ESTIMATION AND CONTROL IN ELECTRIC ENERGY SYSTEMS BASED ON TIME-STAMPED SIGNALS

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BACKGROUND, TERMINOLOGY AND CHALLENGES

Network-controlled power system: a closed-loop system consisting of

- Energy flow layer – an "open loop" system for generation, transmission and distribution of electrical power.
- Information/control layer – a feedback path with sensing (waveform analysis, state and parameter estimation) and control (compensation, switching, protection) functionality.

A communication network connects between sensors and actuators (attached to the energy-flow layer) on one side, and the information-flow layer on the other side,

Existing power systems: often have inadequate information/control layer.

Technology needed:

(i) pervasive distributed sensing and feature (dynamic phasors) extraction, and

(ii) multiscale estimation with multirate distributed sensing (MEMDS).

BACKGROUND, TERMINOLOGY AND CHALLENGES (2)

Network interconnection configuration:

- **Type O:** Sensors and actuators are all concentrated at a single location, and the information layer is also concentrated at a single, but separate, location (a.k.a "single loop").
- **Type A:** Sensors and actuators are distributed among several distinct locations, communicating via a network with a single estimation/control center.
- **Type B:** Sensors, actuators, estimators and controllers are all distributed among several locations, communicating with each other via a network.
- **Type AB:** Same as "Type B" but including a master estimation/control center that coordinates the activity of the local estimation/control units.

1st priority: focus on **Type A**.

BACKGROUND, TERMINOLOGY AND CHALLENGES (3)

Challenges posed by communication network:

- **Delays** result in reducing the quality of estimation (and control). The level of estimation error increases with increasing delay, with an attendant degradation in the quality of control actions based on this estimator.

- **Packet dropouts** translate into missing observations (and possibly missing control signal updates). A missed observation can also be interpreted as a random change in the inter-measurement interval, so that the effect of observation packet dropouts can also be analyzed within the framework of estimation with random measurement times.

- **Data-rate limitation** (indirectly) increases the level of measurement noise, resulting in higher estimation error.

OUTLINE

- Continuous-discrete state-space model
- Networked estimation and control
- Effects of communication delay (with available time-stamp)
- Delay-mitigating control
- Concluding remarks

MODEL FOR "TYPE-A" NETWORK CONFIGURATION

Multirate continuous-discrete state space model:

$$\dot{x}(t) \;=\; A\,x(t) + B\,u(t) \quad , \qquad y_k(t_i^{(k)}) \;=\; C_k\,x(t_i^{(k)}) + v_i^{(k)}$$

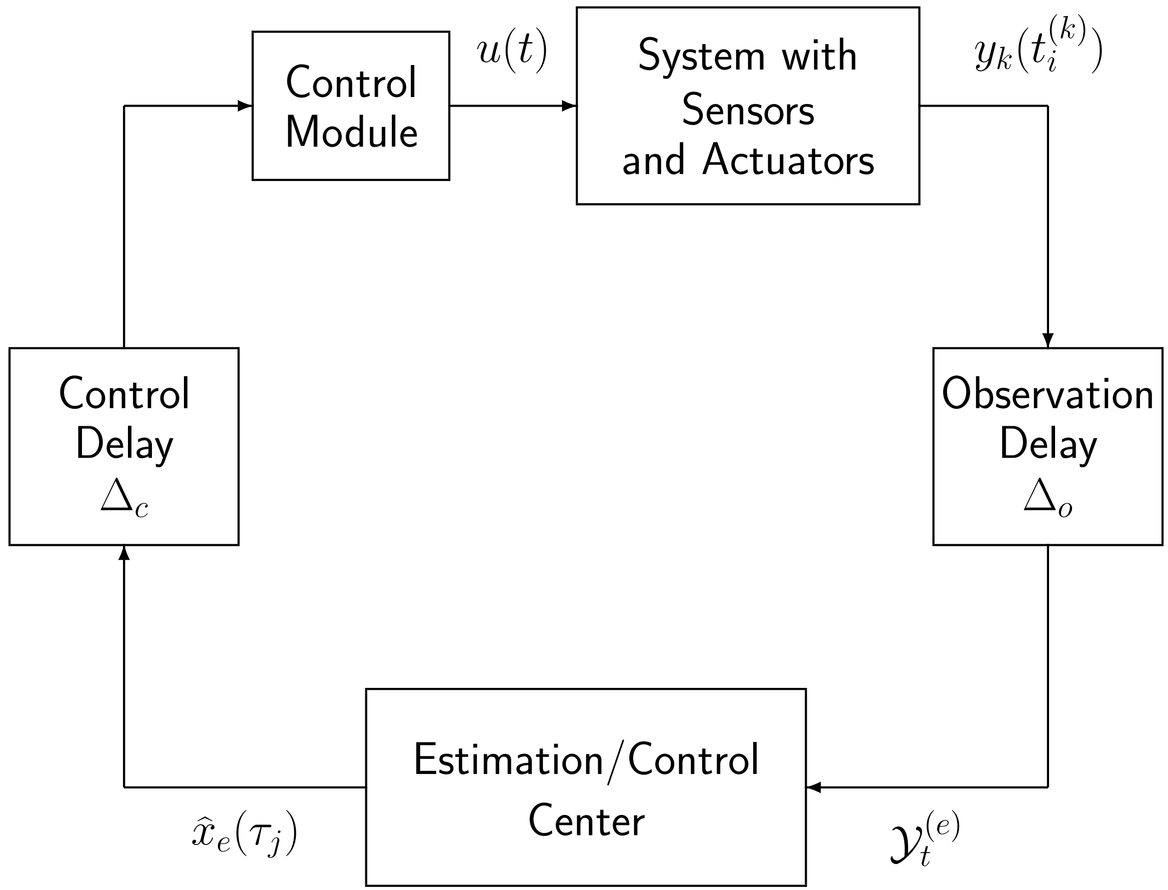
where:

- Sampling time sequence for k-th sensor – $\{\, t_i^{(k)}\,;\; 1 \leq i < \infty \,\}$
- State-to-sensor map for k-th sensor – C_k .
- Measurement noise covariance – $E\,\{v_i^{(k)} v_j^{(\ell)}\} \;=\; R_k\,\delta_{ij}\,\delta_{k\ell}$

Network configuration:

- Single estimation/control center
- Multiple distributed sensors, but a single actuator (for presentation simplicity).
- Arbitrary (time-variant) observation and control path delays.

MODEL FOR "TYPE-A" NETWORK CONFIGURATION - continued



Estimation with multirate distributed measurements:

- The time-stamped measurement, namely the triplet $\{\, k \,,\, t_i^{(k)} \,,\, y_k(t_i^{(k)}) \,\}$, is transmitted through a communication network, reaches destination (estimation/control center) at time $\zeta_i^{(k)} = t_i^{(k)} + \Delta_{o,i}^{(k)}$.

- State estimates are updated whenever a measurement becomes available.

$$\mathcal{Y}_t^{(e)} \stackrel{\text{def}}{=} \bigcup_{(k,i)} \{ y_k(t_i^{(k)});\;\; 0 \leq t_i^{(k)} + \Delta_{o,i}^{(k)} \leq t \}$$

- Time-stamping facilitates "delay-insensitive" estimation and control in the presence of communications delays – the level of state estimation error increases, but closed-loop dynamics remain essentially unaltered.

- The state error covariance matrix $P(t)$ need not be time-invariant in steady-state, so we choose $\mathcal{P}_{+,av} \stackrel{\text{def}}{=} \langle\, P_+(\cdot)\,\rangle$ and $\mathcal{P}_{-,av} \stackrel{\text{def}}{=} \langle\, P_-(\cdot)\,\rangle$ as measures of performance.

EFFECTS OF COMMUNICATION DELAY

- The optimal state estimate $\hat{x}_e(t)$ in the presence of delay, and the associated state-error covariance $P_e(t)$, are related to their delay-free counterparts $\hat{x}(t)$ and $P(t)$ via a standard time-update over the interval $t_i^{(k)} \leq t \leq \zeta_i^{(k)}$.
- The optimal estimate in the presence of communication delay can be determined by augmenting the standard Kalman filter with additional storage, which allows "computational back-tracking" of measurement updates from $\zeta_i^{(k)}$ to $t_i^{(k)}$. In particular, when a new measurement is received (at $t = \zeta_i^{(k)}$, say), the corresponding (standard) measurement update $\hat{x}_-(t_i^{(k)}) \longrightarrow \hat{x}_+(t_i^{(k)})$ is carried out.
- The net effect of communication delay (apart from increased implementation complexity) is an increase in $\mathcal{P}_{\pm,av}$. This increase is directly related to the **average delay**.

