AN IMPROVED DOPPLER DIVERSITY TECHNIQUE FOR OFDM SYSTEMS IN TIME-VARYING MULTIPATH FADING CHANNELS

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ABSTRACT

Inter-channel interference(ICI), which results in an irreducible error floor, can be utilized as a source of Doppler diversity for OFDM systems in time-varying multipath channels. The proposed technique can enhance diversity gain by a new criterion for ICI cancellation in addition to enable the reduction of computational complexity and total detection time.

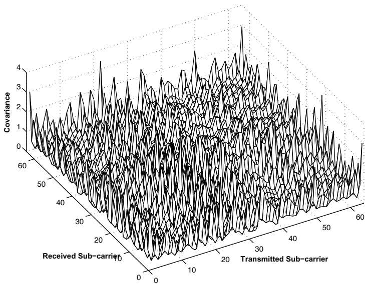
1. INTRODUCTION

Orthogonal Frequency Division Multiplexing(OFDM) is a promising communication scheme to achieve high data rate transmission. However, the long symbol duration of OFDM causes two problems in time-varying channels. Firstly, the symbol-by-symbol channel variation makes an accurate channel estimation difficult. Moreover, the time variations of the channel within an OFDM symbol lead to a loss of subcarrier orthogonality, resulting in inter-channel interference(ICI) that occurs an irreducible error floor in conventional detection schemes.

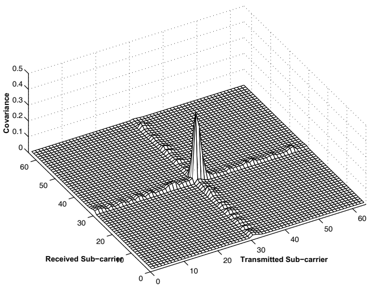
Most of the previous algorithms to mitigate the effects of the time-varying channel are to deal with ICI cancellation, which are just focused on mitigating the irreducible error floor[1]. Recently, the researches that ICI can be utilized as a source of diversity are presented. In [5], the Doppler diversity scheme is proposed that combines outputs of several receivers with artificially shifted frequency offset. The algorithm using minimum mean square error(MMSE) equalizer and successive detection(SD) is proposed that can obtain a temporal diversity by time-domain signal processing[3]. However, this algorithm has some limitations that total processing time is increased with the number of sub-carriers and it needs additional arithmetic loads because of the time-domain approach. Also, it has the enormous computational complexity due to the update of the MMSE equalizer.

In this paper, we propose an improved Doppler diversity technique that can overcome the limitation of the processing time and the complexity by parallel signal processing. Moreover, a Doppler diversity gain can be enhanced by a new criterion that is based on an intuitive observation for the time-varying characteristics of fading channels.

The following is an overview of the paper organization. Section II describes a fundamental concept of Doppler diversity for OFDM systems. Section III develops an improved Doppler diversity technique and a new criterion to enhance Doppler diversity gain. In Section IV, the proposed algorithm is verified by simulation results. We conclude with some discussions in Section V.



(a) The ICI-mixed signals



(b) The ICI-free signal

Figure 1: The covariance matrix in time-varying channels (N = 64, $f_d T_s$ =1.0 , f_d : maximum Doppler spread, T_s : an OFDM symbol duration, SNR = 30 dB)

2. THE PRINCIPLE OF DOPPLER DIVERSITY FOR OFDM

A new diversity concept can be developed in time-varying channels : *"Doppler diversity"*. Generally, Doppler diversity is a scheme that obtain a diversity gain by combining the signals transmitted on a set of frequencies within Doppler spreads[2]. Because a frequency included in the set can be a independent replica for the transmitted signal assuming wide-sense stationary uncorrelated scattering(WSSUS)[4].

In this paper, we utilize the ICI at the FFT output signals as a source of Doppler diversity in time-varying multipath fading channels. The Doppler spread invokes an ICI between sub-carriers for an OFDM symbol. A transmitted power through a sub-carrier leaks out to the other sub-carriers. In the consequence, all of sub-carriers for the received OFDM signal suffer from the ICI leaked by the other sub-carrier. In Fig. 1(a), the covariance matrix of a received OFDM symbol has significant off-diagonal terms which denote the correlation between sub-carriers. This mean that the orthogonality between sub-carriers is lost, resulting in ICI. In Fig. 1(b), the covariance matrix of ICI-free signal for a specific sub-carrier is described. It shows that the transmitted signal from a sub-carrier is received to multiple sub-carriers adjacent to the sub-carrier without the ICI. If only the power dispersion for each subcarrier is extracted from the ICI-mixed signals, the sub-carriers within the power dispersion become independent fading channels for diversity.

