Simultaneous Localization of Multiple Jammers and Receivers Using Probability Hypothesis Density

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Time Critical Applications

- Transport
- Banking, Finance
- Communications
- Power Grid

Densely distributed (>2000) Phasor Measurement Units (PMUs) across USA
Timing sources for Power Substations

Monitoring power substations via Phasor Measurement Units (PMUs)

Precise Time Protocol (PTP)

Global Positioning Systems

Clocks: TCXO, Atomic, XCXO
GPS Timing for PMUs

Advantages
- Global coverage
- Freely available
- $\mu$s-level accurate global time

Disadvantages
- Low signal power
- Unencrypted structure
- Vulnerable to attacks
Outline

Background on GPS and Jamming Attacks

Simultaneous Localization of Multiple Jammers and Receivers

Experimental Verification and Validation

Summary
Traditional GPS Algorithm

• Methodology
  • Trilateration with ≥ 4 satellites
  • Track carrier frequency and code phase

• Inputs
  • Center: 3D satellite position
  • Radius: Pseudoranges

• Unknowns to be estimated:
  • 3D position, Clock bias

By computing clock bias, we can estimate UTC time with satellite atomic clock level accuracy

[Trilateration technique]

By computing clock bias, we can estimate UTC time with satellite atomic clock level accuracy

[GPS Signal Structure]

[Larson GPS Research Group]
What is GPS Jamming?

High powered signals transmitted in GPS frequency band

Jamming: Makes timing unavailable for PMUs

Authentic conditions

Jamming conditions
GPS Jamming Incidents

• Around 80 GPS jamming incidents between 2013 — 2016 [1]
• Few notable ones:
  • San Diego harbor, 2007 for 3 days [2]
  • Over 1000 planes, 250 ships in South Korea, 2012 for 16 days [3]
  • London Stock Exchange, 2012 everyday 10 mins [3]
  • Newark Liberty International Airport, 2013 2 months to track [1]
  • Cairo airport, 2016 [4]

Increasing number of GPS jamming incidents due to the ease of operation and low-cost availability

[1] Aviation today 01/31/2017
[2] GPS world 02/2014
[4] Flight service bureau 05/24/2017
Multiple jammers

• Increasing risk due of low cost jammers ~$50-100

• Challenges due to multiple jammers:
  • Presence of unknown number of jammers
  • Unknown contribution of each jammer at receiver
  • Increase in complexity of localization

• Existing GPS anti-jamming techniques
  • Directional antenna, time difference of arrival and so on
  • Address single jammer scenario
  • Mostly don’t estimate receiver Position, Velocity and Time (PVT)

“Jaguar” mounted with directional antenna

[Perkins et.al, ION GNSS 2015]
Our Objectives

• Locate multiple jammers instead of one
• Improve the robustness of the Position, Velocity and Time (PVT) solution of the receivers experiencing jamming
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SLMR: Our Approach

- Multiple receivers
  - Geographical diversity
  - Variation in the received GPS signal power
- Probability Hypothesis Density (PHD) Filter [5]
  - Estimation of unknown number of jammers
- Inspired from Simultaneous Localization and Mapping (SLAM) [5] for robotics
  - Robots: GPS receivers
  - Features: Jammers
  - Graph optimization

SLMR: Our Architecture

Received signal power and receiver dynamics

PHD filter

Graph optimization

$M_t$: Estimated number of jammers

$S_t$: Distances between jammers-receivers

Number of jammers

Location of multiple jammers

PVT solution

Jammers

Receivers
Intuitive Explanation of PHD Filter

- Multiple jammers are observed via multi-modal Gaussian distributed peaks
- State and measurements modelled as Random Finite Sets
- Cardinality modeled as a random variable
- Non-linearity is due to received signal strength measurements

[Vo and Ma, 2006]
Non-Linear Gaussian Mixture PHD Filter

- Propagate posterior intensity modeled as Gaussian Mixture
  \[ \nu_t = \sum w_t N(x; \mu_t, \Sigma_t) \]
- Estimated number of jammers
  \[ M_t = \sum \mathbb{1}(w_t > \text{Threshold}) \]

