The impact of QoT on Estimation and Control

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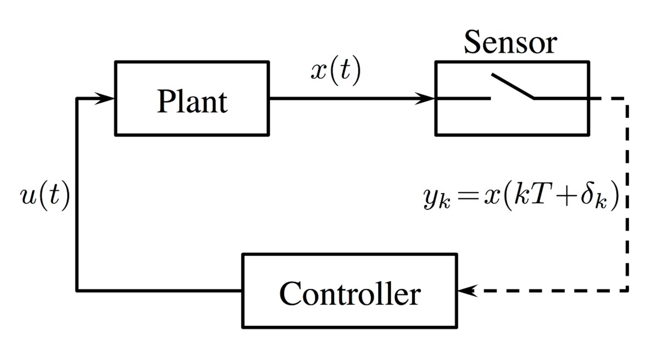
João P. Hespanha (UCSB)

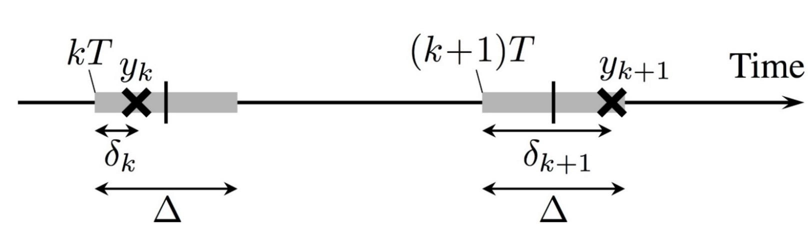
Guosong Yang, Henrique Ferraz

hespanha@ece.ucsb.edu, guosongyang@ece.ucsb.edu, henrique@ece.ucsb.edu

Stabilization under clock offsets

Q: What if sensor/controller clocks are not synchronized?
A: Clock offset introduces distortion and may render the system unstable.



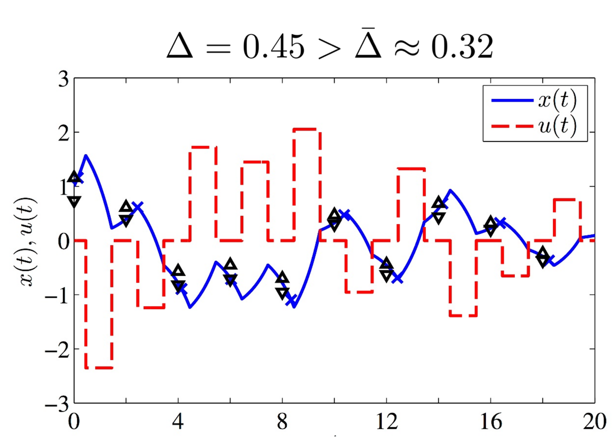


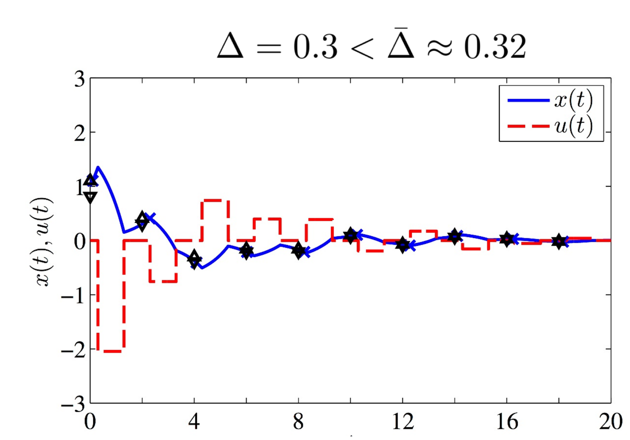
Goal: Determine limitations on the clock offset tolerable for stabilization.

Stabilizability with infinite bit-rate

Plant with scalar-valued state: $\dot{x} = \lambda x + b\,u, x \in \mathbb{R}$

- If $\lambda > 0$ is small enough, then all clock offsets $\delta_k < T$ are tolerable.
- Otherwise an upper bound Δ on δ_k is derived.

