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

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Research purpose:

This research is focused on a high-performance and low-complexity OFDM receiver by taking account of inter symbol interference (ISI) and inter carrier interference (ICI) suppression.
Background-1: **Multi-path Fading Channel**

- **radiation pattern (RP)**
- **delay profile:**
  \[ E(\tau) \]
  - \[ \tau_1, \tau_2, \tau_3, \tau_4, \tau_5, \tau_L \]
- **Doppler power spectrum:**
  \[ S(f) \]
  - \[ f_c - f_d, f_c, f_c + f_d \]

**ISI, delay-ICI and Doppler-ICI**
the Channel Transfer Function (CTF) Estimating

- **Linear interpolated in symbol direction**
- **Window-sinc filtered in subcarrier direction**

**delay profile:**

**Doppler power spectrum:**

$H(f)$

$S(f)$

$H(f, t)$ will be effected by **ISI, delay-ICI and Doppler-ICI**
Background-2: Conventional post-FFT Carrier Diversity (CD) Combining Receiver

Signal processing on sub-carrier basis

High-complexity

The challenge of accurate estimating of CTF

Channel Transfer Function (CTF)
background 3: **pre-FFT adaptive array (AA) receiver**

**low-complexity:**

1. **decreasing the number of FFT processors**

2. **Only 1-set of AA-weigh is required in one OFDM symbol duration**

**undesired signals depressing:**

1. **ISI-suppression**

2. **more accurate estimating**
Hybrid AA/CD two-layer Receiver

1. Depressed maxi-excess delay profile.
2. Modified SINR
   
   (by using MMSE criteria)

2nd layer:
1. High quality of CTF estimation
2. High performance Carrier Diversity (CD)
**1st layer:** pre-FFT Adaptive Array (AA) Using Guard Interval (GI) of OFDM Symbol *(based on 2-element)*

\[
\begin{align*}
\mathbf{r}_h^{\text{MRC}} & = \mathbf{E} \left[ \mathbf{r}_h(i) \mathbf{y}_t^*(i) \right] \\
\mathbf{w}_{SMI} & = \mathbf{R}_{rr}^{-1} \mathbf{E} \left[ \mathbf{r}_h(i) \mathbf{y}_t^*(i) \right] \\
\mathbf{R}_{rr} & = \mathbf{E} \left[ \mathbf{r}_h \mathbf{r}_h^H \right]
\end{align*}
\]

* GI is the copying in front of a symbol from its own end.
1st layer: pre-FFT

SMI and MRC Adaptive Array (AA) Schemes

Maxi-ratio Combining (MRC): \[ w_{MRC} = E \left[ r_h(i) y_t^*(i) \right] \]

(using the cross-correlation vector)

Sample Matrix Inversion (SMI): \[ R_{rr} = E \left[ r_h r_h^H \right] \]

(MMSE criteria)

\[ w_{SMI} = R^{-1}_{rr} E \left[ r_h(i) y_t^*(i) \right] \]
Maxi-ratio Combining (MRC): \[ w_l(m, p) = \frac{H_l^*(m, p)}{\sum_{l=1}^{L} |H_l(m, p)|^2} \]

Equal Gain Combining (EGC): \[ w_l(m, p) = \frac{H_l^*(m, p)}{|H_l(m, p)|\sum_{l=1}^{L} |H_l(m, p)|} \]

\[ w_l(m, p) = \frac{H_l^*(m, p)}{\alpha_l} \], where \( \alpha_l \) is a real factor.
Simulation: 5 Kinds of the Receiver Models

Conventional CD Receiver

Hybrid AA / CD Receiver

convention:
“cd-MRC”

hybrid:
“aa-MRC / cd-MRC”
“aa-MRC / cd-EGC”
“aa-SMI / cd-MRC”
“aa-SMI / cd-EGC”
ICI-1: the CTF Estimation in Doppler Channel

\[
H_l(t) = \frac{x_l(m, p)}{d(m, p)}
\]

CTF estimation in symbol direction at each pilot position

\[
x_l(m, p) = d(m, p) \frac{\sin \pi f_{Dl} T}{N \sin (\pi f_{Dl} T / N)} e^{j \pi f_{Dl} T \frac{N-1}{N}} + \sum_{k=0, k \neq p}^{N-1} d(m, k) I_{k-p}^{l}
\]

\[= d(m, p) I_{0,l} + I_l(m, p) \quad \text{(Attenuation and phase-rotate + ICI)}\]
ICI-2: post-FFT CD Combining Over Doppler Branches

\[
Y_{m,p} = \sum_l \frac{1}{\alpha_l} H^*_l (m, p) x_l (m, p) \quad \text{(CD combining output)}
\]

\[
d(m,p)I_0 + I = \text{d(m,p)} \{ \text{Re}(I_0) + j \times \text{Im}(I_0) \} + I
\]

\[
I_0 = \sum_l \frac{1}{\alpha_l} \left( |I_{0l}|^2 + \frac{I^*_l (m, p) I_{0l}}{d^* (m, p)} \right)
\]

\[
I = \sum_l \frac{1}{\alpha_l} \left( \frac{|I_l (m, p)|^2}{d^* (m, p)} + I_{0l}^* I_l (m, p) \right)
\]
ICI-3: **post-FFT CD Combining Over Doppler Branches**

**Case-1:** all the CD branch signal arrived from only the **Forward / or Rear** directions.

CD over \(+ f_{DL}T\) or \(- f_{DL}T\)

**Case-2:** all the CD branch signal arrived from the **Forward-Rear** directions.

CD over \(\pm f_{DL}T\).
ICI-4: Using CD for ICI and Extra-noise Suppression

- The CD over both CASE-1 (see left) and CASE-2 (see right) can depress the extra noise by comparing with 1-branch EQ. In CASE-2 is more effective.

