Update on CE-OFDM Waveforms
For Use on HF Channels

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Presentation Overview

- OFDM Waveform
- CE-OFDM Waveform
- RF Power Amplifiers
- System Models
- Performance
- Summary
OFDM Waveform

• OFDM
  – Orthogonal Frequency Division Multiplexing
  – An OFDM frame is created by transmitting data using N orthogonal tones in parallel
  – Addition of a guard-time removes inter-frame interference
  – Coherent Modulation
    • Equalizer in frequency domain becomes a single complex tap per OFDM tone
  – Differential Modulation
    • No equalizer required
  – IFFT (TX) and FFT (RX) are very efficient signal processing blocks that can be used to generate and demodulate OFDM
  – Can use complex modulations
    • 2-PSK, 4-PSK, 8-PSK, 16-QAM
OFDM Waveform

• Disadvantage of OFDM
  – High Peak-power to Average-power Ratio (PAR)
    • Worst case - 10 log10(N)
    • Typical – 10-14 dB for N > 16
  – Requires very linear power amplifier (PA)
    • Class A or Class A-B
    • Distortion and spectral re-growth caused by PA
  – For some applications (i.e. handheld devices, battery powered), Class C amplifiers desired ??
### OFDM Waveform Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame Size (samples)</td>
<td>256 (i.e. FFT Size)</td>
</tr>
<tr>
<td>Number of Data Tones</td>
<td>64</td>
</tr>
<tr>
<td>Guard Time (samples)</td>
<td>32</td>
</tr>
<tr>
<td>Sample Rate (samples per second)</td>
<td>9600</td>
</tr>
<tr>
<td>Frame Time (ms)</td>
<td>30</td>
</tr>
<tr>
<td>First Tone Location</td>
<td>8</td>
</tr>
<tr>
<td>Tone-to-Tone Bandwidth (Hz)</td>
<td>2400</td>
</tr>
<tr>
<td>Modulation</td>
<td>2-PSK, 4-PSK, 8-PSK, 16-QAM</td>
</tr>
<tr>
<td>FEC</td>
<td>Rate 1/2 k=7</td>
</tr>
<tr>
<td>APBO*</td>
<td>6 dB</td>
</tr>
<tr>
<td>Clip Level</td>
<td>6 dB</td>
</tr>
</tbody>
</table>

*APBO is the Average Power Backoff into PA*
Constant Envelope Orthogonal Frequency Division Multiplexing (CE-OFDM)

- Exploit some of the ideas used in OFDM
  - Phase modulate a carrier with a time-domain waveform similar to OFDM
  - Constraints imposed by phase modulation
    - One-dimensional modulation
      - M-ary Pulse-amplitude modulation (M-PAM)
        \[ \pm 1, \pm 3, \ldots, \pm (M - 1) \]
      - Real-valued message signals (i.e. sub-carriers)
        - Half-wave cosines
        - Half-wave sines
        - Full-Wave cosines and sines
  - Cyclic prefix (guard-time) allows the use of a frequency-domain equalizer prior to phase demodulation
CE-OFDM Waveform

• 64 Sub-Carriers, 2-PAM modulation (-1, 1 symbols), CN=square root of (2.0/64.0), TB is CE-OFDM frame time (not including guard time), h=modulation index

\[
q_k(t) = \begin{cases}
  \cos(\pi k t / T_B), & 0 \leq t \leq T_B \\
  0, & \text{otherwise}
\end{cases}
\]  (1)

\[
\phi(t) = \phi_i + 2\pi h C_N \sum_{k=1}^{N} I_{i,k} q_k(t - i T_B), i T_B \leq t \leq (i + 1) T_B
\]

\[
s(t) = A e^{j \phi(t)}
\]  (2)
# CE-OFDM Waveform Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame Size (samples)</td>
<td>1024</td>
</tr>
<tr>
<td>Number of Data Tones</td>
<td>64</td>
</tr>
<tr>
<td>Guard Time (samples)</td>
<td>128</td>
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<tr>
<td>Sample Rate (samples per second)</td>
<td>38400</td>
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<tr>
<td>Frame Time (ms)</td>
<td>30</td>
</tr>
<tr>
<td>First Tone Location</td>
<td>-</td>
</tr>
<tr>
<td>Tone-to-Tone Bandwidth (Hz)</td>
<td>-</td>
</tr>
<tr>
<td>Modulation</td>
<td>2-PAM, 4-PAM, 8-PAM, 16-PAM</td>
</tr>
<tr>
<td>FEC</td>
<td>Rate 1/2 k=7</td>
</tr>
<tr>
<td>Modulation Index</td>
<td>$h=0.62/\text{TWO}_\pi$</td>
</tr>
</tbody>
</table>
RF POWER AMPLIFIERS

