# ISI and ICI Suppression for Mobile OFDM System by Using a Hybrid 2-Layer Diversity Receiver

Jing Gao, Tomohisa Wada

Graduate School of Engineering and Science, University of the Ryukyus,
1 Senbaru, Nishihara, Okinawa, 903-0213, Japan
{gaojing722@yahoo.com,wada@ie.u-ryukyu.ac.jp}

**Abstract.** An OFDM system is very sensitive to orthogonality relation. For a mobile wireless system, it is impossible to avoid Doppler-induced inter carrier interference (ICI). Moreover, while beyond guard interval delayed signal exists in channel, the delay-induced ICI and inter symbol interference (ISI) will occur. Although a conventional carrier diversity (CD) receiver can render the OFDM system less sensitive to the white-noise-likely ICI, but it requires significant channel knowledge. On the other hand, a pre-FFT adaptive array (AA) receiver can improve the instantaneous signal to interference-and-noise ratio (SINR) at the input of FFT. In this paper, a hybrid AA/CD two layers receiver is investigated not only on a tradeoff between high performance and low complexity, but also into a method for both ISI and ICI suppression. Simulation results show that a suitable combination of pre-FFT AA and post-FFT CD can provide good performance by comparison with conventional OFDM receiver in mobile wireless channel, especially, while ISI and ICI occur at the same time.

**Keywords:** beyond GI delay, Doppler, adaptive array, carrier diversity.

## 1 Introduction

An orthogonal frequency division multiplexing (OFDM) is adopted as a modulation method for wireless communication system because 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. 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 system performance and the accuracy of channel estimation. As well known, 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 [4]-[6], a post-FFT carrier diversity (CD) combiner and a post-FFT adaptive array (AA) for interference and noise suppression have been proposed. Although the proposed post-FFT CD and

AA type combiners can optimize signal-to-interference-and-noise (SINR), it is costly to implement such a multi-antenna-multi-FFT receiver. In [7], 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 [7].

In this paper, a hybrid time-domain AA and frequency-domain CD two-layer multi-antenna receiver is proposed for a tradeoff between high-performance and low-complexity. Benefiting by the AA layer, the hybrid receiver can halve the number of CD branches, and improve the channel estimation quality through the depressing of maximum excess delay ($\tau_{max}$) [9]. The proposed AA/CD receiver is studied based on the AA criteria of maxi-ratio combining (MRC) and MMSE [8], while the CD combiner exploits MRC and equal gain combining (EGC) schemes. Therefore, total four approaches of the hybrid receiver are studied by focusing on vehicle mobile multi-path application.

This paper is organized as follows. Section II introduces the proposed hybrid AA/CD receiver. Section III discusses the approach of AA/CD combination for ISI and ICI suppression. 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.

## 2 Hybrid AA/CD Receiver

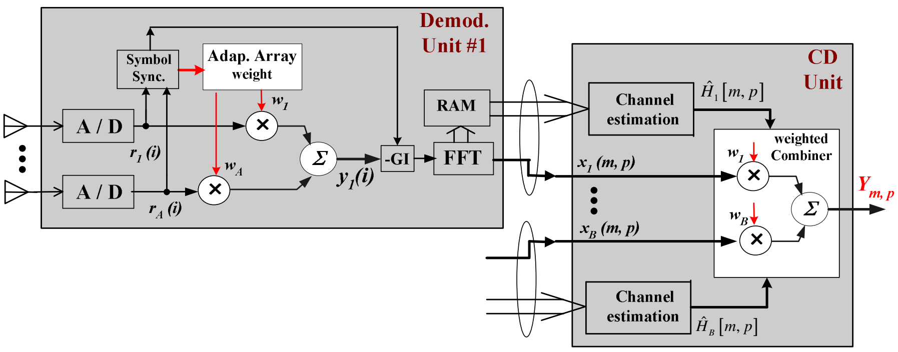



**Fig. 1.** Diagram block of the hybrid adaptive array and carrier diversity two layers receiver

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 $B$ ($>1$) sets of AA which consist of a number of $A$ ($>1$) antennas. The $B$ 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. Here, we consider an OFDM system using an inverse fast Fourier transform (IFFT) of length $N$ with subcarrier spacing $f_0$. By defining the sampling duration as ($T_c=1/Nf_0$) and the length of guard interval (GI) as $G=N/8$ samples, then the length of resulting baseband OFDM symbol is ($N_s=G+N$) or ($T_s=T_g+T$) in time. The GI is a copy from the last part of the effective symbol. Throughout this paper, the added GI is referred to as "*h-GI,*" the original part is distinguished as "*t-GI*."

