Correlation and Tracking
Schemes for the new BOC signals

Electronics and Signal Processing Laboratory
EPFL-STI-IMT-ESPLAB
Rue A.-L. Breguet 2
CH-2000 Neuchâtel

Head: Prof. P.-A. Farine
Team Leader: Dr. C. Botteron
Authors: Aleksandar Jovanovic, Youssef Tawk
Outline

- CBOC/TMBOC concept (A. Jovanovic)
  - Tracking metrics & Tracking algorithms for MBOC
  - Comparison of MBOC algorithms
  - Results and recommendations for MBOC tracking

- AltBOC concept (Y. Tawk)
  - Tracking metrics & Tracking algorithms for AltBOC
  - Comparison of AltBOC algorithms
  - Results and recommendations for AltBOC tracking
Correlation and Tracking of MBOC

- Overview of MBOC receiver tracking schemes
- Perform comparison w.r.t. tracking metrics
  - ACF peak amplitude
  - Multipath error envelope
  - Code tracking error
- Provide advantages/disadvantages of each algorithm
- Recommendations to reduce receiver complexity
CBOC/TMBOC definition

- CBOC vs. TMBOC
- Same power spectral density (PSD)
  \[ G_{MBOC} = \frac{10}{11} G_{BOC(1,1)}(f) + \frac{1}{11} G_{BOC(6,1)}(f) \]
  - Pilot and data channels have different structures
- Different tracking performance for CBOC/TMBOC
CBOC/TMBOC signals

- **GPS L1C OS TMBOC (6,1,4/33)**
  - BOC(1,1) on data channel (25%), TMBOC on pilot (75%)
  - Multiplex wide-band BOC(6,1) with narrow-band BOC(1,1)
- **Galileo E1 OS CBOC (6,1,1/11,’+/−’)**
  - Equally split power (50%), signals in antiphase
  - Weighted sum of BOC(1,1) and BOC(6,1) on data+pilot
Tracking in general

- First step to consider: *Autocorrelation function (ACF)*
- Main tracking parameters:
  - Tracking sensitivity
    - *Minimum SNR to maintain tracking*
  - Tracking robustness
    - *Stability tracking region*
  - Tracking accuracy
    - *Errors: multipath, noise, interference*
      - Multipath main source of error
- Phase tracking (PLL)
- Code delay tracking (DLL)
Traditional CBOC receiver architecture

- Same replica for $E, P, L$ correlator
Traditional tracking performance

- Traditional CBOC tracking requires replication of four-level replica
  - *Complicates the receiver architecture*
- Improvement in tracking comparing to BOC(1,1) is different for data and data+pilot channels
  => *C/No criterion for comparison*
- CBOC(6,1,1/11,’-’) better than TMBOC modulation

| Tracking Error Improvement vs BOC(1,1) in Terms of Equivalent C/No (dB) with BW2 = 24 MHz and E-L = 1/12 Chips |
|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| CBOC(6,1,1/11,’+’)                             | TMBOC(6,1,4/33)                                | CBOC(6,1,1/11,’-’)                             |
| 1.9                                            | 2.4                                            | 3.1                                            |

6/24/09
TM61 tracking architecture

- Use one-bit replica, using BOC(1,1) and BOC(6,1) only
TM61 for TMBOC tracking

- TMBOC tracking using TM61 is more complicated
  - *Correlation losses high when only BOC(6,1) is used*

<table>
<thead>
<tr>
<th>Signal vs. Receiver</th>
<th>BOC(1,1)</th>
<th>BOC(6,1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMBOC (6,1,4/33)</td>
<td>0.85</td>
<td>0.15</td>
</tr>
<tr>
<td>CBOC (6,1,11,’-’)</td>
<td>0.95</td>
<td>0.3</td>
</tr>
</tbody>
</table>

- This can be avoided using time-multiplex subcarriers
  - *Using zero-padding*
  - When BOC(6,1) is tracked, BOC(1,1) replica contains zeros
    - and vice-versa
  - Using this method TMBOC tracking is similar to CBOC tracking
    - *Still 0.2 dB worst in tracking than CBOC*
Dual Correlator tracking

