the signal power is given as

$$P_S = \left| \frac{1}{M} \sum_{k=0}^{M-1} \mathbf{G}\mathbf{H}_v \right|^2 = \left| \frac{1}{M} \sum_{k=0}^{M-1} \frac{\sum_{j=0}^{J-1} \left| H_{v,k}^{j} \right|^2}{\sum_{j=0}^{J-1} \left| H_{v,k}^{j} \right|^2 + \sigma^2} \right|^2 \tag{8}$$

The noise variance is estimated by

$$\hat{\sigma}^2 = \frac{1}{M} \sum_{k=0}^{M-1} \left| \mathbf{G} \right|^2 \sigma^2 = \frac{1}{M} \sum_{k=0}^{M-1} \sum_{j=0}^{J-1} \left| G_k^j \right|^2 \sigma^2 \tag{9}$$

In addition, the multi-stream interference (I) is given as

$$\begin{aligned} I &= P_T - P_S \\ &= \frac{1}{M} \sum_{k=0}^{M-1} \left| \frac{\sum_{j=0}^{J-1} \left| H_{v,k}^{j} \right|^2}{\sum_{j=0}^{J-1} \left| H_{v,k}^{j} \right|^2 + \sigma^2} \right|^2 - \left| \frac{1}{M} \sum_{k=0}^{M-1} \frac{\sum_{j=0}^{J-1} \left| H_{v,k}^{j} \right|^2}{\sum_{j=0}^{J-1} \left| H_{v,k}^{j} \right|^2 + \sigma^2} \right|^2 \end{aligned} \tag{10}$$

where P_T is the total transmitted power.

As a result, the SINR for DFT-SOFDMA MIMO receiver with single stream is derived by

$$SINR = \frac{P_S}{I + \hat{\sigma}^2} = \left(\left(\frac{1}{M} \sum_{k=0}^{M-1} \frac{\sum_{j=0}^{J-1} \left| H_{v,k}^{j} \right|^2}{\sum_{j=0}^{J-1} \left| H_{v,k}^{j} \right|^2 + \sigma^2} \right)^{-1} - 1 \right)^{-1} \tag{11}$$

3.2 Two streams transmission

In case of two data streams, the precoding matrix can be denoted as $P_\nu = I_2/\sqrt{2}$, then. $H_\nu = H/\sqrt{2}$. The MMSE equalization vector for spatial multiplexing, G is given as

$$\begin{aligned} \mathbf{G} &= \left(\mathbf{H}_v^H \mathbf{H}_v + L \cdot \sigma^2 \mathbf{I}_L \right)^{-1} \mathbf{H}_v^H \\ &= \frac{1}{Det} \begin{bmatrix} \alpha_0 & \alpha_1 & \alpha_2 & \alpha_3 \\ \beta_0 & \beta_1 & \beta_2 & \beta_3 \end{bmatrix} \end{aligned} \tag{12}$$

where

$$\begin{aligned} Det &= \sum_{j=0}^{J-1} \left| H_{v,k}^{0j} \right|^2 \sum_{j=0}^{J-1} \left| H_{v,k}^{1j} \right|^2 + 2 \sum_{j=0}^{J-1} \left| H_{v,k}^{0j} \right|^2 \sigma^2 \\ &\quad + 2 \sum_{j=0}^{J-1} \left| H_{v,k}^{1j} \right|^2 \sigma^2 + 4\sigma^4 - \left| \sum_{j=0}^{J-1} H_{v,k}^{0j*} \cdot H_{v,k}^{1j} \right|^2 \end{aligned}$$

In DFT-SOFDMA, all symbols transmitted on M subcarriers have the same signal power for each stream.

$$P_S^l = \left| \frac{1}{M} \sum_{k=0}^{M-1} \mathbf{G}_l \mathbf{H}_v \right|^2 \tag{13}$$

where l indicates the stream index and G_l represents the lth row of G.

The estimated noise variance for each stream is given as

$$\hat{\sigma}_l^2 = \frac{1}{M} \sum_{k=0}^{M-1} \left| \mathbf{G}_l \right|^2 \sigma^2 \tag{14}$$

Also, all symbols transmitted on M subcarriers experience the same amount of multi-stream interference. Therefore, the multi-stream interference (I_l) is given as

$$I_l = P_T^l - P_S^l = \frac{1}{M} \sum_{k=0}^{M-1} \left| \mathbf{G}_l \mathbf{H}_v \right|^2 - \left| \frac{1}{M} \sum_{k=0}^{M-1} \mathbf{G}_l \mathbf{H}_v \right|^2 \tag{15}$$

