HDTV Performance Improvement with Multiple Antennas

Feb. 25, 2004

Dong-Seog Han
Department of Electrical & Computer Engineering
University of Florida
dshan@dsp.ufl.edu
Contents

- DTV Standards
- DTV Channel
- Conventional Equalization
- Beamforming Techniques
- Beampattern for Broadcasting Frequencies
- Performance of DOA Estimation-based DTV Receiver
- Implementation
- Conclusions
DTV Standards
# DTV Standards

<table>
<thead>
<tr>
<th></th>
<th>ATSC</th>
<th>DVB-T</th>
<th>ISDB-T</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Video</strong></td>
<td>MPEG-2</td>
<td>MPEG-2</td>
<td>MPEG-2</td>
</tr>
<tr>
<td><strong>Audio</strong></td>
<td>Dolby AC-3</td>
<td>MPEG-2</td>
<td>MPEG-2</td>
</tr>
<tr>
<td><strong>Multiplexing</strong></td>
<td>MPEG-2</td>
<td>MPEG-2</td>
<td>MPEG-2</td>
</tr>
<tr>
<td><strong>Modulation</strong></td>
<td>8-VSB</td>
<td>COFDM</td>
<td>Band segmented COFDM</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>6MHz</td>
<td>6,7,8MHz</td>
<td>6MHz</td>
</tr>
<tr>
<td><strong>Service</strong></td>
<td>SDTV / HDTV</td>
<td>SDTV</td>
<td>SDTV / HDTV</td>
</tr>
</tbody>
</table>

- **HDTV vs. Mobility?**
ATSC 8-VSB

RS(207,187) t=1C

Data Randomizer → Reed-Solomon Encoder → Data Interleaver → Trellis Encoder r=2/3 → MUX → Pilot Insertion → Pre-equalizer → VSB Mod. → RF Up-Conv.

Segment Sync → Field Sync

Field Sync #1

Data+FEC

Field Sync #2

Data+FEC

832 symbols 1 Seg. (77.6us)

313 Segments

24.2 ms

Magnitude dB

SPAN: 20 MHz
VERT SCALE: 10 dB/div

50mC

5200ns
DVB-T COFDM

MPEG-2
Source coding & Multiplexing
Program MUX
Video Coder
Audio Coder
Data Coder
Transport MUX
Splitter

MUX Adaptation Energy Dispersal
Outer Coder
Outer Interleaver
Inner Coder
Inner Interleaver
Mapper
Frame Adaptation
OFDM
Guaranteed Interval Insertion
D/A
To Aerial
Front End

Terrestrial Channel Adapter

RS(204,188)
t=8
Constraint length=7
CC_r=1/2

"High Priority" stream bits
"Low Priority" stream bits

Subcarriers

6816 (8k model)
1704 (2k model)

C 1 2
S0 S1 S2

Time

Busted pilot Data
DTV Channel
DTV Channel

- Brazilian ch. B

- Brazilian ch. C
DTV Channel

- Brazilian ch. D

- Brazilian ch. E
DTV Channel

- **Dermot Nolan**, a director of Telecommunications and Broadcast Services, a well-known digital terrestrial consultancy

  - **DTV RF channels are time varying**, even in the case of directional outdoor antennas. This indicates that the most appropriate channel model for DTV system designers is **Rayleighian with time-varying multipath**.
Conventional Equalization
Conventional Equalizer

- Decision Feedback Equalizer
  - FFF (feed-forward filter)
    Filter length: 15 (Brazil A, B, D, E chs), 50 (Brazil C CH)
  - FBF (feed-backward filter)
    Filter length: 150
  - Algorithm: LMS with training sequence and Stop & Go blind equalizer
Conventional Equalizer

- SNR 20dB

<table>
<thead>
<tr>
<th>Channel type</th>
<th>Before equalization</th>
<th>After equalization</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Output S/NR</td>
<td>SER</td>
</tr>
<tr>
<td>Brazil A</td>
<td>7.6018</td>
<td>0.5314</td>
</tr>
<tr>
<td>Brazil B</td>
<td>1.4956</td>
<td>0.7052</td>
</tr>
<tr>
<td>Brazil C</td>
<td>-5.0707</td>
<td>0.7914</td>
</tr>
<tr>
<td>Brazil D</td>
<td>-5.2609</td>
<td>0.7931</td>
</tr>
<tr>
<td>Brazil E</td>
<td>-3.0279</td>
<td>0.7641</td>
</tr>
</tbody>
</table>

