Downlink Transmission of Broadband OFCDM Systems—Part III: Turbo-Coded

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Abstract—Orthogonal frequency and code-division multiplexing (OFCDM) systems have been introduced for high-speed data transmission in future wireless mobile communications. In this paper, a hybrid multicode interference cancellation (MCI) and minimum mean-square error (MMSE) detection scheme is presented for the turbo-coded OFCDM systems. Channel estimation based on a code-multiplexed pilot channel is employed. The weights of the hybrid detection are derived theoretically and an effective method to generate the weights in practical applications is proposed. By means of computer simulation, the effects of system parameters on the performance are studied extensively. It is shown that the hybrid detection outperforms pure MMSE detection in various channel conditions, especially for high-level modulation schemes. To carry out interference regeneration for the hybrid detection, the conventional turbo decoding algorithm which only decodes systematic bits should be extended to decode parity bits as well. Moreover, two iterations in turbo decoding are sufficient to provide good performance for the system with the multistage hybrid detection. Finally, given time-domain spreading factor \( N_T \), the system performance improves with frequency-domain spreading factor \( N_F \). However, the frequency diversity gain is saturated when \( N_F \) is large (i.e., \( N_F \geq 16 \)).

Index Terms—Interference cancellation, minimum mean-square error (MMSE) detection, orthogonal frequency-division multiplexing (OFDM), turbo codes.

I. INTRODUCTION

The era of high-speed data transmission in mobile communications is approaching rapidly. Coupled with enhanced techniques, the fourth-generation (4G) wireless networks aim to provide ultra-high-speed data transmissions, such as 100 Mb/s, especially, in downlink. The orthogonal frequency and code-division multiplexing (OFCDM) system [1] is one of the promising candidates for downlink broadband 4G wireless access. Based on orthogonal frequency-division multiplexing (OFDM) techniques, the OFCDM system is robust to the severe multipath interference in a broadband wireless channel. Moreover, the OFCDM system employs two-dimensional (2-D) spreading: time-domain spreading and frequency-domain spreading. Each data symbol in the OFCDM system is spread in time-domain with \( N_T \) chips and in frequency-domain with \( N_F \) chips. Therefore, totally \( N = N_T \times N_F \) spread chips per data symbol are involved in the 2-D spreading.

The OFCDM system employs multicode techniques as an efficient way to achieve ultra-high-speed data transmission in downlink. That is, when a user requests for high-speed multimedia services, the base station may allocate multiple or even all available code channels to this user to provide the high-speed transmission. The system adopts packet switch instead of circuit switch, so that multiple-user interference does not exist. However, the interference among multiple codes of one single user may occur. Using orthogonal variable spreading factor (OVSF) codes [2], there would be no interference among the multiple code channels in an additive white Gaussian noise (AWGN) channel. However, in a realistic mobile channel, the code orthogonality may be destroyed by the possible fast fading in time-domain and especially the different fading among subcarriers in frequency-domain. Therefore, multicode interference (MCI) will occur. In order to improve the performance, MCI should be cancelled out as much as possible. However, it should be noted that the MCI cancellation in time-domain is difficult because near perfect channel estimation for each time instant is required in the presence of large Doppler shift. Therefore, in time-domain, a simple equal gain combining (EGC) technique is employed and no MCI cancellation will be carried out. On the other hand, in frequency-domain, the MCI is serious. Therefore, MCI cancellation is considered in conjunction with minimum mean-square error (MMSE) detection. So far, there has been no paper discussing the MCI cancellation in the turbo-coded OFCDM system. Thus, it is desirable to investigate the performance of the coded OFCDM when multistage MCI cancellation is employed. Parallel-type interference cancellation is considered because it is more practical than the serial type due to its short processing delay. Furthermore, interference cancellation can be implemented in either hard decision or soft decision. Although soft decision can provide better performance than hard decision, it is complicated to choose a suitable soft decision function in a channel-coded system. Therefore, hard decision is considered in this paper due to its simple realization in practical systems. Moreover, to carry out coherent detection and multistage MCI cancellation, a good channel estimation technique is needed. Pilot aided channel estimation is considered. In the OFCDM system, there are three types of pilot channels: code-multiplexed, time-multiplexed, and frequency-multiplexed. A code-multiplexed pilot channel is preferred since it provides precise estimations, as well as more flexibility [3].

