Turbo Equalized Double Window Cancellation and Combining
Robust to Large Delay Spread Channel

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SUMMARY In orthogonal frequency division multiplexing (OFDM) the multipath exceeding the guard interval (GI) causes inter-symbol interference (ISI) and inter-carrier interference (ICI), thereby making it difficult to achieve high data rate transmission. In this paper, the double window cancellation and combining (DWCC), introduced in [14], is analyzed by investigating SINR distribution under different delay spread channels. The analysis indicates that the extension of processing window in iterative cancellation can have an adverse effect on the performance for small interference levels. In addition, the optimal combining of DWCC and turbo equalization (TE), named TE-DWCC, is investigated by varying the iterative cancellation procedure between DWCC and channel decoder and the decision feedback type such as hard decision feedback (HDF) or soft decision feedback (SDF). Finally, by changing interference level, code rate, and decision feedback type, the performance of TE-DWCC is compared with the conventional canceller that adopts turbo equalization in the exponentially distributed slow fading channel.

key words: OFDM, ISI, ICI, TE, DWCC, HDF, SDF

1. Introduction

In a wireless communication Orthogonal Frequency Division Multiplexing (OFDM) that simultaneously carries a number of subcarriers bearing low data rate symbols is a promising transmission technique to increase capacity with a limited radio resource [1]–[3]. Moreover, the advantages of OFDM can be found in the receiver structure, which can be implemented with a simple equalizer what so called one-tap frequency domain equalizer (FDE) by inserting guard interval (GI) and in the flexible management of subcarriers with Adaptive Modulation and Coding (AMC), and so on. In particular, the adoption of OFDM has been very attractive to the terrestrial broadcasting known as single frequency network (SFN) such as Integrated Services Digital Broadcasting (ISDB) in Japan [4], Digital Audio Broadcasting (DVB) and Digital Terrestrial Television Broadcasting (DTTB) in Europe [5], [6], and is also a candidate to the cooperative communication field [7]. A high signal to noise ratio (SNR) in SFN can be achieved by combining all the same information from base stations, but the delayed versions of a transmitted signal from each base station is likely to surpass GI. This causes inter-symbol interference (ISI) and inter-carrier interference (ICI) and hence the system performance is severely degraded. Even if the control of the GI length and OFDM symbol length is to be a countermeasure, it is also limited to the frequency efficiency loss and power loss, respectively. Hence, interference canceller is demanding to suppress those detrimental effects.

The previously proposed cancellers can be grouped into the time domain canceller (TDC) and frequency domain canceller (FDC) with time domain equalization (TDE) or frequency domain equalization (FDE). The representative TDC-FDE has been proposed in [8], referred to as the residual ISI cancellation (RISIC) that is the simplest canceller ever known. Meanwhile, the TDC-TDE was introduced in [9], [10] where the cancellers, named as TE (Turbo Equalized C canceller) and STE (Simplified Turbo Equalized C canceller) adopt turbo equalization. The former is sensitive to the amount of ISI and to deep fading since the tentative symbol detection is performed before channel decoding. On the other hand, the latter could dramatically improve the performance with the channel coding gain in combining the guard interval in iterative canceller operation. However, the canceller has two defects. One is the computational complexity in ICI cancellation, and the other is the positive feedback by including the non-interfered part of a received symbol in the processing window. In the meantime, other types of the previous cancellers can be referred to [11]–[13].

The proposed canceller in this paper is based on Double Window Cancellation and Combining (DWCC) whose basic concept was proposed by the authors [14]. The intent of DWCC is to enjoy the coherent combining gain in canceller operation by readily extending the processing window to entire symbol length. However, since the canceller operation of DWCC is performed before channel decoding, it is still susceptible to deep fading. To overcome the drawback in DWCC, the DWCC combined with channel coding gain, named TE-DWCC, is proposed. Under different delay spread channels, assumed in [9], it is found that TE-DWCC is more robust to ISI and ICI than the conventional canceller [9], [10] that adopts turbo equalization. In the meantime, it is found that the performance of TE-DWCC relies on the iterative cancellation procedure involving DWCC and channel decoder, and TE-DWCC is more compatible with hard decision feedback (HDF) than with soft decision feedback (SDF) due to the characteristic of the canceller operation. Furthermore, the DWCC algorithm is analyzed by investigating the effective SINR distribution under different delay spread channels and it is found that the interference adaptive operation of DWCC algorithm is advantageous to the performance.

