BeiDou Next Generation Signal Design and Expected Performance

Challenges and Proposed Solutions

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The views and opinions expressed in this presentation are those of the author and do not necessarily reflect the official policy or position of any agency of the funding organizations.
Outline

1 Background and Motivation
2 Constraints and Challenges
3 New Signal Structures for BeiDou
4 Some Test Results
5 Summary
1 Background and Motivation

- Development of GNSS Worldwide
  - Modernization of existing systems: GPS, GLONASS
  - Construction of emerging systems: Galileo, BeiDou
  - Development of regional systems: QZSS, IRNSS
1 Background and Motivation

- BeiDou Navigation Satellite System
  - Three-step Plan
  - First Step: BeiDou Phase I, 2000~2012
    - Experimental system
    - SVs: 3 GEO satellites
    - Signals: L+S Band
    - Coverage: regional (China and its surrounding areas)
    - Status: closed
1 Background and Motivation

- **BeiDou Navigation Satellite System (cont.)**
  - **Second Step**: BeiDou Phase II, by 2012
    - Regional System
    - SVs: 14 satellites in orbit
      - (5GEO+5IGSO+4MEO)
    - Signal: B1, B2, B3 (L Band)
    - Coverage: China and its surrounding areas
    - Status: FOC
1 Background and Motivation

- BeiDou Navigation Satellite System (cont.)
  - Third Step: BeiDou Phase III, by 2020
    - Global System
    - SVs: 35 satellites
      (5GEO+30nonGEO)
    - Signals: New B1, B2, B3 (L Band)
    - Coverage: global
    - Status: under construction
1 Background and Motivation

- Existing BeiDou Phase II (regional) Signals
  - Two services: authorized service and open service
  - Two open service signals: B1(I), B2(I)
    - BPSK(2), 2.046Mcps
    - OS and AS signals (B1Q & B2Q) are in quadrature
    - The ICD of B1I and B2I released in 2012, 2013

<table>
<thead>
<tr>
<th>Component</th>
<th>Carrier Frequency (MHz)</th>
<th>Chip Rate (cps)</th>
<th>Bandwidth (MHz)</th>
<th>Modulation Type</th>
<th>Service Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1(I)</td>
<td>1561.098</td>
<td>2.046</td>
<td>4.092</td>
<td>QPSK</td>
<td>OS</td>
</tr>
<tr>
<td>B1(Q)</td>
<td></td>
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<td></td>
<td></td>
<td>AS</td>
</tr>
<tr>
<td>B2(I)</td>
<td>1207.14</td>
<td>2.046</td>
<td>24</td>
<td>QPSK</td>
<td>OS</td>
</tr>
<tr>
<td>B2(Q)</td>
<td>1207.14</td>
<td>10.23</td>
<td></td>
<td></td>
<td>AS</td>
</tr>
<tr>
<td>B3</td>
<td>1268.52</td>
<td>10.23</td>
<td>24</td>
<td>QPSK</td>
<td>AS</td>
</tr>
</tbody>
</table>
1 Background and Motivation

- Signal Design for BeiDou Phase III (global)
  
  The design of open service signal is the one of a series of challenges in BeiDou global system construction.

  In the past years, signal design aroused wide attention from academia and industry in China, and a number of research results has been achieved.
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Top-level Design of Signal Architecture

- **New Signals of BeiDou Phase III in the Plan**
  - Two different services will be provided: authorized service and open service
  - At least two distinct signals for open service will be deployed in L band: new B1 and new B2
  - New open service signals in the plan
    - B1C: 1575.42MHz (L1/E1)
    - B2: B2a 1176.45 MHz (L5/E5a), B2b 1207.14 MHz (E5b)
Where and How GNSS Signals Will be Used?

- GNSS is a large infrastructure system
  - Long construction cycle
  - Long expected service life

- Impossible to accurately predict the future

- The requirement from different applications may be conflicting
Typical Receiver Modes

- **High-end Mode (HM)**
  - Accuracy is most important while realization complexity is secondary.
  - Computationally intensive algorithms are acceptable as long as accuracy benefit can be obtained.

- **Low-end Mode (LM)**
  - Sensitive to complexity (cost and power consumption) and sensitivity.
  - Accuracy is not critical.

