Abstract - In the Release (Rel.) 11 Long Term Evolution (LTE)-Advanced radio interface, the Enhanced Physical Downlink Control Channel (EPDCCH) is specified, which transmits downlink control information (DCI) signals. The EPDCCH is frequency-domain-multiplexed with data symbols and is used to transmit more DCI signals than the Physical Downlink Control Channel (PDCCH) for Rel. 8 LTE due to the application of multiuser multiple-input multiple-output (MIMO) and coordinated multi-point (CoMP) transmission and reception. This paper presents the effect of decision-feedback channel estimation (DFCE) using soft-symbol estimation of the DCI signals for the EPDCCH. We propose a DFCE method that improves the channel estimation accuracy by using soft-symbol estimation of the control signals based on the a posteriori log-likelihood ratio (LLR) at the soft output Viterbi algorithm (SOVA) for convolutional coding in addition to the demodulation reference signals (DM-RSs). Computer simulation results show that the DFCE is effective in decreasing the transmission power of the DM-RSs to approximately half compared to that for only conventional DM-RSs to achieve the same target block error rate from a low to high Doppler frequency region in a frequency-selective Rayleigh fading channel.

Keywords - OFDMA; control signal; decision-feedback channel estimation; EPDCCH; LTE-Advanced

I. INTRODUCTION
Orthogonal Frequency Division Multiple Access (OFDMA) is adopted as the multi-access scheme in the downlink for Long Term Evolution (LTE) and LTE-Advanced [1]-[3]. In LTE, only packet based radio access is supported. Hence, all traffic types are carried by packet radio access including real-time type traffic with a restrictive delay requirement. In the downlink, key techniques including frequency and time domain channel-dependent scheduling, adaptive modulation and coding (AMC), and hybrid automatic repeat request (HARQ) with soft combining [1]-[3] are applied to shared channels that carry user traffic data. To enable accurate operation of these techniques in the downlink shared channel, a control signal for multiple accessing-sets of user equipment (UE) is necessary, which is called downlink control information (DCI). The DCI is multiplexed into the Physical Downlink Control Channel (PDCCH). The DCI comprises control signals related to downlink scheduling, those for demodulation such as the modulation scheme and transport block size, those for HARQ of the downlink shared channel, and the scheduling grant signal for the uplink shared channel. In addition, an acknowledgement (ACK)/ negative-acknowledgement (NACK) bit for HARQ associated with uplink data transmission is carried by the Physical HARQ Indicator Channel (PHICH) [1]. We refer to these control signals as Layer 1 (L1) /Layer 2 (L2) control signals in the paper.

In LTE, time division multiplexing (TDM) based multiplexing of the L1/L2 control channels in the shared channel is adopted [1]-[3]. The L1/L2 control channels are multiplexed into the first to third FFT blocks (or fourth if the system bandwidth is 1.4 MHz) at the beginning of each subframe. The first reason to adopt TDM based multiplexing is that a UE can wake up to demodulate and decode the control signals during a limited time duration within a subframe. This intermittent reception yields power savings for a UE. The second reason is to decrease the processing delay to demodulate and decode the succeeding shared channel within the same subframe. We presented the effect of decision-feedback channel estimation (DFCE) using soft-symbol estimation for L1/L2 control signals in addition to the reference signal (RS) symbols for TDM based control channels assuming the PDCCH [4]. We showed that the DFCE achieves a required average received signal-to-noise power ratio (SNR) that satisfies the target block error rate (BLER) that is almost identical to that when using all the RS symbols within a subframe.

In the LTE-Advanced Rel. 11 radio interface, enhanced techniques including multiuser multiple-input multiple-output (MIMO) spatial division multiplexing (SDM) and coordinated multi-point (CoMP) transmission and reception are adopted to improve the frequency efficiency and cell throughput. The required number of control bits is increased to enable the enhanced techniques. In addition, LTE-Advanced must support legacy LTE UEs. To carry the increased number of control signaling bits, the downlink control channel called the Enhanced Physical Downlink Control Channel (EPDCCH) has been specified for the Rel. 11 radio interface [1],[5]. In the EPDCCH, frequency division multiplexing (FDM) with a shared channel is adopted. This is because the legacy UEs based on the Rel. 8 radio interface are supported in the same system bandwidth based on the Rel. 10 radio interface and that inter-cell interference coordination (ICIC) is achieved between the different cell sites. The ICIC decreases the interference from the EPDCCH in neighboring cells, while the transmission efficiency of the DCI is reduced. In a cell with high traffic, the offered DCI is increased. Even under such conditions, the decrease in the required received SNR that satisfies the target BLER is effective in achieving efficient EPDCCH transmission.