TOV (threshold of visibility): BER 20%

- How we can improve the reception performance in indoor and mobile environments?
  - Sophisticated antenna, Equalizer, ...
Beamforming Techniques
Beamformer Structures

- Switched beam system
- Adaptive array

Diagram showing a switched beam system with a M x M beamforming network, receivers for User 1 and User N, and control switches for each user. The output is combined using weights w₁, w₂, ..., w_N before being processed by the array output. The diagram includes a signal processor and control algorithm.
Principle

\[
\begin{align*}
\text{Down Conversion} & \quad w_0 \\
\text{Down Conversion} & \quad w_1 \\
\text{Down Conversion} & \quad w_2
\end{align*}
\]

\[
\begin{align*}
\text{ang}(w_0) &= 0^\circ \\
\text{ang}(w_1) &= 0^\circ \\
\text{ang}(w_2) &= 0^\circ \\
\text{ang}(w_0) &= 0^\circ \\
\text{ang}(w_1) &= 90^\circ \\
\text{ang}(w_2) &= 180^\circ
\end{align*}
\]
Adaptive Beamformer

\[ z(t) = w^H u(t) \]
\[ = w^H \left[ s(t) a(\theta, \phi) + n(t) \right] \]

- Cost function
\[ J(w) = E \left\{ |w^H u(t) - s(t)|^2 \right\} \]
\[ = w^H E \left\{ u(t) u^H(t) \right\} w - w^H E \left\{ u(t) s^*(t) \right\} \]
\[ - E \left\{ s(t) u^H(t) \right\} w + E \left\{ |s(t)|^2 \right\} \]
\[ = w^H R w - w^H p - p^H w + E \left\{ |s(t)|^2 \right\} \]

\[ \nabla J(w) = 2Rw - 2p = 0 \]

\[ w_{opt} = R^{-1} p : \text{ Normal equation} \quad \text{Power gain} = N \]
Adaptive Array

- Adaptive array based on received data
  - LMS (least mean square): requires reference signal
  - MV (minimum variance): uses directional constraint
  - CMA (constant modulus algorithm): restores the array output to a constant envelope signal on average

- DOA based array
  - SLC (sidelobe canceller)
  - Frost array
  - GSC (generalized sidelobe canceller)
Signal Processing Algorithms

- DOA estimation-based algorithm
  - Estimate DOA with signal covariance matrix
  - Beam-steering to the estimated DOA
  - MUSIC, Pisarenko, ESPRIT, ML

- Training sequence-based algorithm
  - Pilot channel in wireless systems
  - SMI, LMS, RLS

- Blind algorithms
  - CMA, Cyclo-stationary, Higher order statistic
DOA Estimation

- Delay and sum

\[
\max_w \left\{ w^H a(\theta) a^H(\theta) w \right\} = \max_w \left| w^H a(\theta) \right|^2, \quad \text{subject to} \quad w^H w = 1
\]

\[
V_{BF}(\theta) = \frac{a^H(\theta) R a(\theta)}{a^H(\theta) a(\theta)} \quad \Rightarrow \quad w_{BF} = \frac{a(\theta_{\text{max}})}{\sqrt{a^H(\theta_{\text{max}}) a(\theta_{\text{max}})}}
\]

- Advantage: the most simple
- Disadvantage
  Spatial resolution: highly depending on the number of antenna elements and SNR
  Estimation error: due to signals from other directions
DOA Estimation

- Capon’s minimum variance method

\[
\min_w w^H R w \quad \text{subject to} \quad w^H a(\theta) = 1
\]

\[
V_{CAP}(\theta) = \frac{1}{a^H(\theta) R^{-1} a(\theta)} \quad \Rightarrow \quad w_{CAP} = \frac{R^{-1} a(\theta_{\text{max}})}{a^H(\theta_{\text{max}}) R^{-1} a(\theta_{\text{max}})}
\]