Simple stable example:

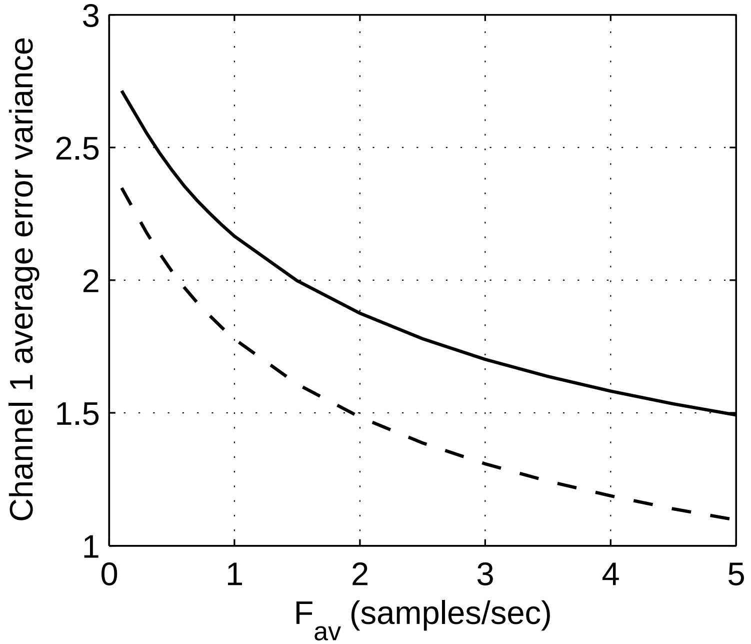
$$A = \begin{pmatrix} -0.2 & 0.4 \\ 0.1 & -0.5 \end{pmatrix} \quad , \qquad \mathsf{eig}\,(A) = \{ -0.1 \ , \ -0.6 \}$$

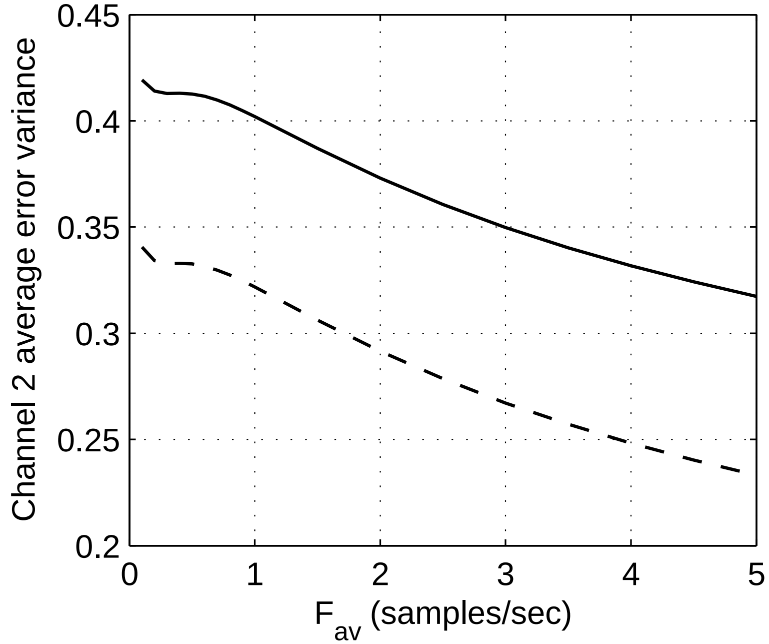
$$B = \begin{pmatrix} 2 \\ 1 \end{pmatrix} \quad , \qquad Q = 1$$

$$C = [\, 1 \ \ 0 \,] \quad , \qquad R = 2.62 \quad (\mathsf{SNR} = 10\mathsf{dB})$$