- Dual Correlator technique compares two parallel correlations:
  - *Incoming MBOC with BOC(1,1) replica*
  - *Incoming MBOC with BOC(6,1) replica*
- Correlations are weighted, with parameters:
  - $\beta$ for $BOC(1,1)$ and $\rho$ for $BOC(6,1)$
- Optimal $\beta/\rho$ is in the range $[1.6, 3.2]$ w.r.t. MEE (Multipath error)
- This method uses twice as many correlators
  - *And binary replicas*
- Good multipath performance
- Easily configurable in the software
S-Curve shaping method

- Method proposed is to find the ideal discriminator
  - Using ideal S-curve
  - Fitting the curve, parameters of the correlator are found
    - Correlator spacing
    - Weight of the correlator
- Great number of correlators needed
  - Multipath reduced strongly
- Uses multicorrelator structure
  - Narrow correlator
  - Double delay correlator
ASPeCT BOC(1,1) algorithm

- ASPeCT has been proposed for BOC(n,n) signals
  - *Unambiguous technique - elimination of the side peaks of ACF*
  - *Limited degradation [0.6-1dB] comparing to traditional*
- ASPeCT can be applied to CBOC(6,1,1/11,‘-’)
- Price to pay:
  - *Reducing the BOC(6,1) in the local CBOC replica by half*
- This implies:
  - a negligible reduction of resistance to noise
  - a slight degradation of the multipath error envelope
Composite tracking algorithm

- Composite tracking
  - Data and pilot together
- Convex combination of discriminator outputs
- **Non-coherent + coherent channel combining**
- Tracking jitter reduced
- SER (Sign Error Rate)
  - **New tracking metrics**
Tracking CBOC/TMBOC with BOC(1,1)

- Narrowband receivers (BW<<12 MHz) do not have access to full range of MBOC characteristics

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>BOC(1,1)</td>
<td>0.0</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>CBOC</td>
<td>BOC(1,1)</td>
<td>+0.3</td>
<td>0.94</td>
<td>0.97</td>
</tr>
<tr>
<td>TMBOC</td>
<td>BOC(1,1)</td>
<td>+1.7</td>
<td>1.31</td>
<td>1.03</td>
</tr>
<tr>
<td>CBOC</td>
<td>CBOC</td>
<td>0.0</td>
<td>0.76</td>
<td>0.84</td>
</tr>
<tr>
<td>TMBOC</td>
<td>CBOC</td>
<td>+0.3</td>
<td>0.71</td>
<td>0.84</td>
</tr>
</tbody>
</table>

- Optimal tracking performance is reached with the matching channel

Reference: [Dr. Massimo Crisci, ESTEC, GIOVE workshop, Oct 2008]
# Tracking algorithms comparison

<table>
<thead>
<tr>
<th>Tracking scheme</th>
<th>Tracking complexity</th>
<th>Tracking robustness</th>
<th>Tracking accuracy</th>
<th>Applicability to mass-market receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM61</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Dual Correlator</td>
<td>+/-</td>
<td>-</td>
<td>+/-</td>
<td>+/-</td>
</tr>
<tr>
<td>S-Curve shaping</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>ASPeCT</td>
<td>+</td>
<td>+/-</td>
<td>-</td>
<td>+/-</td>
</tr>
<tr>
<td>Composite tracking</td>
<td>-</td>
<td>+/-</td>
<td>+</td>
<td>+/-</td>
</tr>
</tbody>
</table>
Multipath performance

- Multipath error envelopes:
- TM61 provides *better results* than pure CBOC tracking
  - If DP discriminator used
- HRC not good solution
  - for CBOC tracking
- S-curve shaping
  - *Provides the best results*
- Use of advanced correlators:
  - Strobe
  - Narrow, Double Delta