As a result, the SINR for each stream is derived by

$$SINR^l = \frac{P_S^l}{I_l + \hat{\sigma}_l^2} = \left(\left(\frac{\Lambda_l}{M} \right)^{-1} - 1 \right)^{-1}, l = 0,1 \tag{16}$$

where $\Lambda_l = N_l / D_l$

$$N_0 = \left| \sum_{k=0}^{M-1} \frac{\sum_{j=0}^{J-1} \left| H_{v,k}^{0j} \right|^2 \sum_{j=0}^{J-1} \left| H_{v,k}^{1j} \right|^2 + 2 \sum_{j=0}^{J-1} \left| H_{v,k}^{0j} \right|^2 \sigma^2 - \left| \sum_{j=0}^{J-1} H_{v,k}^{0j*} \cdot H_{v,k}^{1j} \right|^2}{Det} \right|^2$$

$$D_0 = \sum_{k=0}^{M-1} \frac{\left(\sum_{j=0}^{J-1} \left| H_{v,k}^{0j} \right|^2 \sum_{j=0}^{J-1} \left| H_{v,k}^{1j} \right|^2 + 2 \sum_{j=0}^{J-1} \left| H_{v,k}^{0j} \right|^2 \sigma^2 - \left| \sum_{j=0}^{J-1} H_{v,k}^{0j*} \cdot H_{v,k}^{1j} \right|^2 \right)^2 + \sigma^2 \left(4 \left| \sum_{j=0}^{J-1} H_{v,k}^{0j*} \cdot H_{v,k}^{1j} \right|^2 \sigma^2 + \sum_{j=0}^{J-1} \left| \alpha_j \right|^2 \right)}{Det^2}$$

$$N_1 = \left| \sum_{k=0}^{M-1} \frac{\left(\sum_{j=0}^{J-1} \left| H_{v,k}^{0j} \right|^2 \sum_{j=0}^{J-1} \left| H_{v,k}^{1j} \right|^2 + 2 \sum_{j=0}^{J-1} \left| H_{v,k}^{1j} \right|^2 \sigma^2 - \left| \sum_{j=0}^{J-1} H_{v,k}^{0j*} \cdot H_{v,k}^{1j} \right|^2 \right)}{Det} \right|^2$$

$$D_1 = \sum_{k=0}^{M-1} \frac{\left(\sum_{j=0}^{J-1} \left| H_{v,k}^{0j} \right|^2 \sum_{j=0}^{J-1} \left| H_{v,k}^{1j} \right|^2 + 2 \sum_{j=0}^{J-1} \left| H_{v,k}^{1j} \right|^2 \sigma^2 - \left| \sum_{j=0}^{J-1} H_{v,k}^{0j*} \cdot H_{v,k}^{1j} \right|^2 \right)^2 + \sigma^2 \left(4 \left| \sum_{j=0}^{J-1} H_{v,k}^{0j*} \cdot H_{v,k}^{1j} \right|^2 \sigma^2 + \sum_{j=0}^{J-1} \left| \beta_j \right|^2 \right)}{Det^2}$$

Ⅳ. Rank Adaptation Scheme

We consider the MIMO DFT-SOFDMA with two transmit antennas and four receive antennas as shown in Fig. 2. In particular, sounding reference signals (SRS) shall be transmitted in the uplink to enable the eNodeB to estimate MIMO channel matrix jointly from consecutive SRS transmissions. Then, the precoding matrix can be selected based on the derived SINR for each data stream at the eNodeB side.

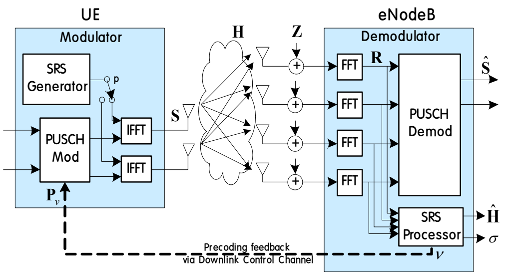

Fig. 2. Precoding selection and feedback for 2x4 Uplink MIMO

4.1 Uplink MIMO channel estimation

In order to calculate the post-detection SINR for multiple data stream as described in section Ⅲ, the MIMO channel response should be estimated utilizing the sounding reference signal.

However, in the existing LTE system, the sounding reference signal is non-precoded and transmitted by single antenna at time n. In case of multi-antenna transmission, the index p of the UE antenna that transmits the sounding reference signal at time n should be selected in order to obtain MIMO channel response at the eNodeB.

In this paper, we assume that a wideband sounding reference signal transmission is configured even though UE antenna selection is disabled[11], then the antenna index is given by

$$p = n \bmod P \tag{17}$$

Fig. 3 illustrates the instances of wideband sounding reference signal transmission using two transmit antennas. The sounding reference signal is transmitted in the last symbol of the SRS transmission subframe over M_{SRS} subcarriers with the antenna of p=0 or p=1 alternately. The SRS transmission subframe is spaced at intervals of SRS periodicity. We assume that single transmission over M_{SRS} shall cover the entire frequency band[12]. When the channel is fast varying, SRS periodicity should be as short as possible to track channel variations.