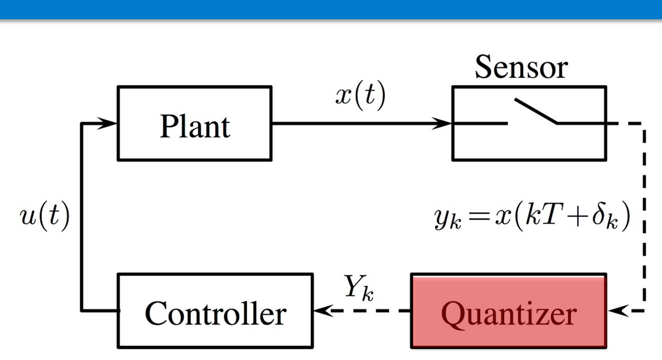




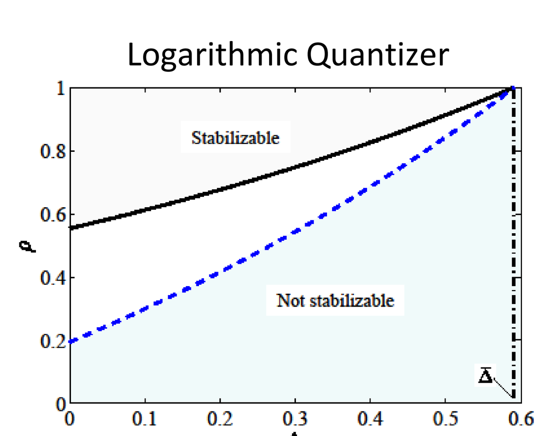
Plant with vector-valued state: $\dot{x} = A\,x + B\,u, x \in \mathbb{R}^n$

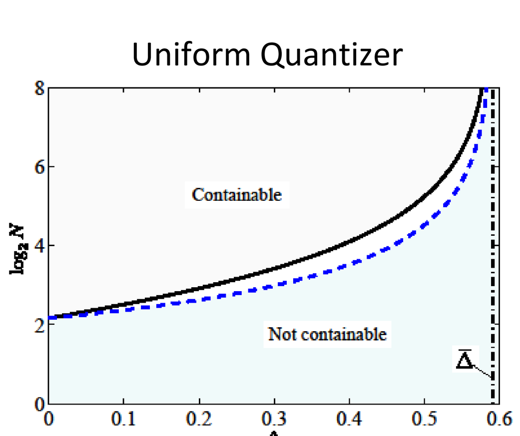
- If the matrix A has at least two distinct eigenvalues, then all clock offsets $\delta_k < T$ are tolerable.