By combining MMSE detection and parallel interference cancellation techniques in frequency-domain, hybrid MCI cancellation and MMSE detection has been proposed for the uncoded OFCDM system [4]. In the turbo-coded OFCDM...
system with hybrid detection, the tentative recovered bits after decoding are used to regenerate the MCI replicas. Moreover, the MMSE weight should be updated stage by stage due to the reduction of MCI in the input signals. An effective method to estimate MMSE weights is proposed. The objective of this work is to evaluate the performance of the hybrid detection in the turbo-coded OFCDM systems, when the channel estimation based on a code-multiplexed pilot channel is employed. The effects of key system parameters, such as the number of MCI cancellation stages, the iterations in turbo decoding, the spreading factors, etc., are investigated extensively.

The rest of this paper is organized as follows. Section II describes the OFCDM system and the channel model. The channel estimation technique and the hybrid MCI cancellation and MMSE detection are presented in Section III. Then, computer simulation results are presented in Section IV. Finally, conclusions are drawn in Section V.

II. SYSTEM DESCRIPTION

A. Transmitter

The packet transmission on the synchronous downlink broadband channel is considered. 2-D OVSF codes are employed as short channelization codes. For the spreading factor $N = N_T \times N_F$, it is assumed that totally $K (K < N)$ 2-D codes are assigned to a user for high-speed data transmission. The 2-D code assigned to the $k$th channel is denoted as $\{C_{N_T}^{(k)}(n), C_{N_F}^{(k)}(n)\}$ as in [4], where $C_{N_T}^{(k)}(n) = \{c_{N_T}^{(k)}, \ldots, c_{N_T}^{(k)}(N_T-1)\}$ is the time-domain spreading code and $C_{N_F}^{(k)}(n) = \{c_{N_F}^{(k)}, \ldots, c_{N_F}^{(k)}(N_F-1)\}$ is the frequency-domain spreading code. $c_{N_T}^{(k)}$ and $c_{N_F}^{(k)}$ are the $(k_T)$th and $(k_F)$th codes on the $(\log_2 N_T)$th and $(\log_2 N_F)$th layers, respectively, in the OVSF code tree [2].

At the transmitter side (see Fig. 1), information bits of each data code channel are first turbo encoded [5], then Gray mapped into multilevel quadrature amplitude modulation (MQAM) symbols by a 4 quadrature amplitude modulation (QAM)- [i.e., quadrature phase-shift keying (QPSK)] or 16 QAM-modulator. The resultant symbol sequence is then processed by the symbol interleaver [6]. Interleaved data symbols are serial-to-parallel (S/P) converted into $N_B = M_C/N_F$ streams, where $M_C$ is the total number of subcarriers, $N_F$ of which carry the same data symbol. After S/P conversion, 2-D spreading is carried out, where each data symbol is first spread into $N_T$ chips in time-domain with the spreading code $C_{N_T}^{(k)}$, then, the time-domain spread signal is duplicated into $N_F$ copies and multiplied by the frequency-domain spreading code $C_{N_F}^{(k)}$. At the same time, the same known QPSK pilot symbol is first spread in-time domain with the pilot code $C_{P}^{(k)}$ and spreading factor of $N_T P$, then repeated into $M_C$ streams, corresponding to $M_C$ subcarriers. The spread signals from $K$ data channels and one pilot channel are added together by the code-multiplexer. After that, a frequency interleaver [6] is employed in order for the system to benefit from frequency diversity due to the different fading among interleaved subcarriers. Scrambling is then carried out. The resultant signals will be up-converted into $M_C$ subcarriers by an $M$-point IFFT, where $M \geq M_C$ and the value of $M$ is a power of 2. The $M_C$ subcarriers are located in the middle of the inverse fast Fourier transform (IFFT) points and zeros are padded at each side of the $M_C$ points. After IFFT, an effective time chip (or OFCDM symbol) is obtained with $M$ samples, whose duration is $T_c = MT_s$ and $T_s$ is the sampling time. Then, a guard interval of $T_g$ is inserted between OFCDM symbols to prevent intersymbol interference. Therefore, the time duration of a complete OFCDM symbol is $T = T_c + T_g$. Finally, the complete OFCDM symbol passes through the pulse shaping filter, which gives rise to the baseband transmitted signal.

