Positioning using Signals-of Opportunity based on OFDM

Olivier Julien, P. Thevenon (now CNES), D. Serant
ojulien@recherche.enac.fr

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ENAC Field

The Civil Aviation domain

A complex domain in perpetual evolution

AIRCRAFT

AIRPORT

METEO

AIRSPACE

CNS SYSTEMS

AIR TRAFFIC CONTROL
ENAC Key Figures

- Initial Training: 1,700 students enrolled in 15 different cursus (engineer/Master, technicians, air traffic controllers, pilots, dispatchers)
- 6 "Mastère Specialisé" degrees (1 year) + 3 in China
- 2 Master of Science degrees (2 years)
- Lifelong training: 5,000 attendants
- Research and Innovation
- International
  - 6,000 foreign students trained
  - 35 exchange agreements with universities
ENAC Research and Innovation

Innovation and Research Unit

URI-ENAC

Economics

Control

Maximisation of Airline revenue
Air traffic ground scheduling and control
Ground Taxiing Automation
Relative Navigation between aeroplanes

Modeling

Automatic conflict resolution
Ground Traffic simulation
Airspace design
Air Traffic Flow Management
Airspace and Traffic Complexity

Com., Nav. & Surveillance

Electromagnetic wave Propagation over earth
Special Antenna
Near Field for Radar Antennas
Global Navigation Satellite System
Networks for Air Transport System
IP Networks

System Integration

Human Computer Interaction, CSWI, Software Engineering, Psychology

UAV
ENAC Research in GNSS

LTST (Signal Processing and Telecom Laboratory):

- Human Resources (as of May 2011)
  - 6 permanent staffs and 7 Ph.D. students

- Fields of Research
  - GNSS for Civil Aviation (integrity, augmentation, signal processing)
  - Urban Navigation (high sensitivity, hybridization, integrity, SoO, precise positioning)
  - Precise positioning (RTK, PPP)
  - GNSS Signal Design (satellite payload, modulation, navigation message)
  - GNSS Software Receiver

- Key elements
  - 15 Ph.D. thesis defended, 3 post-docs
  - 50+ expertise contracts, 100+ papers published
  - 4 collaborative patents
Context

- Urban & indoor positioning represents a huge market:
  - Regulatory incentives (E911)
  - Convergence of telecommunication and localization services
  - Military application

- It is known that urban and indoor environment is challenging for GNSS because of interference, signal blockage, multipath, etc…

- To deal with this challenge, specific GNSS developments have been done (high-sensitivity, Aided-GNSS, system-level GNSS upgrades). However, they only provide limited position availability, accuracy, continuity in challenging environments
Context

- Alternative solutions are linked to the use of systems/signals that are complementary to GNSS:
  - Other navigation sensors: Inertial sensors, magnetometers, Wheel Speed Sensors, laser, video cameras, …
  - Dedicated radio-location systems: pseudolites, RFID, UWB
  - Systems of signals of opportunity (SoO) that are not meant for positioning a priori: Mobile telephony (2G or 3G), TV, Radio, WiFi signals

- SoO have several advantages, even if they are not meant primarily for navigation:
  - Availability in urban centers
  - Plurality of potential systems
  - Integration with telecommunication services

- The presentation will look at a subset of SoOs that are based on OFDM modulation
Presentation Outline

1. Introduction to OFDM and test signals
2. Propagation channel-related issues for positioning
3. Positioning principle
4. Proposed pseudo-range estimation algorithms
5. Results on pseudo-range estimation
6. Results on positioning
7. Conclusion and future work
8. Publications on this topic
OFDM Principle

- Frequency selectivity of multipath channel causes distortions that degrade a wideband transmission performance

- OFDM solution:
  - Transmit symbols on narrow-band orthogonal sub-carriers, where channel distortion can be easily corrected.
  - 1 symbol per sub-carrier
  - Implemented by iFFT / FFT in DSP
  - A guard interval called Cyclic Prefix (CP) is introduced to avoid Inter-Symbol Interferences and allows demodulation in loose synchronization conditions. The CP is the replica of the end of the OFDM symbol

\[ N_{CP} \] samples

\[ \text{CP} \] \hspace{1cm} \text{OFDM symbol } k \hspace{1cm} \text{CP} \] \hspace{1cm} \text{OFDM symbol } k+1

