Multi-Receiver GPS-based Direct Time Estimation for PMUs

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BIOGRAPHIES

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***Abstract*— Modern power distribution systems are incorporating Phasor Measurement Units (PMUs) to measure the instantaneous voltage and current phasors at different nodes in the power grid. These PMU devices depend on GPS for precise time and synchronization. However, GPS L1 C/A signals are vulnerable because of its low power and unencrypted signal structure. Therefore, there is a need for the development of robust time transfer techniques to ensure power grid stability.**

We propose a novel multi-receiver direct time estimation (MRDTE) algorithm by utilizing the measurements from multiple receivers triggered by a common clock. We first implement a novel signal processing technique known as the Direct Time Estimation (DTE) that directly correlates the received GPS signal with the corresponding signal replica for each of the pre-generated set of clock states. The most optimal set of clock candidates is then estimated based on the principle of maximum likelihood estimation. By leveraging upon the known geographical diversity of multiple receiver positions, we employ a overall Kalman Filter to obtain a robust corrected clock bias and clock drift at any instant.

We demonstrate the increased resilience of our MRDTE algorithm against malicious timing attacks that include jamming and meaconing through outdoor field experiments.

I. INTRODUCTION

Incorporation of real-time synchronized phasor measurements in the control of power grids, can play an important role in maintaining the overall closed-loop stability of the power system.The currently used devices known as Supervisory Control and Data Acquisition (SCADA) outputs unsynchronized measurements thereby decreasing the reliability and robustness of the electricity grid [1].

Modern power systems can benefit from deploying Phasor Measurement Units (PMUs) as they provide synchronized measurements of upto 60 observations per second in regard to the current state of the system [2], [3]. The operation of PMUs greatly relies on precise time-keeping sources, such as GPS signals, to obtain absolute time for synchronization. However, traditional GPS signals are unencrypted and susceptible to external interference whose impact may range from local perturbations to large-scale blackouts [4].

In this paper, we propose a novel multi-receiver direct time estimation (MRDTE) algorithm which utilizes the concept of maximum likelihood estimation [5]. This current setup is an extension of our earlier work [6] focusing on single receiver direct time estimation (DTE). The ability of DTE to detect meaconing attacks at an early stage and tolerate high noise levels have been illustrated and verified in the prior publication. In this multi-receiver architecture, the information from spatially dispersed receiver locations is utilized to improve noise resilience and reduce the influence of external timing attacks.

The rest of the paper is organized as follows: Section-II describes the underlying concept behind the multi-receiver direct time estimation and provides details in regard to its initialization and implementation. Section-III outlines the experimental setup considered for the validation of the MRDTE algorithm. In Section-IV, results obtained from scalar tracking and MRDTE are compared. Section-V concludes the paper.

II. MULTI-RECEIVER DIRECT TIME ESTIMATION

With an aim to improve the robustness of system, we developed an extension that we named as multi-receiver direct time estimation. We propose the placement of multiple static antennas with pre-evaluated 3D position and velocity at different corners in the same power sub-station. Utilizing the geographical diversity in the receiver locations, the signals from different receivers are collectively analyzed to mitigate the effect of localized spurious signals.

In our setup, there are L different receivers that receive GPS signals from N visible satellites at any time instant t.

All the receivers are triggered by the same common external clock. Different cable lengths introduce a bias across the receivers that can be pre-accounted for. Thereby, the clock states are considered to be the same across the receivers.

$$\begin{aligned} N &: \text{Number of visible satellites} \\ L &: \text{Number of receivers in MRDTE setup} \\ i &: \text{1.. N superscript denote the } i^{th} \text{ satellite} \\ k &: \text{1,.., L subscript to denote the } k^{th} \text{ receiver} \end{aligned} \tag{1}$$

$$\begin{aligned} X_{t,k} &: \text{3D Position and velocity of the } k^{th} \text{ receiver at} \\ & \quad t^{th} \text{ time instant} \\ &= [x_k, y_k, z_k, \dot{x}_k, \dot{y}_k, \dot{z}_k]_t \\ T_{t,k} &: \text{Clock states of the } k^{th} \text{ receiver at } t^{th} \text{ time instant} \\ &= [c\delta t_k, c\delta \dot{t}_k]_t \end{aligned} \tag{2}$$

The higher level architecture of the MRDTE described in Fig. 1 consists of two major steps. The first step involves applying a novel signal processing technique known as DTE.