- The CD over \( \{\pm f_D T\} \) branches (right CASE-2) can suppress the ICI-noise significantly (58%).
Configuration of Antennas Mounted on Car

2. Front AA: \((F1+F2)\)
3. Rear AA: \((R1+R2)\)
Mobile application-2: the Radiation Character of the Used Four Array Elements (half power BW=120°)
## Simulated three Channel Models

<table>
<thead>
<tr>
<th>Path</th>
<th>D/U (dB)</th>
<th>AOA (deg.)</th>
<th>Delay time</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>0</td>
<td>10</td>
<td>0.01*(Tg/8)</td>
</tr>
<tr>
<td>#2</td>
<td>3</td>
<td>90</td>
<td>3.0*(Tg/8)</td>
</tr>
<tr>
<td>#3</td>
<td>5</td>
<td>170</td>
<td>6.0*(Tg/8)</td>
</tr>
<tr>
<td>#4</td>
<td>1.5</td>
<td>190</td>
<td>0.5*(Tg/8)</td>
</tr>
<tr>
<td>#5</td>
<td>2</td>
<td>270</td>
<td>1.0*(Tg/8)</td>
</tr>
<tr>
<td>#6</td>
<td>4</td>
<td>350</td>
<td>3.0*(Tg/8)</td>
</tr>
</tbody>
</table>
Adaptive Array-1: Beam-pattern of AA Schemes (SNR=35dB)
Adaptive Array-2: Normalized CTF Varying With Subcarrier Index (with $SNR=35dB$, no Doppler shift)

- - - short delay

CHANNEL-I

____ beyond-GI delay

CHANNEL-III
Adaptive Array-3: Normalized CTF Varying With Subcarrier Index (in beyond-GI delayed CHANNEL-III)

--- no Doppler

___ $f_D = 30 \text{ Hz}$

($f_D T = 0.03$)
## Simulation System Parameter
*(ISDB-T Digital TV Standard of Japan and Brazil)*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency</td>
<td>$f_c$</td>
<td>563.143 MHz (UHF-28ch)</td>
</tr>
<tr>
<td>Subcarrier spacing</td>
<td>$f_0$</td>
<td>0.992 kHz</td>
</tr>
<tr>
<td>Number of carriers</td>
<td>$N$</td>
<td>8192</td>
</tr>
<tr>
<td>Number of effective carriers</td>
<td>$N_e$</td>
<td>5617</td>
</tr>
<tr>
<td>Effective symbol duration</td>
<td>$T_e$</td>
<td>1008us</td>
</tr>
<tr>
<td>Guard interval duration</td>
<td>$T_g$</td>
<td>$(1/8)T_e$</td>
</tr>
<tr>
<td>Digital modulation</td>
<td></td>
<td>64QAM</td>
</tr>
</tbody>
</table>
Simulation result-1:

BER Performance in Channel-1 (short-delay)

![Graph showing BER performance with varying SNR and Maximum Doppler Frequency (Hz). The graph compares conventional cd-MRC and hybrid aa-MRC / cd-MRC methods. The SNR values are labeled as 20dB, 25dB, and 35dB.]
Simulation result-2:

BER Performance in Channel-2 (short delay)

SNR=35dB

Maximum Doppler Frequency (Hz)

BER

0 10 20 30 40 50 60 70 80 90 100

1.E+00

1.E-01

1.E-02

1.E-03

1.E-04

- convention: cd-MRC
- hybrid: aa-MRC / cd-MRC
- hybrid: aa-MRC / cd-EGC
- hybrid: aa-SMI / cd-MRC
- hybrid: aa-SMI / cd-EGC
Simulation result-3:

BER Performance in Channel-3 (long delay)

**SNR=35dB**

The graph shows the BER performance as a function of Maximum Doppler Frequency (Hz). The x-axis represents the Maximum Doppler Frequency, ranging from 0 to 100 Hz, while the y-axis represents BER, ranging from $1 \times 10^{-4}$ to $1 \times 10^0$. The graph compares different signal processing techniques, including:

- **convention: cd-MRC**
- **hybrid: aa-MRC / cd-MRC**
- **hybrid: aa-MRC / cd-EGC**
- **hybrid: aa-SMI / cd-MRC**
- **hybrid: aa-SMI / cd-EGC**

The performance of these techniques is evaluated at various SNR levels, with the specific SNR of 35dB highlighted in the graph.
conclusion

1. Proposed hybrid AA/CD two layers receiver is analyzed.

2. The Hybrid receiver is a low-complexity method, it can halve CD branches in comparison with the conventional CD receiver.

3. The hybrid receiver is a high-performance approach. Especially, when the received signal suffers from large delayed or beyond GI delayed path conditions, by using the SMI AA in 1st layer, the proposed hybrid AA/CD 2-layer receiver show good performance while that of the conventional post-FFT CD receiver is degraded significantly.