• Radio Frequency (RF) Power Amplifier (PA)
  – Typically peak-power limited
  – PAs deviate from ideal ones in region where maximum input/output power levels are approached
    • Produce non-linear behavior
      – Amplitude distortion
      – Phase distortion
      – Spectral re-growth
  – Most systems constrain the out-of-band power emissions by defining a spectral mask and a percent power bandwidth
Power Spectrum

Frequency (Hertz)

Relative Power (dB)

MASK  OFDM  2_PI_h=1.10  2_PI_h=0.62  2_PI_h=0.50

-9600 -7200 -4800 -2400 0 2400 4800 7200 9600
Percent Power Bandwidths

<table>
<thead>
<tr>
<th></th>
<th>99.00 % (Hertz)</th>
<th>99.90 % (Hertz)</th>
<th>99.99 % (Hertz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFDM</td>
<td>2475</td>
<td>5100</td>
<td>9488</td>
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<tr>
<td>2_PI_h=1.10</td>
<td>4664</td>
<td>7399</td>
<td>28453</td>
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<tr>
<td>2_PI_h=0.80</td>
<td>3792</td>
<td>5944</td>
<td>25458</td>
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<tr>
<td>2_PI_h=0.62</td>
<td>3028</td>
<td>4816</td>
<td>21551</td>
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<tr>
<td>2_PI_h=0.60</td>
<td>2910</td>
<td>4713</td>
<td>20960</td>
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<tr>
<td>2_PI_h=0.50</td>
<td>2407</td>
<td>4312</td>
<td>17461</td>
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<tr>
<td>2_PI_h=0.40</td>
<td>2316</td>
<td>3811</td>
<td>13094</td>
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</tbody>
</table>

For OFDM, backing off the PA by 6 dB reduces actual on-air average transmitted power by 6 dB

For performance testing, CE-OFDM will use 2_PI_h=0.62
OFDM System Model

- Input Data
- Serial-to-parallel buffer
- Modulator (IFFT) N=256
- Parallel-to-serial convert and GT addition
- TX Waveform (1 frame)
- HF Channel
- Perfect Channel Estimate
- Demodulator (FFT)
- Serial-to-parallel Convert and GT removal
- RX Waveform (1 frame)
- Output Data
- Parallel-to-serial buffer
CE-OFDM System Model

- **Input Data**
  - Serial-to-parallel buffer
  - Cosine Tone Generator
    - Equation (1)
    - N=64
  - Addition of all tones, GT equation (2)
  - TX Waveform (1 frame)

- **Output Data**
  - Parallel-to-serial buffer
  - Matched Filter Demodulator
    - N=64
  - Serial-to-Parallel Convert
  - Phase demod and Phase unwrapper
  - Perfect Channel Estimate
  - Remove Guard Time, Filter and FDE
  - HF Channel
  - TX Waveform (1 frame)

- **HF Channel**
PERFORMANCE

- Channels used for BER performance testing
  - AWGN channel (label = AWGN)
  - Non-Fading multipath channel (label = 2PNF)
    - 2 equal power paths
    - 2 ms apart
  - HF Channel (label = Poor)
    - ITU Mid-Latitude Disturbed Channel
      - 2 equal power paths
      - Each path fades independently with a 1 Hz fade rate
      - 2 ms apart
Uncoded OFDM and CE-OFDM Waveforms (2-PSK, 2133.33 bps)

SNR in 3 kHz (2 dB per division)

BER

-6 -4 -2 0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46

SNR - OFDM - AWGN - OFDM - 2PNF - OFDM - Poor

CE-OFDM - AWGN - CE-OFDM - 2PNF - CE-OFDM - Poor

1.00E-03 1.00E-04 1.00E-05 1.00E-06

1.00E-02 1.00E-01
PERFORMANCE

Rate 1/2 2-PSK OFDM and CE-OFDM Waveforms (1067 bps)

![Graph showing BER vs. SNR for OFDM and CE-OFDM waveforms.]

