A Hybrid Adaptive Array and Carrier Diversity Receiver for OFDM Fading Channels

——High-Performance and Low-Complexity——

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***Abstract*— An OFDM system performance is very sensitive to the estimation accuracy of the channel transfer function (CTF) when the scattered pilots were used. Conventional carrier diversity (CD) receiver requires multiple FFT processors and corresponding number of channel estimators according to the increase of the number of diversity antennas. On the other hand, only one FFT processor is need in a pre-FFT antenna array (AA) receiver, and the AA can improve the instantaneous signal-to-interference-and-noise ratio (SINR) at the input of the FFT. As a result, the accuracy of channel estimation can be improved after FFT. In this paper, a hybrid AA/CD receiver's performance tradeoff with complexity is analyzed. The hybrid receiver can halve the number of the FFT processors by comparing with the conventional CD receiver. Simulation results show that the combination of minimum mean square error (MMSE) AA and equal gain combing (EGC) CD and maximum-ratio combing (MRC) CD scheme can provide better performance in multi-path channel under slow and fast fading.**

I. INTRODUCTION

An orthogonal frequency division multiplexing (OFDM) is adopted as a modulation method for the terrestrial Integrated Services Digital Broadcasting (ISDB-T) standard in Japan. It is robust to frequency-selective fading due to the using of guard interval (GI) [1]. However, while the beyond GI delayed signal exists, not only inter-symbol interference (ISI) but also inter-carrier interference (delay-ICI, namely) occurs. Furthermore, in mobile application, a Doppler spread results in inter-carrier interference (Doppler-ICI, to distinguish from delay-ICI) [2]. Since these effects degrade the OFDM signal, it is a severe challenge to increase the accuracy of channel estimation. It is well-know that an OFDM system is very sensitive to the quality of channel estimation, and apart from the FFT, which is the most complex unit of the receiver [3].

In paper [4]-[5], a post-FFT diversity combiner and a post-FFT adaptive array (AA) for interference-noise suppression have been proposed. Although the proposed post-FFT carrier diversity (CD) and AA type combiner can optimize signal-to-interference-and-noise (SINR), it is costly to implement such a multi-antenna-multi-FFT CD receiver. In [6], a pre-FFT adaptive array (AA) was proposed for suppressing the beyond GI delayed signal based on the maximized SINR and the minimum mean square error (MMSE) criteria in time domain, and authors gave the optimum array weights. Otherwise, only one-FFT-one-branch was considered as the receiver in [6].

In this paper, a hybrid time-domain-AA/frequency-domain-CD two-layer multi-antenna receiver is proposed for a tradeoff between high-performance and low-complexity. It can halve the number of CD branches, and the channel estimation quality can be improved through the depressing of maximum excess delay [7] due to its AA layer. The proposed AA/CD receiver is studied based on the AA criteria of maxi-ratio combining (MRC) and MMSE, while the CD combiner exploits MRC and equal gain combining (EGC) schemes. Therefore, in total four kinds of approaches of the hybrid receiver are studied by focusing on vehicle mobile multi-path application.

The paper is organized as follows. Section II introduces the proposed hybrid AA/CD receiver. Section III shows channel estimation. Section IV presents the performance of the proposed receiver as compared to a conventional CD receiver by computer simulation. Conclusion is given in section V.

II. HYBRID AA AND CD RECEIVER

The proposed hybrid AA/CD receiver is structured on two layers of time-domain AA and frequency-domain CD with channel estimations as shown in Fig. 1.