Fig. 4 depicts the functional block diagram of SRS processor using four receive antennas (J=4) based on least-square estimation[13],[14]. The SRS processor estimates subband channel quality indicators (CQI) and selects a wideband precoding matrix index (PMI) based on the previously estimated SINRs.

When a UE transmits sounding reference signal with the pth transmit antenna at time n, the

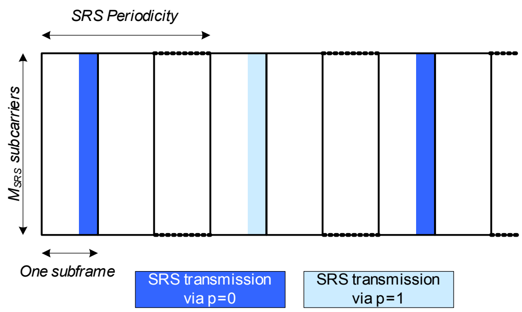

Fig. 3. Wideband SRS transmission (P=2)

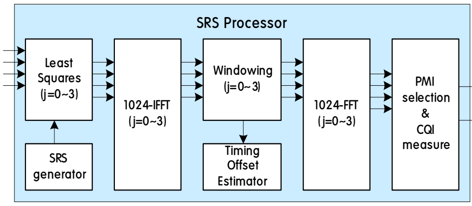

Fig. 4. SRS processing using four receive antennas

eNodeB can extract the partial frequency domain channel response, $\left[H_k^{p0}\ H_k^{p1}\ \cdots\ H_k^{p(J-1)}\right]^T$ over M_{SRS} subcarriers (k=0,1,⋯, M_{SRS}-1). Without delay consideration, the MIMO channel matrix at time n can be obtained by combining the currently estimated partial channel response with the previously estimated partial channel response at time (n-1).

In addition, the noise variance σ^2 shall be calculated by applying MMSE equalization to the received sounding reference signals from J receive antennas.

$$\sigma^2 = \frac{1}{2J(M_{SRS}-1)} \sum_{k=0}^{M_{SRS}-2} \sum_{j=0}^{J-1} \left| \frac{\hat{d}_k}{d_k} - \frac{\hat{d}_{k+1}}{d_{k+1}} \right|^2 \tag{18}$$

where d_k and $\widehat{d_k}$ are the transmitted sounding reference signal and the detected sounding reference signal at kth subcarrier, respectively.

4.2 Precoding selection criteria

The demodulator shall select an optimal precoding matrix depending on MIMO channel states. We propose that the selected precoding matrix index for uplink spatial multiplexing should be newly included in a scheduling grant, which is transmitted via downlink control channel. For uplink spatial multiplexing with two transmit antennas, the 3-bit feedback of precoding matrix index, v is mapped onto a precoding matrix (P_v) by the modulator. Consequently, the transmission rank can be adapted dynamically according to the precoding feedback.

We assume that the eNodeB selects an optimal precoding matrix per UE based on capacity maximizing criteria. Therefore, an optimal precoding matrix to be feedback to the UE is given as

Table 1. Precoding Codebook (P=2)

PMI (v)	Precoding matrix (P_v)	Number of layers
0	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\end{bmatrix}^T$	1
1	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & -1\end{bmatrix}^T$	1
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & j\end{bmatrix}^T$	1
3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & -j\end{bmatrix}^T$	1
4	$\begin{bmatrix}1 & 0\end{bmatrix}^T$	1
5	$\begin{bmatrix}0 & 1\end{bmatrix}^T$	1
6	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$	2

$$\mathbf{P}_v = \underset{\mathbf{P}_v \in \Omega}{\arg\max} \left\{ \sum_{l=0}^{L-1} \log_2\left(1 + SINR^{(l)}\right) \right\} \tag{19}$$

where Ω is the precoding codebook set defined in Table 1. The channel capacity can be calculated by summing the Shannon capacity for each data stream varying precoding matrix in the codebook. Seven channel capacities are compared and then one precoding matrix is selected provided that the capacity is the maximum.

Ⅴ. Performance Evaluations

We evaluated average block-error-rate (BLER) performance of LTE-Advanced uplink adapted by the feedback of selected precoding matrix for two transmit and four receive antennas configuration.

The main simulation parameters are listed in Table 2. The MIMO channel shall be simulated by the Spatial Channel Model Extended (SCME) model. We assume that the size of allocated resource blocks (RB) is 8 and the layer shifting is configured. A wideband sounding reference signal is considered to be transmitted over 96 resource blocks with the periodicity of 2ms.

