Synchronization Techniques for Navigation and Communication Systems

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**What is Synchronization?**
- Aligning the time scales between two or more processes
- Necessary convention for the aggregation of human behaviors
- Key element for the evolution of human beings

**But in the last years...**
- Necessity of a finer synchronization grown together with the increased possibilities enabled by modern technologies
- Synchronization has strained from a powerful concept to a critical and harmful design issue

**What about the future of synchronization?**
- Iterative approaches and a very strict combining between equalization and synchronization
- Novel aiding paradigms
- Synchronization in every bandwidth and with any possible standard

**... and the future of the world?**
- From the social perspective, synchronization will come back to be the main aspect for national or international identity
- Future technological innovations will push the limits of globalization, and synchronization will become the effective common point for human collaboration and cooperation
Where we are now...

Navigation Systems
- GALILEO
- GPS
- GLONASS
- COMPASS
- QZSS

Augmentation Systems
- EGNOS
- WAAS

Communications Systems
- 2G - 3G - 4G
- WiMAX
- LTE
- DVB-T2
- DVB-RCS
- DVB-SH

Terrestrial Network
- enhanced terminal
- standard terminal
Convergence between systems

**Navigation**
- GPS and Glonass have been introduced in 80’s
- Growing interest in the last ten years
  - Galileo
- New modulations adopted
- Better performance required
- Integration with communication needed to guarantee new services and applications

**Communication**
- Two great revolutions in the past two decades
- Spread spectrum
  - CDMA
  - UMTS – 3G
  - DS-SS
  - DVB-RCS
  - UWB
- OFDM
  - Explosion as a very hot topic in scientific community in 2002
- Ubiquitous service is the target

Synchronization is the basic principle for both the systems
Where we are going...
What is my PhD about?

Synchronization

Navigation
- BOC(1,1)
- BOCc(15,2.5)
  - Robust detection of BOC Modulated Signals
- Dual Band Receivers
- High-Sensitivity GNSS
  - Acquisition and Tracking in the presence of signal distortion
- Aiding Concepts
  - P2P
  - Assisted GNSS
  - GNSS/INS Hybridization
- Interference Mitigation

Communication
- DVB-RCS+M
  - Future OFDM Standards
    - Preamble insertion in future Satellite-Terrestrial Broadcasting Standards
  - LTE
    - WiMAX
Galileo is the European global navigation satellite system

Highly accurate, guaranteed global positioning service under civilian control

Interoperable with GPS and GLONASS (frequency bands, waveforms)

Constellation: 30 satellites (27 operational + 3 active spares), positioned in three circular Medium Earth Orbit (MEO) planes at 23 222 km altitude above the Earth

High system reliability is of primary importance

- Especially for operation in critical environments, like for air navigation and SoL services
New challenges in the Galileo context

- **Binary Offset Carrier (BOC) Modulation**
  - **Acquisition**
    - is in charge of exploring the entire code epoch domain (uncertainty region) in order to get a first rough estimate
  - **Tracking**
    - is asked to eventually detect erroneous synchronization events and to refine the estimate to a higher precision

- **Low complexity receivers**
  - Limiting complexity with no performance loss

- **Professional receivers**
  - Extracting information from different signals in different bands

- **Multipath**

- **Signal distortion**

- **Interference**

- **Aiding Concepts**
  - Assisted GNSS
  - GNSS/INS Hybridization
  - P2P Positioning
We have to estimate the code epoch (transmission delay)

The uncertainty region (epoch domain) is discretized into cells or hypotheses

- Estimation problem → detection problem

Search for the autocorrelation peak

- $H_1$: synchronous hypothesis (about the peak)
- $H_0$: misaligned hypothesis
Galileo: the BOC modulation

- **BOC (1,1) waveform**

- Spreading of the input signal with a square wave subcarrier that has a frequency multiple of the code rate

- Adopted in order to guarantee interoperability with the GPS system
Galileo: Challenges due to BOC

- BOC autocorrelation function opens two challenges
  - Code Acquisition
  - Code Tracking
- It decreases rapidly and becomes equal to zero for $d=1/3T_c$. After this value, a secondary peak is present for $d=0.5T_c$. This very peculiar shape of $R_{BOC}(\delta)$ directly reflects on detection performance.

**Graphical Explanation:**
- **Secondary Peak:** the tracking block can lock onto this outlier peak.
- **Zero Value:** Code Acquisition block collects only noise.
Higher-order BOC: higher-order problems!

- **BOCc(15,2.5)**
  - The highest ratio of sub-carrier frequency to code chip rate of any GPS or Galileo signals
  - Low energy around the carrier frequency
    - to avoid interference with the other GNSS signals
  - Two main spectral lobes further away from the carrier
    - Centered in 15.345MHz
  - Autocorrelation function (ACF) with a large number of false peaks
2D Autocorrelation function

- Considering
  - $c(t)$ as the BPSK reference consisting only of the code
  - $s(t)$ as the BOC waveform with an entire spreading length of ones

- It is possible to obtain the 2D correlation for all the possible combination of $(\tau_s, \tau_c)$

- Note that the classical 1D correlation is the one on the diagonal $(\tau_s = \tau_c)$
  - Without signal distortion the maximum lies on the diagonal
In the following a Butterworth 6-taps filter with 40MHz bandwidth is considered as an example.