This paper is organized as follows. In Sect. 2 a brief
review on OFDM is given and ISI and ICI, caused by different delay spread channels are evaluated. In Sect. 3 the basic concept of DWCC and its analysis are presented. In Sect. 4 the optimal combining method of TE-DWCC is introduced. Finally, the performance comparison with the conventional canceller is shown in Sect. 5 and the concluding remarks follow in Sect. 6.

2. OFDM

The N-points IFFT of the channel coded i-th OFDM symbol vector, $s_i$, with guard interval $(G)$ in the transmit packet results in

$$x_{i,n} = \frac{1}{N} \sum_{k=0}^{N-1} s_{i,k} \exp \left( \frac{2\pi}{N} nk \right)$$

(1)

where $-G \leq n < N$, and $s_{i,k}$ and $x_{i,n}$ are the data symbol at the k-th subcarrier and the i-th OFDM sample in the time domain, respectively. The i-th transmit symbol goes through the wireless channel $h_{i,n}$ with the number of multipaths, $L$ and is added by thermal noise $\omega_{i,n}$ at the receiver. The wireless channel, $h_{i,n}$, can be expressed by

$$h_{i,n} = \sum_{l=0}^{L-1} \beta_{i,l} \delta(n-l)$$

(2)

where $\beta_{i,l}$ is the complex coefficient of the l-th multipath from the independent Rayleigh distribution in the i-th symbol. If the maximum channel delay (MCD) is smaller than $G$, the i-th received symbol after removing the guard interval where $0 \leq n < N$ is

$$r_{i,n} = x_{i,n} \ast h_{i,n} + \omega_{i,n}$$

$$= \sum_{l=0}^{L-1} \beta_{i,l} x_{i,n-l} + \omega_{i,n}$$

$$= \sqrt{\frac{N}{\sum_{k=0}^{N-1} s_{i,k} \exp \left( \frac{2\pi}{N} nk \right) H_{i,k} + \omega_{i,n}}$$

(3)

where * denotes linear convolution, and $\delta(n)$ defines modulo operation of $N$, and $H_{i,k}$ is $\sum_{l=0}^{L-1} \beta_{i,l} \exp(-j2\pi lk/N)$ and $\omega_{i,n}$ is white Gaussian noise. Figure 1 shows the delayed version of the transmit signal at the receiver, where MCD stands for the maximum channel delay. When MCD is smaller than $G$, the FFT to (3) is performed and the transmit data symbols, distorted by wireless channel are compensated by one-tap frequency domain equalizer (FDE). However, when MCD is larger than the guard interval, the i-th received symbol, interfered by the $(i-1)$th symbol can be divided into the interfered and non-interfered area. The interfered area, $r_{i,n}^{int}$, is given by (4), while the non-interfered area, $r_{i,n}^{free}$ is given by (5).

$$r_{i,n}^{int} = \sum_{l=0}^{G+n} \beta_{i,l} x_{i,n-l} + \sum_{l=0}^{L-1} \beta_{i,l} x_{i,n-l} \exp \left( \frac{2\pi}{N} nk \right) H_{i,k} + \omega_{i,n}$$

(4)

where $0 \leq n < (L-G-1)$.

$$r_{i,n}^{free} = \sum_{l=0}^{L-1} \beta_{i,l} x_{i,n-l} + \omega_{i,n}$$

(5)

where $(L-G-1) \leq n < N$. In (4), the ISI from the $(i-1)$th symbol destroys the orthogonality among subcarriers within a symbol. After the FFT to $r_{i,n}^{N-1}$, the symbol per subcarrier is expressed by

$$z_{i,k} = H_{i,k} s_{i,k} + W_{i,k} + W_{int}^{int}$$

(6)

where $W_{i,k}$ and $W_{int}^{int}$ imply the thermal noise and the interference at the k-th subcarrier, respectively. From the bias function in [15], the variance of the interference can be analytically estimated by (7).

$$E \left[ \left| W_{i,k} \right|^2 \right] = \sum_{l=0}^{L-1} \left( \frac{d_{i,l}}{N} \right) E \left[ \left| \beta_{i,l} \right|^2 \right]$$

$$+ \sum_{l=0}^{L-1} \left( \frac{d_{i,l}}{N} \right) \left( \frac{N+G-d_{i,l}}{N} \right) E \left[ \left| \beta_{i,l} \right|^2 \right]$$

(7)

where $d_{i,l}$ is the l-th multipath delay in the i-th symbol, normalized by the sampling period of OFDM symbol. In Fig. 2 the variance of the interference is shown in different delay spread channels, where the PDB implies the power difference between multipath in dB scale as shown in Fig. 3. As the PDB decreases, the interference increases and deteriorates the system performance. For the simulation in Fig. 2,
it is assumed that the OFDM symbols are 64 points with 16 samples of $G$ and the multipath tap delay is 2 OFDM samples interval, and the interference level is controlled by the PDB.