3. AN IMPROVED DOPPLER DIVERSITY TECHNIQUE FOR OFDM SYSTEMS

3.1 Doppler diversity technique with hybrid interference cancellation and Wiener filter(DHIW)

A block diagram of an improved Doppler diversity technique is described as shown in Fig. 2. The output signals of FFT for an OFDM symbol can be presented as

$$\mathbf{Y} = \mathbf{H}_{var}\mathbf{X} + \mathbf{W}, \tag{1}$$

where

$$\begin{aligned}\mathbf{H}_{var} &= \begin{pmatrix} a_{0,0} & a_{0,1} & \cdots & a_{0,N-1} \\ a_{1,0} & a_{1,1} & \ddots & a_{1,N-1} \\ \vdots & \ddots & \ddots & \vdots \\ a_{N-1,0} & a_{N-1,1} & \cdots & a_{N-1,N-1} \end{pmatrix} \\ &= \left[\vec{h}_0, \vec{h}_1, \ldots, \vec{h}_{N-1}\right],\end{aligned} \tag{2}$$

is the time-varying channels matrix, which has column vectors $\vec{h}_p = [a_{0,p}, a_{1,p}, \ldots, a_{N-1,p}]^T$ $(0 \leqslant p \leqslant N-1)$, $a_{i,j}$ is a channel coefficient of the ith sub-carrier affected by the jth sub-carrier, N is the number of total sub-carriers, $\mathbf{X}$ is the input data symbol of IFFT, and $\mathbf{W}$ is an additive white Gaussian noise (AWGN) with zero mean and variance σ^2.

The initially detected signals for $\mathbf{Y}$ by Wiener filter can be written as

$$\mathbf{Z} = \mathbf{G}\mathbf{Y} = [z_0, z_1, \ldots, z_{N-1}]^T, \tag{3}$$

where

$$\begin{aligned}\mathbf{G} &= \left(\mathbf{H}_{var}^H \mathbf{H}_{var} + \sigma^2 \mathbf{I}_N\right)^{-1} \mathbf{H}_{var}^H \\ &= [\vec{g}_0, \vec{g}_1, \ldots, \vec{g}_{N-1}]^T,\end{aligned} \tag{4}$$

is a matrix of Wiener filter, $\vec{g}_q^{\,T}$ $(0 \leqslant q \leqslant N-1)$ is a row vector corresponding to the qth sub-carrier, and $\mathbf{I_N}$ is N-by-N identity matrix. The initial detection plays an important role in the performance of whole systems. Wiener filter, which is the optimum linear filter, can improve a reliability of initially detected signals[6].

At the 2nd step, the initially detected signals are sorted for the descending order as their signal-to-interference and noise ratio(SINR). SINR of the mth sub-carrier can be defined as follows

$$SINR_m = \frac{|\langle \vec{g}_m, \vec{h}_m \rangle|^2}{\sum_{n=0,\ n\neq m}^{N-1} |\langle \vec{g}_m, \vec{h}_n \rangle|^2 + \sigma^2 \|\vec{g}_m\|^2}, \tag{5}$$

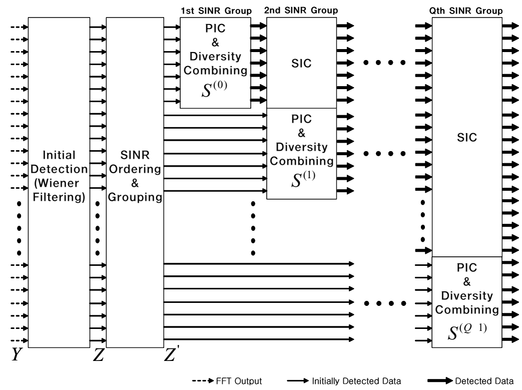


Figure 2: The block diagram of Doppler diversity technique with hybrid interference cancellation and Wiener filter (DHIW)

where $\langle \cdot, \cdot \rangle$ is an inner product and $\|\cdot\|$ is the Euclidean norm. The sorted signals and a SINR group can be defined as

$$\begin{aligned}\mathbf{Z}' &= \left[z_0', z_1', \ldots, z_{N-1}'\right]^T, \\ S^{(i)} &= \left[\, z_n' \mid i \times P < n < i \times P + P - 1 \right],\end{aligned} \tag{6}$$

where $\mathbf{Z}'$ is the sorted signals of $\mathbf{Z}$ for the descending order as their SINR: $z_0' > z_1' > \ldots > z_{N-1}'$ and the set $S^{(i)}$ is the ith SINR group $(0 \leqslant i \leqslant Q-1)$, which is the ith group dividing $\mathbf{Z}'$ into Q groups with each P elements.