- **OFDM - AWGN**
- **OFDM - 2PNF**
- **OFDM - Poor**
- **CE-OFDM - AWGN**
- **CE-OFDM - 2PNF**
- **CE-OFDM - Poor**
PERFORMANCE

• Based purely on SNR
  – Uncoded @ BER = 10^{-4}
    • OFDM 4 dB better on AWGN
    • OFDM 5 dB better on 2PNF
    • CE-OFDM 7 dB better on Poor
  – Coded @ BER = 10^{-5}
    • OFDM 5.3 dB better on AWGN
    • OFDM 6.7 dB better on 2PNF
    • OFDM 10.2 dB better on Poor
PERFORMANCE

- Based on SNR + Average Power Backoff (APBO)
  - Uncoded @ BER = $10^{-4}$
    - CE-OFDM 2 dB better on AWGN
    - CE-OFDM 1 dB better on 2PNF
    - CE-OFDM 13 dB better on Poor
  - Coded @ BER = $10^{-5}$
    - CE-OFDM 0.7 dB better on AWGN
    - OFDM 0.7 dB better on 2PNF
    - OFDM 4.2 dB better on Poor
PERFORMANCE

Rate 1/2 4-PSK OFDM and 4-PAM CE-OFDM Waveforms (2133 bps)

SNR in 3 kHz (dB)

BER

OFDM - AWGN
OFDM - 2PNF
OFDM - Poor
CE-OFDM - AWGN
CE-OFDM - 2PNF
CE-OFDM - Poor
Performance

Rate 1/2 8-PSK OFDM and 8-PAM CE-OFDM Waveforms (3200 bps)

![Graph showing BER vs SNR for OFDM and CE-OFDM waveforms](image-url)
Performance

Rate 1/2 16-QAM OFDM and 16-PAM CE-OFDM Waveforms (4267 bps)
## Performance

<table>
<thead>
<tr>
<th>OFDM</th>
<th>OFDM</th>
<th>CE-OFDM</th>
<th>Delta</th>
<th>Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR (dB)</td>
<td>SNR + APBO (dB)</td>
<td>SNR (dB)</td>
<td>(dB)</td>
<td></td>
</tr>
<tr>
<td>2-PSK (OFDM)</td>
<td>0.5</td>
<td>6.5</td>
<td>5.8</td>
<td>-0.7</td>
</tr>
<tr>
<td>2-PAM (CE-OFDM)</td>
<td>2.3</td>
<td>8.3</td>
<td>9.0</td>
<td>0.7</td>
</tr>
<tr>
<td>4-PSK (OFDM)</td>
<td>4.0</td>
<td>10.0</td>
<td>10.5</td>
<td>0.5</td>
</tr>
<tr>
<td>4-PAM (CE-OFDM)</td>
<td>5.5</td>
<td>11.5</td>
<td>15.5</td>
<td>4.0</td>
</tr>
<tr>
<td>8-PSK (OFDM)</td>
<td>9.0</td>
<td>15.0</td>
<td>16.5</td>
<td>1.5</td>
</tr>
<tr>
<td>8-PAM (CE-OFDM)</td>
<td>9.5</td>
<td>15.5</td>
<td>23.0</td>
<td>7.5</td>
</tr>
<tr>
<td>16-QAM (OFDM)</td>
<td>12.8</td>
<td>18.8</td>
<td>23.0</td>
<td>4.2</td>
</tr>
<tr>
<td>16-PAM (CE-OFDM)</td>
<td>10.0</td>
<td>16.0</td>
<td>19.5</td>
<td>3.5</td>
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<td></td>
<td>11.5</td>
<td>17.5</td>
<td>29.0</td>
<td>11.5</td>
</tr>
<tr>
<td></td>
<td>15.5</td>
<td>21.5</td>
<td>30.0</td>
<td>8.5</td>
</tr>
</tbody>
</table>
Performance

Rate 1/2 16-QAM and 16-PAM OFDM Waveform

BER vs SNR in 3 kHz (dB)

- 16-QAM - AWGN
- 16-QAM - 2PNF
- 16-QAM - Poor
- 16-PAM - AWGN
- 16-PAM - 2PNF
- 16-PAM - Poor
Summary

• CE-OFDM’s constraint of purely real modulations requires much higher SNR per added bit than complex modulations (i.e. 16-PAM instead of 16-QAM)
• The use of a linear frequency domain equalizer provides poor performance on multipath fading channels
• Unless new demodulation techniques can be developed to improve the performance of CE-OFDM, its constant envelope property comes at too high an SNR price to make it a practical high data rate solution for HF
• Note that CE-OFDM’s demodulation process is significantly more computationally complex than OFDM
• Even if PA efficiency is used instead of APBO (i.e. additional 1.1 dB penalty for OFDM waveform), CE-OFDM will not outperform OFDM above 4-ary modulations