There are L (>1) sets of AA which consist of a number of A (>1) antennas. The L sets of AA should be located far each other so that uncorrelated CD can be achieved. Inversely, the elements among each AA set must be configured close enough, hence strong correlation AA combining can be easily provided. By defining the length of GI and effective symbol as G and N in OFDM samples, which corresponds with the time duration T_g and T, respectively, the length of resulting symbol is (N_s=G+N) or (T_s=T_g+T). The GI (be of length $T/8$) is a copy from the last part of the effective symbol. Throughout this paper, the added GI is referred to "*h-GI,*" the original part is distinguished as "*t-GI.*"

A. Time-domain Antenna Array (AA)

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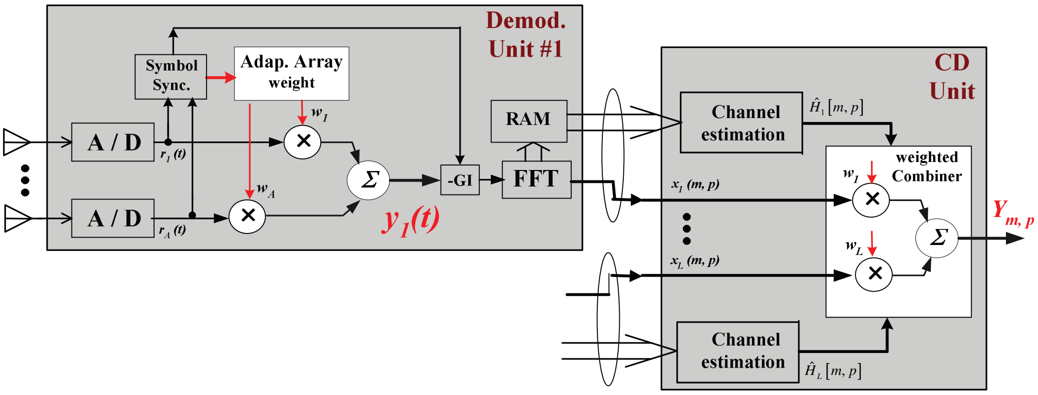


Fig. 1 Diagram block of the proposed hybrid AA/CD two-layer receiver.

In an OFDM system, the AA can improve the SINR before FFT demodulation. This can increase the accuracy of the channel estimation after FFT, and in result, a more effective channel equalization (EQ) can be achieved. Since each OFDM symbol only needs one AA weighted vector $\{w_i(t)\}$, it is an attractive solution due to low computation complexity. However, a high correlation between the antenna signals is preferable. The left part of Fig.1 shows the AA structure.

Two AA algorithms are used, one is maximizing ratio combining (MRC) algorithm, which exploits the *h-GI* and *t-GI* of the same OFDM symbol [8]. Another one is the sample matrix inversion (SMI), which is based on MMSE criteria. By defining the weight vector of the *A* elements array as

$$\mathbf{w} = [w_1, w_2, \ldots, w_A]^T \ , \tag{1}$$

and the (A x N_s) received signal vector is expressed as

$$\mathbf{r}(i) = [r_1(i), r_2(i), \ldots, r_A(i)]^T \ , \quad (-G \le i \le N)\ , \tag{2}$$

then the combing output of AA can be written as

$$y(i) = \mathbf{w}^H \mathbf{r} \quad , \tag{3}$$

where above and follow, the superscripts T , H and * denote transposing, conjugate-transposing and conjugating operator respectively.

Then, weighted vector of MRC can be derived as

$$\mathbf{w}_{MRC} = E\left[\mathbf{r}_h(i)\, y_t^*(i)\right] \ , \tag{4}$$

where $E[-]$ stands for expectation function, and $\mathbf{r}_h(i)$ denotes *h-GI* of received signal, $y_t(i)$ is the *t-GI* of array output.