3. Analysis of DWCC

The basic concept of the double window cancellation and combining (DWCC) is to readily extend the canceller processing window to the entire symbol length and to exploit the coherent combining gain in the canceller operation. The DWCC-I and DWCC-II have different processing window lengths in iterative canceller operation. The processing window length of DWCC-I is the NFFT length ($N$) in both initial and iterative canceller operations as shown in Fig. 4(a).

In contrast, the processing window length of DWCC-II is the NFFT length ($N$) in initial canceller operation while it is the entire symbol duration in iterative canceller operation as shown in Fig. 4(b). Meanwhile, DWCC-I performs the double window cancellation and combining once right before the entire symbol duration in iterative canceller operation as shown in Fig. 4(c). In DWCC-II, the processing window to the entire symbol length and to exploit the coherent combining gain in the canceller operation. The processing window length of DWCC-I is the NFFT length ($N$) in both initial and iterative canceller operations as shown in Fig. 4(a).

In this section it is intended to investigate DWCC with respect to the SNIR distribution under different delay spread channels. As shown in Fig. 4(b), if the entire $i$th received symbol duration is considered as a processing window, each of pre- and post-windows can be taken with the size of $N$ samples. For the pre-window the interfered area, $r_{i,n}^{\text{pre-isi}}$ from the $(i-1)$th symbol is expressed by

$$r_{i,n}^{\text{pre-isi}} = \sum_{l=0}^{G-1} \beta_{i,l} x_{i,(n-l)N} + \sum_{l=G+1}^{L-1} \beta_{i,l} x_{i,(n-l+G)N} + \omega_{i,n}$$

where $-G \leq n < L - G - 1$. Meanwhile, the post-window, $r_{i,n}^{\text{post-isi}}$, interfered by the $(i+1)$th is given by

$$r_{i,n}^{\text{post-isi}} = \sum_{l=0}^{G-1} \beta_{i,l} x_{i,(n-l)N} + \sum_{l=G+1}^{L-1} \beta_{i,l} (\tilde{x}_{i,(n-l)N} - \tilde{x}_{i,(n-l+G)N})$$

where $-G \leq n < L - G - 1$, and $\tilde{x}$ denotes the IFFT output to the $i$th symbol replica.
where \( N \leq n < N + L - 1 \). Finally, as shown in Fig. 4(d), the reconstructed \( i \)th symbol can be separated into pre- and post-windows, where each window includes \( N \) samples and the overlapping length \( (M) \) is obtained by \( [N - (G + \text{MCD})] \). By taking FFT to each window, the pre- and post-windows are given by:

\[
R_{i,k}^{\text{pre-win}} = H_{i,k}^{\text{pre}} s_{i,k} + W_{i,k}^{\text{pre}}
\]

\[
R_{i,k}^{\text{post-win}} = H_{i,k}^{\text{post}} s_{i,k} + W_{i,k}^{\text{post}}
\]

where \( H_{i,k}^{\text{pre}} \) and \( H_{i,k}^{\text{post}} \) are wireless channel coefficients at the \( k \)th subcarrier, and \( W_{i,k}^{\text{pre}} \) and \( W_{i,k}^{\text{post}} \) include the thermal noise and the residual ISI and ICI at the \( k \)th subcarrier in each window. In a slow fading channel, the channel coefficient of each window per subcarrier can be approximated by (15).

\[
H_{i,k}^{\text{pre}} \approx H_{i,k}^{\text{post}} \cdot \left[ \exp \left( \frac{2\pi}{N} Mk \right) \right]
\]

where \( M \) is the overlapped window length between double windows, noted by ‘OL’ in Fig. 8 of [14]. After channel equalization, the combined output, \( R_{i,k}^{\text{comb}} \) is given by (16).