Assuming that at least one beyond GI delayed signal exits in the multipath channel excepting the synchronizing desired one. The receiver input signal of $i^{th}$ sampling during the $m^{th}$ OFDM symbol at $a^{th}$ element can be written as

$$r_a(m,i)=\sum_{n=-\infty}^{+\infty}\sum_{k=0}^{N-1} d_{n,k}\, e^{j2\pi k f_0\{(m-n)T_s+iT_c\}} h_a(m,i,n,k)+n_a(i)\,. \tag{1}$$

where $d_{n,k}$ is the data symbol modulating the $k^{th}$ tone during the $n^{th}$ OFDM symbol. $h_a(m,i,n,k)$ is the multipath channel impulse response (CIR) by taking the transmission filter into account. $n_a(i)$ is additive white Gaussian noise (AWGN).

### 2.1 Time-domain Adaptive Array (AA)

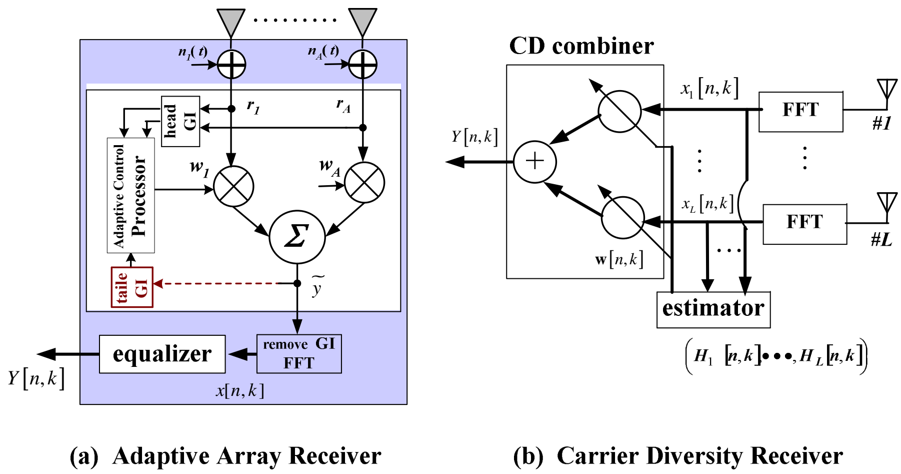



**Fig. 2.** Two types of OFDM receiver

A multi-antenna adaptive array (AA) can improve the SINR by the performing of spatial filtering to desired/undesired path-signal in time domain. Moreover, in an OFDM system, this can increase the accuracy of the channel estimation after FFT, so a more effective channel equalization (EQ) is available. In addition, since each OFDM symbol only needs one weighted vector $\{w_i(t)\}$, the AA is an attractive solution due to low computation complexity. However, a high correlation between the antenna signals is preferred. Fig. 2 (a) shows the AA structure.

Two AA algorithms are used, the one is maximizing ratio combining (MRC) algorithm, which exploits the *h-GI* and *t-GI* of the same OFDM symbol [8] [10]. The other one is the sample matrix inversion (SMI), which is based on MMSE criteria. By defining the weight vector of the *A* elements array as

$$\mathbf{w} = \left[ w_1, w_2, ..., w_A \right]^T . \quad (2)$$

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

$$\mathbf{r}(i) = \left[ r_1(i), r_2(i), ..., r_A(i) \right]^T , \quad (-G \le i \le N) . \quad (3)$$

The combining output of AA can be written as

$$y(i) = \mathbf{w}^H \mathbf{r} . \quad (4)$$

where above and follow, the superscripts $T$ , $H$ and * denote transposing, conjugate-transposing and conjugating operator respectively. Then, weighting vector of MRC can be derived as

$$\mathbf{w}_{MRC} = E\left[ \mathbf{r}_h(i)\, y_t^*(i) \right] . \quad (5)$$

where *E[-]* stands for expectation function, and $\boldsymbol{r_h(i)}$ 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

$$\mathbf{R}_{rr} = E\left[ \mathbf{r}_h \mathbf{r}_h^H \right] . \quad (6)$$

then the weighting vector of SMI is given as

$$\mathbf{w}_{SMI} = \mathbf{R}_{rr}^{-1} E\left[ \mathbf{r}_h(i)\, y_t^*(i) \right] . \quad (7)$$

The inversion of autocorrelation matrix $\mathbf{R}_{rr}$ performs null-steering to the interference. As this, the SMI scheme is more effective than MRC on undesired signal suppressing.