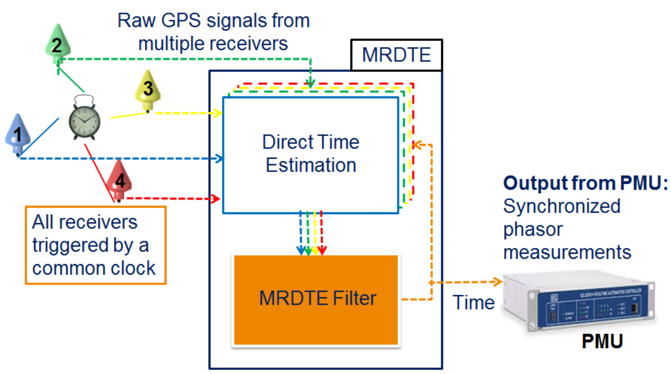


Fig. 1: Architecture of MRDTE

In second step known as MRDTE filter, the DTE output obtained from the receivers are collectively processed through an overall kalman filter. The corrected overall clock vector $T_{t,overall}$ at any time instant t obtained as the output from MRDTE, is given as input to the PMUs. This strategy is adopted to reduce the search space from $8L$ $(X_{t,k}, T_{t,k})$ to 2 $(T_{t,overall})$ thereby increasing the speed and decreasing the computational complexity.

A. Direct Time Estimation

DTE estimates the cumulative satellite vector correlation of the raw received GPS signal with the signal replica produced from each grid point in a pre-generated 2D-search space.

$$\begin{aligned} M &: \text{Number of grid points in 2-D search space} \\ g_j &: j^{th} \text{ grid point in 2-D search space} \\ &= [c\delta t_j, c\delta \dot{t}_j] \\ j &: \text{1.. M subscript denote the } j^{th} \text{ grid point} \end{aligned} \tag{3}$$

Taking the 3D position and velocity of the static receiver as the aprior information, the most plausible clock state of the receiver is evaluated based on the principle of maximum likelihood estimation.

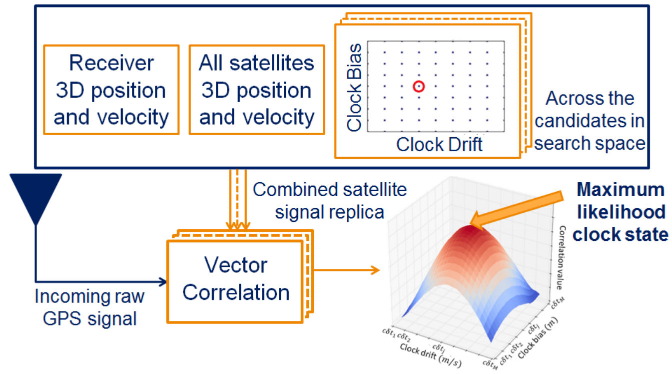


Fig. 2: Direct Time Estimation

$$\begin{aligned} R &: \text{raw received GPS signal} \\ Y &: \text{signal replica of the GPS signal} \\ &= \sum_{i=1}^{N} Y^i \\ Y^i &: \text{signal replica corresponding to } i^{th} \text{ satellite} \end{aligned} \tag{4}$$