For SMI algorithm, by defining the (G x G) received signal auto correlation matrix as

$$\mathbf{R}_{rr} = E\left[\mathbf{r}_h \mathbf{r}_h^H\right] \ , \tag{5}$$

then weight vector of SMI is given as

$$\mathbf{w}_{SMI} = \mathbf{R}_{rr}^{-1} E\left[\mathbf{r}_h(i)\, y_t^*(i)\right] \ . \tag{6}$$

B. Frequency-domain Carrier Diversity (CD)

The CD scheme utilizes a few branches independent OFDM signals for subcarrier-by-subcarrier diversity combing in frequency-domain, therefore, it can suppress the noise-interference power. However, it requires accurate channel estimation for high performance. As shown in the right of Fig. 1, L branches independent post-FFT signals are combined. The subcarrier signal from the lth branch at the pth tone of the mth OFDM symbol can be expressed as

$$x_l(m,p) = d_{m,p} H_l(m,p) + n_l(m,p) \quad , \tag{7}$$

where $n_l(m,\ p)$ is additive white Gaussian noise (AWGN) from the lth branch. $H_l(m,p)$ is the channel transfer function (CTF), which is assumed independent for different branch. $d_{m,p}$ is the transmitted complex signal modulating the pth tone of mth symbol. By using the MRC and the EGC scheme, the derived combing weight of the lth branch can be written as

$$\text{MRC:}\quad w_l(m,p) = \frac{H_l^*(m,p)}{\sum_{l=1}^{L} \left|H_l(m,p)\right|^2} \tag{8}$$

$$\text{EGC:}\quad w_l(m,p) = \frac{H_l^*(m,p)}{\left|H_l(m,p)\right| \sum_{l=1}^{L} \left|H_l(m,p)\right|} \tag{9}$$

The $d_{m,p}$ can be estimated as $\hat{Y}_{m,p}$ by the CD combiner

$$\hat{Y}_{m,p} = \sum_{l=1}^{L} w_l(m,p)\, x_l(m,p) \ . \tag{10}$$

It is worth noting that, in the MRC scheme, the diversity combing weight are determined corresponding to their instantaneous signal power on each subcarrier, while the EGC selects equal gain factors.

III. CHANNEL ESTIMATION

Since the performance of OFDM receiver is very sensitive to channel estimation, in this paper, to evaluate performance, the same estimation method is used in both the proposed hybrid and conventional receiver. 2-dimesion (2D) channel estimation based on the scattered pilots (SPs, circle with P) is separated into symbol and subcarrier direction estimation as shown in Fig. 2. At first, the CTF of the tone with red circle is estimated using 2-tap linear interpolation in symbol direction. Then, in subcarrier direction, after down/up sampling by factor of 3, a 36-tap Window-sinc-filter is used to estimate the CTF at the position with grey circle.

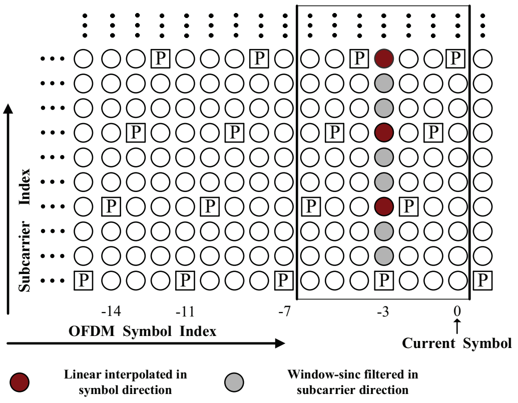
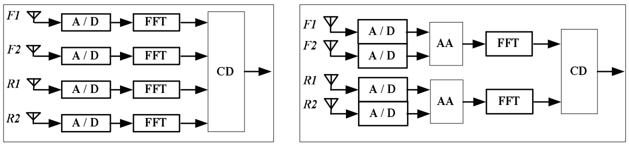


Fig. 2 Scattered pilots pattern and the interpolation zone.

IV. COMPUTER SIMULATION RESULTS AND DISCUSSIONS

In this section, the bit error rate (BER) performance of the proposed hybrid AA/CD receiver is shown as compared with a conventional post-FFT CD receiver without error correction.

A. Simulated Receiver Models



Conventional CD Receiver

Hybrid AA / CD Receiver

Fig. 3 Simulated receiver models.