Therefore, the spread modulated data signal on the $m$th subcarrier in the $i$th OFCDM symbol duration can be written as

$$S_{k,m,i}(t) = \sqrt{P_d} d_{k,m,i} c_{N_T}^{(k)} c_{N_F}^{(k)} s_{m,i} e^{j2\pi f_{m}(t-IT)} p(t-IT)$$

(1)

where $P_d$ is the signal power of one data code on one subcarrier, $d_{k,m,i}$ is the modulated data symbol of the $k$th data channel with unitary power, $c_{N_T}^{(k)} c_{N_F}^{(k)}$ is the 2-D spreading code, $s_{m,i}$ is the cell-specific spreading code, $f_{m}$ is the baseband equivalent frequency of the $m$th subcarrier, and $p(t)$ is the impulse response (unitary rectangular pulse) of the pulse shaping filter. Furthermore, the spread signal on the code-multiplexed pilot channel can be written as

$$S_{P,m,i}(t) = \sqrt{\beta P_d} c_{P,i} s_{m,i} e^{j2\pi f_{m}(t-IT)} p(t-IT)$$

(2)

where $\beta$ is the power ratio of pilot to one data channel and $d_{P,i}$ is the known QPSK modulated pilot symbol with unitary power.
Finally, the transmitted signal on the $M_C$ subcarriers in one packet duration is given by

$$S(t) = \sum_{i=0}^{N_t-1} \sum_{m=-\frac{M_C}{2}}^{\frac{M_C}{2} - 1} \sum_{k=0}^{K-1} \left[ S_{k,m,i}(t) + S_{P,m,i}(t) \right]$$

(3)

where $N_t$ is the number of OFCDM symbols in one packet duration.

In downlink, all code signals are synchronized and experience the same multipath fading channel with the low-pass equivalent impulse response

$$h(t) = \sum_{l=0}^{L-1} h_l(t) \delta(t - \tau_l)$$

(4)

where $h_l(t)$ is the complex time-varying channel fading for the $l$th path and $\tau_l$ is the time delay of the $l$th path, uniformly distributed in $[0, T_g]$. The amplitude and phase of $h_l(t)$ are Rayleigh distributed and uniformly distributed in $[0, 2\pi]$, respectively. Furthermore, $h_{l_1}(t)$ and $h_{l_2}(t)$ are assumed to be statistically independent for $l_1 \neq l_2$. Finally, the average frequency response over the $i$th OFCDM symbol on the $m$th subcarrier is given by

$$H_m(i) = \sum_{l=0}^{L-1} e^{-j2\pi f_m \tau_l} \left[ \frac{1}{T_c} \int_{iT}^{iT+T_c} h_l(t) dt \right], \quad 0 \leq m \leq M - 1.$$

(5)

B. Receiver

Assuming that the guard interval is larger than the maximum path delay spread, there is no intersymbol interference in the received signals. After passing through a matched filter, down-converted by an FFT block, descrambled and deinterleaved, the received signal on the $r_{m,i}$ subcarrier in the $j$th OFCDM symbol duration is denoted as $r_{m,i}$, which is input to $K$ parallel processors, corresponding to $K$ data channels. Fig. 2 shows the receiver block diagram of the $k$th data code channel. First of all, the channel fading on each subcarrier is estimated by using the code-multiplexed pilot channel. With the estimated channel information, the EG weights can be obtained and time-domain despreading is carried out for data channels. At the zeroth stage (without MCI cancellation), using the signals $\gamma_{k,m,i}$ after equal-gain combining (EGC) detection, and the estimated channel fading, MMSE weights can be generated. Then, $\gamma_{k,m,i}$ is despread in frequency-domain and combined at the MMSE detector using the estimated MMSE weights. After that, the signals are processed by the symbol deinterleaver. To provide soft-valued bit streams to the turbo decoder, a soft MQAM demodulator is needed, where a maximum-a-posterior algorithm (Max_Log_MAP [7]) is employed. Moreover, in a conventional turbo decoder, only the information bits (or systematic bits) are concerned. Therefore, only systematic bits are recovered after decoding. However, in the interference cancellation, data replica must be regenerated. Therefore, all coded bits should be recovered. There are two methods to recover the parity bits. One method is to encode the recovered systematic bits. This method is simple but the errors in systematic bits will propagate to parity bits due to the recursive encoder. The other way is to recover
parity bits directly from turbo decoding, using a similar decoding algorithm, as illustrated in [5] and [8]. It will be shown later that without error propagation, the second method provides better performance than the first method. Therefore, the calculation of the logarithm of likelihood ratio (LLR) for parity bits is added in the conventional turbo decoding and this extended algorithm will recover both systematic and parity bits. Based on the outputs of turbo decoder, the tentative data decision on the zeroth stage for the $k$th code channel is obtained and denoted as $\hat{d}_k^{(0)}$. Using $\hat{d}_k^{(0)}$ and the estimated channel condition, the data replica for the current code channel $\hat{I}_m^{(0)}$ can be generated.