Multi-modal peaks modeled as Gaussian Mixture (GM)

\( \mu_t \): mean  
\( \Sigma_t \): covariance  
\( w_t \): weight  
\( S_t \): jammers-receivers distance

Measurement update of PHD Based on mis-detection and measurements

Time update of PHD based on survival and birth

Subgraph optimization

\[ M_t, S_t \]
SLMR: Graph Framework

• Bipartite graph framework
  • $M_t$ number of jammers $\vec{y}$
  • $L$ receivers $\vec{x}$
  • Receiver dynamics $u$
    (Ex: static, uniform velocity or IMU)
• Sub-graph optimization at time each instant
• Periodically, full-graph optimization to account for drifts
SLMR: Graph Optimization

- Levenberg-Marquardt minimizer [7]
  - Initial constraints of receivers
  - Constraints from PHD Filter
  - Constraints from receiver dynamics

- After jamming detected, SLMR initialized as follows:
  - Non-jammed received GPS signal power at each receiver
  - Single jammer with the initial location at the centroid of receivers
  - Graph based on the initial constraints of receivers and jammer
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Timing Attack Setup

GPS signals under jamming attack

Authentic GPS signals

According to IEEE C37.118, max allowable phase angle error is 0.573° (~time error of 26.5 µs)
GPS jamming causes inoperability of PMUs to record phasor values
Experimental Setup

- Three stationary simulated jammers
  - Transmit power 50.3 W
  - Sweep continuous attack with frequency
    - $2.5 \text{ kHz}$ to $2.5 \text{ kHz}$
- Five moving GPS receivers
- GPS signals collected
  - Sampling rate $5 MHz$
  - Received power computed using $\Delta T = 10 ms$
- Post-processed using our python framework pyGNSS
SLMR: Localization Accuracy of Jammers

Number of unknown jammers converges to 3 and positioning error of jammers estimated to within 5 m accuracy.
SLMR: Different Levels of Jamming

Under 12 dB and 18 dB added jamming, mean position error of all jammers is within 4.8 m and mean position error of all receivers is within 5.6 m.
Summary

• Demonstrated the impact of GPS jamming attack on the stability of the power grid

• Proposed our Simultaneous Localization of Multiple Jammers and Receivers (SLMR) algorithm

• Demonstrated successful localization of jammers with $5 \text{ m}$ accuracy while simultaneously locating receivers with $6 \text{ m}$ accuracy under various levels of jamming attack
Future work | DT-NAVFEST Jamming Event

Teams from the **University of Illinois Champaign Urbana** and Stanford University, CA were invited to the first-ever DT NAVFEST at Edwards Air Force Base, CA, to test projects in a GPS degraded environment (U.S. Air Force photo by Wei Lee).

[Heatmap of jammer to signal ratio]

*[Perkins et.al, ION GNSS 2017]*
Our Published Work

• Position-Information Aided Vector Tracking [Chou, Heng and Gao ION GNSS 2014]

• Multi-Receiver Position-Information Aided Vector Tracking [Chou, Ng and Gao ION ITM 2015]

• Advanced Multi-Receiver Position-Information Aided Vector Tracking [Chou, Ng and Gao ION GNSS+ 2015]

• Direct Time Estimation [Ng and Gao IEEE PLANS 2016]

• Multi-Receiver Direct Time Estimation for PMUs [Bhamidipati, Ng and Gao ION GNSS+2016]

• Spoofer Localization based Multi-Receiver Direct Time Estimation [Bhamidipati and Gao ION GNSS+2017]

• Improved Jamming Resilience using Position-Information Aided Vector Tracking [Bhamidipati and Gao ION GNSS 2017]

• Simultaneous Localization of Multiple Jammers and Receivers using Probability Hypothesis Density [Bhamidipati and Gao ION PLANS 2018]
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Thank You

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