- Advantage
  Removing signals from other directions
  Relatively simple

- Disadvantage
  Spatial resolution: highly depending on the number of antenna elements and SNR
DOA Estimation

- MUSIC (MUltiple SIgnal Classification)
  - Define the signal and noise subspaces from the eigen decomposition
    \[
    R = [U_s \quad U_n] \text{diag}\{\lambda_1, \ldots, \lambda_M\} [U_s \quad U_n]^H
    \]
  - From the orthogonality of the signal and noise subspaces, finding the peaks in the estimator function
    \[
    a^H(\theta) U_n U_n^H a(\theta) = 0
    \]
    \[
    V_M(\theta) = \frac{1}{a^H(\theta) U_n U_n^H a(\theta)}
    \]
  - Advantage: High spatial resolution
  - Disadvantage
    - The number of antenna elements > the number of incoming signals
    - Complexity
DOA Estimation (Spatial Spectrum)

Incoming signals
- DOA: 10°, 20°
- Amplitude: 1, 0.8

Incoming signals
- DOA: 10°, 30°
- Amplitude: 1, 0.8
SNR Improvement in AWGN for 8-VSB

- Signal constellations at 4 antenna elements (SNR: 20dB)
SNR Improvement in AWGN for 8-VSB

- Without beamforming
  - SNR=20dB
- After beamforming
  - SNR=26dB (6dB ↑)
Beampattern for Broadcasting Frequencies
Beampattern in terms of Number of Antenna Elements

No. of antenna elements: 1

No. of antenna elements: 2

No. of antenna elements: 3

No. of antenna elements: 4
Beampattern in terms of Antenna Distance

$d/\lambda$: 0.25

$d/\lambda$: 0.5

$d/\lambda$: 0.75

$d/\lambda$: 1
Beampattern for ATSC D-TV

- Frequency bands for terrestrial broadcasting

<table>
<thead>
<tr>
<th>Band</th>
<th>Channel</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>VHF Low</td>
<td>Ch. 2 ~ Ch. 6</td>
<td>52<del>72MHz, 76</del>88MHz</td>
</tr>
<tr>
<td>VHF High</td>
<td>Ch. 7 ~ Ch. 13</td>
<td>174~216MHz</td>
</tr>
<tr>
<td>UHF</td>
<td>Ch. 14 ~ Ch. 83</td>
<td>470~890MHz</td>
</tr>
</tbody>
</table>

- Linear array structure
  - No. of antenna elements: 4
  - Reference frequency: 600 MHz
  - Distance between adjacent antenna elements: 0.25 m
Beampattern for ATSC D-TV

- 60MHz (half wavelength: 2.5m)
Beampattern for ATSC D-TV

- **80MHz** (half wavelength: 1.875m)
Beampattern for ATSC D-TV

- 200MHz (half wavelength: 0.75 m)
Beampattern for ATSC D-TV

- 700MHz (half wavelength: 0.2143 m)
Performance of DOA Estimation-based DTV Receiver
DOA Estimation-based DTV Receiver

- Scheme
  - DOA estimation
  - Beamforming
  - Equalization
  - Analysis the performance
  - Switching Algorithm

- Capon beamforming
- Spatial spectrum
- Remove multipath through spatial filtering
- Remove remained multipath
- Can we see DTV?
- Estimate other DOA

35
DOA Estimation-based DTV Receiver

- DOA Estimation
- Beamforming to the estimated DOA
- Equalization
- DOA estimation
- Equalizer
Simulation Condition

- 4 linear antennas
- SNR: 20 dB
- DOA estimation
  - Capon method with 1 field sync signals
- DFE (decision feedback equalizer)
  - FFF (feed-forward filter)
    - Filter length: 50
  - FBF (feed-backward filter)
    - Filter length: 150
- SAG (stop and go) algorithm
Brazilian Channel A