- **Mid-end Mode (MM)**
  - Cost and power consumption are important but restrictions are not as rigorous as in low-end mode.
  - Balance between performance and complexity.
Requirements of Different Modes

- **LM Rx**
  - Single frequency processing
  - Higher carrier frequency, lower ionospheric correction error
  - Narrow band receiving with relatively simple processing strategy

- **HM Rx & a part of MM Rx**
  - Dual-frequency processing estimates ionospheric group delay
  - Multipath and thermal noise become the major error sources
  - Signals with wider RMS bandwidths are desired

- For some single frequency receivers which can obtain differential correction information, wider RMS bandwidth is also desired
# Feature Requirements of B1C

<table>
<thead>
<tr>
<th>B1C</th>
<th>Feature Requirements</th>
<th>Representative Users</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Has multiple possible processing strategies for diversified applications</td>
<td>LM: Consumer electronics, Sensors in IoT, etc.</td>
</tr>
<tr>
<td></td>
<td>Wide RMS bandwidth to improve inherent accuracy and anti-multipath ability</td>
<td>HM/MM: Primary signal in dual-frequency Rx.</td>
</tr>
<tr>
<td></td>
<td>Narrowband low complexity processing strategy for low-end receivers</td>
<td>Geodesy, precise engineering surveying, and precision agriculture etc.</td>
</tr>
<tr>
<td></td>
<td>Compatibility and Interoperability with GPS and Galileo</td>
<td></td>
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</table>
# Feature Requirements of B2a/B2b

<table>
<thead>
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<th>Feature Requirements</th>
<th>Representative Users</th>
</tr>
</thead>
<tbody>
<tr>
<td>Works along with B1C, optimized for high precision ranging measuring</td>
<td><strong>HM:</strong> Primary signal in dual-frequency Rx.</td>
</tr>
<tr>
<td>Wide RMS bandwidth to improve inherent accuracy and anti-multipath ability</td>
<td>Geodesy, precise engineering surveying, and precision agriculture etc.</td>
</tr>
<tr>
<td>Robust to enable tracking in challenging environments</td>
<td></td>
</tr>
<tr>
<td>Compatibility and Interoperability with GPS and Galileo</td>
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</tbody>
</table>
Main Challenges in GNSS Signal Design

- The primary contradiction between performance improvement vs. resource limitation

- Limitation of spectrum and payload power
  - Unrealistic to broadcast multiple signals each specialized for a specific types of application

- One challenge is designing flexible signals
  - Allow using different processing strategies to meet the requirements of both LM and HM applications
Challenges in GNSS Signal Design

Additional Challenges

- Coexistence of legacy and new signals / Smooth transition from Phase II to Phase III
- Compatibility and interoperability between multiple GNSSs
- .......

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3.1 Quadrature Multiplexed BOC

- B1C signal should meet varied requirements simultaneously
  - Inherent high ranging accuracy
  - Low-complexity processing strategies
  - Good interoperability with GPS L1C and Galileo E1 OS

Quadrature Multiplexed BOC (QMBOC) [1]
- BOC(1,1) and BOC(6,1) are modulated on two quadrature phases, with same PRN code or different PRN codes

\[
s_d(t) = c_d(t) d(t) S_{QMBOC}(t)
\]
\[
= \sqrt{1-\gamma} c_d(t) d(t) S_{BOC(n,n)}(t) \pm j \sqrt{\gamma} c_d(t) d(t) S_{BOC(m,n)}(t)
\]

Different MBOC Implementations

- **Time-multiplexed BOC (TMBOC)**
  - Combining BOC(1,1) and BOC(6,1) in *time multiplexing* way

- **Composite BOC (CBOC)**
  - *Weighted summation* of BOC(1,1) and BOC(6,1)

- **Quadrature multiplexed BOC (QMBOC)**
  - BOC(1,1) and BOC(6,1) are modulated in *phase quadrature* with each other
Typical Receiving Strategies

- **Narrowband receiving**
  - For low-complexity receivers, QMBOC can be treated as BOC(1,1)
  - Common channel can be used to process B1C, L1C and E1 OS signals
  - Interoperability with GPS and Galileo

- **Wideband Receiving**
  - For wideband receivers, QMBOC can be received and processed with full-band.
  - Better performance in anti-multipath
  - Similar baseband process with GPS L1C and Galileo E1 OS
**QMBOC vs. TMBOC**

- In matching receiver, QMBOC and TMBOC have the same performance.

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**Acquisition Performance**

![Graph showing acquisition performance](graph.png)
QMBOC vs. TMBOC

- In BOC_{11}-like receivers, QMBOC has better performance
  - QMBOC: SNR loss -0.56 dB (=29/33)
  - TMBOC: SNR loss -1.12 dB (=29/33)^2

  - in BOC(6,1) slot, there is no signal, but noise can enter correlator.
Tracking Performance

- **Equivalent RMS bandwidth**
  - Local de-spreading signal waveform dependent

- **QMBOC vs. TMBOC**
  - With MBOC local replica and a wide front-end bandwidth, both QMBOC and TMBOC can have a high tracking accuracy
  - In BOC_{11}-like receivers, with wide bandwidth, QMBOC is superior to TMBOC
3.2 Asymmetric Constant Envelope BOC