With the replicas of all data channels ($\hat{I}_m^{(0)}, k = 0, \ldots, K - 1$) at the zeroth stage, hybrid MCI cancellation and MMSE detection can be carried out at the first stage. As shown in Fig. 2, in the hybrid detection, the MCI from interfering data channels, $\sum_{k \in \Omega_k} \hat{I}_{km}$, is cancelled out from the received signal, where $\Omega_k$ is the set of 2-D codes which have the same time-domain spreading code as the desired code $\bar{F}$, but different frequency-domain spreading codes from the desired code $\bar{F}$. Then, MMSE weights must be updated due to the MCI reduction in the input signal. Using the new weights of the hybrid detection, the signal after MCI cancellation $\hat{I}_m^{(1)}$ will be processed in the same way as that in the zeroth stage. Similarly, data replicas ($\hat{I}_m^{(1)}$) are generated and used in the next stage for the hybrid detection. Generally speaking, as the decoding outputs become more reliable stage by stage, MCI can be regenerated with higher accuracy stage by stage. After subtraction, MCI can be cancelled out much from the input signal $\hat{I}_m$. Thus, the system performance can be improved stage by stage.

III. HYBRID DETECTION

A. Channel Estimation and EGC

Channel estimation is carried out on each subcarrier by using the code-multiplexed pilot channel. First of all, the input signal $r_{m,i}$ to the channel estimator on the $m$th subcarrier in the $i$th OFCDM symbol duration is given by

$$r_{m,i} = \sum_{k=0}^{K-1} \sqrt{P_d d_k^{(m)} c_{N_P, r} c_{N_T, m,i}} + \sqrt{P_d P_c P_d} s_{m,i} \cdot H_m(i) + \eta_m(i),$$  \hspace{1cm} (6)

where $\eta_m(i)$ is sum of the background noise and the intercarrier interference due to Doppler shift. $r_{m,i}$ is then descrambled and despread in time-domain using the pilot code. The preliminary channel fading factor for the $m$th subcarrier and $i$th pilot symbol is given by

$$\xi_{m,n} = \frac{1}{N_P r} \sum_{i = nN_P - 1}^{(n+1)N_P - 1} r_{m,i} c_{N_P, r} s_{m,i},$$  \hspace{1cm} (7)

In practice, the number of pilot symbols can be small in a packet. When there are three pilot symbols in one packet, three preliminary channel estimations can be obtained from (7). Using $\xi_{m,n}$ ($n = 0, 1, 2$), the channel fading factor on the $m$th subcarrier in the $i$th OFCDM symbol duration, $\xi_m(i)$ ($i = 0, 1, \ldots, N_d - 1$), can be approximated by linear interpolation, which is given by

$$\xi_m(i) = \begin{cases} \xi_{m,0} - \frac{\xi_{m,0} - \xi_{m,1}}{N_d - 1} \cdot \frac{i - \frac{N_d}{2}}{\frac{N_d}{2}}, & 0 \leq i < \frac{N_d}{2}, \\ \xi_{m,2} - \frac{\xi_{m,2} - \xi_{m,1}}{N_d - 1} \cdot \frac{i - \frac{3N_d}{2}}{\frac{N_d}{2}}, & \frac{N_d}{2} \leq i \leq N_d - 1 \end{cases}.$$  \hspace{1cm} (8)

Since the channels on adjacent subcarriers in frequency-domain are highly correlated, $\xi_m(i)$ can be averaged over adjacent subcarriers to improve the reliability of channel estimation. Using a sliding window average, the final channel estimation $\hat{H}_m(i)$ for the $m$th subcarrier in the $i$th OFCDM symbol duration is given by

$$\hat{H}_m(i) = \frac{1}{2N_{avg} + 1} \sum_{j=-N_{avg}}^{m+N_{avg}} \xi_j(i),$$  \hspace{1cm} (9)

where $2N_{avg} + 1$ is the average size of the sliding window.