### 2.2 Frequency-domain Carrier Diversity (CD)

A CD scheme utilizes a few branches of independent OFDM signal for subcarrier-by-subcarrier diversity combining in frequency domain. It can modify the SNR on subcarrier base after FFT. However, it requires accurate channel estimation for high performance. As shown in Fig. 2 (b), *L* branches of independent post-FFT signal are combined. The subcarrier signal from the $l^{th}$ branch at the $p^{th}$ tone of the $m^{th}$ OFDM symbol can be written as

$$x_l\left(m,p\right)=d_{m,p}H_l\left(m,p\right)+n_l\left(m,p\right). \qquad (8)$$

where $n_l(m, p)$ is additive white Gaussian noise (AWGN) from the $l^{th}$ branch. $H_l(m,p)$ is the channel transfer function (CTF), which is independent for different branch. $d_{m,p}$ is the transmitted complex signal modulating the $p^{th}$ tone of $m^{th}$ symbol. The derived MRC and EGC weight of the $l^{th}$ branch can be written as

MRC: $$w_l\left(m,p\right)=\frac{H_l^*\left(m,p\right)}{\sum_{l=1}^{L}\left|H_l\left(m,p\right)\right|^2}. \qquad (9)$$

SMI: $$w_l\left(m,p\right)=\frac{H_l^*\left(m,p\right)}{\left|H_l\left(m,p\right)\right|\sum_{l=1}^{L}\left|H_l\left(m,p\right)\right|}. \qquad (10)$$

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

$$\widehat{Y}_{m,p}=\sum_{l=1}^{L}w_l\left(m,p\right)x_l\left(m,p\right). \qquad (11)$$

It is worth noting that, the MRC diversity combining are weighted corresponding to the instantaneous signal power of each branch, while the EGC selects equal gain factors.

### 2.3 Channel Estimation

For scattered pilots based 2-dimesion (2D) channel estimation, the CTF at the pilot $d_{m,p}$ can be obtained as

$$H_{m,p}=\frac{x\left(m,p\right)}{d_{m,p}}. \qquad (12)$$

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, box with P) is separated into symbol and subcarrier direction estimation as shown in Fig. 3. At first, the CTF of the tone with black 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.

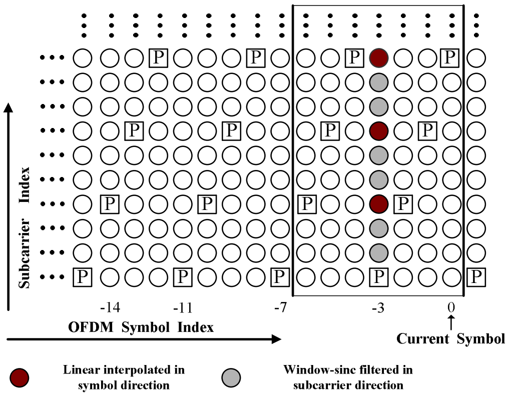



**Fig. 3.** The scattered pilot pattern and the interpolation zone

# 3 The Approach of AA/CD Combination for ISI/ICI Suppression

In section 2, the two AA schemes (MRC and SMI) and the two CD combiners (MRC and EGC) were described. Our purpose here is to find the high performance hybrid joint of the AA and CD even in hard conditions of fading channel.