In Fig. 5 and Fig. 6, the performance of MIMO DFT-SOFDMA is compared between full-rank transmission and rank adapted transmission by precoding selection in the suburban macro environment. In case of full-rank transmission, two codewords are mapped to two layers and identity precoding matrix is applied[15]. In order to emphasize the effect of precoding selection, an adaptive modulation and coding scheme (MCS) shall not be performed. Also, we consider ideal precoding with no feedback delay. In [16], the performance of MIMO precoding was evaluated using different feedback schemes and feedback delay instead of fulfilling the requirements of LTE-Advanced.

Fig. 5 shows the performance of rank adapted transmission using feedback of precoding matrix index (PMIFB) is better than that of full-rank transmission.

However, Fig. 6 illustrates that the gain decreases significantly for higher modulation order and coding rate (R). Especially, in case of 64-QAM, the proposed scheme shows almost identical performance with full-rank transmission. The reason is that the proposed scheme selects the full-rank precoding matrix as an optimum for higher MCS, by and large.

Table 3. summarizes the gain due to the proposed precoding selection scheme over the full-rank transmission in the suburban macro scenario when BLER is equal to 10^{-1}. We observe that the gain due to precoding selection is higher in the case of lower MCS, which tends to be allocated in the severe channel fading environment.

Fig. 7 shows the performance results in the urban micro scenario. The proposed precoding selection scheme mostly decides full-rank transmission, so that the gain due to precoding selection is negligible. As a consequence, the results confirm that the full-rank transmission is suitable for the urban micro scenario.

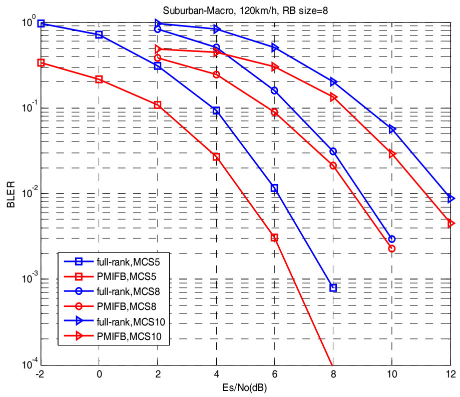

Fig. 5. Performance of MIMO DTF-SOFDMA due to precoding selection with high mobility(QPSK)

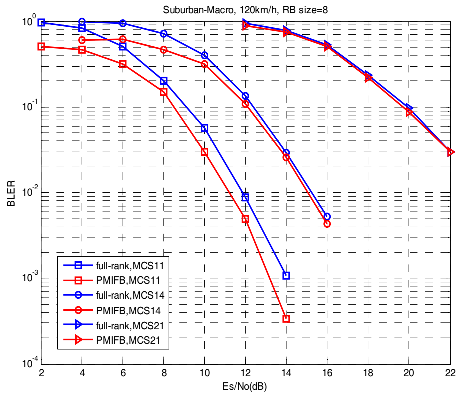

Fig. 6. Performance of MIMO DFT-SOFDMA due to precoding selection with high mobility (16-QAM, 64-QAM)

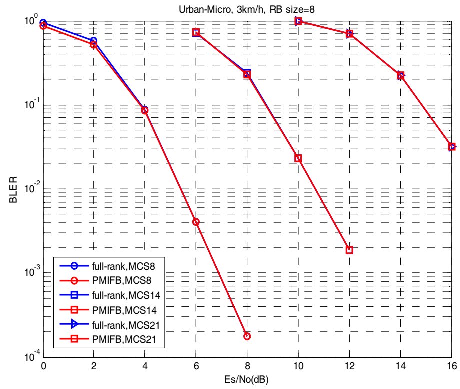

Fig. 7. Performance of MIMO DFT-SOFDMA due to precoding selection with low mobility

Ⅵ. Conclusions

In this paper, we presented new architecture and features required for 2x4 MIMO DFT-SOFDMA of LTE-Advanced. Also, a precoding selection scheme based on precise SINR calculation for LTE-Advanced uplink MIMO has been proposed in order that the transmission rank can be adapted dynamically. We have observed that the precoding selection scheme outperforms full-rank transmission in terms of BLER especially in suburban macro scenarios. On the other hand, the precoding selection scheme has no gain in the urban micro scenario since it decides that only identity precoding matrix is optimal.

We expect that further performance improvement is provided by the proposed scheme combined with adaptive modulation and coding scheme[17] as well as power controls for uplink physical channels. Therefore, an optimum channel-dependent scheduling is considered as a key technology to be studied as our future work.

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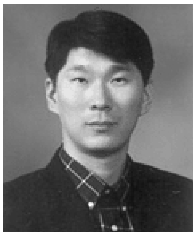

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