$$\begin{aligned} \text{corr}_j &: \text{DTE correlation for the } j^{th} \text{ clock candidate set} \\ &= corr(R, \sum_{i=1}^{N} Y^i(g_j)) \\ &= \sum_{i=1}^{N} corr(R, Y^i(c\delta t_j, c\delta \dot{t}_j)) \end{aligned} \tag{5}$$

$$\text{corr-overall} = \max_{j=1}^{M} \text{corr}_j \tag{6}$$

The incoming GPS signal is dependent on four signal parameters namely f^i_{code}, ϕ^i_{code}, f^i_{carr}, ϕ^i_{carr}. The channel delay residual is directly proportional to the clock bias residual and the channel doppler residual is proportional to the clock drift residual as described in the Eq. 7-8. Given this, the channel delay and carrier doppler estimation are split into two parallel threads and independently estimated.

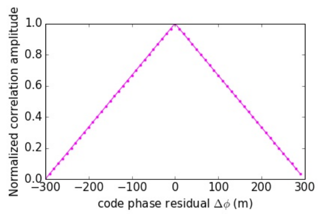
$$\Delta\phi^i_{code,j} = -\frac{f_{C/A}}{c}\Delta c\delta t_j \tag{7}$$

$$\Delta f^i_{carr,j} = -\frac{f_{L1}}{c}\Delta c\delta \dot{t}_j \tag{8}$$

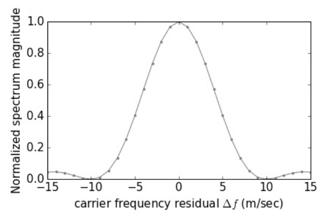
$$\begin{aligned} \Delta c\delta t_j &: \text{Clock bias residual} \\ \Delta c\delta \dot{t}_j &: \text{Clock drift residual} \\ c &: \text{Velocity of light, 299792458 (m/s)} \\ f_{C/A} &: \text{Chiprate of C/A code, 1.023 MHz} \\ f_{L1} &: \text{Frequency of L1 signal carrier, 1575.42 MHz} \end{aligned} \tag{9}$$

Correlations are performed on a per satellite channel basis to obtain the correlation amplitude with respect to the code residual in Fig. 3a while fourier transforms are carried out in parallel to obtain the spectrum magnitude with respect to the carrier doppler residual as shown in Fig. 3b.

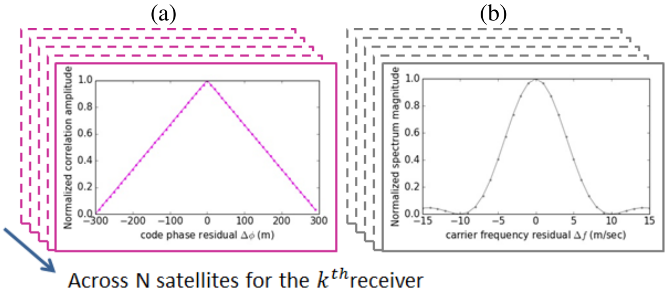
Non-coherent summation of the correlation amplitudes and spectrum magnitudes is computed respectively across the N visible satellites. These obtained summation of correlation values are allocated as weights that represent the likelihood of a particular g_j in the 2D-search space.



(a)



(b)



(c)

Fig. 3: (a) shows the correlation amplitude plotted against the code phase residual. (b) shows the spectrum magnitude with respect to the carrier doppler frequency residual. (c) represents the non-coherent summation across satellites