Using the estimated channel, EGC can be employed with time-domain despreading to accumulate useful signals from different OFCDM symbols. The EGC weight is given by

$$\hat{\varphi}_m(i) = \frac{\hat{H}^*_m(i)}{\hat{H}_m(i)} \hspace{1cm} (10)$$

A. Pure MMSE Detection

As explained before, in a broadband channel, MCI in frequency-domain is serious. Pure MMSE detection is employed in frequency-domain at the zeroth stage. To recover the data symbol of the $k$th code channel $d_k$, where $d_k = d_k^{(m)}$ for the concerned $N_P$ subcarriers, a set of weighting factors are needed which should satisfy the MMSE criterion

$$\min_{w_m(k)} \mathbb{E} \left\{ \left| \sqrt{P_d d_k - \sum_{m=0}^{N_P-1} w_m(k) \gamma_{k,m}} \right|^2 \right\}. \hspace{1cm} (12)$$

It is difficult to obtain a closed-form solution of (12). However, in case of full load, i.e., all $N_P$ frequency-domain spreading codes are assigned for data transmission (each code channel has the same power), a simplified MMSE is obtainable due to the orthogonal property of OVSF codes. In practical applications, the exact MMSE weights should be different from
the simplified weights obtained under the assumption of full load. Nevertheless, since a high load is expected in high-speed data communications, the simplified version of the pure MMSE weighting factor is approximated as

\[
w_m(k) = \frac{E\left\{ \sqrt{T_d}d_k^{*}\gamma_{km}^{*} \middle| \alpha_m \right\}}{E\left\{ \left| \gamma_{km} \right|^2 \middle| \alpha_m \right\}} = \frac{P_d\alpha_m c_{N,F,m}^{(k)}}{(K_C + 1)P_d|m|^2 + \sigma^2} \tag{13}
\]

where \( K_C \) is the number of code channels in \( \Omega_F \) and \( \sigma^2 \) is the variance of the additive noise.

C. Hybrid MCI Cancellation and MMSE Detection

When multistage MCI cancellation is employed, the MMSE weight in (13) should be updated due to the reduction of MCI stage by stage. Using the signal replicas of interfering data channels (\( K_{km}, \ k \in \Omega_F \)) at the previous stage, the MCI in frequency-domain for the \( k \)th data channel can be regenerated, which is given by

\[
MCI_m^{(k)} = \sum_{k \in \Omega_F} I_{k,m}^{(s-1)} = \sum_{k \in \Omega_F} \sqrt{T_d}d_k^{(s-1)} c_{N,F,m}^{(k)} \alpha_m \tag{14}
\]

where \( d_k^{(s-1)} \) denotes the tentative hard data decision at the \( (s-1) \)th stage for the \( k \)th data channel, and \( \alpha_m = (1/N_T) \sum_{i=0}^{N_T-1} |\hat{H}_m(i)| \) is the estimated channel factor of the \( m \)th subcarrier. As shown in Fig. 2, at the \( s \)th stage, the regenerated MCI for the \( k \)th data channel \( MC_l^{(k,m)} \) is removed from the input signal \( \gamma_{km}^{(s-1)} \), and the resultant signal is given by

\[
\gamma_{km}^{(s)} = \gamma_{km} - MC_l^{(k,m)} = \sqrt{T_d}d_k^{(k)} c_{N,F,m}^{(k)} + \sum_{k \in \Omega_F} \left[ \sqrt{T_d}d_k \alpha_m - \sqrt{T_d}d_k^{(s-1)} \alpha_m \right] c_{N,F,m}^{(k)}
\]

\[
+ \eta_{km}^{(s-1)} \tag{15}
\]

It can be seen from (15) that the residual MCI on the \( s \)th stage depends on the reliability of \( d_k^{(s-1)} \) and the quality of the channel estimation \( \hat{H}_m(i) \) because of \( \alpha_m \).

After MCI cancellation, the MMSE weights of the hybrid detection should be updated and given by

\[
w_m^{(s)}(k) = \frac{E\left\{ \sqrt{T_d}d_k^{(k)} \gamma_{km}^{(s)} \middle| \alpha_m \right\}}{E\left\{ \left| \gamma_{km}^{(s)} \right|^2 \middle| \alpha_m \right\}} = \frac{P_d\alpha_m c_{N,F,m}^{(k)}}{(K_C + 1)P_d|m|^2 + \sigma^2} \tag{16}
\]

Setting \( \gamma_{km}^{(0)} = \gamma_{km} \) for \( k = 0, \cdots, K - 1 \), the pure MMSE weights in (13) can be obtained from (16) as \( w_m^{(0)}(k) \).