Spectrum of orthogonal subcarriers

Multipath channel spectrum

Channel effect on the subcarriers
OFDM Modulator and Demodulator

Modulator

- $c_i$: Tx symbols

Demodulator

- $r_n$: Rx samples
OFDM Transmission Model

- Synchronization chain:

- Timing Synchronization
  - FFT windows positioning
- Frequency Synchronization
  - Frequency Correction
- Sampling Clock Synchronization
  - Resampling

Modulator → DAC → Multipath channel → ADC → Synchronization & demodulator

Emitter

Receiver

Rx samples → Demodulator
OFDM pilot sub-carriers

- In order to be able to correct the distortion brought by the channel, pilot symbols are introduced among the transmitted data.
  - Known symbols that can be compared to the corresponding demodulated symbols for channel estimation.
- Possibility to obtain the channel impulse response (CIR) for equalization.
- Ex: Pilot distribution in the DVB-SH/DVB-T standard:

![Pilot distribution diagram]

- Continuous pilots
- Scattered pilots
- Data & TPS
OFDM and Single Frequency Network

- A SFN is a network where all emitters emit the same signal, on the same frequency.

- They are used to
  - reach users in zones that could be shaded if only one powerful emitter was used,
  - to ensure smooth transition between emitters.

- OFDM is well adapted for SFN thanks to the use of circular FFTs, of the CP and of narrow sub-carriers. However, to be useful, the delay spread of all received signals should be within the CP duration → very stringent emitters’ synchronization.

- Emitter synchronization is very interesting for positioning when using multilateration: there is no need for station monitoring the emitter clock drift + the emitter synchronization is usually done with respect to the GPS time.
The DVB-T standard

- European Digital terrestrial TV standard, worldwide adopted
- Base for the European mobile TV standards DVB-H (Handheld) and DVB-SH (Satellite-to-Handheld)
- Multi- or single frequency networks (MFN/SFN) are possible
- Interest for urban/indoor positioning:
  - High power signals → potentially high availability (even indoor) of the positioning service
  - Deployed in VHF and UHF bands, signal is less attenuated by walls than in GNSS band
  - Fixed emitters
  - Large signal bandwidth: good for precise synchronization
  - SFN
- It is already available
The DVB-SH standard

- European digital mobile TV standard
- Emitters network composed of
  - A network of terrestrial emitters
  - One or several GEO satellites
- Possibility of SFN
- Interest for urban/indoor positioning:
  - Dense coverage in urban centers
  - Wideband signals (up to 8 MHz is foreseen)
  - SFN
  - Convergence with other telecommunication systems
    - The DVB-SH band is at 2.2 GHz, close to other telecommunication bands (e.g., 3G band at 2.1 GHz, WiFi band at 2.45 GHz).
Terrestrial network propagation issues

- The presence of multipaths
  - Fast and strong fading of the received signal power for short multipath delays,
  - Multiple replicas of the signal for large multipath delays,
- Large average power decay vs distance created by the overall environment.
- Masking / blocking of the line-of-sight (LOS)
  - NLOS multipath may be received with a stronger power.
SFN propagation channel issues

- **Delay overlap**
  - At certain locations of the coverage called iso-delay zones, signals from different emitters may arrive simultaneously.
  
  ➜ Emitter identification issue.

- **Near-Far Effect** (commonplace in all terrestrial networks)
  - A signal received from a closer emitter will have a significantly stronger power than from remote emitters and may prevent their detection.
  
  ➜ Emitter detection issue (>3 required for 2D positioning).
Example of SFN CIR measurements

- No model taking into account all these characteristics was found, in particular for the fine multipath delay modeling → Use of Channel Impulse Response (CIR) measurements.

- CNES conducted a channel sounding campaign to characterize the SFN CIR in urban environment (DVB-SH).
  - 2 terrestrial emitters + 1 helicopter acting as a GEO sat emitter
  - Urban + dynamic
Positioning principle

- The multi-lateration principle is used (as in GNSS)
  - Emitters’ locations are known.
  - Tight synchronization of the emitters is required.
  - The Line-of-Sight transit time from an emitter to the receiver is measured, thanks to receiver synchronization processes.
  - A minimum of 3 timing measurements are required for 2D positioning.