B. MRDTE Filter

After obtaining, the measurement error vectors e_k for each of the individual receivers, an individual receiver level measurement update $T_{t,k}$ is done using a kalman filter. The measurement update for k^{th} receiver at any instant t:

$$\begin{aligned}
H_k &: \text{Observation matrix, } 2\times 2 \text{ Identity matrix}\\
\hat{P}_{t,k} &: \text{Predicted state error covariance matrix}\\
R_{t,k} &: \text{measurement noise covariance matrix}\\
K_{t,k} &: \text{Kalman gain matrix}\\
&= \hat{P}_{t,k}H_k^T(H_k\hat{P}_{t,k}H_k^T + R_{t,k})^{-1}\\
\Delta T_{t,k} &: \text{State error vector}\\
&= K_{t,k}e_{t,k}\\
T_{t,k} &: \text{Corrected state vector of the } k^{th} \text{ receiver}\\
&= \hat{T}_{t,k} + \Delta T_{t,k}\\
P_{t,k} &: \text{Corrected state error covariance matrix}\\
&= (I - K_{t,k}H_k)\hat{P}_{t,k}
\end{aligned} \tag{10, 11}$$

After this stage, the clock parameters $T_{t,k}$ are incorporated into an overall kalman filter to obtain the final corrected clock state $T_{t,overall}$ corresponding to the common shared clock.

The overall measurement update at any instant t is:

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

$$\begin{aligned}
H &: \text{Observation matrix}\\
&= \begin{bmatrix} 1 & 1 & 0 & .. & 0 \\ 0 & 1 & 1 & .. & 0 \\ \vdots & \vdots & \vdots & .. & \vdots \\ 0 & 0 & 0 & 1 & 1 \end{bmatrix}_{(L+1)\times(L+1)}
\end{aligned} \tag{12}$$

$$\begin{aligned}
\hat{P}_t &: \text{Predicted state error covariance matrix}\\
R_t &: \text{measurement noise covariance matrix}\\
&= \begin{bmatrix} R_{t,1} & .. & 0 & .. & 0 \\ \vdots & \vdots & R_{t,k} & \vdots & \vdots \\ 0 & .. & 0 & .. & R_{t,L} \end{bmatrix}
\end{aligned} \tag{13}$$

$$\begin{aligned}
K_t &: \text{Kalman gain matrix}\\
&= \hat{P}_t H^T(H\hat{P}_t H^T + R_t)^{-1}\\
\Delta T_{t,overall} &: \text{State error vector}\\
&: K_t e_{t,overall}\\
T_{t,overall} &: \text{Corrected state vector of the } k^{th} \text{ receiver}\\
&= \hat{T}_{t,overall} + \Delta T_{t,overall}\\
P_t &: \text{Corrected state error covariance matrix}\\
&= (I - K_t H)\hat{P}_t
\end{aligned} \tag{14}$$

The prediction of the overall and the individual receiver states for the next time instant $t+1$ is achieved by linearly propagating the clock parameters based on the first order state transition matrix.

The time update equations for the k^{th} receiver are:

$$\begin{aligned}
\Delta T &: \text{Update interval}\\
F_k &: \text{State transition matrix, } 2\times 2\\
&= \begin{bmatrix} 1 & \Delta T \\ 0 & 1 \end{bmatrix}\\
Q_{t,k} &: \text{State process noise covariance matrix}\\
&= F_k \begin{bmatrix} 0 & \Delta T \\ 0 & (c\sigma_\tau)^2 \end{bmatrix} F_k^T\\
\sigma_\tau &: \text{allan deviation of the front-end oscillator}\\
\hat{T}_{t+1,k} &: \text{Predicted state vector for the } (t+1)^{th} \text{ instant}\\
&= F_k T_{t,overall}\\
\hat{P}_{t+1,k} &: \text{Predicted state error covariance matrix}\\
&= F_k P_{t,k} F_k^T + Q_{t,k}
\end{aligned} \tag{15}$$

C. Initialization of MRDTE

The initialization $T_{0,k}$ for each receiver can be done using any commercial techniques like scalar tracking etc or by considering an optimum initial search space. Given that power grid is a static system, the receiver locations can be accurately pre-determined using the already available off-the shelf techniques and averaged over time to get the best 3D position and velocity estimate.

