Robust GPS-Based Timing for Phasor Measurement Units

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How to Make GPS-based Timing Robust?
Facts about GPS

- GPS provides timing for many applications, such as PMUs

- GPS civil signals are unencrypted
  - Only GPS military signals are encrypted
  - Civil users (e.g. PMUs) do not have access to the military codes

- GPS civil signal structures are completely open
  - GPS civil signal definition is published in its Interface Control Documents (ICD)

- GPS received signals are extremely weak
  - GPS satellites are 20,200 km (12,550 miles) away

- GPS is operational
  - Satellites in orbits
  - Signals being broadcast
  - Billions of GPS receivers in use
Outline

– GPS Cooperative Authentication
  • Pairwise check
  • Decision aggregation

– Position-Information-Aided Vector Tracking
  • Approach
  • Implementation
  • Experimental Results

– Conclusions
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Cooperative Authentication: Architecture

Our proposed approach: cooperative authentication

I got my location. Can you guys check if I was spoofed?

A snippet of baseband GNSS signal

User receiver

Cross-check receiver #1

Your snippet matches mine. You are not spoofed!

Cross-check receiver #2

A high correlation! You are good, bro.

Cross-check receiver #N

It doesn’t match mine. You might be spoofed.

Merits: *network* and *geographical* redundancy
Pair-wise Checking: Cross-correlation of P(Y) Code

Known in-phase C/A code used for tracking in both receivers

Unknown encrypted quadrature P(Y) code used for cross-correlation spoofing detection

Correlated portions of P(Y) code based on C/A code to match timing between receivers

Lo et al., 2009
Psiaki, Humphreys et al., 2013
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Pairwise Check

Received GPS signal from one satellite:
\[
s(t) = C(t - \tau)D_C(t - \tau) \sin(2\pi(f + f_D)(t - \tau) + \phi) + P(t - \tau)D_P(t - \tau)\cos(2\pi(f + f_D)(t - \tau) + \phi)
\]

We want to cross correlate the \( P(t)D_P(t) \) signals from two different receivers.

Estimate:
- Doppler frequency, \( f_D \)
- Phase shift, \( \phi \)

Wipe off Doppler and align phase:
\[
P(t - \tau)D_P(t - \tau) = \text{LPF}[\cos(2\pi(f + f_D)(t - \tau) + \phi) \cdot s(t)]
\]
Pairwise Check – Ideal Results

- **In-phase Baseband Correlation (C/A)**
  - Not Spoofed
  - Spoofed
  - 40 ms
  - 40 Correlation peaks

- **Quadrature-phase Baseband Correlation (P(Y))**
  - Single Correlation peak
  - No Correlation peak
  - Spoofer cannot generate
Modeling Pairwise Check

- Probability of false alarm $\alpha$
- Probability of missed detection $\beta$
Experiments with Different Scenarios

San Francisco CA and Champaign IL, static

3000km

Rantoul IL, moving at ~45 mph and Champaign IL, static

22km
Experiments: San Francisco & UIUC Everitt Lab

SiGe Sampler
Pairwise Results for Different Separations

3000km separation

- Near ideal Correlation
- Could detect spoofing

22km separation

- Almost no Residual Correlation
- Some Residual Correlation

- Could detect spoofing
SNR Affects Pair-wise Check Performance

3000 km apart
one receiver in urban canyon
both receivers were static
C/N₀ = 47 dB-Hz

22 km apart
both receivers had an open sky
one receiver was moving at 45 mph
C/N₀ = 51 dB-Hz
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Modeling Unreliable Cross-Check Receivers

**Definition**

- \( S \) Actual status of user receiver
- \( A_i \) Authentication result using the \( i \)th cross-check receiver
  - \( S = 0 \) authentic
  - \( S = 1 \) spoofed

**Cross-check receiver is authentic**

\[
\begin{align*}
S &= 0 & 1 - \alpha & A_i &= 0 \\
\alpha & \quad & & \\
1 - \beta & \quad & & \\
S &= 1 & 1 - \beta & A_i &= 1 \\
\beta & \quad & & \\
\end{align*}
\]

with a probability \( 1 - P_{SD} - P_{SS} \)

**Cross-check receiver is spoofed by a different spooper**

\[
\begin{align*}
S &= 0 & \beta & A_i &= 0 \\
1 - \beta & \quad & & \\
S &= 1 & 1 - \beta & A_i &= 1 \\
\beta & \quad & & \\
\end{align*}
\]

with a probability \( P_{SD} \)

**Cross-check receiver is spoofed by the same spooper**

\[
\begin{align*}
S &= 0 & \beta & A_i &= 0 \\
1 - \beta & \quad & & \\
S &= 1 & 1 - \alpha & A_i &= 1 \\
\alpha & \quad & & \\
\end{align*}
\]

with a probability \( P_{SS} \)
Authentication Performance, Theoretical Results

\[ P_{FA} = P_{MD} \leq \exp(-N\lambda^2). \]
\[ \lambda = (1 - \alpha - \beta)(1 - P_{SD} - 2P_{SS}). \]

- Authentication performance improves *exponentially* with increasing number of cross-check receivers.
- \( P_{SS} \) causes twice as great performance deterioration as \( P_{SD} \) does.
  - Choose a cross-check receiver far from the user receiver.
Receiver Operating Characteristic (ROC) Curves