Control with quantized measurements

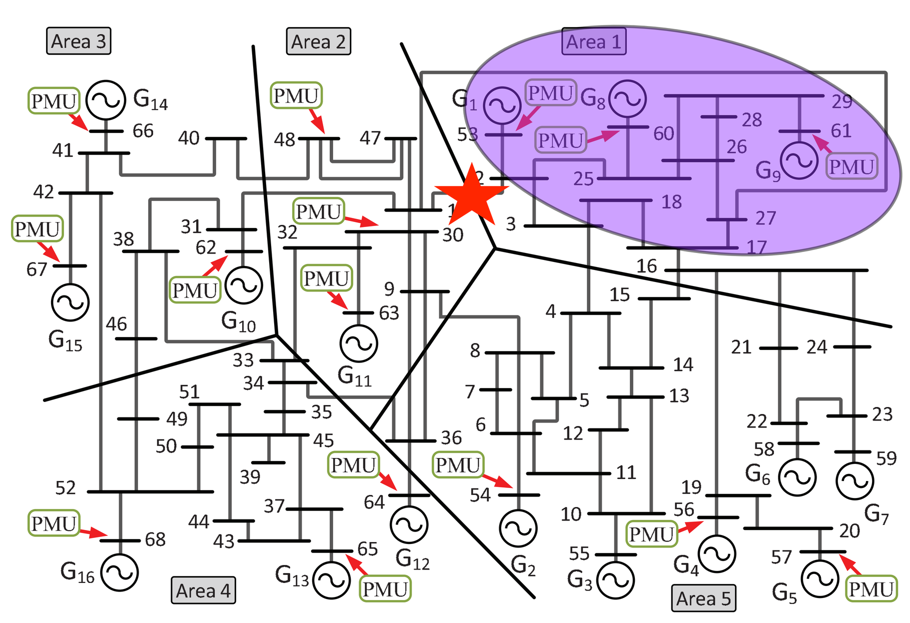


- A larger clock offset requires a finer quantization.
- Necessary conditions and sufficient conditions for stabilizability.





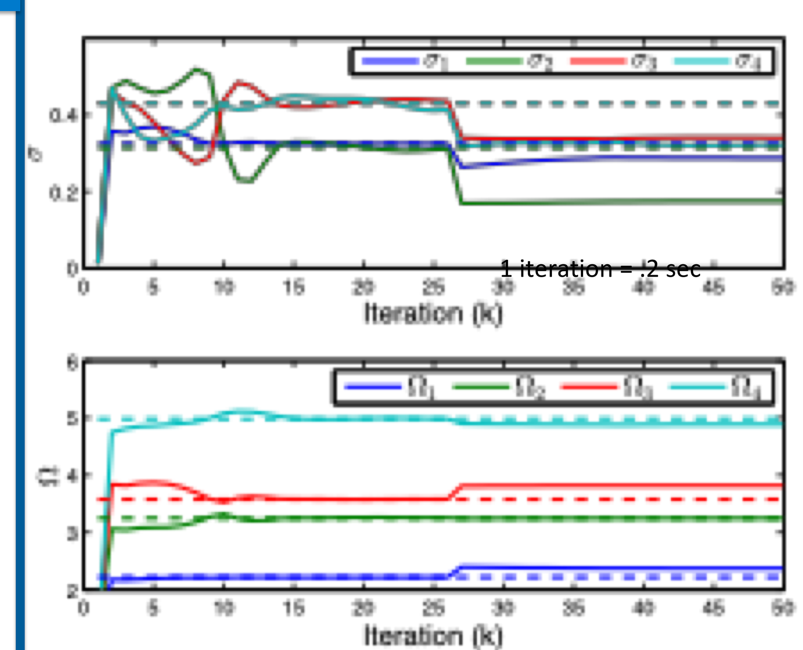
Detection of grid oscillations under attacks



Disturbances lead to oscillations in voltage/current phase and frequency

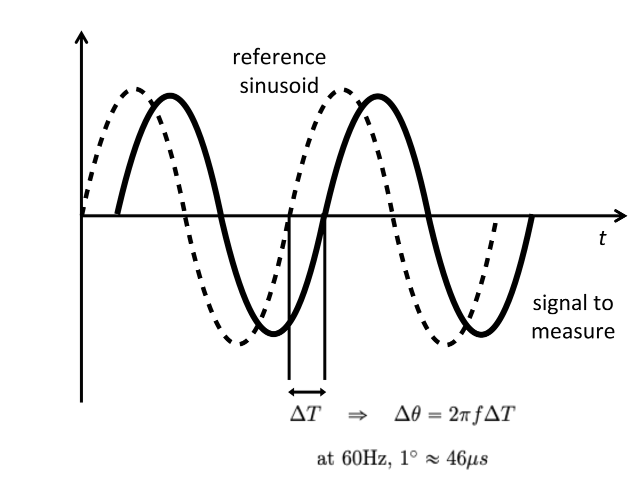
PMU (phase) measurements can be used to estimate complex eigenvalues associated with these oscillation—*hopefully stable!*

$$y_i(t) = \sum_{k=1}^{N} \alpha_{k,i} e^{-\sigma_k t} \cos(\Omega_k t + \phi_{k,i})$$