At the 3rd step, we extract a power dispersion of each sub-carrier by hybrid interference cancellation(HIC) as described in Section 2. The MMSE-SD receiver needs the update of MMSE filter and the interference cancellation for the detection of each sub-carrier[3]. It results in the long detection time and the enormous computational complexity. The DHIW reduces the computational complexity by parallel signal detection in addition to enhance Doppler diversity gain by a new criterion. A block diagram of the HIC block is presented in Fig. 3. Above all, the power dispersions in the ith SINR group are extracted by the PIC procedure of the HIC block as follows where

$$\widetilde{\mathbf{Z}}^{(i)} = \left[\widetilde{\mathbf{Z}}_a^{\,T}, \widetilde{\mathbf{Z}}_b^{\,T}, \ldots, \widetilde{\mathbf{Z}}_z^{\,T}\right]^T \quad \left(\forall z_a', z_b', \ldots, z_z' \in S^{(i)}\right), \tag{7}$$

where

$$\begin{aligned}\widetilde{\mathbf{Z}}_k &= \mathbf{Y} - \sum_{z_n' \in C_k^{(i)}} \vec{h}_n\, z_n' \\ &= [\widetilde{z}_0, \widetilde{z}_1, \ldots, \widetilde{z}_{N-1}]^T,\end{aligned} \tag{8}$$

is the power dispersion of the kth sub-carrier and $C_k^{(i)}$ is a new criterion to enhance a diversity effect for kth sub-carrier in the ith SINR group (See Subsection 3.2 for further details). The ineffective extraction, which is feasible because of the parallel processing of the PIC procedure, can be mitigated by the new criterion. The power dispersions of P sub-carriers in the ith SINR group are extracted simultaneously by the PIC procedure. A Doppler diversity is obtained as a consequence that the power dispersions $\widetilde{\mathbf{Z}}^{(i)}$ of the ith SINR

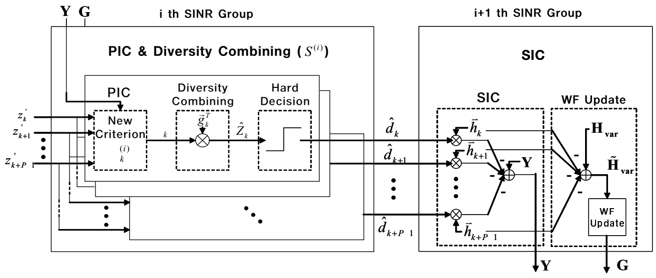


Figure 3: A block diagram of the HIC block using a new criterion

are combined by Wiener filter, which can suppress the ICI modeled to AWGN. The diversity combined signals for the ith SINR can be obtained as

$$\begin{aligned}\hat{\mathbf{Z}}^{(i)} &= \mathbf{G}^{(i)}\widetilde{\mathbf{Z}}^{(i)} \\ &= \left[\hat{Z}_a, \hat{Z}_b, \ldots, \hat{Z}_z\right]^T \quad \left(\forall z_a^{'}, z_b^{'}, \ldots, z_z^{'} \in S^{(i)}\right),\end{aligned} \tag{9}$$

where

$$\mathbf{G}^{(i)} = \begin{pmatrix} \vec{0}^T & \vec{g}_b^{\,T} & \ldots & \vec{0}^T \\ \vdots & \vec{0}^T & \ddots & \vdots \\ \vec{g}_a^{\,T} & \vdots & \ddots & \vdots \\ \vec{0}^T & \ldots & \ldots & \vec{g}_z^{\,T} \end{pmatrix}, \tag{10}$$

is the combining matrix using the row vectors $\vec{g}_q^{\,T}\,(\forall z_q^{'} \in S^{(i)})$ of Wiener filter corresponding to the sub-carriers of the ith SINR group and $\vec{0}$ is N-by-1 null vector. Next, the SIC procedure can be described as follows

$$\mathbf{Y} = \mathbf{Y} - \sum_{\hat{d}_k \in S_d^{(i)}} \vec{h}_k\, \hat{d}_k, \tag{11}$$