(a) Reliable cross-check receivers

\[ P_{SS} = P_{SD} = 0 \]

(b) Unreliable cross-check receivers

\[ P_{SS} = P_{SD} = 0.1 \]

Assumptions:

- High-quality reference receiver: \( \alpha = 0.0001 \) and \( \beta = 0.05 \).
- Low-quality cross-check receiver: \( \alpha = 0.001 \) and \( \beta = 0.15 \).
Performance of Cooperative Authentication

Assume 20% of the cross-check receivers are spoofed (an extremely challenging assumption)

- Robustness grows **exponentially** with the number of cross-check receivers
- A small number of unreliable cross-check receivers are on par with a reliable cross-check receiver.
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Approach: Position-Information-Aided (P.I.A.) Vector Tracking

Approach:
- Vector tracking
- Reduces the search space
  - Aided by the true position
- Kalman filtering
  - Recursively predict and update the errors
- Narrowband loop filter
Scalar Tracking

Incoming Signal

GPS Front-end

Channel 1-N

\( \hat{f}_d, \hat{\phi} \)

NCO

Correlator

Code and Carrier Discriminators

Navigation Processing

Position and Time Solutions \((x, y, z, t)\)
Implementation: P.I.A. Vector Tracking

Channel 1-N
- LOS Projection
  - Code and Carrier Predictions
    - $\tilde{f}_d, \tilde{\phi}$
    - NCO
    - Correlator
  - Code and Carrier Discriminators
- Navigation Prediction
  - Position, Velocity, Timing, Code, and Carrier Correction
    - Timing Errors
    - Position analysis
    - Kalman Filter: Navigation Prediction

Incoming Signal

GPS Front-end

Known True Position ($x, y, z$)
Time Solution ($t$)
Implementation: Kalman Filter

- States: $\delta X, \delta V, \delta t_b, \delta t_d$
- State Transition Matrix

$$F_k = \begin{bmatrix} 0 & 0 & 0 & \Delta t & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \Delta t & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \Delta t & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \Delta t & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \Delta t \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}$$

- Predictions:
  - $\delta X_{k+1} = X_{True} - (X_k + V_k \Delta t)$
  - $\delta V_{k+1} = V_{True} - V_k$
- Calculation of receiver clock bias:

$$t_b = \frac{1}{\sum_{k=1}^{K} \omega_k} \sum_{k=1}^{K} \omega_k (\hat{\rho}^{(k)} - |x^{(k)} - x|)$$
P.I.A. Vector Tracking Improves Accuracy

- Loop filter bandwidth of 5Hz for both scalar and P.I.A tracking loops.
- 9 satellites in view

Maximum errors:
- Traditional tracking
  • ~50ns
- Proposed vector tracking
  • ~15ns

No Noise Added
P.I.A. Tracking Increases Noise Tolerance

- Increased noise leads to loss of lock in scalar tracking.
- At 4 dB of additional noise, the scalar tracking was able to produce navigation bits for 4 satellites.

<table>
<thead>
<tr>
<th>Noise Added</th>
<th># of Satellites Tracked</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 dB</td>
<td>9</td>
</tr>
<tr>
<td>1 dB</td>
<td>8</td>
</tr>
<tr>
<td>3 dB</td>
<td>5</td>
</tr>
<tr>
<td>4 dB</td>
<td>4</td>
</tr>
</tbody>
</table>

1 dB Noise Added

![Graph showing P.I.A. Time Errors with 1 dB Noise Added]

4 dB Noise Added

![Graph showing P.I.A. Time Errors with 4 dB Noise Added]
P.I.A. Tracking is Robust Against Jamming

- Scalar tracking fails at 5 dB of added noise.
- P.I.A. Vector Tracking continued to operate up until 9 dB of additional noise (5 dB more noise tolerance over scalar tracking)
- Reduces a jammer’s effective radius.

![5 dB Noise Added](image1)

Scalar tracking fails
P.I.A. still tracking

![9 dB Noise Added](image2)

Scalar tracking fails
P.I.A. still tracking
P.I.A. Tracking Detects Meaconing

- Meaconing: record and replay legitimate GPS signal.
- Meaconing attack simulated.
- P.I.A. Vector Tracking loop fails to converge in the event of a meaconing attack.
- 200 meter difference in known position and meaconing position.
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- GPS cooperative authentication
  - A modest number of low-reliable cross-check receivers outperform a high-quality reliable receiver.
  - Robustness grows exponentially with the number of cross-check receivers.

- Position-Information-Aided Vector
  - Robust against jamming (5dB more noise tolerance compared with scalar tracking);
  - Successfully detects meaconing attacks;
  - Improves the accuracy of the timing solutions (15 ns vs 50 ns).
Acknowledgement

- Prof. Jonathan Makela
- TCIPG

References


Multi-layer Countermeasures

Signal conditioning

[C1] Check signal power

Code & carrier tracking

[C2] Cross-correlation of military P(Y) code between receivers
[C3] Narrow-band tracking loops
[C4] Multi-receiver vector tracking loops

Navigation data decoding

[C5] Check navigation data against external archives
[C6] Reverse-calculate satellite positions and compare them with navigation data

Position & time calculation

[C7] Check position solution against known PMU locations
[C8] Check time solution against learnt statistics of receiver clocks