III. Experimental setup

A. Hardware setup

The robustness of the proposed multi-receiver DTE is validated using four AntCom 3GNSSA4-XT-1 GNSS antennas mounted onto the roof of Talbot Laboratory, University of Illinois, as shown in Fig. 4. They are connected to a common Microsemi Quantum SA.45s Chip Scale Atomic clock (CSAC), chosen for its low drift rate, to form a receiver network, and the raw voltage data are logged using respective Universal Software Radio Peripherals (USRPs) each equipped with a DBSRX2 daughterboard as in Fig. 5.

Fig. 4: Four antennas located on roof of Talbot Laboratory, University of Illinois at Urbana-Champaign. Reference image of the setup taken from [7]

B. Software setup

GNUradio was used for collecting the raw GPS L1 signal samples from USRP at a sampling rate of 2MHz. We chose to implement this technique in the python software defined radio developed in our lab (pyGNSS), given its flexible and object oriented framework. In our case, the 3D position and velocity of the receivers are calculated using MRVT [8]. For the vector correlation, we opted for a coherent integration time of $\Delta T = 20ms$. The measurement noise covariance matrix is evaluated using the covariance of the last 20 individual measurement residuals.

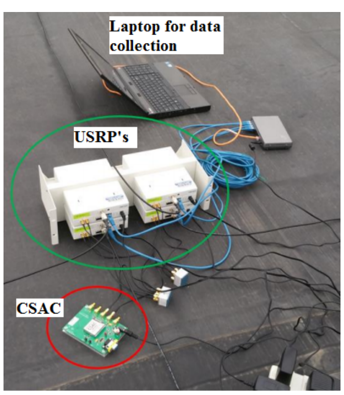


Fig. 5: Hardware setup used for the experimental testing of MRDTE. Reference image of the setup taken from [7]

IV. Results and Analysis

Virtual timing attacks which include jamming and meaconing are simulated and added onto the field data collected after which they are processed using MRDTE discussed in the Section-II. While subjected to these external attack scenarios, we test the performance of MRDTE to that of conventional scalar tracking.

A. Jamming

Jamming involves broadcasting a high-power noise signal near the GPS frequency range thereby causing the GPS receivers to lose track of the signal being acquired. The conditions of jamming are generated by adding an additional white Gaussian noise $Ae^{j2\pi\phi t}$ onto the incoming received signal. This noisy signal includes two components: random amplitude A which is a measure of the strength of the noise being introduced and random phase ϕ.

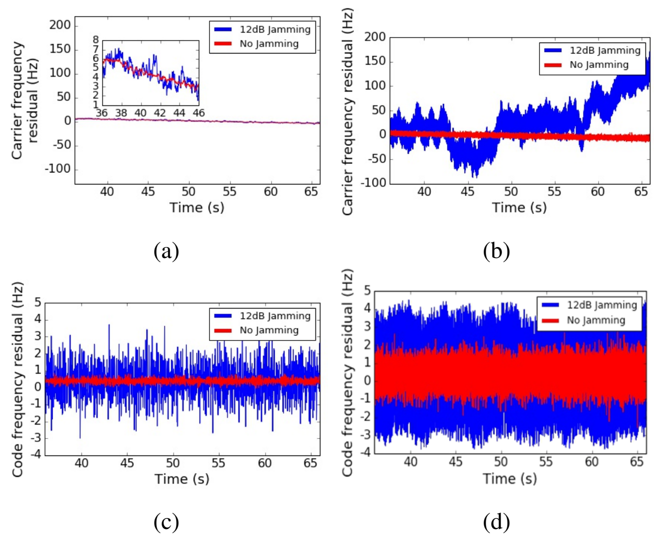


Fig. 6: (a) Carrier doppler frequency residual using MRDTE; (b) carrier doppler residual using scalar tracking; (c) code frequency residual using MRDTE; and (d) code frequency residual using scalar tracking. Scalar tracking loses track at 12dB of added noise, whereas MRDTE still remains robust.