## 3.1 Using the AA for ISI suppression

In a multipath channel, once the beyond GI delayed signal exists, the ISI and delay-induced ICI will occur at the same time. After FFT-demodulating such an antenna signal, the modified data symbol in synchronized $m^{th}$ OFDM block can be written as

$$x_a(m,p) = H(m,p)\, d_{m,p} + \sum_{\substack{k=0 \\ k\neq p}}^{N-1} H(m,k)\, d_{m,k} + \sum_{k=0}^{N-1} e^{j2\pi k f_0 T_s} H(m-1,k)\, d_{m-1,k} \,. \quad (13)$$

where the $1^{st}$ right term is the desired contribution of data $d_{m,p}$ in the $m^{th}$ block transmitted over multipath. The rest two right terms are the contribution due to beyond GI delayed path, and the $2^{nd}$ right term denotes the delay-ICI that rose from the destroyed orthogonality among tones of the $m^{th}$ block, the $3^{rd}$ right term includes the ISI and delay-ICI components caused by the tones in the $(m\text{-}1)^{th}$ block. The power of the delay-ICI and ISI is proportional to the power of the beyond-GI path signal in a positive factor that is less than one [11]. For combating with this, using AA to depress the delayed path signal in time-domain is an effective method.

An 8K-point-FFT OFDM signal with GI length of (*T/8*) is used for computation testing the two AA schemes (SMI and MRC). The channel with 5-path delayed signal (arrived at $10^0$/0dB, $70^0$/3dB, $170^0$/1dB, $270^0$/2dB, $350^0$/4dB) is divided to two cases.

The one is a normal short-delay channel (notated as “S_CH”), all of the five paths signal in which are transmitted within GI duration (at $350^0$/4dB with $\tau = 48T_g/128$). The second one is a long-delay channel (notated as “L_CH”), in which one beyond-GI delayed signal exists (at $350^0$/4dB with $\tau_{max} = 129T_g/128$).

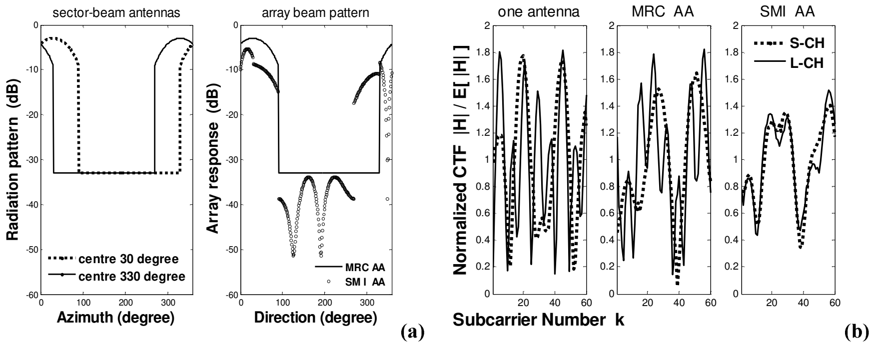



**Fig. 4.** (**a**) The radiation pattern of two 120-degree sector-beam antennas and the beam patterns formed by MRC/SMI adaptive array (AA); (**b**) the varying of channel transfer function (CTF) versus subcarrier index in short-delay channel (“S-CH”) and long-delay channel (“L-CH”)

Fig. 4 (a) shows the radio patterns (RP) of the two 120-degree sector-beam antennas and the array beam-pattern (BP) of them under ‘L-CH” condition. The desired signal is at $10^0$. Differing from the MRC, the SMI scheme AA gives the lower relative side-lobe-level and deepest nulls toward undesired path. Fig. 4 (b) shows the CTF varying ($|H|$ / $E[|H|]$) over continual 60 subcarriers by using different AA methods. Clearly, the SMI AA can greatly improve the dispersion in subcarrier direction by comparison with the MRC scheme, especially, while large long delayed signal exits (referring to condition “L-CH”). This means that, by using the SMI scheme, not only the ISI and delay-ICI can be depressed, but also the more accurate CTF estimation in subcarrier direction can be achieved.