This paper presents the average BLER performance of the DCI using DFCE based on soft-symbol estimation of the control signals for the EPDCCH. The DFCE achieves accurate channel estimation by employing the soft-symbol estimation
of the control signals based on the a posteriori log-likelihood ratio (LLR) at the soft output Viterbi algorithm (SOVA) [6] decoder in addition to the UE-specific demodulation RS (DM-RS) symbols. Moreover, one FFT block contains 66.67 ms cyclic prefix (CP). The corresponding subcarrier spacing is 15 kHz. One PRB pair comprises 12 subcarriers (= 180 kHz) in the frequency domain and 1 ms in the time domain.

In the Rel. 11 LTE-Advanced radio interface, multiplexing schemes for the EPDCCH are specified [1],[5],[8],[9]. The DCI format for the PDCCH is also used for the EPDCCH. For the EPDCCH, frequency domain multiplexing with the Physical Downlink Shared Channel (PDSCH) is adopted to facilitate frequency domain channel-dependent scheduling and frequency domain ICIC. Each UE can be configured with up to two EPDCCH sets with each set comprising 2, 4, or 8 PRB pairs. The EPDCCH is transmitted using one or more enhanced control channel elements (ECCEs). Moreover, one ECCE consists of four or eight enhanced resource element groups (EREGs). Fig. 1 shows the EREG to RE mapping scheme in the case of the normal CP length for frequency division duplex (FDD) [5]. There are 16 EREGs in a PRB pair, where each EREG comprises 9 REs normally. Hence, the number of available REs in an ECCE is 36 when an ECCE comprises 4 EREGs. Unlike a CCE for the PDCCH, the number of available REs in an ECCE varies depending on the presence of other signals such as the RS and legacy downlink control signals. As shown in the figure, the EREG indices are sequentially mapped to the REs except for the REs used for the DM-RS within a PRB pair. The remaining 24 REs are used for the DM-RS. An EREG is formed by all the REs corresponding to the index for this EREG. The resources of the EREG are spread evenly within a PRB pair, which provides balanced performance for all EREGs. The EREGs are grouped as follows based on the EREG indices:

- EREG group 0 consists of EREGs with indices (0, 4, 8, 12)
- EREG group 1 consists of EREGs with indices (1, 5, 9, 13)
- EREG group 2 consists of EREGs with indices (2, 6, 10, 14)
- EREG group 3 consists of EREGs with indices (3, 7, 11, 15)

When an ECCE consists of four (eight) EREGs, one (two) EREG group(s) forms an ECCE. The EREGs in an EREG group used to form an ECCE can be from the same or different PRB pairs depending on the EPDCCH transmission type. Two types of multiplexing schemes are defined for the EPDCCH: localized and distributed multiplexing schemes. The localized multiplexing scheme improves the spectrum efficiency by using the frequency domain channel-dependent scheduling reliable CSI feedback as well as the PDSCH. The distributed multiplexing scheme takes full advantage of the averaging effect for the received channel response suffering from frequency-selective fading over the entire transmission bandwidth. In this paper, we investigate the effect of the DFCE for distributed EPDCCH multiplexing. The DM-RS for each antenna port is multiplexed into 12 REs within a PRB pair for the EPDCCH. In this case, the REs for antenna port 107 (or 108) are multiplexed with those for antenna port 109 (or 110) using FDM. Moreover, the REs for antenna port 107 (or 109) are multiplexed with those for antenna port 108 (or 110) using code division multiplexing (CDM).