\[
R_{i,k}^{\text{comb}} = \left[ |H_{i,k}^{\text{pre}}|^2 + |H_{i,k}^{\text{post}}|^2 \right] s_{i,k}
\]

\[+ (H_{i,k}^{\text{pre}})^* W_{i,k}^{\text{pre}} + (H_{i,k}^{\text{pre}})^* W_{i,k}^{\text{post}} \]

\[= \hat{H}_{i,k} s_{i,k} + (H_{i,k}^{\text{pre}})^* W_{i,k}^{\text{pre}} + (H_{i,k}^{\text{pre}})^* W_{i,k}^{\text{post}} \]

\[
\sigma_{i,k}^2 = E[|R_{i,k}^{\text{comb}} - \hat{H}_{i,k} s_{i,k}|^2]
\]

\[= (\sigma_{i,k}^2)^{\text{pre}} + (\sigma_{i,k}^2)^{\text{post}} \]

where it is assumed that \( E[|H_{i,k}^{\text{pre}}|^2] = E[|H_{i,k}^{\text{post}}|^2] = 1 \), and \( \sigma_{i,k}^2 \) is the total variance of residual interference and thermal noise at the \( k \)th subcarrier, where the increase of thermal noise at the \( k \)th subcarrier due to the overlapping double windows, \( \text{NCR} \cdot \sigma_{\text{thermal}}^2 \) is included in \( \sigma_{i,k}^2 \) and the noise correlation ratio (NCR) is defined by \( 1 - (G + \text{MCD})/N \). Finally, the average SNIR of the combined double windows per packet can be expressed as in (18) by using (16) and (17).

\[
\text{SNIR}_{\text{packet}} = \frac{1}{N_S} \sum_{i=0}^{N_i-1} \text{SNIR}_i
\]

\[= \frac{1}{N_S} \sum_{i=0}^{N_i-1} \frac{1}{N_d} \sum_{k=0}^{N_d-1} \frac{2 \left( |H_{i,k}^{\text{pre}} s_{i,k}|^2 + |H_{i,k}^{\text{post}} s_{i,k}|^2 \right)}{\sigma_{i,k}^2} \]

where \( N_S \) is the number of OFDM symbols per packet and \( N_d \) is the number of data symbols per OFDM symbol.

The analysis of the SINR distribution depending on PDB is presented through the simulation in this paper. The average SNIR for 200000 packets and the packet error rate (PER) are shown in Figs. 5 and 6, respectively. From the results, it is found that DWCC outperforms the conventional canceller [8] in all PDBs. In particular, the PER performance of DWCC-II is better than those of the others even in the region where the average SINR is lower than those of the others. For the verification of the fact, the \( \text{SNIR}_{\text{th}} \) that satisfies 1% probability in the cumulative density function (CDF) is investigated in Fig. 7 where it explains the reason why DWCC-II shows the better performance even in
the low average SINR region. In the meantime, the performance of DWCC-II is rather worse than that of DWCC-I up to the PDB of 1.0. The difference of DWCC-I and -II can be found in iterative canceller operation, where DWCC-I and -II take NFFT length and the entire symbol length as a processing window, respectively. In other words, the interference caused by extending a processing window in DWCC-II could dominate the combining gain in a non-interference dominant channel environment. Based on the analysis result, it is concluded that the interference adaptive operation of DWCC algorithms is advantageous for the performance.

4. TE-DWCC

In this section the optimal combining method of DWCC-II and turbo equalization is presented by investigating the iterative cancellation procedure between DWCC and channel decoder and the required number of iterations in DWCC and turbo equalization. In addition, it is explained that TE-DWCC is combined well with hard decision feedback (HDF) rather than with soft decision feedback (SDF).

4.1 Initial C canceller Operation

Figure 8 shows the algorithm flow chart of TE-DWCC in initial canceller operation. The processing window in initial canceller operation is restricted to NFFT length and the operation is summarized as follows.

S-1. Conventional one-tap frequency domain equalization is taken to the \((i-1)\)th interfered symbol with NFFT length and its symbol replica is determined.

S-2. When the \(i\)th symbol is input, ISI cancellation is performed with the \((i-1)\)th symbol replica and the result follows the first step (S-1). These two steps are executed to all the symbols in a packet and initial canceller operation ends. The initial operation in TE-DWCC is the same as [8].