[M.Fantino, L.Presti]
Conclusions and outlook MBOC

- BOC(1,1) receivers receiving CBOC/TMBOC
  - *Losses too high*

- New specific tracking algorithms proposed:
  - *TM61 and Dual Correlator outperform BOC(1,1)*

- **Future work**:
  - *Composite tracking*
    - *To be further investigated*
  - Common tracking CBOC/TMBOC architecture
    - *Real challenge*
  - Separate algorithm for CBOC and TMBOC?
    - *Need for advanced multipath mitigation algorithms*
    - *Use of new correlator types*
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- AltBOC concept (Y. Tawk)
  - Tracking metrics & Tracking algorithms for AltBOC
  - Comparison of AltBOC algorithms
  - Results and recommendations for AltBOC tracking
Galileo E5 Signal

- AltBOC(15,10) is the new modulation on the Galileo E5 Band.

\[
s_{E5}(t) = \exp \left( j \frac{\pi}{4} k(t) \right) \quad \text{with} \quad k(t) \in \{1,2,3,4,5,6,7,8\},
\]

<table>
<thead>
<tr>
<th>i</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 AS</td>
<td>(\sqrt{2} + 1)</td>
<td>(\sqrt{2} - 1)</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>2 AP</td>
<td>-(\sqrt{2} + 1)</td>
<td>1</td>
<td>-1</td>
<td>(\sqrt{2} - 1)</td>
<td>(\sqrt{2} - 1)</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
</tr>
</tbody>
</table>
Constant Envelope

\[ s(t) = c_A(t) \cdot \text{SC}_{B, \text{SSB}}(t) + c_B(t) \cdot \text{SC}_{B, \text{SSB}}(t) \]

<table>
<thead>
<tr>
<th>( C_A )</th>
<th>( C_B )</th>
<th>( C_A^+ C_B )</th>
<th>( C_A^- C_B )</th>
<th>Fresnel plot</th>
<th>Phasing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td></td>
<td></td>
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<tr>
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<td>-1</td>
<td>-2</td>
<td>0</td>
<td></td>
<td></td>
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<tr>
<td>1</td>
<td>-1</td>
<td>0</td>
<td>2</td>
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<td></td>
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<tr>
<td>-1</td>
<td>1</td>
<td>0</td>
<td>-2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SC\(_{4, \text{SSB}}\)
SC\(_{4, \text{SSB}}^*\)
Constant Envelope (cont’)

\[ s(t) = \left[ c_A(t) + jc'_A(t) \right] \cdot SC_{4,SSB}^*(t) + \left[ c_B(t) + jc'_B(t) \right] \cdot SC_{4,SSB}(t) \]
Constant Envelope (cont’)

\[ s_{ES}(t) = \frac{1}{2\sqrt{2}} \left( e_{ESa-I}(t) + j e_{ESa-Q}(t) \right) \left[ sc_{ES-S}(t) - j sc_{ES-S}(t-T_{ES}/4) \right] + \]
\[ \frac{1}{2\sqrt{2}} \left( e_{ESb-I}(t) + j e_{ESb-Q}(t) \right) \left[ sc_{ES-S}(t) + j sc_{ES-S}(t-T_{ES}/4) \right] + \]
\[ \frac{1}{2\sqrt{2}} \left( \bar{e}_{ESa-I}(t) + j \bar{e}_{ESa-Q}(t) \right) \left[ sc_{ES-P}(t) - j sc_{ES-P}(t-T_{ES}/4) \right] + \]
\[ \frac{1}{2\sqrt{2}} \left( \bar{e}_{ESb-I}(t) + j \bar{e}_{ESb-Q}(t) \right) \left[ sc_{ES-P}(t) + j sc_{ES-P}(t-T_{ES}/4) \right] \]
AltBOC Characteristics