In practice, \( w_m^{(s)}(k) \) \((s \geq 0)\) can be obtained by estimating \( E\left\{ \left| \gamma_{km}^{(s)} \right|^2 \middle| \alpha_m \right\} \). First of all, since there are totally \( N_d \) OFCDM symbols in time-domain, the output of the time-domain despreader of the \((jN_T)\)th to the \([j + 1]N_T - 1\)th OFCDM symbols is denoted as \( \gamma_{km}^{(s)}(j), \) where \( j = 0, \cdots, (N_d/N_T) - 1, \) Actually, \( \gamma_{km}^{(s)} \) in (15) corresponds to \( \gamma_{km}^{(0)}(0) \). Then, it is assumed that the residual MCIIs on all data channels have the same variance. Moreover, due to the high correlation between channel fading among adjacent OFCDM symbols and subcarriers, over the time window from the \((j - I_{Favg})\)th to the \((j + I_{Favg})\)th signals after EGC, the channel fading factors on the \((m - I_{Favg})\)th to the \((m + I_{Favg})\)th subcarriers are assumed to be the same. Therefore, \( E\left\{ \left| \gamma_{km}^{(s)} \right|^2 \middle| \alpha_m \right\} \) can be approximated as

\[
E\left\{ \left| \gamma_{km}^{(s)} \right|^2 \middle| \alpha_m \right\} \approx \frac{1}{K_C + 1} \frac{1}{(2I_{Favg} + 1)} \sum_{k=0}^{K-1} \sum_{j=0}^{I_{Favg}} \sum_{m=0}^{I_{Favg}} \left| \gamma_{km}^{(s)}(j') \right|^2 \tag{17}
\]

where \( 2I_{Favg} + 1 \) and \( 1 + I_{Favg} \) are the average window sizes over time and frequency-domains, respectively. Since \( P_d \) and \( c_{N,F,m}^{(k)} \) are known, and \( H_m(i) \) is estimated as \( \hat{H}_m(i) \), \( w_m^{(s)}(k) \) can be approximated as

\[
w_m^{(s)}(k) \approx \frac{P_d \left( \sum_{i=0}^{N_T-1} |\hat{H}_m(i)| \right)}{NT} \frac{1}{(2I_{Favg} + 1)} \sum_{k=0}^{K-1} \sum_{j=0}^{I_{Favg}} \sum_{m=0}^{I_{Favg}} \left| \gamma_{km}^{(s)}(j') \right|^2
\]

By means of the estimated MMSE weights \( w_m^{(s)}(k) \) the hybrid detection can be carried out. The resultant signals are further processed by the soft demodulator and turbo decoder. Finally, based on the decoding output, the new MCI to be used for next stage will be regenerated.

IV. SIMULATION RESULTS

A. Configurations

Computer simulation is carried out to show the performance of hybrid MCI cancellation and MMSE detection in the turbo-coded OFCDM system. The major radio link parameters are given in Table I. The effective bandwidth is 101.5 MHz. Based on the optimization to compensate for the maximum multipath delay and to avoid the influence of Doppler shift, the number of subcarriers \( M \) is chosen to be 768 with the subcarrier spacing of 131.836 kHz. The number of IFFT points \( M \) is set to 1024. Therefore, the sampling rate after IFFT is 101.5 \times 1024/768 \approx 135 \) Ms/s. A guard interval of 226 samples, or \( T_g = 1.67 \) \mu s, equivalently, is assigned between two OFCDM symbols. The packet length is 0.444 ms, which is composed of \( N_d = 48 \) OFCDM symbols per subcarrier. Setting the time-domain spreading factor of pilot channel \( N_{T,F} \) to 16, there are \( 48/16 = 3 \) pilot symbols on each subcarrier in one packet duration. For data channel, the spreading factor in time-domain \( N_T \) can be 4, 8, or 16. Information bits transmitted on each data channel are individually encoded by a turbo code of 1/2 rate. On the receiver side, the Max_Log_MAP algorithm is employed in the soft demodulator and turbo decoder (with iterative structure). Furthermore, a general exponential decay
multipath model is considered with 12 paths and an equal separation of $20T_n$ between adjacent paths. The power difference between adjacent paths is set to 1 dB, and the total power in the power delay profile is one. Doppler shift $f_d$ is 50 Hz. In computer simulations, a modified Jake’s model [9] is employed to generate multiple uncorrelated paths. Finally, the effective signal-to-noise ratio (SNR) per information bit is defined as

$$SNR_{\text{eff}} = \frac{P_0 N(1 + \beta/K)}{Q_{\text{eff}}r_{\text{eff}} \sigma_n^2},$$

where $Q_{\text{eff}}$ is 2 for QPSK and 4 for 16 QAM, $r_{\text{eff}}$ is the effective code rate and $\sigma_n^2$ is the variance of the channel noise.