4.2 Iterative C canceller Operation

4.2.1 MAP Detector & Symbol Mapper

In iterative canceller operation of Fig. 9, the data symbol replicas from initial canceller operation are applied in the first iterative canceller operation. The output of DWCC for each symbol is used to calculate the Log-Likelihood Ratio (LLR) for coded bits by using the MAP detector. The LLRs from MAP detector is calculated by (19).

\[
LLR_n = \ln \frac{\max_{s^+ \in S|b_n=1} \exp \left\{ \frac{[R_{s^+}^{comb} - \hat{H} s^+]^2}{2\sigma_i^2} \right\}}{\max_{s^- \in S|b_n=-1} \exp \left\{ \frac{[R_{s^-}^{comb} - \hat{H} s^-]^2}{2\sigma_i^2} \right\}} \\
\approx \frac{1}{2\sigma_i^2} \left[ \min_{s^+ \in S|b_n=1} [R_{s^+}^{comb} - \hat{H} s^+]^2 \right] - \min_{s^- \in S|b_n=-1} [R_{s^-}^{comb} - \hat{H} s^-]^2 \tag{19}
\]

where the transmit coded bit, \(b_n\) is +1 or -1, and \(s^+\) and \(s^-\) denote the modulated data symbols with \(b_n = +1\) or \(b_n = -1\) in a set \((S)\) of the constellation of the modulated symbols, respectively, and \(\hat{H}_{s^+}^{2}, \sigma_i^2\) and \(R_{s^+}^{comb}\) are referred to (16) and (17).

Meanwhile, the symbol mapping is performed in DWCC with the LLRs from DWCC combined output and channel decoder in turbo equalization. The channel decoder output consists of the updated systematic bit and two parity bits from the final iteration of turbo decoder, and the parity bits from turbo decoder are also updated with the final systematic bits from turbo decoder. In other words, likewise in the update of the systematic bits, the update of the parity bits can be calculated by the forward state probability, \(\alpha_{k-1}\), the transition probability, \(\gamma_k\) and the backward state probability, \(\beta_k\) at time \(k\). The state transition information to the input bit is already known in the channel decoder and a posteriori LLRs for the parity bits can be obtained by (20).

\[
LLR(p_k) = \ln \left\{ \frac{\sum_{p_{k+1}=1,\vec{s}_{k+1}} \alpha_{k-1}(\vec{s}) \gamma_k(\vec{s}, s) \beta_k(s)}{\sum_{p_{k+1}=1,\vec{s}_{k+1}} \alpha_{k-1}(\vec{s}) \gamma_k(\vec{s}, s) \beta_k(s)} \right\} \tag{20}
\]

where \((\vec{s}, s)\) is the state transition set from the previous state, \(\vec{s}\) to the present state, \(s\), and \(\alpha\), \(\beta\), and \(\gamma\) denote forward state, backward state, and transition probability, respectively. The calculations of those parameters are well described in [16],[17] so that the detail explanation is omitted in this paper. The updated systematic and parity bits are converted to data symbols with symbol mapper for ISI and ICI cancellation in DWCC block. There are two types of symbol mapping, and particularly the soft symbol mapping requires some manipulation depending on the Gray mapping rule in the transmitter. The Gray mapping used in this paper is shown in...
Fig. 9 Algorithm flow in the iterative processing.

\[ \hat{s}_n = E \{ s_n(b_n)|r(t) \} = \sum_{b_n} s_n(b_n) \prod_{j=1}^{m} \Pr \{ b_{nj}(b_n)|r(t) \} \]  \hspace{1cm} (21)

where \( r(t) \) and \( s_n(b_n) \) denote the received symbol at time \( t \) and the modulated symbol, respectively, where \( b_n \) is the set of the bits composing the \( n \)th symbol, and \( m \) implies \( \log_2(\sqrt{M}) \) and \( b_{nj} \) is the \( j \)th bit in the \( n \)th symbol in \( s_n(b_n) \). The soft symbol mapping rule in (22) is applied in this paper.

\[ \hat{P}_{\text{64QAM}} = \frac{1}{\sqrt{42}} \left[ \tanh \left( \frac{\lambda_0}{2} \right) \left( \frac{4 - 2 \tanh \left( \frac{\lambda_1}{2} \right)}{\tanh \left( \frac{\lambda_2}{2} \right)} \right) + \tanh \left( \frac{\lambda_3}{2} \right) \tanh \left( \frac{\lambda_2}{2} \right) \right] \]  \hspace{1cm} (22)

where \( \lambda_k \) denotes the \( \text{LLR} \) of the \( k \)th bit for the real and imaginary part of a data symbol.