III. COMPUTER SIMULATION MODEL

Fig. 2 shows a block diagram of the OFDM transmitter assumed in the paper. The 40 DCI bits are channel-encoded using convolutional coding with the coding rate of $R = 1/3$ and with the constraint length of 9 bits. The generator polynomials of the convolutional codes are 557, 663, 711 in octal notation [10]. The number of encoded bits is 144 including 8 tail bits. The bit-interleaver within the duration of one subframe is applied as a channel interleaver. The channel interleaver achieves a frequency diversity effect, i.e., a randomization effect from burst error in the frequency domain. The coded bit sequence after interleaving, $b_n$, is grouped in $\Gamma \rho$-length blocks $\{b_{0,0}, ..., b_{0,\rho-1}\}, \{b_{1,0}, ..., b_{1,\rho-1}\}$. Each block is mapped into a complex symbol, $s_g = \mu(b_n)$, among the QPSK constellations, where $\mu$ is a mapping function to the $\Sigma$ candidates, $s' (i = 0, 2, ..., \ Sigma - 1)$ and $\Sigma = 2^n = 4$. Each $s'$ corresponds to a binary bit pattern, $\left[ b_{g,0} \cdots b_{g,n-1} \right]$, $b_{g,n} \in [0,1]$. The 72 modulated symbols for the DCI are multiplexed into 8

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**Fig. 1. EREG mapping scheme to RE.**

**II. EPDCCH OUTLINE**

We assume the same subframe structure as that for the Rel. 8 LTE specifications [1]. One channel-coded block is mapped into a subframe with the length of 1 ms. One subframe comprises 14 FFT blocks, which correspond to the OFDM symbols. Moreover, 1 FFT block contains a 66.67 ms effective OFDM symbol and a 4.75 ms cyclic prefix (CP). The corresponding subcarrier spacing becomes 15 kHz. One PRB pair comprises 12 subcarriers (= 180 kHz) in the frequency domain and 1 ms in the time domain.

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EREgs assuming 1 ECCE transmission. We use EREG groups 0 and 2 and assume that the EREGs belonging to the two EREG groups are fully overlapped. The DCI symbols are multiplexed into EREGs 0 and 2 in PRB pair #10, EREGs 4 and 6 in PRB pair #20, EREGs 8 and 10 in PRB pair #30, and EREGs 12 and 14 in PRB pair #40. We also assume that there are 2 other UEs and each UE transmits the same number of DCI bits as that for the desired UE. In addition, the ECCEs of the two UEs comprise eight EREGs and these are multiplexed into the aforementioned four PRB pairs. As described earlier, the DM-RS symbols for the four antenna ports are specified for the EPDCCH for UE-specific beamforming. In the paper, we assume one antenna transmission. Hence, the DM-RS is multiplexed into the RE for antenna port 107. The symbol sequence including both the DCI signals and DM-RS is serial-to-parallel-converted to 600 parallel symbol sequences. The parallel symbol sequences are fed into an inverse fast Fourier transform (IFFT) with parallel symbol sequences converted to 600 parallel symbol sequences. The sequence including both the DCI signals and DM-RS is serially-parallel-converted to 600 parallel symbol sequences. The parallel symbol sequence is multiplied by the FFT block index and subcarrier index in the subframe, i.e., the k-th subcarrier position (k = 0, ..., 119). The DM-RS symbols are multiplexed at the subcarrier positions of the respective. The DM-RS symbols are multiplexed at the subcarrier positions of respectively. The DM-RS symbols are multiplexed at the subcarrier positions of respectively. The DM-RS symbols are multiplexed at the subcarrier positions of respectively. We consider that the EREGs of the ECCEs for other UEs are the FFT block index and subcarrier index in a subframe, i.e., the k-th subcarrier, as the center. Similarly, we compute the channel response at the l-th FFT block using the LS estimation for the DM-RS symbols in the time domain based on the model [11]. By using the estimated channel response at each RE position, \( h_i^{(l)} \), the control symbols of two receiver antennas are combined with maximal ratio combining (MRC). From the soft symbol sequence after receiver diversity combining, we compute the squared Euclidean distance between the received symbol and the symbol replica candidate using the estimated channel impulse response for both bits “0” and “1.” We compute the a posteriori probability using the minimum squared Euclidean distance for bits “0” and “1,” individually [12]. After de-interleaving in the frequency domain, the a posteriori LLR is fed into the SOVA [6] decoder.