- Asymmetric Constant Envelope BOC (ACE-BOC)
  - A general deal-frequency multiplexing/modulation technique
  - Combine 4 or fewer codes with arbitrary power splitting into a spectrum-split constant envelope signal

- Higher proportion of the transmission power can be allocated to pilot channels or primary service components
- Any component can be halted without influencing the constant envelope property


Typical Embodiments of ACE-BOC

Case 1: Allocating more power to pilot channels to improve the acquisition and tracking performance

Case 2: augment the power of one sideband

Case 3: Deal with the smooth transition issue in system updating
3.2 Asymmetric Constant Envelope BOC

The scheme for BeiDou B2 is a specific implementation of ACE-BOC.

- PRN rate 10.23Mcps, subcarrier rate 15.345MHz
- B2a and B2b have equaled power
- On each sideband, data : pilot = 1 : 3, modulation phase is orthogonal
3.2 Asymmetric Constant Envelope BOC

- **Main Advantages of ACE-BOC**
  - More power in pilot, acquisition and tracking performance is improved by 1.8dB
  - Interoperability with GPS L5 and Galileo E5
    - All of these three signals can be treated as QPSK(10) and share the same channel structure
  - Flexible processing strategies
    - Fullband matched receiving (FMR)
    - Independent matched receiving (IMR)
    - BPSK-like receiving (BLR)
Flexible Processing Strategies

- **Fullband matched receiving (FMR)**
  - Entire ACEBOC signal can be as the local replica, make the best use of the signal power, but with the highest processing complexity

- **Independent matched receiving (IMR)**
  - Receive every signal component separately with local replica of multi-level subcarrier

- **BPSK-like receiving (BLR)**
  - Treated as two QPSK signals and received separately
  - Requires less front-end bandwidth and processing complexity
  - The most commonly accepted receiving mode
Flexible Processing Strategies

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4 Some Test Results

- **Main items in performance analysis and evaluation**
  - Acquisition sensitivity
  - Tracking sensitivity
  - Ranging accuracy
  - Demodulation performance
  - Interference resistance
  - Compatibility
  - .......

- A series of performance evaluation has been carried out for each signal structure option of BeiDou global system
  - Theoretical analysis
  - Computer simulations in signal-level
  - Ground test with signal simulator and receivers prototype
  - Satellite-to-receiver validation
4 Some Test Results

- GNSS signal simulation and evaluation system

Signal Generator (Baseband Unit + VSG)

GNSS Receiver
4 Some Test Results

A Case Study

Tracking Performance: ACE-BOC vs AltBOC

- ACE-BOC and AltBOC with same total transmit power
- BPSK-like receiving strategy, sharing channel
- Acquisition and tracking channels for them are totally the same
- Pilot component tracking, aiding data demodulation
Under the same total transmit power, ACE-BOC has a higher pilot $C/N_0$, but relative lower data $C/N_0$.

<table>
<thead>
<tr>
<th>Signal</th>
<th>PRN</th>
<th>Status</th>
<th>Lock Value</th>
<th>Pilot $C/N_0$</th>
<th>Data $C/N_0$</th>
<th>Doppler</th>
</tr>
</thead>
<tbody>
<tr>
<td>AltBOC</td>
<td>31</td>
<td>CCBF</td>
<td>0.73</td>
<td>34.22</td>
<td>34.44</td>
<td>104.46226155</td>
</tr>
<tr>
<td>ACE-BOC</td>
<td>32</td>
<td>CCBF</td>
<td>0.82</td>
<td>36.59</td>
<td>31.36</td>
<td>104.43930937</td>
</tr>
</tbody>
</table>

ACE-BOC has a higher loop locked Value of pilot, more robust tracking.
In the same transmit power conditions, AltBOC loop has lost lock, while ACE-BOC remained stable tracking.
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- As new generation GNSS evolves, a number of new signal structures are emerging.

- Although GNSS future cannot be predicted accurately, the inherent various receiving strategies can make signals construct multiple balance points between complexity and performance for both transmitters and receivers, thus provide more diversified choices for system designers as well as users.

- According to the system construction requirements, two novel GNSS signal structures, QMBOC and ACE-BOC, are proposed for China’s BeiDou global navigation system.
5 Summary

- QMBOC is a new signal structure with better performance and flexible receiving techniques.

- ACE-BOC is a general modulation/multiplexing technique, which allows the combination of 4 or fewer signal components with any power allocation.

- The scheme for BeiDou B2 is a specific implementation of ACE-BOC, with significant performance improvement, and diversified receiving strategies.

- Both of these two signal structures have good compatibility and interoperability with GPS and Galileo.
Thank you for your attention!