E5 Signal Parameter

<table>
<thead>
<tr>
<th>Channel</th>
<th>Code Rate [Mchip/s]</th>
<th>Subcarrier Freq.[MHz]</th>
<th>Symbol Rate [symbols/s]</th>
<th>Service</th>
</tr>
</thead>
<tbody>
<tr>
<td>E5a-I</td>
<td>10.23</td>
<td>15.345</td>
<td>50</td>
<td>F/NAV</td>
</tr>
<tr>
<td>E5a-Q</td>
<td>10.23</td>
<td>15.345</td>
<td>No data</td>
<td>Pilot</td>
</tr>
<tr>
<td>E5b-I</td>
<td>10.23</td>
<td>15.345</td>
<td>250</td>
<td>I/NAV</td>
</tr>
<tr>
<td>E5b-Q</td>
<td>10.23</td>
<td>15.345</td>
<td>No data</td>
<td>Pilot</td>
</tr>
</tbody>
</table>

E5 Spreading Code Lengths

<table>
<thead>
<tr>
<th>Channel</th>
<th>Code length [chips]</th>
<th>Code length [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Primary</td>
<td>Secondary</td>
</tr>
<tr>
<td>E5a-I</td>
<td>10230</td>
<td>20</td>
</tr>
<tr>
<td>E5a-Q</td>
<td>10230</td>
<td>100</td>
</tr>
<tr>
<td>E5b-I</td>
<td>10230</td>
<td>4</td>
</tr>
<tr>
<td>E5b-Q</td>
<td>10230</td>
<td>100</td>
</tr>
</tbody>
</table>

E5 Signal Spectrum
# Power Distribution

<table>
<thead>
<tr>
<th></th>
<th>Power</th>
<th>1\textsuperscript{st} Harmonic (Power Distribution)</th>
<th>2nd Harmonic (Power Distribution)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSC</td>
<td>85.36%</td>
<td>+fs/-fs (94.36%)</td>
<td>+7fs/-7fs (1.36%)</td>
</tr>
<tr>
<td>PSC</td>
<td>14.64%</td>
<td>+3fs/-3fs (61.5%)</td>
<td>+5fs/-5fs (22.2%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bandwidth</th>
<th>Theoretical Power</th>
<th>Power Transmitted</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 MHz</td>
<td>85.34%</td>
<td>100%</td>
</tr>
<tr>
<td>75 MHz</td>
<td>80.54%</td>
<td>94.37%</td>
</tr>
<tr>
<td>51 MHz</td>
<td>77.88%</td>
<td>91.25%</td>
</tr>
</tbody>
</table>

N.B: Power is shared equally between the four components of the E5 signal
Autocorrelation Function

Autocorrelation vs. Bandwidth
Tracking Possibilities

- The presence of 4 components on the E5 signal allow the receiver designers to have different possibilities in tracking this signal:
  - Free subcarriers Local generated signal
  - Full Band Correlation
  - 8-PSK like processing

- Several combination of signal components are possible:
  - E5a-I, E5a-Q, E5b-I or E5a-Q
  - Data or pilot
  - E5
Free Subcarriers

- The local signal is generated free of subcarriers
- The E5 signal components are translated to base band from their center frequencies
- E5a-I, E5a-Q, E5b-I, E5b-Q, E5a and E5b can be tracked individually resulting in a BPSK(10) correlation

\[ \exp\left[ -j(\hat{\omega}_0 + \hat{\theta} \pm \hat{\omega}_s) \right] \]
Free Subcarriers (cont’)

Autocorrelation Function for a single E5 component with a 20 MHz Bandwidth

Comparison between an infinite bandwidth and a 20 MHz AltBOC receiver
Full band Correlation

- The local signal is generated with subcarrier for the required signal component
- Additional power is gained comparing to the free subcarrier method
- E5ab, E5-pilot and E5-data can be tracked in addition to the other signal components

\[ \exp(-j(\hat{w}_0 + \hat{\theta})) \]
Full Band Correlation

Comparison between autocorrelation function for a single E5 component with a 75 MHz Full Band correlation and a 20 MHz Free Subcarrier correlation

Full Band Correlation for different signal components with a 75 MHz bandwidth receiver
8-PSK Like Processing