where $S_d^{(i)} = \left[\hat{d}_k \mid \hat{d}_k = hard\ decision\ of\ \hat{Z}_k, \forall \hat{Z}_k \in \hat{\mathbf{Z}}^{(i)}\right]$. The SIC to $\mathbf{Y}$ using $\hat{\mathbf{Z}}^{(i)}$ suppress the ICI of signals in next SINR groups, resulting in more reliable signal detection. Finally, the matrix of Wiener filter $\mathbf{G}$ is updated as follows

$$\mathbf{G} = \left(\widetilde{\mathbf{H}}_{var}^H \widetilde{\mathbf{H}}_{var} + \sigma^2 \mathbf{I}_N\right)^{-1} \widetilde{\mathbf{H}}_{var}^H, \tag{12}$$

where $\widetilde{\mathbf{H}}_{var} = \left[\ldots, \vec{h}_{a-1}, \vec{h}_{a+1}, \ldots, \vec{h}_{z-1}, \vec{h}_{z+1} \ldots\right]$. The matrix update of Wiener filter can improve an effect of combining Doppler diversity because the ICI of the remained sub-carriers can be more suppressed by removing the channel vector $\vec{h}$ corresponding to the detected signal.

The HIC procedure is repeated until the last Q SINR group.

3.2 A new criterion for the Doppler diversity enhancement

An inefficient power extraction is possible due to the parallel processing of the HIC block. Because the linear PIC cannot cancel out the ICI. We propose a new criterion to solve an inefficient ICI cancellation of the linear PIC procedure. If the PIC detector cannot guarantee a reliable initial

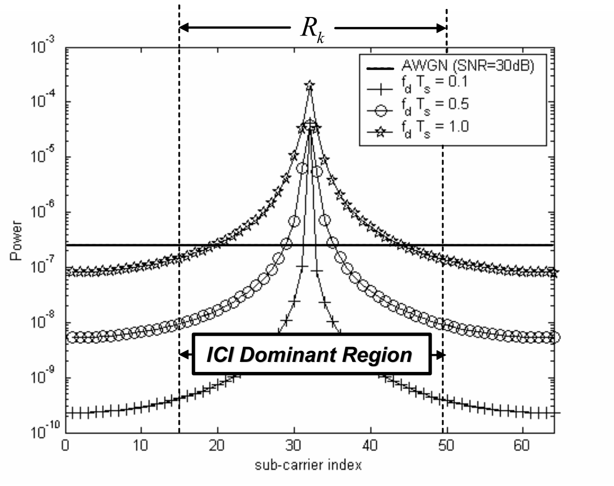


Figure 4: The ICI distribution to the kth sub-carrier in time-varying multipath channels (k = 32 : the index of the ICI-corrupted sub-carrier, $f_d T_s$: normalized Doppler frequency)

detection, this can cause an additional interference for the following decision. We define this as the ICI enhancement. The proposed criterion makes efforts to choose proper sub-carriers for the efficient PIC without the ICI enhancement. The proposed criterion $C_k^{(i)}$ for the kth sub-carrier in ith SINR group can be described as follows

$$\begin{aligned}&R_k = [\, z_p \mid p = ((a))_N, |a-k| \leqslant N/\delta\ \ , and\ p \neq k\,], \\ &C_k^{(i)} = S^{(i)} \cap R_k,\end{aligned} \tag{13}$$

where δ is a ranging factor, $S^{(i)}$ is the ith SINR group defined in Eq. (6), the set R_k consists of sub-carriers close to the kth sub-carrier, and $((a))_N = a$ in case of $a \geqslant 0$, or $N+a$ in case of $a < 0$. The PIC using all initially detected signals in $S^{(i)}$ can commit to the ICI enhancement. We utilize the set R_k as a constraint for $S^{(i)}$. The propose criterion $C_k^{(i)}$ choose only sub-carriers which cause a significant ICI for the kth sub-carrier because R_k consists of sub-carriers which cause most of the ICI for the kth sub-carrier as shown in Fig. 4. OFDM system in time-varying channels has the characteristic that the sub-carriers to cause most of the ICI for the kth sub-carrier is limited in a specific range (*i.e.* R_k) even in high mobility. The PIC can cancel out ICI efficiently without the ICI enhancement by regenerating the reliable information signals in $C_k^{(i)}$, resulting in an efficient power extraction for the kth sub-carrier. In consequence, we improve a Doppler diversity gain.

4. SIMULATION RESULTS AND DISCUSSIONS

For simulations, an OFDM system with $N = 64$ and cyclic prefix = 8 is considered. Data bits are BPSK-modulated and the time-varying three-ray channel is considered.

