Multi-Receiver GPS-based Direct Time Estimation for PMUs
Sriramya Bhamidipati, Yuting Ng and Grace Xingxinxin Gao
Motivation

• Supply and demand of electricity should be balanced to maintain power grid stability

• Power grid vulnerable to
  - External attacks
  - Natural disasters
  - Man-made errors
Massive power blackouts

Northeast USA 2003
Java-Bali 2005
Brazil 2009
India 2012

50 million people affected
100 million people affected
87 million people affected
670 million people affected
Goals of US power community

- Synchronized phasor measurements
- Reliable communication network
- Real-time information monitoring
- Automation of the power grid
- Improving the security margins

Development of reliable and robust Smart Power Grid
Goals of US power community

- Synchronized phasor measurements
- Reliable communication network
- Real-time information monitoring
- Automation of the power grid
- Improving the security margins

In use currently:
Supervisory Control and Data Acquisition (SCADA)
Goals of US power community

- Synchronized phasor measurements
- Reliable communication network
- Real-time information monitoring
- Automation of the power grid
- Improving the security margins

In use currently
Supervisory Control and Data Acquisition (SCADA)

Switching to Phasor Measurement Units (PMUs)
Phasor Measurement Unit (PMU)

- Highly synchronized measurements
- PMU measures current and voltage in power grid

PMU data reveal dynamic behavior as the system responds to a disturbance
Data comparison example, voltage disturbance on April 5, 2011
voltage magnitude, indexed

SCADA (old tech) measures voltage every few seconds

PMU (new tech) measures 30 times per second showing oscillations
GPS Timing for PMUs

GPS used for time synchronization

GPS Antenna → GPS clock → PMU

Advantages
- Global coverage
- Freely available
- \( \mu s \)-level accurate time
GPS Conventional Approach

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

- Unknowns to be estimated:
  - 3D position \((x, y, z)\)

- Methodology
  - Trilateration technique
GPS Conventional Approach

- Inputs
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- Unknowns to be estimated:
  - 3D position \((x, y, z)\)
  - Clock bias \((c\delta t)\)

- Methodology
  - Trilateration technique
  - Minimum 4 satellites required

Trilateration technique
GPS Timing for PMUs

GPS used for time synchronization

Power grid

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

Disadvantages
- Unencrypted structure
- Low signal power
- Vulnerable to attacks
GPS Timing Attacks

Jamming: Makes timing unavailable for PMUs

Meaconing: Mislead PMU with wrong time
Objectives

Propose a robust GPS time transfer technique to:

• Mitigate the effect of external timing attacks
• Improve tolerance against noise and interference
Outline

Motivation and Objectives

GPS Conventional approach

Multi-Receiver Direct Time Estimation (MRDTE)

Experimental setup

Results and Analysis

Ongoing Work

Summary
MRDTE: Approach

Power substation, Sidney, IL
MRDTE: Approach

- Multiple receivers
  - Geographical diversity

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  - Static receiver location

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- Direct Time Estimation (DTE)
  - Works with timing parameters
  - No intermediate pseudoranges

Power substation, Sidney, IL
MRDTE: Approach

- Multiple receivers
  - Geographical diversity

- Position Aiding
  - Static receiver location

- Direct Time Estimation (DTE)
  - Works with timing parameters
  - No intermediate pseudoranges

- Triggered by common external clock

Reduction in no. of unknowns from
8 \((x, y, z, c\delta t, \dot{x}, \dot{y}, \dot{z}, c\delta \dot{t})\) \times \# \text{ of receivers} to 2 \((c\delta t, c\delta \dot{t})\)
MRDTE: Architecture

Raw GPS signals from multiple receivers

All receivers triggered by a common clock

Direct Time Estimation

Output from PMU: Synchronized phasor measurements

MRDTE Filter

PMU
MRDTE: Architecture

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Direct Time Estimation

Output from PMU: Synchronized phasor measurements

PMU
Direct Time Estimation

- Receiver 3D position and velocity
- All satellites 3D position and velocity

Combined satellite signal replica

Clock Bias

Clock Drift

Across the candidates in search space
Direct Time Estimation

- Receiver 3D position and velocity
- All satellites 3D position and velocity

Combined satellite signal replica

Incoming raw GPS signal

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Direct Time Estimation

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Across the candidates in search space

Incoming raw GPS signal

Vector Correlation

Maximum likelihood clock state

Clock Bias

Clock Drift

Correlation Value

\[ \text{Clock drift (m/s)} \]

\[ \text{Clock bias (m)} \]
DTE: Vector Correlation

Code phase depends on clock bias

Carrier frequency depends on clock drift

Code residual ($\Delta \phi_{code}$), Carrier residual ($\Delta f_{carr}$) independently estimated in two parallel threads
DTE: Vector Correlation Continued