EFFECTS OF COMMUNICATION DELAY

Degraded performance $(\mathcal{P}_{+,av})$**:** stable system

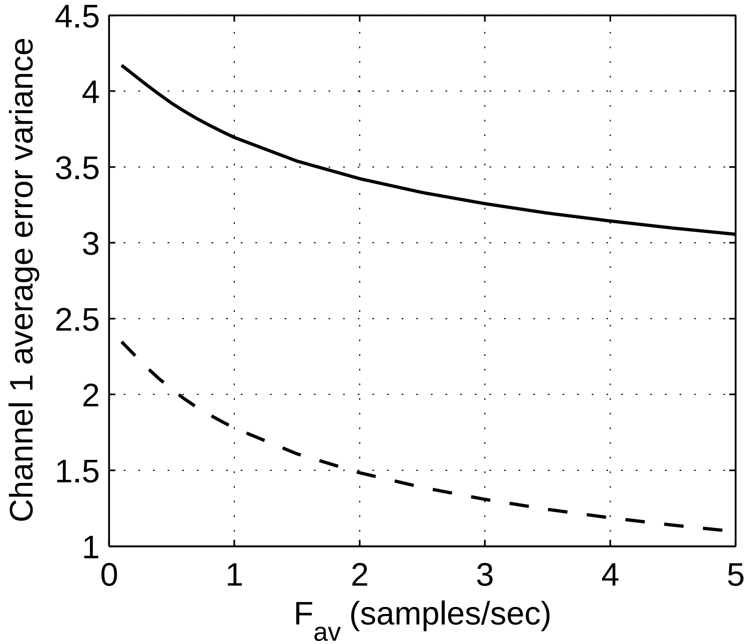


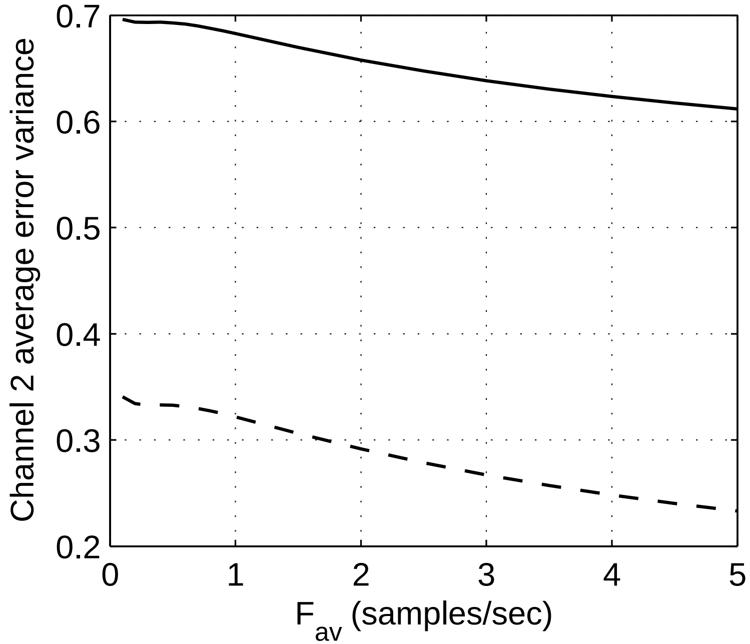


Average delay: 0.1 sec

EFFECTS OF COMMUNICATION DELAY

Degraded performance $(\mathcal{P}_{+,av})$**:** stable system





Average delay: 0.5 sec

DELAY-MITIGATING CONTROL

Time stamping:

- The state estimate $\hat{x}_e(t)$ is transmitted over the communication network at the discrete times $\tau_0,\ \tau_1,\ \tau_2, \ldots,$ where the sequence $\{\tau_j\}$ includes, *at least*, all the times when $\hat{x}_e(t)$ underwent a *measurement update*, i.e., all times of the form $t_i^{(k)} + \Delta_{o,i}^{(k)}$.
- Each $\hat{x}_e(t)$ is transmitted as an $(n+1)$-tuple $\{\tau_j, \hat{x}_e(\tau_j)\}$, reaches control module at time $\theta_j = \tau_j + \Delta_{c,j}$.
- The control path delay $\Delta_{c,j}$ can de accurately determined from knowledge of the time stamp τ_j and the time-instant of reception θ_j .