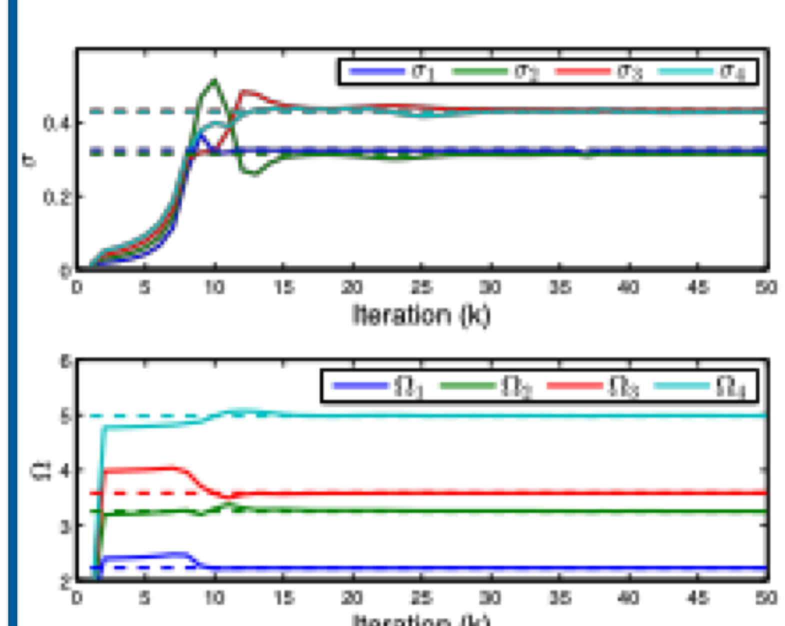
Estimation using distributed Prony algorithm

- Oscillations due to a simulated three-phase fault at line connecting buses 1 and 2
- Estimation of 4 dominant oscillation modes
- Iterative version of two-step Prony algorithm with computation distributed among 5 Phase Data Concentrators (PDCs)
- Attack on Area 1 PMUs at iteration $k = 26$
- Apparent decrease in estimated decay-rates σ_k



GPS spoofing

- Broadcast radio signals that resemble a set of normal GPS signals that would be received at a different location and/or time
- Can be done with hardware under $500 (Software Defined Radio), all software available for free download



Estimation using resilient distributed algorithm:

Spatial consistency:

- compute *median* of estimates across PDCs
- estimates that remain away from *median* by more than δ cause PDC estimates to be ignored

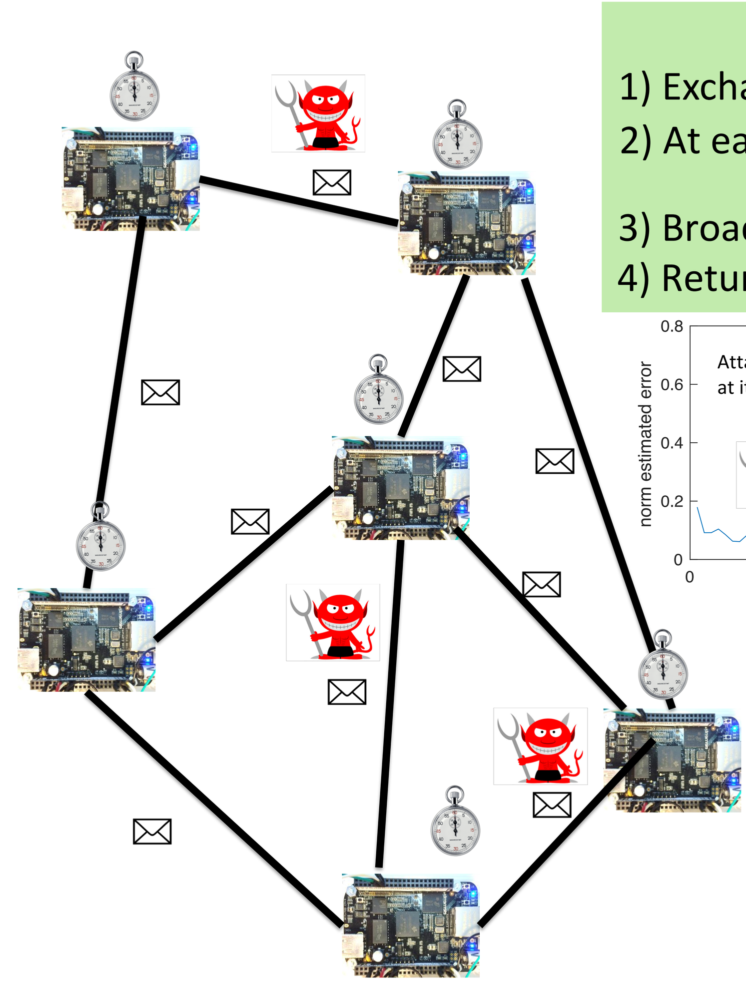
Time consistency (across iterations)