- Can be done:
  - with Time of Arrival
  - with Time Difference of Arrival
Positioning principle using SFN

**Hypotheses**

- Emitters’ locations are known: Terrestrial emitters are fixed (for DVB-SH, the geo-stationary satellite should provide precise orbit information)
- Tight emitter synchronization:
  - Current SFN deployments: ±1 µs / 300 m
  - Current state-of-the-art: ±50 ns / 15 m
  - Assumption here: perfect sync or clock correction (currently under analysis on DVB-T emitters)

**Challenges**

- Emitter identification in SFN: Same signal emitted synchronously from every emitter.
- Fine pseudo-range estimation using OFDM signals in urban environment:
  - OFDM does not need fine synchronization for telecommunication.
  - Urban environment creates NLOS bias and heavy multipaths.
Proposition for solving the SFN issues

- Introduction of artificial delay
  - One delay per emitter
  - Known by the receiver
  - Does not degrade data demodulation if the overall delay is inferior to the CP length
    - Avoids the delay overlap issue;
    - Mitigates the near far effect;
    - Enable emitter identification.

\[ r(t) = \sum_{k=1}^{N_{Tx}} s(t - \frac{d_k}{c} - \tau_k) \cdot l(d_k) \]

- Positioning Principle
Emitter identification in SFN

- Emitter identification by reverse positioning
  - Thanks to the introduction of artificial delays, only one combination of pseudo-range measurements should correspond to a given location.
  - With sufficient *a priori* knowledge, it is possible to find the association between a set of anonymous pseudo-ranges and their emitter of origin.
  - The required *a priori* information is an approximate position and the characteristics of the present emitters.

- Mathematical formulation
  - A cost function is defined
  - All combinations of association between measurements and emitters are tested. The one giving the smallest cost function corresponds to the estimated emitter identities.

\[
V(p, \hat{p}, \sigma) = \sum_{i=1}^{N_{Tx}} (\rho_i - d_i - c \cdot \tau_i)^2
\]
1. **CIR estimation**
2. **Multipath delay acquisition:**
   - Extraction of the delay of the main multipath components in the CIR
3. **Multipath delay tracking:**
   - Parallel tracking of previously acquired delays
4. **Pseudo-range calculation:**
   - Selection of the earliest estimated delay for each emitter
CIR Estimation

- CIR estimation by correlating the received signal with a local replica containing the pilot sub-carriers only
- The correlation peak’s sidelobes can mask the correlation peaks from the other emitters.

Ex: CNES DVB-SH CIR

- Emitter #1
- Emitter #2
- Sat Emitter
4- Proposed Pseudo-Range Estimation Technique

**CIR Estimation using Windowing**

- Windowing techniques are used to reduce the sidelobes’ amplitude of the correlation function.
  - Use of rectangular, Hamming and Blackman-Harris windows
- The use of windowing significantly reduces the near-far effect problem:
  - The satellite is visible and emitter #2 is not shadowed
- Drawback: the main lobe is wider, meaning that the detection of the peak location will likely be less accurate.

Ex: CNES DVB-SH CIR

- Hamming
- Blackman-Harris

Ex: CNES DVB-SH CIR
From a CIR vector estimate, estimate the delay of a set of multipath (Matching Pursuit, ESPRIT, etc…):

1. Find the multipath with the highest amplitude
2. Subtract the multipath from the CIR estimation
3. Loop (1-2) with corrected CIR estimate
Multiple DLLs are launched from previously estimated delays

- Discriminator: normalized $|E|^2 - |L|^2$
- Tracking loop: 2nd order, with 10Hz of noise loop equivalent bandwidth
- Sensitivity around 20 to 30 dB below demodulation threshold
- Tracking error in AWGN conditions (no multipaths)
  - Sub-meter accuracy for low SNR (> -10 dB)
  - Tracking could be possible for remote emitters or in indoor environment.
● Delay selection for pseudo-range estimation
  - Group the estimated delays by emitters (via clustering techniques).
  - Take the earliest delay for each emitter.
  - BUT, we could lose the LOS signal or even not track the LOS at all

● Pseudo-range estimation strategy
  - New acquisitions are periodically launched
  - DLLs are stopped if converging towards the same delay, or tracking a weak part of the CIR.
Semi-Simulated data

- The proposed pseudo-range estimation technique was applied to the CNES SFN measurements including artificial delay.
  - Moving van in urban environment
  - 3 emitters
  - 1000s of CIR measurements