Direct correlation involves non-coherent summation

- Non-coherent summation across satellites to track code phase and carrier frequency.
DTE: Max Likelihood Estimation

$$corr_j = corr \left( R, \sum_{i=1}^{N} Y^i (c \delta t_j, c \delta t_j) \right)$$

Maximum likelihood clock state $$T_{MLE}$$

$$T_{MLE} = \max_{j=1,\ldots,P} corr_j$$

$$= [c \delta t_{MLE}, c \delta t_{MLE}]$$

Where,

- $$P =$$ number of grid points
- $$R =$$ incoming raw GPS signal
- $$Y^i =$$ $$i^{th}$$ satellite signal replica
DTE: Robustness

Strong signal environment

Weak signal environment

Direct Time Estimation

More robust than Scalar Tracking
MRDTE: Architecture

Raw GPS signals from multiple receivers

All receivers triggered by a common clock

Direct Time Estimation

MRDTE Filter

Output from PMU: Synchronized phasor measurements

Time

PMU
MRDTE Filter: Kalman Filter

- Prediction model:
  \[
  \hat{T}_{t+1,k} = \begin{bmatrix}
  1 & \Delta T \\
  0 & 1
  \end{bmatrix} T_{t, overall}
  \]

- State vector
  \[
  T_{t,k} = \begin{bmatrix}
  c\delta t_k \\
  c\delta t_k
  \end{bmatrix}
  \]

- Error covariance matrix is calculated by processing the last 19 measurement errors
MRDTE Filter: Overall Filter

- Overall filter to obtain the final corrected clock state $T_{t,overall}$

- Measurement error matrix

\[
e_{t,overall} = \begin{bmatrix}
T_{t,1} - \hat{T}_{t,overall} \\
\vdots \\
T_{t,k} - \hat{T}_{t,overall} \\
T_{t,L} - \hat{T}_{t,overall}
\end{bmatrix}
\]

Where $T_{t,k} = \begin{bmatrix} c\delta t_k \\ c\delta t'_k \end{bmatrix}$ $k = 1 \ldots L$
Outline

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Ongoing Work

Summary
Experimental Setup

- 4 receivers on the rooftop of Talbot Lab, Urbana, Illinois
- Placed along the corners of square with diagonal length 10m
- Mimic the setup of a original power substation
Experimental Setup: Continued

- 4 USRP’s used for collecting GPS signals
- All the receivers triggered by a common external clock - Chip Scale Atomic Clock (CSAC)
- For processing the data: pyGNSS - object oriented python platform developed by our lab
Outline

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Summary
Jamming: Carrier Frequency

MRDTE (loses track at 17dB added jamming) offers **5dB** more noise tolerance than Scalar Tracking (loses track at 12dB added jamming)
Jamming: Code Frequency

MRDTE

Scalar

MRDTE offers better convergence and smaller variance to external noise interference
At 12dB jamming, MRDTE maintains a residual in clock bias of < 100 ns and clock drift of < 1.5 ns/s
Jamming: Single vs Multiple

Clock bias

Clock drift

Multiple receivers show smaller variance in the clock bias as compared to single receiver.
Meaconing: Carrier Frequency

Scalar tracking is operational until 2dB of added meaconed signal while MRDTE is operational till 5dB.
Outline

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Summary
Ongoing Work

- Objective:
  - Comparison of the performance robustness of the MRDTE and Scalar tracking using RTDS setup

Timing: Scalar tracking

Raw GPS signals

SEL-2488

Used to trigger virtual PMUs in RTDS

RTDS stability analyzed
Ongoing Work

• Raw GPS signals are supplied to SEL-2488 (external clock) to trigger virtual PMU and the hardware PMU is triggered using our MRDTE algorithm.

RTDS stability analyzed

Raw GPS signals → SEL-2488

Timing: Scalar tracking

SEL-2488 → USRP-LFTX

Timing: MRDTE

USRP-LFTX → PMU

Used to trigger virtual PMUs in RTDS

PMU → RTDS

Used to trigger hardware PMU connected to RTDS
Work done till now

- Generated the IRIG-B000 timing pulse: Input to PMU
- Created a voltage shifter to convert the transmitted USRP-LFTX 0-1v IRIG-B signal to 0-5v IRIG-B000 signal
Upcoming Work

- Timing attacks are simulated and added to the raw GPS signals being supplied to the SEL-2488 and USRP-LFTX.
Summary

• Proposed a novel Multi-Receiver Direct Time Estimation (MRDTE) algorithm

• Verified the increased noise tolerance and successful mitigation of meaconing attack

<table>
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<th>Timing Attack</th>
<th>MRDTE</th>
<th>Scalar</th>
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<td>17dB</td>
<td>12dB</td>
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<tr>
<td>Meaconing</td>
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<td>2dB</td>
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• Work being done in evaluating the impact of the MRDTE on power grid
Thank You

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