4.2.2 Optimum Combining Method

In [19], the effectiveness of the equalizer and channel coder against the interference was discussed and it was emphasized that the powerful channel coder can be one of solutions to mitigate ISI and ICI. From [19], it can be inferred that there is a priority between the coherent combining gain from DWCC and channel coding gain from channel coder. In this section, the effects of two different operating modes on the performance of TE-DWCC are investigated. One is the canceller operation after channel decoding (COAD) and the other is the canceller operation before channel decoding (COBD). The selection between the two modes can be controlled by setting the parameter ‘\( T_{\text{START}} \)’ in Fig. 9 and the corresponding number of DWCC and turbo equalization is shown in Fig. 11. For example, ‘\( T_{\text{START}} \)’ equal to ‘0’ implies the COAD. Otherwise, it implies the COBD where DWCC is performed first before turbo equalization with a different number of DWCC and turbo equalization. After all, the selection between the COAD and COBD is controlled by the priority between DWCC and turbo equalization.

The performance of COAD and COBD on the iterative processing procedure and the optimum number of iterations in DWCC and turbo equalization are investigated through simulations. Figure 12 shows the minimum required SNRs satisfying the packet error rate (PER) of \( 10^{-3} \) and \( 10^{-2} \) in 16 QAM and 64 QAM, respectively, where, for example, ‘5C2T’ implies that turbo equalization starts when ‘\( c_{\text{itr}} \)’
equals 2 with \( I_{\text{max}} \) set to 5, and ‘5C4T’ implies the pure DWCC-II operation without turbo equalization. From the simulation results, it is found that the COBD has a lower minimum required \( \text{SNR} \) than the COAD in the given channel conditions. In the meantime, the optimum number of iterations in COBD can be found at ‘5C2T’ or ‘5C3T’ where the required number of turbo equalization is two and one, respectively. Figure 13 shows the performance dependence of COBD on the number of iterations in DWCC and turbo equalization for 64 QAM at the \( \text{SNR} \) of 24 dB. It is found that the optimal number of DWCC and turbo equalization is two and one, respectively, and the performance does not severely depend on the number of turbo equalization. Consequently, the performance of TE-DWCC is largely affected by the priority between coherent combining gain and channel decoding gain in the interference dominant channel. In addition, it is also found that the powerful channel coder such as turbo coder by itself is not efficient for suppressing the large interference.

Regarding computational complexity and latency, the required number of FFT operation and turbo equalization in TE-DWCC is comparable to the conventional canceller in [9], [10]. The system parameters are listed in Table 2. The total bandwidth is 20 MHz and all the subcarriers bear data symbols. The sampling time is 50 ns. The Max-Log-MAP for turbo decoding is applied and the maximum number of iterations in turbo decoder is set to 8. For the wireless channel model, the exponentially distributed 18 multipath delay profile [9] is assumed as already shown in Fig. 3, where the number of taps and tap delay are 18 and 2 samples delay, respectively. The tap weights are independent and identically distributed Rayleigh fading random variables referring to [20]. The \( \text{rms} \) delay spread is controlled by the multipath power difference in \( \text{dB} \) scale (PDB) with the maximum channel delay fixed. Table 3 describes the \( \text{rms} \) delay depending on PDB. The smaller PDB is, the larger ISI and ICI are, whereas the channel coding gain by the multipath increases. Meanwhile,
### Table 2  System parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>System bandwidth</td>
<td>20 MHz</td>
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<tr>
<td>Number of IFFT/FFT</td>
<td>64</td>
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<tr>
<td>Subcarrier spacing</td>
<td>312.5 kHz</td>
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<tr>
<td>Packet frame length</td>
<td>10 OFDM symbols</td>
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<td></td>
<td>(pilot: 2, data: 8)</td>
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<tr>
<td>Data modulation</td>
<td>16 QAM, 64 QAM</td>
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<tr>
<td>Channel coding / decoding</td>
<td>RSC (13, 15, 15)</td>
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<td></td>
<td>Max-Log-MAP (8 iterations)</td>
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<tr>
<td>Constraint length</td>
<td>4</td>
</tr>
<tr>
<td>Puncture</td>
<td>1/2, 2/3 (RCPT)</td>
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<tr>
<td>Channel estimation</td>
<td>Perfect</td>
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</tbody>
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### Table 3  rms delay spread depending on PDB.