- The simulation parameters were chosen based on early publications on DVB-SH system deployments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFT size – $N_{\text{FFT}}$</td>
<td>2048</td>
</tr>
<tr>
<td>CP length</td>
<td>1/4</td>
</tr>
<tr>
<td>Signal bandwidth $B$</td>
<td>5 MHz</td>
</tr>
<tr>
<td>Emitter EIRP</td>
<td>53.2 dBm [12]</td>
</tr>
<tr>
<td>Noise floor level</td>
<td>-102.6 dBm [10]</td>
</tr>
<tr>
<td>SNR</td>
<td>Between 9.2 - 49.2 dB</td>
</tr>
<tr>
<td>Noise equivalent loop bandwidth $B_l$</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Time between 2 tracking updates $T_i$</td>
<td>448 $\mu$s</td>
</tr>
<tr>
<td>Time between 2 acquisition phases $T_{\text{ACQ}}$</td>
<td>14.336s</td>
</tr>
<tr>
<td>Acquisition threshold</td>
<td>-120 dBm</td>
</tr>
<tr>
<td>Tracking threshold</td>
<td>-140 dBm</td>
</tr>
<tr>
<td>Clustering threshold</td>
<td>2.5 $\mu$s</td>
</tr>
<tr>
<td>Max number of DLL launched after each acquisition</td>
<td>15</td>
</tr>
</tbody>
</table>
Simulated data: Hamming window

• Result analysis:
  – Clustering is working: 3 delay clusters, 1 for each emitter
  – Tracking of sidelobes especially for emitter #1 (improved compared to rectangular window)
  – Unavailability of Emitter #3

<table>
<thead>
<tr>
<th>Emitter #</th>
<th>Availability (%)</th>
<th>Mean error (m)</th>
<th>Error standard deviation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>overall</td>
<td>median</td>
</tr>
<tr>
<td>Emitter #1</td>
<td>100</td>
<td>-150.2</td>
<td>-0.06</td>
</tr>
<tr>
<td>Emitter #2</td>
<td>100</td>
<td>26.7</td>
<td>0.41</td>
</tr>
<tr>
<td>Emitter #3 (sat)</td>
<td>88.6</td>
<td>29.7</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Simulated data: Blackman-Harris

- Result analysis:
  - Tracking of sidelobes solved
  - Availability of Emitter #3
  - Frequent leaps between first and second multipath for Emitter #2

<table>
<thead>
<tr>
<th></th>
<th>Availability (%)</th>
<th>Mean error (m)</th>
<th>Error standard deviation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>overall</td>
<td>median</td>
</tr>
<tr>
<td>Emitter #1</td>
<td>98.6</td>
<td>35.0</td>
<td>8.3</td>
</tr>
<tr>
<td>Emitter #2</td>
<td>92.9</td>
<td>62.0</td>
<td>70.4</td>
</tr>
<tr>
<td>Emitter #3 (sat)</td>
<td>100</td>
<td>0.003</td>
<td>0.000</td>
</tr>
</tbody>
</table>
Real Signals: Test Bench Description

- Test on DVB-T (already available)
- 2 devices:
  - A GPS receiver for time reference,
  - An USRP2/WBX for TV signal down-conversion and digitization.
- Recording a signal from a French digital TV emitter:
  - EIRP of 5kW,
  - distance 80 km,
  - frequency 554 MHz
- No reference distance is used (only PR variations are investigated)
Real Signal Test – Static Scenario

- The correlation image illustrates the evolution of the absolute value of the correlation function over time.

- In both cases: 2 strong peaks spaced by 4 km.
- In the indoor case: higher noise floor and more multipaths
- Uncertainty in knowing if this is the direct signal
Real Signal Test – Static Scenario

- A zoom on the main signal shows a very difficult environment indoor. Still the strong transmitted signal ensures availability, but with an unknown precision
5 - Results on Pseudo-Range Estimation

Real Signal Test – Static Scenario

- Tracking with a 1 Hz loop bandwidth:

<table>
<thead>
<tr>
<th></th>
<th>Estimated SNR</th>
<th>Pseudorange Error Std Dev</th>
<th>Theoretically predicted result*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Outdoor case</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First peak</td>
<td>-3.5 dB</td>
<td>~8 cm</td>
<td>~3 cm</td>
</tr>
<tr>
<td>Second peak</td>
<td>-9 dB</td>
<td>~8 cm</td>
<td>~6 cm</td>
</tr>
<tr>
<td><strong>Indoor case</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First peak</td>
<td>-13 dB</td>
<td>~0.7 m</td>
<td>0.1 m</td>
</tr>
<tr>
<td>Second peak</td>
<td>-25 dB</td>
<td>~2.3 m</td>
<td>0.5 m</td>
</tr>
</tbody>
</table>

- The tracking error STD is quite low when considering the environment.
- Note that results show only the tracking error STD but a bias can be present if a reflection is tracked instead of the direct signal.