- Only the complete E5 signal is tracked
- Correlation is done using a look up table (LUT) of 8 values

Look up table for AltBOC phase states

<table>
<thead>
<tr>
<th>Input Quadruples</th>
<th>$e_{E5-t}$</th>
<th>$e_{E5-t}$</th>
<th>$e_{E5-Q}$</th>
<th>$e_{E5-Q}$</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td>-1</td>
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<td></td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
</tbody>
</table>

$\tau' = \tau \mod T_{E5}$

<table>
<thead>
<tr>
<th>$i_{T_1}$</th>
<th>$\tau'$</th>
<th>$k$ according to $s_{E5}(\tau) = \exp(jk\pi/4)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>[0, $T_{E5}/8$]</td>
<td>5 4 4 3 6 3 1 2 6 5 7 2 7 8 8 1</td>
</tr>
<tr>
<td>1</td>
<td>[$T_{E5}/8$, 2 $T_{E5}/8$]</td>
<td>5 4 8 3 2 3 1 2 6 5 7 6 7 4 8 1</td>
</tr>
<tr>
<td>2</td>
<td>[2 $T_{E5}/8$, 3 $T_{E5}/8$]</td>
<td>1 4 8 7 2 3 1 2 6 5 7 6 3 4 8 5</td>
</tr>
<tr>
<td>3</td>
<td>[3 $T_{E5}/8$, 4 $T_{E5}/8$]</td>
<td>1 8 8 7 2 3 1 6 2 5 7 6 3 4 4 5</td>
</tr>
<tr>
<td>4</td>
<td>[4 $T_{E5}/8$, 5 $T_{E5}/8$]</td>
<td>1 8 8 7 2 7 5 6 2 1 3 6 3 4 4 5</td>
</tr>
<tr>
<td>5</td>
<td>[5 $T_{E5}/8$, 6 $T_{E5}/8$]</td>
<td>1 8 4 7 6 7 5 6 2 1 3 2 3 8 4 5</td>
</tr>
<tr>
<td>6</td>
<td>[6 $T_{E5}/8$, 7 $T_{E5}/8$]</td>
<td>5 8 4 3 6 7 5 6 2 1 3 2 7 8 4 1</td>
</tr>
<tr>
<td>7</td>
<td>[7 $T_{E5}/8$, $T_{E5}$]</td>
<td>5 4 4 3 6 7 5 2 6 1 3 2 7 8 8 1</td>
</tr>
</tbody>
</table>
## AltBOC Summary

<table>
<thead>
<tr>
<th></th>
<th>Power Sharing</th>
<th>Code Phase Jitter</th>
<th>Receiver Complexity</th>
<th>Multipath Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Subcarrier</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Full Band</td>
<td>+/-</td>
<td>+/-</td>
<td>+/-</td>
<td>+</td>
</tr>
<tr>
<td>8-PSK</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>

Performance of the different tracking architectures
Conclusions

- Good tracking performance of new BOC signals
  - Better multipath mitigation
  - Improved code tracking performance
  - New tracking strategies requirements
- More complex receiver architecture
  - More processing power, higher $fs$, more correlators
  - High cost– need simplifications
• Thank You for the attention
  • Q&A?

• Contacts:

  Aleksandar Jovanovic
  PhD student
  EPFL-IMT-ESPLAB
  Rue A.-L. Breguet 2
  CH-2000 Neuchâtel
  Phone: +41 32 718 34 39
  Fax. +41 32 718 34 02
  E-mail: aleksandar.jovanovic@epfl.ch

  Youssef Tawk
  PhD student
  EPFL-IMT-ESPLAB
  Rue A.-L. Breguet 2
  CH-2000 Neuchâtel
  Phone: +41 32 718 34 42
  Fax: +41 32 718 34 02
  Email: youssef.tawk@epfl.ch
Back – up slides
Algorithm comparison

- False correlation peaks at 0.6 chips

- Correlation losses TM61

- ACF peak variation $\alpha = [0.1, 1]$