Fig. 3 shows two block diagrams of the conventional CD and the hybrid AA/CD receiver based on 4-antennas F_1, F_2, R_1 and R_2. The spacing between F_1 and F_2, R_1 and R_2 is half of the carry wavelength, while the pair of $\{F_1, F_2\}$ is far from the $\{R_1, R_2\}$. In the conventional receiver, after 4-FFTs, the four branches signals are CD combined using MRC criteria. In the hybrid receiver, the two AA weighting sets is determined using the MRC or SMI scheme, and the CD performs the MRC or EGC combing. So, in total four configurations of the hybrid receiver are realized. They are notated as following: "hybrid aa-SMI/cd-EGC", "hybrid aa-SMI/cd-MRC", "hybrid aa-MRC/cd-EGC" and "hybrid aa-MRC/cd-MRC".

A. Use of Directionality Constrained Antenna

Since car antenna is typically mounted on windshield glass, its radiation pattern (RP) is directionally constrained due to metal of car body. As illustrated in Fig. 4, the distorted RP of the two front antennas $\{F_1, F_2\}$ concentrates in the forward direction, while the two rear $\{R_1, R_2\}$ focuses to the rear direction of vehicle moving. Their centre directions are assumed as (30°, 330°) and (150°, 210°), respectively. When AA is applied, the similar RP antenna set is chosen.

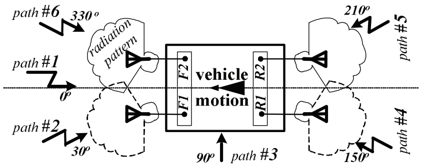


Fig. 4 Car aerial deployment and their constrained RP.

B. System Parameters

Table I shows the system parameters. Mode3 of the ISDB-T standard using 64QAM digital modulation is used.

TABLE I SYSTEM PARAMETERS

Carrier frequency	f_c	563.143 MHz
Subcarrier spacing	f_0	0.992 kHz
Number of carriers	N	8192
Number of effective carriers	N_e	5617
Effective symbol duration	T_e	1008*u*s
Guard interval duration	T_g	$(1/8)T_e$
Digital modulation		64QAM

Table II summaries three channel models for the simulation. Six signals arrive from different paths. The D/U is the desired (path#1) to delayed signal power ratio. In channel I and II, all of the delayed signals arrive within GI duration. In channel III, one beyond GI delayed signal (path#6) exists.

TABLE II SIMULATION CHANNEL

Path	D/U (dB)	Channel-I		DoA (deg)	Channel-II	Channel-III
		DoA (deg)	Delay time		Delay time	
#1	0	10	0.01*(Tg/8)	10	0.01*(Tg/8)	
#2	3	90	3.0*(Tg/8)	90	3.0*(Tg/8)	
#3	5	170	6.0*(Tg/8)	170	6.0*(Tg/8)	
#4	1.5	190	0.5*(Tg/8)	190	0.5*(Tg/8)	
#5	2	270	1.0*(Tg/8)	270	1.0*(Tg/8)	
#6	4	350	3.0*(Tg/8)	300	5.5*(Tg/8)	9.0*(Tg/8)

C. Simulation Results and Discussion

Fig. 5 shows the BER performance for mobile application in channel I under SNR=20dB, SNR=25dB and SNR=35dB. The "aa-MRC/cd-MRC" approach of hybrid receiver was shown as compared to the conventional CD receiver.

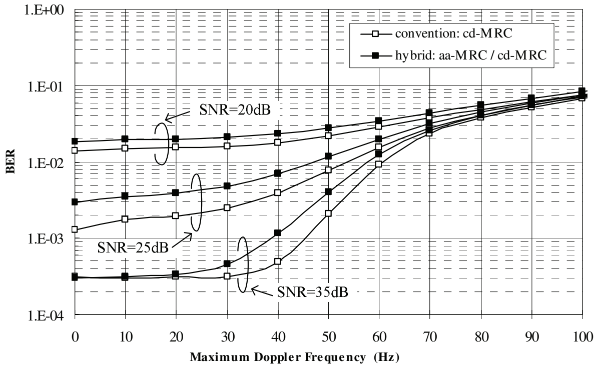


Fig. 5 BER versus maximum Doppler shifts in Channel-I.