- Estimated DOA
  - Capon: -0.5°, Delay sum: -0.5°

Spatial Spectrum  Beampattern
Brazilian Channel A

Delay profile

Constellation
Brazilian Channel B

- Estimated DOA
  - Capon: 1.5°, Delay sum: 3°

Spatial Spectrum

Beampattern
Brazilian Channel B

Delay profile

Constellation
Brazilian Channel C

- Estimated DOA
  - Capon: -5°, Delay sum: -5°
Brazilian Channel C

Delay profile

Constellation
Brazilian Channel D

Estimated DOA

Capon: 0°, Delay sum: 36°

Spatial Spectrum

Beampattern
Brazilian Channel D

Delay profile

Constellation
Brazilian Channel E

- Estimated DOA
  - Capon: 0°, Delay sum: 11°

Spatial Spectrum

Beampattern
Brazilian Channel E

Delay profile

Constellation
## Summary

<table>
<thead>
<tr>
<th>SNR</th>
<th>Channel</th>
<th>Beamformer</th>
<th>Equalizer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Input SINR</td>
<td>Output SINR</td>
</tr>
<tr>
<td>SNR=15 dB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brazil A</td>
<td>7.1032</td>
<td>11.8262</td>
</tr>
<tr>
<td></td>
<td>Brazil B</td>
<td>1.3582</td>
<td>9.8316</td>
</tr>
<tr>
<td></td>
<td>Brazil C</td>
<td>-5.0924</td>
<td>1.0190</td>
</tr>
<tr>
<td></td>
<td>Brazil D</td>
<td>-5.2659</td>
<td>4.2071</td>
</tr>
<tr>
<td></td>
<td>Brazil E</td>
<td>-3.0608</td>
<td>17.7802</td>
</tr>
<tr>
<td>SNR=10 dB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brazil A</td>
<td>5.8000</td>
<td>11.2354</td>
</tr>
<tr>
<td></td>
<td>Brazil B</td>
<td>0.9738</td>
<td>8.0259</td>
</tr>
<tr>
<td></td>
<td>Brazil C</td>
<td>-5.1768</td>
<td>0.9418</td>
</tr>
<tr>
<td></td>
<td>Brazil D</td>
<td>-5.3521</td>
<td>4.0054</td>
</tr>
<tr>
<td></td>
<td>Brazil E</td>
<td>-3.2019</td>
<td>11.8097</td>
</tr>
</tbody>
</table>
SNR Performance in terms of No. of Antenna Elements

- Linear array
- DOA: [20°, -10°, 0°, 45°, -50°, 60°]
- No. of antenna elements: 3-10
- Input SNR: 10 dB
- Beamformer
  - Beamforming with LMS during training sequences
  - Equalizer: LMS and Blind

![SNR Performance Graph](image)
Implementation
Beam Selection

- Electrically steered fixed beamformer
- Seek out the direction of the highest signal strength automatically

Diagram:
- Circular array antenna
- Step attenuator
- Pre-amplifier
  - Noise Figure: 3 dB
  - Gain: 0, 5, 10, 20 dB
- Microprocessor
  - Beam steering
  - Gain control
  - Ch. control
- Tuner
- SAW
- RSSI

Photo: Display of equipment with text "DTV5000" and software information.
Beam Selection

**DTV-5000 - Amplified & Omni-Directional**
- Can be programmed in 18 different directions via CEA 909 interface
- Omni-directional mode for NTSC TV
- Gain controlled via CEA 909 interface

**DTV-6000 - Amplified with VHF Dipoles**
- Designed for those areas with VHF HDTV signal
- VHF signal can be commanded to four different patterns via CEA 909 interface
Analog Beamformer

- Analog IF weighting and combining
- Easy for timing & carrier recovery
Spatial Diversity and Combining I

- Channel estimation with field sync signal
  - Select main and dominant multipath signals
  - Combining each signal with EQC or MRC
- Advantage
  - Increase of SNR with multipath combining
Spatial Diversity and Combining II

Demod. 1

Equalizer

Demod. 2

Equalizer

Demod. 3

Equalizer

Demod. N

Equalizer

Ch. Estimator

Adaptive Processor

Interference

Multipath

Desired Signal

Mainpath

Array
Conclusions

- Beamforming can be one of ways to improve DTV reception performance
- Beamforming is efficient for UHF bands
- DOA estimation based receiver with Capon method is reasonable for implementation
- Further study
  - Optimization of array structure
  - Synchronization schemes for array systems
  - Joint optimization of DOA and training sequence based algorithms
  - How to calibrate?