Real Signal Test – Dynamic Scenario

- This test is a succession of static and dynamic phases as described in the following table:

<table>
<thead>
<tr>
<th>Phase</th>
<th>Static</th>
<th>Dynamic</th>
<th>Static</th>
<th>Dynamic</th>
<th>Static</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration</td>
<td>15 s</td>
<td>15 s</td>
<td>15 s</td>
<td>12s</td>
<td>15 s</td>
</tr>
</tbody>
</table>

During dynamic phases the correlation is disturbed and the estimated SNR drops.
Real Signal Test – Dynamic Scenario

- Estimated pseudorange variation (1 Hz loop bandwidth):
  - During the static phases: the pseudorange variation is quite stable.
  - But during dynamic phase the pseudorange estimation is clearly disturbed

- WARNING: It is not the pseudorange error that is plotted but only its variation since no reference position was recorded during the test.
Conclusion on PR Estimation

● Error on the pseudo-range estimation is affected by:
  - A potential unavailability of PR due to the Near-Far effect. Reduced when using windowing.
  - Numerous steps of the pseudo-range errors due to the propagation channel.
  - A large error for the terrestrial emitters due to the tracking of strong sidelobes or multipath. This can be due to signal blockage.

● Good performance for slices of the time series
  - Numerous jumps (several hundreds of meters)
  - If detected, PR estimation performances could reach meter-level

● To be published soon:
  - Promising work in reducing measurement jumps
  - Test set up has been significantly improved (multi-receiver + mobile test bench) with availability of reference distance
Position-domain simulation

● The results are shown only using the semi-simulated CNES SFN measurements.

● The PR error calculated previously was done between the simulated delay estimate and the delay provided by the proposed tracking technique.

● However, the CNES measurements may be affected by an unknown NLOS bias.

● In order to observe this phenomenon, the position was computed using the estimated pseudo-ranges:
  – Conventional Non-Linear Least Square algorithm;
  – Position averaged over 1s.

● Comparison between these DVB-SH tracks and the GPS track recorded during the CNES measurement.
With Ideal PR estimates

- Heavy NLOS bias present even with perfect PR estimates

- Mean absolute error at 24.3 m (whole time series).
With Best PR estimate combination

- **Best combination**
  - 2 PR estimates (emit #1 and #3) from Blackman-Harris simulation
  - 1 PR estimate (emit #2) from the Hamming simulation

Mean absolute error at 76.8 m (whole time series)

41.9 m (first 800 s)
Conclusions

- The main contributors to the position error are
  - The NLOS bias
  - The pseudo-range estimation bias due to the tracking of multipath

- The best achieved performance is a mean absolute error around 40m
  - Considering only 3 emitters
  - Considering heavy multipaths

- Performance is improved when combining different windowing techniques.

- To be published:
  - Test with real DVB-T signals
  - Hybridization with GNSS
Conclusions

- The overall results have demonstrated the feasibility of autonomous positioning using a dense terrestrial network of emitters transmitting OFDM-based signals:
  - System level modification to permit emitter identification in an SFN;
  - Emitter identification technique working in SFN;
  - Pseudo-range estimation technique working with OFDM signal, in urban environment.

- The methods were validated by simulation using realistic propagation channel measurements provided by CNES.
  - The best positioning performance is around 40 m (mean absolute error) with the use of only 3 emitters and a moderate signal bandwidth.

- The proposed methods were shown not impact the provision of TV broadcast if the right signal parameters are chosen (not shown in this presentation)
Future work

- The first results look promising. However, improvements can be expected and are all underway:
  - Improving the pseudo-range estimation method and avoiding the measurement jumps (currently underway)
  - Doing extensive real-world measurements to obtain a valid PR error model
  - Implementing an elaborate position calculation technique

- Finally, most results are applicable to other OFDM, SFN-based standards
  - Terrestrial digital radio / TV broadcast: DAB, DVB-x, DMB-x, ISDB
  - Mobile communication: 3GPP LTE, mobile WiMAX
More information