- each PDC should not update its current estimates by more than ϵ per iteration
- changes larger than threshold cause PDC estimates to be ignored

Secure localization based on Time-of-Flight: Distributed Optimization Algorithm

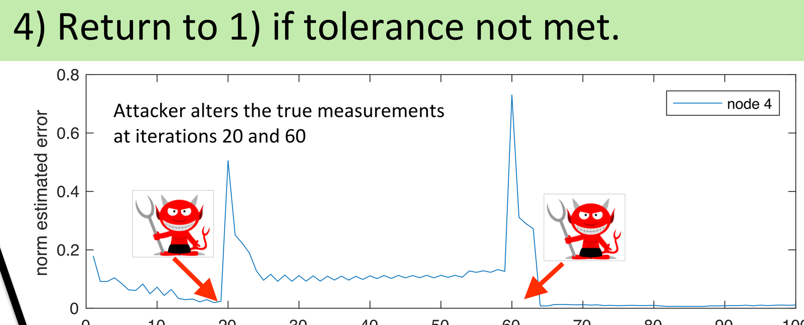
Q: What if sensor clocks are not synchronized and the transmission is subject to a **malicious attacks**?
A: Timing mismatches and incorrect information effectively introduce error in the estimation!

- Devices exchange time-stamped messages between neighbors
- Time-of-flight measurements provide information about relative distance and clock parameters.
- Messages carry the current estimate of device position and clock parameters.
- Malicious agents can hijack some of the messages and alter the estimate or the timing information.



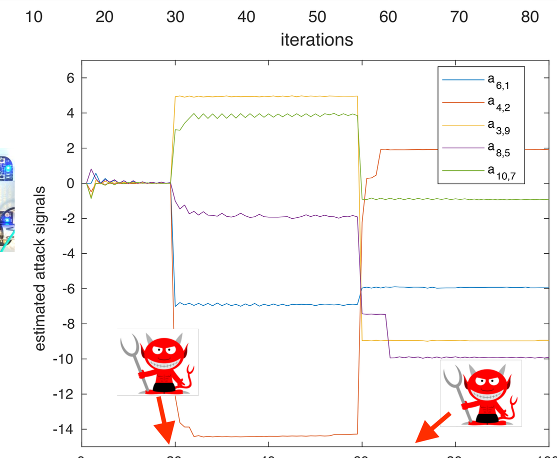
Distributed Optimization Algorithm

1) Exchange messages.
2) At each node solve: $\min_{x_i, \mathbf{a}_i} \; \underbrace{f_i(x_i) + \sum_{j\in\mathcal{N}_i} f_{ij}(x_i, x_j, a_{ij}) + \sum_{j\in\mathcal{N}: i\in\mathcal{N}_j} f_{ji}(x_j, x_i, a_{ij})}_{\text{Maximum Likelihood Estimation}} + \underbrace{\gamma\|\mathbf{a}_i\|_1}_{\text{Regularization}},$
3) Broadcast estimation to neighbors.
4) Return to 1) if tolerance not met.



Additive attacks at several nodes

- The effect of the attack is mitigated.



- The attack signal origin and magnitude can be identified
- **Redundancy** is crucial when detecting outliers! Less measurements, more vulnerable.

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(*) collaboration with other NSF project partners