### 3.2 Using the CD Combining for Doppler-ICI Suppression

As shown above, the AA used as spatial filter can suppress the delay-ICI and ISI by steering the nulls toward the large delayed path signals. However, for mobile channel, the AA receiver cannot render the OFDM signal less sensitive to Doppler shift. In this section, the frequency domain CD combiner is investigated on Doppler-ICI suppression. With assumption of that only Doppler effects are considered, the FFT demodulated OFDM signal on the $p^{th}$ subcarrier of $m^{th}$ symbol can be written as

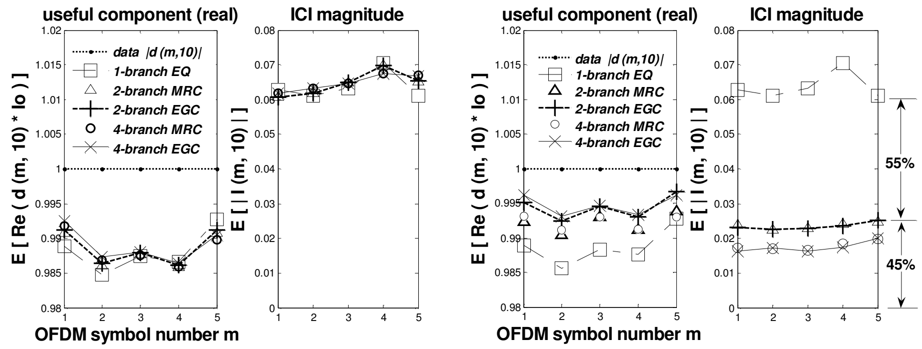
$$\begin{aligned} x_l(m,p) &= d(m,p)\frac{\sin \pi f_{Dl}T}{N\sin(\pi f_{Dl}T/N)}e^{j\pi f_{Dl}T\frac{N-1}{N}} + \sum_{k=0,k\neq p}^{N-1} d(m,k)\, I_{k-p}^{l} \\ &= d(m,p)\, I_{0l} + I_l(m,p)\,. \end{aligned} \tag{14}$$

where, $l$ denotes the CD branch number, $I^{l}_{k-p}$ are the ICI contribution coefficients from the $k^{\text{th}}$ subcarrier [12]. The term $I_{0l}$ impaired the desired data $d(m,p)$ by an amplitude reduction and phase shift due to the Doppler frequency $f_{Dl}$. The component $I_l(m,p)$ is ICI, which smears the useful component $d(m,p)I_{0l}$ with white-likely noise [13-14].

At scattered pilot (SP) positions, by using the CTF estimated from (14) and (12), the CD weighting determined by (8) and (9) can be rewritten as $w_l=H_l^*/\alpha_l$ where $\alpha_l$ is a real coefficient. Then, the CD combining output is obtained from equation (11) as

$$\begin{aligned} Y_{m,p} &= \sum_l \frac{1}{\alpha_l} H_l^*(m,p)\, x_l(m,p) \\ &= d(m,p) \sum_l \frac{1}{\alpha_l}\left( \left|I_{0l}\right|^2 + \frac{I_l^*(m,p)}{d^*(m,p)} I_{0l} \right) + \sum_l \frac{1}{\alpha_l}\left( \frac{\left|I_l(m,p)\right|^2}{d^*(m,p)} + I_{0l}^* I_l(m,p) \right) \\ &= d(m,p)\, I_0 + I(m,p). \end{aligned} \tag{15}$$

where the term $d(m,p)I_0$ and $I(m,p)$ are the combined useful component and ICI component, respectively. In mobile application, since the Doppler coefficient $f_{Dl}$T of $l^{\text{th}}$ branch can be positive or negative according to the relationship between the directions of vehicle motion and signal arriving, therefore the CD performance from which Doppler branches will be different.




**(a):** $0 < (f_{D1}T,\ f_{D2}T,\ f_{D3}T,\ f_{D4}T) < 0.1$ **(b):** $-0.1 < (f_{D1}T,\ f_{D2}T,\ f_{D3}T,\ f_{D4}T) < 0.1$

**Fig. 5.** Expected average of the useful component real part Re($d$(m,10)$*Io$) and the ICI component magnitude |$I$(m,10)| at subcarrier position $d$(m,10) after CD combining. The transmitted complex data sequences by the continual five OFDM symbols are randomly set as {|$d$(m,k)|<$2^{0.5}$; $m$=1,2,...,5; $k$=0,1,...,63} excepting $d$(m,10)$=1+0j$. The two positions $d$(1,10) and $d$(5,10) are the pilots. The CTFs of other three data positions ($H_{2,10}$, $H_{3,10}$, $H_{4,10}$) are estimated by symbol direction linear-interpolation as shown in Fig. 3. The CD combining "2/4-branch MRC/EGC" is performed over **(a)** positive random Doppler coefficient branches; **(b)** positive/or negative random Doppler coefficient branches.