The correlation between antenna signals is low (due to the distorted RP as shown in Fig. 4), the performance of AA is weakened but the CD is enhanced, therefore the conventional cd-MRC shows a better performance on noise and Doppler-ICI suppressing through the two more CD branches in Fig. 5.

The channel II and channel III is set as a low AWGN channel with SNR=35dB. Figs. 6 and 7 show the BER versus maximum Doppler shifts for the four approaches of hybrid AA/CD receiver in channel II and III, respectively.

In Fig. 6, when channel is fast fading ($f_{Doppler} \geqq 40Hz$), the hybrid AA/CD methods of aa-SMI/cd-EGC, aa-MRC/cd-EGC and aa-MRC/cd-MRC show the same robustness to Doppler shifts approximately. Otherwise, when the channel is slow fading, the aa-SMI/cd-EGC and the aa-SMI/cd-MRC methods can improve the performance of hybrid receiver significantly. This is because the SMI AA scheme performs both of beam-forming and null-steering to suppress large delayed signals. In addition, the aa-SMI/cd-EGC method shows higher Doppler performance than the aa-SMI/cd-MRC.

In Fig. 7, since a beyond GI delayed signal exists in channel III, a significant degradation of the BER performance occurred for the conventional CD receiver and the hybrid AA/CD receiver with MRC AA scheme. This degradation is caused by ISI and delay-ICI. However, the aa-SMI/cd-EGC and aa-SMI/cd-MRC methods of the hybrid receiver show better performance. This is because the beyond GI delayed signal was suppressed by the SMI AA scheme.

V. CONCLUSIONS

In this paper, a hybrid AA/CD two-layer receiver, which can halve the number of carrier diversity branches by comparison with the conventional post-FFT carrier diversity receiver, is proposed and analyzed. Although the conventional CD receiver suffers large delayed and beyond-GI delayed multi-path condition, a hybrid AA/CD two-layer receiver with SMI algorithm shows good performance. This approach can effectively suppress the beyond guard interval delayed signals, and depress Doppler effect in mobile multi-path channel by comparison with other approaches.

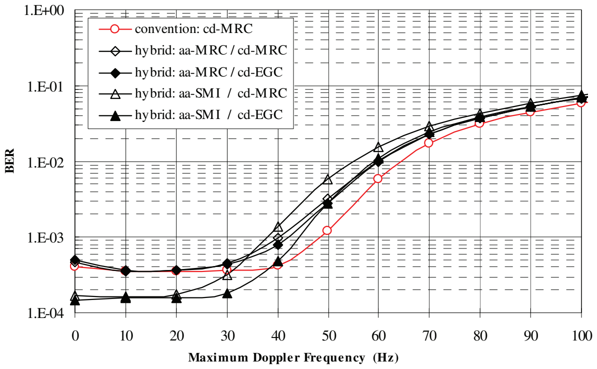


Fig. 6 BER versus maximum Doppler shifts in channel-II for SNR=35dB.

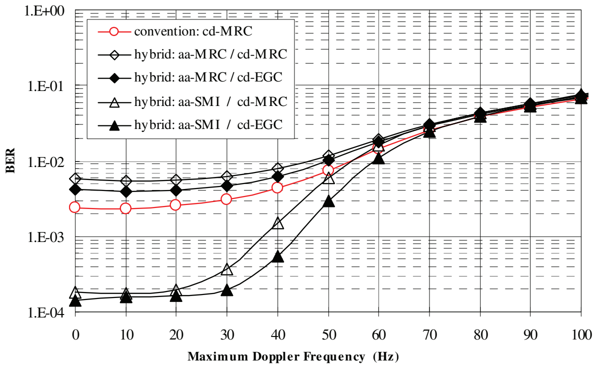


Fig. 7 BER versus maximum Doppler shifts in channel-III with one beyond. GI delayed signal for SNR=35dB.

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