In fig. 5, the average BER performance of the DHIW is compared with basic detection schemes and MMSE-SD receiver[3]. Among two linear schemes(*i.e.* least square(LS) and Wiener filter(WF)), LS can cancel out ICI by the channel matrix inversion, resulting in a noise enhancement, which cause the performance degradation. The performance of WF

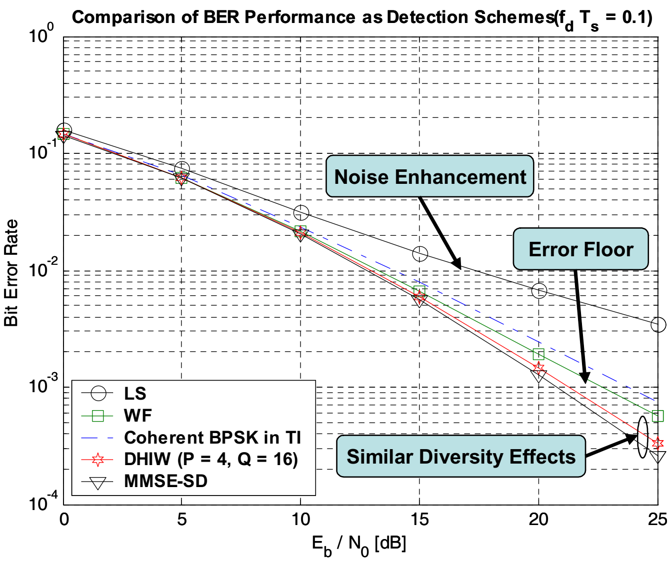


Figure 5: The comparison of average BER performance ; least square(LS), Wiener filter(WF), coherent BPSK in time-invariant channels(TI), Doppler diversity technique with hybrid interference cancellation and Wiener filter(DHIW), minimum mean square error with successive detection(MMSE-SD) (N = 64, P : a number of sub-carriers detected at each stage, Q : total number of stages, $f_d T_s$: normalized Doppler frequency)

is slightly better than coherent BPSK by the ICI suppression, however, exhibits an error floor at high SNR. The small gap between the BER of DHIW and the MMSE-SD receiver shows that we can extract the power dispersion for Doppler diversity by the new criterion in spite of the parallel detection with the linear HIC.

In Table 1, the computational complexity of the DHIW is compared with the MMSE-SD receiver by a number of the arithmetic calculation(*i.e.* +,-,×, and ÷) to update the Wiener filter matrix, which has the complexity of $O(n^3)$[7]. The numbers of arithmetical operation for two systems can be presented as follows

$$\mathbf{C}_{MMSE-SD} = N\left(\frac{N(N-1)(N+1)}{3} + N^2(2N-1) + 3N^2\right), \tag{14}$$

$$\mathbf{C}_{DHIW} = \sum_{a=0}^{Q-1}\left[\frac{(N-Pa)(13(N-Pa)^2-2)}{3} - 2(N-Pa)^2\right], \tag{15}$$

where P is the number of sub-carriers detected simultaneously and Q is the number of stages for the parallel processing. Although the E_b/N_0 gap between the DHIW with $P = 4$ and $Q = 16$ and the MMSE-SD is less than 0.3 dB, the computational complexity of the DHIW with $P = 4$ and $Q = 16$ is less than the a seventh of the MMSE-SD. The total detection time of the DHIW is also smaller than that of the MMSE-SD by the parallel signal detection. Moreover, if P is increased, the computational complexity can be decreased dramatically.

5. CONCLUSIONS

We have proposed an improved Doppler diversity technique that can utilize the ICI as a source of diversity for OFDM systems in time-varying multipath channels. The DHIW has enhanced the diversity gain by the new criterion in spite of the reduction of the computational complexity and the total detection time by the parallel signal detection. Simulation results have shown that the DHIW and the MMSE-SD receiver have the diversity gain in opposition to the severe degradation of the basic detection schemes. Although the BER performance of the DHIW is vary close to that of MMSE-SD, the DHIW has be able to reduce the computational complexity and the total detection time dramatically compared with the MMSE-SD. The future work is the study that considers the effect of imperfect channel state information.

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Table 1: The comparison of computational complexity (P : the number of sub-carriers detected at each stage, Q : total number of stages)

Algorithm	Complextity
MMSE-SD	39,669,760
DHIW(P = 2, Q = 32)	9,573,696
DHIW(P = 4, Q = 16)	5,082,048
DHIW(P = 8, Q = 8)	2,849,472
DHIW(P = 16, Q = 4)	1,759,680