### B. Effect of System Parameters

Unless noted otherwise, the following parameters are used. The 2-D spreading factor is $N = 8 \times 8$ and the number of data channels is $K = 56$. The power ratio $\beta/K$ between the pilot and all data channels is set to 0.20. The iterations in turbo decoding are two. The average window size in frequency-domain for channel estimation is $2N_{\text{avg}} + 1 = 3$. The average window sizes in time and frequency-domain for MMSE weight estimates are $2T_{\text{avg}} + 1 = 3$ and $2T_{\text{avg}} + 1 = 3$, respectively. Finally, the parity bits of turbo codes are obtained directly from decoding for the MCI regeneration. First of all, the packet error rate (PER) performance of the turbo-coded OFCDM system is shown in Fig. 3 as a function of $SNR_{\text{eff}}$ when both hybrid detection and pure MMSE are employed. It can be seen that for both modulation schemes, the PER decreases as the number of stages increases due to the reduction of MCI in each stage, especially when $SNR_{\text{eff}}$ is large. The most significant reduction in PER is obtained from the zeroth stage to the first stage, then the reduction becomes smaller as the number of stages increases. The hybrid detection works much more effectively in 16 QAM than in QPSK. This is because 16 QAM is more vulnerable to MCI than QPSK, so significant improvement can be obtained in 16 QAM by using hybrid detection. Although the PER performance gets better when the number of stages increases, the improvement becomes insignificant after the second stage for QPSK and fifth stage for 16 QAM. Therefore, the hybrid detection with two stages is sufficient for QPSK, while the hybrid detection with five stages is necessary for 16 QAM.

As described in Section II, the parity bits can be obtained by either encoding recovered systematic bits or by modifying turbo decoding algorithm. Given $SNR_{\text{eff}} = 8$ dB and 12 dB for QPSK and 16 QAM, respectively, Fig. 4 compares the system performance for different parity-bit recovery schemes from encoding and directly from decoding, as a function of the number of stages. It can be seen that for either QPSK or 16 QAM, the performance of using parity bits directly from decoding is better than indirectly from encoding. This is because when the parity bits are obtained from encoding, the errors in the systematic bits

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### TABLE I

<table>
<thead>
<tr>
<th>Simulation Parameters</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Bandwidth/Baseband sampling rate</td>
<td>101.5 MHz/135 Mbps</td>
</tr>
<tr>
<td>Number of sub-carriers (M)</td>
<td>768</td>
</tr>
<tr>
<td>Number of IFFT/FFT points</td>
<td>1024</td>
</tr>
<tr>
<td>Complete OFCDM symbol duration (Effective data + Guard interval)</td>
<td>9.259 μs (7.585+1.674 μs)</td>
</tr>
<tr>
<td>Packet length (No. of OFCDM symbols per sub-carrier)</td>
<td>0.444 ms (N_r=48 OFCDM symbols)</td>
</tr>
<tr>
<td>Spreading code</td>
<td>2-D OVSF</td>
</tr>
<tr>
<td>Modulation</td>
<td>Data: QPSK, 16 QAM</td>
</tr>
<tr>
<td>Spreading length</td>
<td>Data: $N_r=4, 8, 16$</td>
</tr>
<tr>
<td>Channel estimation</td>
<td>Pilot-aided</td>
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<td>Despreading</td>
<td>EGC in time domain and hybrid detection in frequency domain</td>
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<td>Demodulation</td>
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<td>Channel coding/decoding</td>
<td>1/2 rate turbo/Iterative Max_Log_MAP decoding</td>
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<td>Channel parameters</td>
<td>Paths: 12, Path separation: 0.1481 μs ($20T_n$)</td>
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will propagate into parity bits due to the recursive systematic encoding. The effect of error propagation accumulates as the iterative MCI cancellation goes on, and the performance gap between both schemes increases with stages increasing. Therefore, to get better performance, parity bits should be recovered directly from decoding algorithms which avoids the error propagation.

Using the hybrid detection of two stages and five stages for QPSK and 16QAM, respectively, the PER performance is shown in Fig. 5 as a function of the number of iterations in turbo decoding. The system performance of the pure MMSE is also shown as a comparison. It can be seen that the PER performance of the pure MMSE improves gradually as the number of iterations increases. However, in the hybrid detection, a sharp reduction in PER is observed from the first iteration to the second iteration, afterwards the PER curve tends to be flat. Using the pure MMSE, at least four iterations are needed, while using the hybrid detection, two iterations are sufficient to provide good performance for the turbo-coded OFCDM system. This is because for the pure MMSE (or the hybrid detection with the zeroth stage) there is too much MCI so that turbo decoding needs more iterations. However, for the hybrid detection with more stages, much MCI has been cancelled out, and few iterations (i.e., two iterations) are sufficient.