Assuming here, the continual five symbols of OFDM signal modulated by 64-point FFT are received from four Doppler branches with random coefficients ($f_{D1}$T, $f_{D2}$T, $f_{D3}$T, $f_{D4}$T). The time-variant phase is assumed to be ($2\pi f_D T_s/10$) from one OFDM symbol to the next. In Fig. 5, the two branches ($f_{D1}$T, $f_{D3}$T) CD (2-branch MRC/EGC) and the four branches CD (4-branch MRC/ EGC ) combiners are compared with one branch ($f_{Dl}T$) equalizing (1-branch EQ) on the term of useful component real part and ICI magnitude. In Fig. 5 (a), the CD is combined with positive Doppler coefficient $\{f_{Dl}T\}$ branches. It means that only the branch signals arriving from the forward direction of vehicle moving are combined on subcarrier basis. In Fig. 5 (b), the CD is performed over the received signals with forward or rear arriving directions.

It is obvious that, the CD combining over only positive Doppler branches (Fig. 5 a) shows little ICI-suppression as good as the 1-branch EQ, while the combining over positive/negative Doppler branches (Fig. 5 b) can depress the ICI effectively (by 55% relative to 1-branch EQ). In addition, for ICI-suppression, the MRC and EGC carrier diversity are about the same, the 4-branch CD just gives a little improvement by comparison with the 2-branch CD. The rest combining error is mainly due to the error of linear interpolation CTF estimation in symbol index.

## 4 Computation Simulation Results

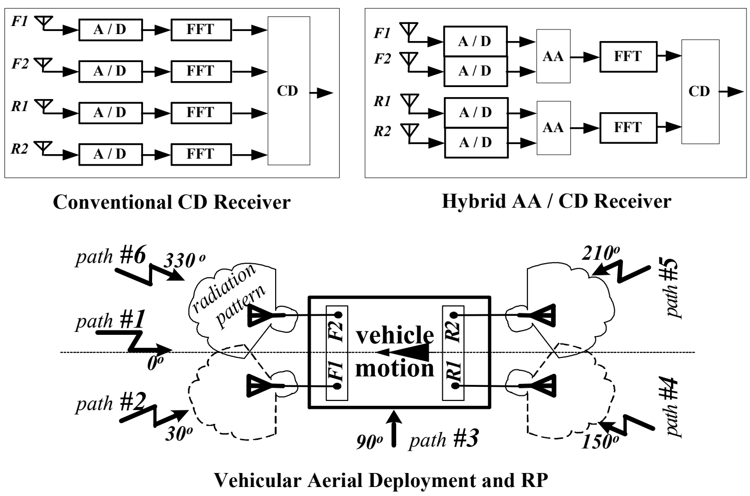



**Fig. 6.** The simulated receiver models and the vehicular antenna radiation patterns (RP)

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.

The upside of Fig. 6 shows the block diagrams of the two receiver models: the conventional CD and the hybrid AA/CD receiver. They are based on four 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 $\{R_1, R_2\}$. The conventional CD receiver performs the MRC criteria (convention cd-MRC). For the hybrid receiver, the two AA weighting sets are determined using the MRC or SMI scheme, and the post-FFT CD performs the MRC or EGC combining. In this paper, following notations are used to denote the hybrid configurations: “hybrid aa-SMI/cd-EGC”, “hybrid aa-SMI/cd-MRC”, “hybrid aa-MRC/cd-EGC” and “hybrid aa-MRC/cd-MRC”.

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 the south of Fig. 6, the distorted RP of the two front antennas $\{F_1, F_2\}$ concentrates on the forward direction, while the two rear ones $\{R_1, R_2\}$ focuses to the rear direction of vehicle moving. Here, their centre directions are assumed to be ($30^o$, $330^o$) and ($150^o$, $210^o$), respectively, and their half-power-beam-width is the same 120-degree (see Fig. 4 **a**). When AA is applied, the antenna set with similar RP is chosen.

### 4.1 System Parameters and Channel Profile

Table I shows the simulation system parameters. Mode3 of the ISDB-T standard with 64QAM digital modulation is used. Table II summaries three channel models with typical six path delayed signals (TU6) for the simulation. The D/U is the desired signal (path#1) to delayed signal power ratio. In channel I an II, all of the signals arrive within GI duration. In channel III, one beyond GI delayed signal (#6) exists.