Since it is a non-linear filter: group delay and phase delay are different.
The filtered case shows that a shift of \((\tau_\Phi, \tau_g)\) in the space \((\tau_s, \tau_c)\) is obtained.

The maximum is outside the diagonal.

In this case for a 40MHz Butterworth the maximum of the correlation function is in the point \((4; 5)\), which is the rounded value of the \((\tau_\Phi, \tau_g)\).
Effects of signal filtering on the classical 1D ACF

- 1D correlation function: only the diagonal of the 2D
- Increase of the ratio between the first false peak and the correct peak (about 0.9 in the ideal case, about 0.96 using a 40MHz Butterworth 6-taps filter)
  ✷ Rounded effect on the peaks
State-of-the-art Receivers

- **State-of-the-art algorithms**
  - They have been designed for ideal scenarios and they are not robust in the presence of distortion

- **2D correlation to account for different delays ($\tau_s, \tau_c$)**
  - It shows that in the presence of receiver distortion or multipath the two delay are different

- **Two delays combining can increase the robustness of the tracking schemes and maintaining the low tracking errors**
  - The code delay is noisy but not biased while the subcode delay is less noisy but can be biased in the presence of distortion
OFDM Synchronization

- **Pre-FFT synch**
  - The estimation algorithms operate in the time domain
  - Coarse Timing Estimation (CTE)
  - Fractional Frequency Estimation (FFE)
  - The Pre-FFT algorithms are usually Guard Interval (GI) based
    - they exploit the correlation between the useful symbol part and the cyclic prefix of the received signal

- **Post-FFT synch**
  - The estimation algorithms operate in the frequency domain
  - Integer Frequency Estimation (IFE)
  - Fine Timing Estimation (FTE)
  - The Post-FFT algorithms are usually based on a data aided estimation on the pilot tones

- **Frame acquisition**
  - which consists in the detection of the Start of Frame (SoF)
A DVB-T2 based preamble, called P1, has been considered. Introduction of a preamble needs an entirely different optimization in order to minimize the overhead and to be able to transmit all the necessary parameters with a sufficient protection. The work presented herein is focused only on the possibility of estimate jointly timing and frequency, leaving to further works these considerations.

P1 is composed by an OFDM symbol, called ‘A’, of length 1024 samples, with two frequency shifted guard interval portions added at both sides. The length in samples is fixed, regardless of the FFT mode and guard-interval configuration.
A novel detection scheme has been proposed

- Two correlations running in parallel, each one searching for maximum similarity with its respective part of the repetition
- Multiplication of the two outputs

$$e^{-j2\pi f_{SH}t}$$
Fractional carrier frequency offset has to be estimated

- In order to preserve the mutual orthogonality amongst subcarriers

Using P1

- the angle of the correlation between the received part B and the corresponding portion of received part A, and the angle of the correlation between the received part C and the corresponding portion of received part A can be combined to obtain a fractional frequency estimate

\[ \angle(\Lambda) = \angle(M_B) + \angle(M_C) = 2\pi \hat{f}_n + \angle(n'(t)) \]

\[ \hat{f}_n = \hat{\nu} = -\left( \frac{1}{2\pi} \angle(\Lambda) \right) \]

Note that this method is robust against timing misalignment
A comparison with classical Cyclic Prefix approach (Guard Interval Based) has been carried out:

- Taking into account that the CP is 1/8 of the frame length (256 samples)

The proposed approach can overcome the classical Guard Interval Based techniques even for very low SNRs in the Hybrid Channel.

Guard Interval Based

P1 Frequency Estimation
Results

- New acquisition strategies for BOC modulation
  - Quadribranch detector
  - Staggered Time and Frequency Search
- 2D Correlation for High-Order BOC Acquisition and Tracking in the presence of signal distortion
- A novel concept of Aided GNSS
  - Ultra Tight
    - A synthetic correlation function in order to aid the tracking loops
- A joint code acquisition interference mitigation approach for assisted GNSS
  - Analytical model
- Results of acquisition for DVB-RCS+M inserted in Guidelines
- Analysis of synchronization aspects in the most important OFDM standards
  - LTE
  - WiMAX
  - DVB-SH
- A novel broadcasting paradigm: Single Frequency Satellite Networks
Publications (1)

Foreign Fellowship

- European Space Research and Technology Center (ESTEC) - European Space Agency (ESA)
- Division: RF Payloads Systems – Section: Radio Navigation
- 01/02/2009 – 31/07/2009
- Topic: Acquisition and Tracking of Galileo E1-A in the Presence of Signal Distortion

European Reviewers

- Prof. Carlos Mosquera (University of Vigo)
- Dr. Jose Angel Avila Rodriguez (University FAF Munich)

Journal articles:


Conferences articles:


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