In real applications, the MMSE weights are estimated by using (18). Given $f_D = 50$ Hz and $I_{\text{avg}} = 1$, Fig. 6 illustrates the system performance as a function of $I_{\text{avg}}$. When $I_{\text{avg}}$ increases first from zero to one, the PER decreases because the noise in weight estimation is reduced. However, when $I_{\text{avg}}$ is increased beyond one, the system performance degrades. This is because the broadband channel is highly frequency selective. When $I_{\text{avg}}$ is large, the correlation among the $(2I_{\text{avg}} + 1)$ subcarriers decreases, and the distortion of the weight estimation is introduced. In the slow fading and $I_{\text{avg}} = 1$, the optimal $I_{\text{avg}}$ achieving the lowest PER is one for both 16 QAM and QPSK.

When fast fading occurs, the channel variation in one packet duration is serious. For example, for a carrier frequency of 5 GHz, when a mobile terminal moves at a speed of 300 km/h, the resultant maximum Doppler shift can be as high as 1500 Hz. Therefore, it is necessary to investigate the effect of Doppler shift ($f_D$) on the system performance. Fig. 7 shows the PER performance of the hybrid detection as a function of the Doppler shift. Note that the concerned system employs EGC in time-domain, and the hybrid detection is only carried out in frequency-domain. It can be seen that the PER decreases with $f_D$ increasing from 50 Hz and reaches a minimal value when $f_D$ is around 1000 Hz for both QPSK and 16 QAM. This is because although the MCI in time-domain increases with $f_D$,
the channel estimation algorithm with linear interpolation can still track the channel variation. With good channel estimation, MCI cancellation works effectively in frequency-domain and the time-domain diversity gain is obtained. When the gain from time diversity overcomes the loss due to increased MCI in time-domain, the system performance is enhanced. However, if $f_D$ increases further, the system performance degrades rapidly. This is because when $f_D$ is too large, the channel varies so fast that the channel estimation algorithm cannot track the changes. Without precise channel estimation, the hybrid detection fails to work well and the PER is increased dramatically. In summary, the turbo-coded OFCDM system with hybrid detection is robust to channel variations when $f_D$ is less than 1500 Hz.

Finally, for a fixed time-domain spreading factor $N_F = 8$ and system load $K/N = (N_T - 1)/N_T = 0.875$, Fig. 8 shows the PER performance as a function of the frequency-domain spreading factor $N_F$. It can be seen that the system performance is poor when $N_F = 1$. This is because there is no frequency diversity gain although there is no MCI in frequency-domain. As $N_F$ increases, the PER decreases rapidly at first, then the PER drops slowly when $N_F$ is large. This is because when $N_F$ increases from a small value, the frequency diversity gain is large and overcomes the increased MCI in frequency-domain. However, as $N_F$ increases further, the frequency spacing of two closest subcarriers in the $N_F$ subcarriers reduces due to the fixed bandwidth, and the correlation among the $N_F$ subcarriers becomes high. Therefore, the frequency diversity gain is saturated. Although there is still reduction in PER when $N_F$ is large, the performance is almost saturated when $N_F$ is 16 for both QPSK and 16 QAM schemes.

V. CONCLUSION

The performance of the downlink turbo-coded OFCDM system is investigated in this paper with hybrid MCI cancellation and MMSE detection. The following conclusions are drawn.

1) The hybrid detection outperforms pure MMSE. The performance improves as the number of stages increases. For QPSK, the hybrid detection of two stages is sufficient, while for 16 QAM, the hybrid detection of five stages is necessary. The hybrid detection works more effectively for 16 QAM than for QPSK.

2) To carry out interference regeneration for the hybrid detection, the conventional decoding algorithm of turbo codes which only decodes systematic bits should be extended to decode parity bits as well. Furthermore, in the pure MMSE, at least four iterations are needed in the turbo decoding to provide stable performance, while only two iterations are sufficient in the hybrid detection.

3) The proposed method for MMSE weight estimation (see (18)) works well with proper values of the average window size in time-domain ($I_{T_{Dmax}}$) and in frequency-domain ($I_{F_{W_{max}}}$). To achieve good performance, $I_{T_{Dmax}} = 1$ and $I_{F_{W_{max}}} = 1$ should be selected over slow fading channels.

4) Given $N_T$, the system performance improves as $N_F$ increases. However, the performance gain is saturated when $N_F$ is large than 16.

REFERENCES


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