**Table 1.** System parameters.

| | | |
|---|---|---|
| Carrier frequency | $f_c$ | 563.143MHz (*UHF-28ch*) |
| 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 us |
| Guard interval duration | $T_g$ | $(1/8)T_e$ |
| Digital modulation | | 64QAM |

**Table 2.** Simulation channel.

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

### 4.2 Simulation Results and Discussion

Fig. 7 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 is shown as compared to the conventional CD receiver. Since the correlation between antenna signals is low (due to the distorted RP as shown in Fig.6), 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 as shown in Fig. 7.

Channel II and III are set as a low AWGN channel with SNR=35dB. Figs. 8 and 9 show the BER versus maximum Doppler shifts for the four approaches of hybrid AA/CD receiver in channel II and III, respectively.

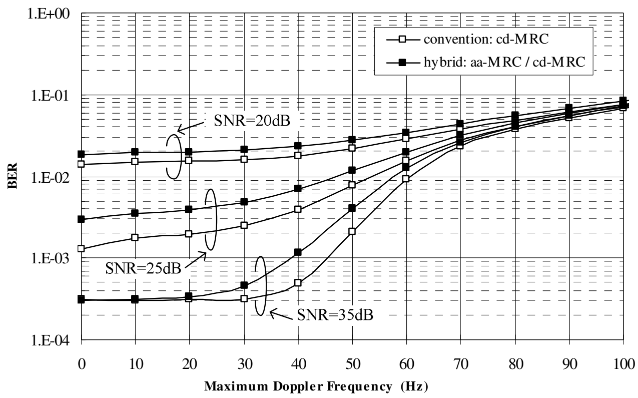



**Fig. 7.** BER versus maximum Doppler shift in Channel-I

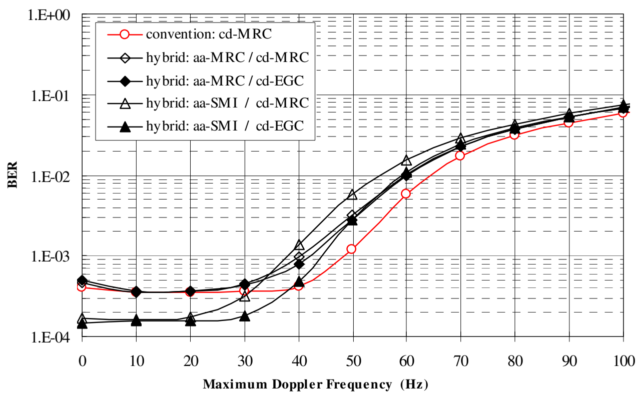



**Fig. 8.** BER versus maximum Doppler shift in Channel-II for SNR=35dB

In Fig. 8, when channel is fast fading ($f_{Doppler} \geqq 40H_Z$), the four types of hybrid AA/CD receiver show the similar robustness to Doppler shifts. 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 performs both the beam forming and null steering to suppress undesired signals. The conventional cd-MRC receiver shows a little more robustness to Doppler than the hybrid one due to ICI-suppression benefiting by the two more CD branches.

In Fig. 9, 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 good performance. This is because the beyond GI delayed signal is suppressed effectively by the SMI AA.

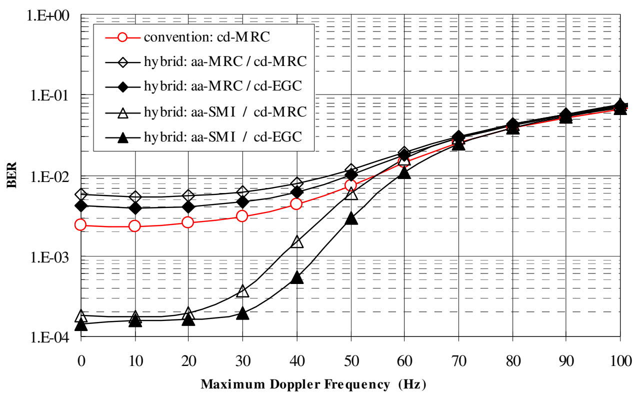



**Fig. 9.** BER versus maximum Doppler shift in Channel-III with one beyond GI delayed signal for SNR=35dB

## 5 Conclusion

It is a severe challenge to implement a conventional antenna-branch based post-FFT subcarrier diversity (CD) receiver in reasons of the system cost and the achievable accuracy of channel estimation while the ISI and ICI occur. On the other hand, a pre-FFT adaptive array (AA) OFDM receiver can depress the ISI and long-delay-induced ICI in time domain, and reduce the number of the required FFT and estimators.