In the second loop of the DFCE, the a posteriori LLR is computed for coded bits after convolutional coding at the SOVA decoder output. Let \( \lambda_i(b_{j,k}) \) be the extrinsic LLR of the j-th bit of the g-th data symbol at the last iteration of the SOVA decoder, which is given as \( \lambda_i(b_{j,k}) = \log[P(b_{j,k}=1)/P(b_{j,k}=0)] \). In general, the extrinsic LLR is used for generating the soft-symbol estimation. However, we employ the a posteriori LLR instead of the extrinsic LLR as \( \lambda_i(b_{j,k}) = \log[P(b_{j,k}=1)/P(b_{j,k}=0)] \). Then, the probability of each coded bit that is equal to “1” or “0” is given as

\[
P_i(b_{j,k}=1) = \frac{\exp[2\lambda_i(b_{j,k})]}{1 + \exp[2\lambda_i(b_{j,k})]}, \quad P_i(b_{j,k}=0) = \frac{1}{1 + \exp[2\lambda_i(b_{j,k})]}. \tag{2}
\]

We compute the \((\Gamma \times \rho) \) a priori symbol probability matrix, \( [P(\bar{\gamma}_g)] \) [13]. Each generic element of \( [P(\bar{\gamma}_g)] \) is defined as

\[
P_{ij} = P(x_{g} = s_{j}) = \prod_{i} P_{ij}(b_{j} = b_{i}). \tag{3}
\]

Here, we assume that the bit interleaver and de-interleaver work ideally. From the low component of the a priori symbol probability matrix, the soft-symbol estimation for the g-th DCI symbol is computed as

\[
\hat{x}_g = E(\bar{\gamma}_g) = \sum_{s} s P(\bar{\gamma}_g | s) \tag{4}
\]

The received DCI symbols are re-modulated by the soft-symbol estimations, \( \hat{x}_g(\hat{y}_g) \). The channel response at the k-th subcarrier and l-th FFT block is estimated based on the

\[
\hat{h}_i^{(l)} = \hat{h}_i^{(l)} = R_k \left( \hat{h}_i + \frac{\beta}{SNR} I \right)^{-1} \hat{h}_i^{(l)} \tag{1}
\]

In (1), \( \beta = \beta \left[ \rho(1,1) / \lambda_i(b_{j,k}) \right] \) is a constant figure that depends on the signal constellation and I is the identity matrix. Term \( h_i^{(l)} \) denotes the least-squares (LS) estimation of the channel response. For the computation, we assume a uniform power-delay profile in the CP duration. Here, the widow size for computing the autocorrelation matrix in the frequency domain is set to \( k = k - 6, ..., k + 6 \) with the target subcarrier, i.e., the k-th subcarrier, as the center. Similarly, we compute the channel response at the l-th FFT block using the LS estimation for the DM-RS symbols in the time domain based on the model [11].
LMMSE based CE by employing both DM-RS symbols and re-modulated DCI symbols. Similar to the initial channel estimation using only the DM-RS symbols, the minimum squared Euclidean distance between the received symbol after MRC and the symbol replica candidates for both bits “0” and “1” are fed into the SOVA decoder. Finally, the output LLR for a posteriori probability of the SOVA decoder is hard-decided to recover the transmitted bit sequence.

IV. COMPUTER SIMULATION EVALUATIONS

We investigate the effect of DFCE in terms of the average BLER of the control signals based on link-level simulations. In the simulations, the 9-path Extended Typical Urban (ETU) channel model with the root mean square (r.m.s.) delay spread of $\tau_{\text{rms}} = 0.99$ $\mu$s [15] is assumed for the multipath delay profile model. We assume that each path follows independent Rayleigh fading with the maximum Doppler frequency of $f_D = 5.55$ Hz except for Fig. 7.