<table>
<thead>
<tr>
<th>PDB [dB]</th>
<th>rms delay [ns]</th>
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<tbody>
<tr>
<td>1.4</td>
<td>292.5</td>
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<tr>
<td>1.2</td>
<td>327.8</td>
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<tr>
<td>1.0</td>
<td>367.1</td>
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<tr>
<td>0.8</td>
<td>408.9</td>
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<td>0.6</td>
<td>450</td>
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<tr>
<td>0.4</td>
<td>485.5</td>
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<tr>
<td>0.2</td>
<td>510</td>
</tr>
<tr>
<td>0.0</td>
<td>518.8</td>
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</table>

5.1 Performance Comparison in 16 QAM/OFDM

In Fig. 15 the simulation is performed in the code rate of 1/2 and the PDB at 1.4 dB and 0.0 dB, where ‘NC’ and ‘CTE’ denote ‘no canceller’ and ‘conventional TE’ [9], [10], respectively. In ‘CTE’ the soft decision feedback is applied. The number of transmit bits is 1000 bits per packet. For simplicity, PDB at 1.4 dB is written by PDB1.4, hereafter. The number of turbo equalization is set to 3 in ‘CTE’ and 2 in TE-DWCC (‘5C2T’), respectively. The PDB1.4 and PDB0.0 in 16 QAM implies the noise dominant and interference dominant environments, respectively. From the result, ‘CTE’ shows the best PER performance in the noise dominant region, whereas its performance is severely degraded when it goes into the interference dominant region. Even though the PER performance of the TE-DWCC is worse than that of ‘CTE’ about 1.7 dB in PDB1.4, it is not overwhelmed by ISI and ICI even in PDB0.0. In the meantime, the PER performance of the TE-DWCC in the PDB0.0 is better than that in the PDB1.4 due to the channel decoding gain from the frequency diversity. In Fig. 16 the PER performance comparison of each scheme is shown in the code rate of 2/3. Since the ‘CTE’ largely depends on the channel decoding gain, the performance shows the floor even at PDB0.6, whereas the TE-DWCC with the double window combining gain is still tolerable against the severe ISI and ICI. Consequently, it is proved that the TE-DWCC with the coherent combining and the channel decoding gain is more robust to the interference dominant channel environment. In Fig. 17 the PER performances in the soft decision feedback (SDF) and hard decision feedback (HDF) are evaluated in ‘CTE’. Unlike the result in Fig. 14, the canceller like ‘CTE’ is compatible with SDF, which is generally known in turbo equalization [16]. On the other hand, the canceller that performs the cyclic reconstruction in the time domain to suppress ICI with symbol replica, generated by soft symbol mapper can cause the variation within OFDM symbol which results in the increased ICI in the frequency domain.
5.2 Performance Comparison in 64 QAM/OFDM

In Fig. 18 the PER performance of the TE-DWCC and ‘CTE’ is compared in 64 QAM at the SNR of 24 dB since the minimum required SNR to satisfy the PER of $10^{-2}$ is about 24 dB in all PDBs as shown in Fig. 12. The number of transmit bits is 1500 bits per packet. In Fig. 18, the frequency diversity gain is not found in 64 QAM since ISI in the operating range of 64 QAM becomes dominant even with the same interference as in 16 QAM. The performance difference between two algorithms is due to the following reason. The canceller, ‘CTE’ mainly depends on the channel decoding gain and the guard interval combining gain in iterative canceller operation, while its operation includes not only the interfered signal part but also the non-interfered signal part to eliminate ICI. Unfortunately, however, the tentative symbol replica is not much reliable in 64 QAM even under the small ISI environment comparing to 16 QAM so that the interference from the non-interfered signal part becomes greater than the guard interval combining gain. Accordingly, the overall performance in TE-DWCC is better than that of ‘CTE.’

6. Concluding Remarks

In conclusion DWCC is analyzed by investigating the effective SINR distribution under different rms delay spread channels. It is found that extending the processing window in iterative canceller operation is not always beneficial to the packet error performance. In addition, it is also proved that the coherent combining gain due to DWCC prior to channel coding gain brings the large performance gain and thus the canceller that largely relies on the channel decoding gain is not efficient in interference dominant channels, particularly for 64QAM. Finally, the optimally incorporated TE-DWCC is shown to be more robust to the ISI and ICI with reduced computational complexity, compared with the conventional canceller. The effect of timing synchronization and channel estimation errors on the cancellers operating in the time domain needs to be further investigated.

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