The Fig. 6 is indicative of the robustness of the MRDTE algorithm. In the presence of 12dB added noise, the scalar tracking loses track. However, the MRDTE still successfully tracks the signal accurately.

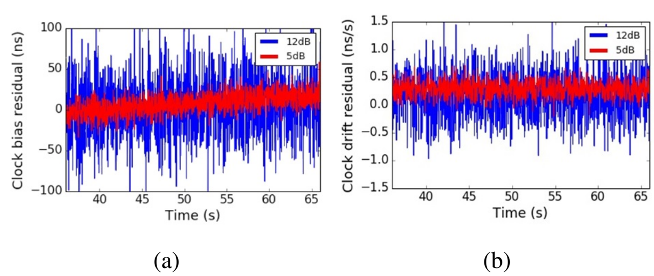


Fig. 7: (a) Clock bias residual comparison for 5dB and 12dB of added noise; and (b) clock drift comparison for 5dB and 12dB of added noise. Even with 12dB of added jamming, clock bias residual is within 100ns and clock drift residual within 1.5ns/s.

In Fig. 7, the clock bias and clock drift residuals are compared for added noise with respect to the signal noise floor. In the presence of 5dB added noise, the clock bias is estimated with an error of within 10ns and in case of 12dB added noise within an error of 100ns. Thus a more robust clock state is estimated by implementing MRDTE algorithm.

B. *Meaconing*

In this case, a replay signal with similar GPS signal structure and signal power 2dB more than that of the authentic signal is added onto the incoming GPS signal. The first 36secs correspond to that of scalar tracking and after which the spurious signal is introduced represented by the thick black dotted line. At this point we turn on the MRDTE algorithm and compare its performance to that of scalar tracking for the next 30 secs.

When meaconing starts, the scalar tracking locks onto the counterfeit signal as shown in Fig. 8 whereas the MRDTE still consistently tracks the authentic signal thereby mitigating the effect of meaconing attack.

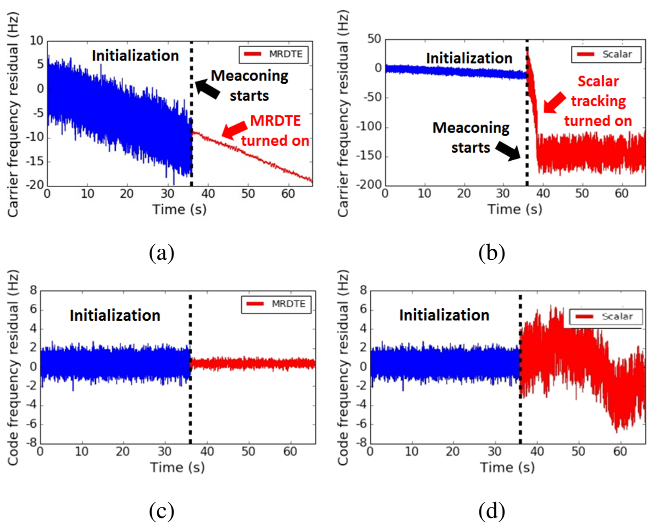


Fig. 8: (a) Carrier doppler frequency residual for MRDTE; (b) carrier doppler frequency residual for scalar tracking; (c) code frequency residual for MRDTE; and (d) code frequency for scalar tracking. Scalar tracking locks onto the meaconed signal whereas MRDTE maintains locking onto the legitimate signal. This demonstrates the robustness of MRDTE against meaconing attacks.

V. CONCLUSIONS

In summary, we proposed a MRDTE for secure and robust GPS time transfer using multiple static receivers sharing a common external clock. We leveraged the information redundancy and the known 3D positions of receivers to improve the robustness of the system. We implemented MRDTE using commercial available front-ends and our software platform -PyGNSS. Through simulations of timing attacks based on GPS signals collected in field experiments, we demonstrate MRDTE's increased resilience against jamming and meaconing attacks.

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