Fig. 4 shows the average BLER performance of the DCI signals using the DFCE as a function of the average received SNR per receiver antenna. The number of iterations for the DFCE is set to $N_{\text{DFCE}} = 1$ and 2. The number of available ECCEs is set to $N_{\text{DFCE}} = 3$. In this case, one ECCE comprising the two EREG groups is for the desired UE and two ECCEs are for the other UEs. The transmission power boosting factor of the DM-RS compared to that for the coded data symbols is set to $\varphi_{\text{Boost}} = 1$. In the figure, we also plot the average BLER performance using only the DM-RSs and that assuming ideal channel estimation. Fig. 4 shows that the improvement in the average BLER performance level with $N_{\text{DFCE}} = 2$ from $N_{\text{DFCE}} = 1$ is slight. Moreover, the required average received SNR satisfying the average BLER of $10^{-2}$ employing the DFCE is decreased by approximately 0.5 dB compared to that with only the DM-RS for $N_{\text{DFCE}} = 3$ and $N_{\text{DFCE}} = 1$. In the subsequent evaluations, we set $N_{\text{DFCE}} = 1$ from the result.

Next, Fig. 5 shows the average BLER performance of the DCI signals using the DFCE as a function of the average received SNR per receiver antenna. The number of available ECCEs, $N_{\text{DFCE}}$, is parameterized. Moreover, similar to Fig. 4, the power boosting factor of the DM-RS is set to $\varphi_{\text{Boost}} = 1$. Fig. 5 shows that the required average received SNR at the average BLER of $10^{-2}$ employing the DFCE with $N_{\text{DFCE}} = 1$ and 3 is decreased by approximately 0.2 dB and 0.5 dB, respectively, compared to that with the DM-RS only. By employing the soft-symbol estimation based on the a posteriori LLR at the SOVA decoder output of the EREGs for the other UEs, the decreasing effect in the required average received SNR is large. Moreover, the gain for reducing the required average received SNR when the EREGs of the ECCE for the other UEs are used for the DFCE in which each ECCE comprises eight EREGs. Hence, the number of available aggregated REs for the ECCEs is 54 REs, while the available DM-RS is 12 REs per PRB pair. Since the number of DM-RS symbols is larger compared to those for the Cell-specific RS (CRS), it is anticipated that the DM-RS would provide higher interference to the collided PRB pairs of the neighboring cells. Hence, we investigate the effect of decreasing the power boosting factor of the DM-RS in the PRB pair where the EPDCCH is multiplexed.

![Fig. 4. Average BLER performance using DFCE as a function of average received SNR per receiver antenna.](image)

![Fig. 5. Average BLER performance using DFCE as a function of average received SNR per receiver antenna.](image)
Finally, Fig. 7 shows the required average received SNR approximately 400 Hz.

Moreover, we showed that the DFCE based on the LMMSE CE weight generations in the time and frequency domains suppresses the increase in the required average received SNR satisfying the target BLER to a low level even in a high Doppler frequency region. We also showed that the DFCE is effective in decreasing the transmission power of the DM-RSs to approximately half compared to that for the conventional DM-RSs only to achieve the same target average BLER, which brings about the decrease in the interference from as many as 12 DM-RS REs per PRB pair to the neighboring cells.

Fig. 7 also shows that the DFCE based on the LMMSE CE weight generations in the time and frequency domains suppresses the increase in the required average received SNR satisfying the target BLER to a low level even in a high Doppler frequency region up to approximately 400 Hz.

V. CONCLUSION

This paper presented the effect of the DFCE employing soft-symbol estimation of the DCI signals for the EPDCCH. In the proposed DFCE method, channel estimation accuracy is improved by using soft-symbol estimation of the DCI signals based on the a posteriori LLR at the SOVA decoder output in addition to the DM-RSs. Computer simulation results showed that when the power boosting factor is $\phi_{\text{Boost}} = 1.0$, the required average received SNR at the average BLER of $10^{-2}$ employing the DFCE with $N_{\text{DFCE}} = 1$ or 3 is decreased by approximately 0.2 dB and 0.5 dB, respectively, compared to that for DM-RS based CE. We also showed that the DFCE is effective in decreasing the transmission power of the DM-RSs to approximately half compared to that for the conventional DM-RSs only to achieve the same target average BLER, which brings about the decrease in the interference from as many as 12 DM-RS REs per PRB pair to the neighboring cells.

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