In this paper, a hybrid AA/CD two layers receiver, which can halve the number of CD branches by comparison with the conventional post-FFT CD receiver, is proposed and analyzed. For a good tradeoff between high performance and low complexity, joint the AA scheme of MRC (/or SMI) and the CD combiners of MRC (/or EGC), total four approaches of the hybrid receiver are studied for ISI and ICI suppression by computer simulation. Although the conventional CD receiver suffers large and beyond-GI delayed multi-path condition, a hybrid AA/CD receiver with SMI AA scheme shows a little performance degradation. This approach can effectively increase the accuracy of CTF estimating in subcarrier axis through suppressing the large delayed path signals, thereby increasing the CD performance in mobile multi-path channel by comparison with other receivers, especially at relatively low $f_D T$.

## References


1. J, A.C.Bingham,: Mlticarrier modulation for data transmission: An idea whose time has come. IEEE Commun. Mag., vol.28,pp.5—14,May 1950.
2. J, Clerk Maxwell.: the Doppler spread effect. IEEE Treaties on Electricity and Magnetism, 3rd ed., vol. 2, pp. 68--73. Oxford, Clarendon Press (1992).
3. Mi, Speth., S. Fechtel, G. Fock, and H. Meyr.: Broadband transmission using OFDM: system Performance and receiver Complexity. The work was supported by the deutsche forschungsgemein-schaft under contract No. Me 651/14-1, In Germany.
4. Ye(G.) Li, Leonard J. Cimini, Jr., and nelson R. Sollenberger : Robust channel estimation for OFDM systems with rapid dipersive fading channels. IEEE Transactions on communications, vol.46, pp.902-915, July 1998.
5. Ye(G.) Li and N. R. Sollenberger : Adaptive antenna arrays for OFDM system with cochannel interference. IEEE Trans. Commun., vol. 47,pp.217-229,Feb.1999.
6. Farrukh Rashid and Athanassios manikas : Diversity reception for OFDM systems using antenna arrays. IEEE Trans. Commun., 0-7803-9410-0/06 ©2006.
7. M. Budsabathon, Y. Hara, and S. Hara : Optimum beamforming for Pre-FFT OFDM adaptive antenna array. IEEE Trans. On Vehicular Technology, vol. 53, pp. 945-955, July 2004.
8. Sathish, Chandran (Ed.).: Adaptive Antenna Arrays (Trends and Applications). Springer. Constrained Adaptive Filters, 42--62 (2004).
9. BERNARD SKLAR. : Digital Communications. Second edition. 15-3, 4. PH PTR, 2001,pp958-974.
10. S.Hori, N.Kikuma, T. Wada, and M. Fujimoto: Experimental study on array beamforming utilizing the guard interval in OFDM. International Symposium on Antennas and propagation ISAP2005,pp.257-260, Korea,Aug.2005.
11. Michael Speth, Stefan A. Fechtel: Optimum Receiver Design for Wireless Broad-Band Systems Using OFDM---Part I, IEEE Trans, Vol. 47,No. 11, Nov 1999.
12. Jean Armstrong.: Analysis of New and Existing Methods of Reducing Intercarrier Interference Due to Carrier Frequency Offset in OFDM, IEEE Trans. ON Communications, VOL. 47, No. 3, Mar. 1999.
13. Paul, H.: A Technique for Orthogonal Frequency Division Multiplexing frequency Offset Correction. In: IEEE Trans on Com.,VOL.42,NO.10, pp. 2908. (Oct. 1994).
14. Thierry POLLET, Mark VAN BLADEL, and Marc MOENECLAEY: BER Sensitivity of OFDM system to Carrier Frequency Offset and Wiener Phase Noise. IEEE Trans on Communications, VOL. 43, NO. 2/3/4, Feb./Mar./Apr. 1995.