Estimate update:

The (delayed) estimate received by the control module is updated via

$$\hat{x}_c(\theta_j) = e^{A(\theta_j - \tau_j)} \hat{x}_e(\tau_j)$$

DELAY-MITIGATING CONTROL – example

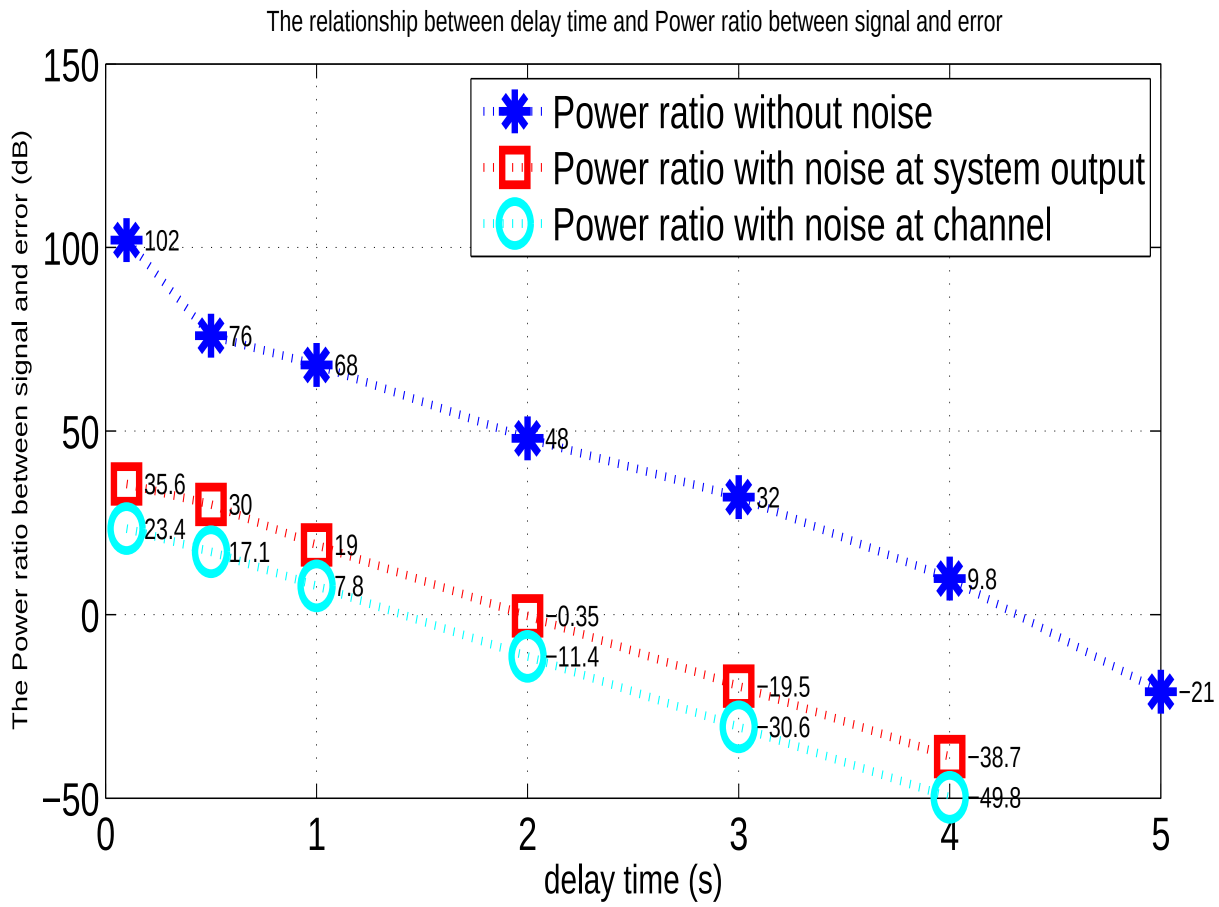
- System parameters (unstable open loop):

$$A = \begin{pmatrix} 0 & 1 \\ 5 & 0 \end{pmatrix} \quad , \qquad \text{eig}\,(A) = \{ -\sqrt{5} \, , \, \sqrt{5} \}$$

$$B = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad , \qquad C = [\, 1 \;\; 0 \,]$$

- Stabilizing control law: $u(t) = -K\hat{x}_c(t) + u_0(t)$, $K = [\,17 \quad 7\,]$ where $u_0(t)$ is some external reference signal (a sinusoid in our example).
- Without delay-mitigation the closed-loop system becomes unstable for $\Delta_c > 0.18$ sec.
- With delay-mitigation the closed loop system is stable for very high values of Δ_c, but the SNR deteriorates with increasing delay.

DELAY-MITIGATING CONTROL – example

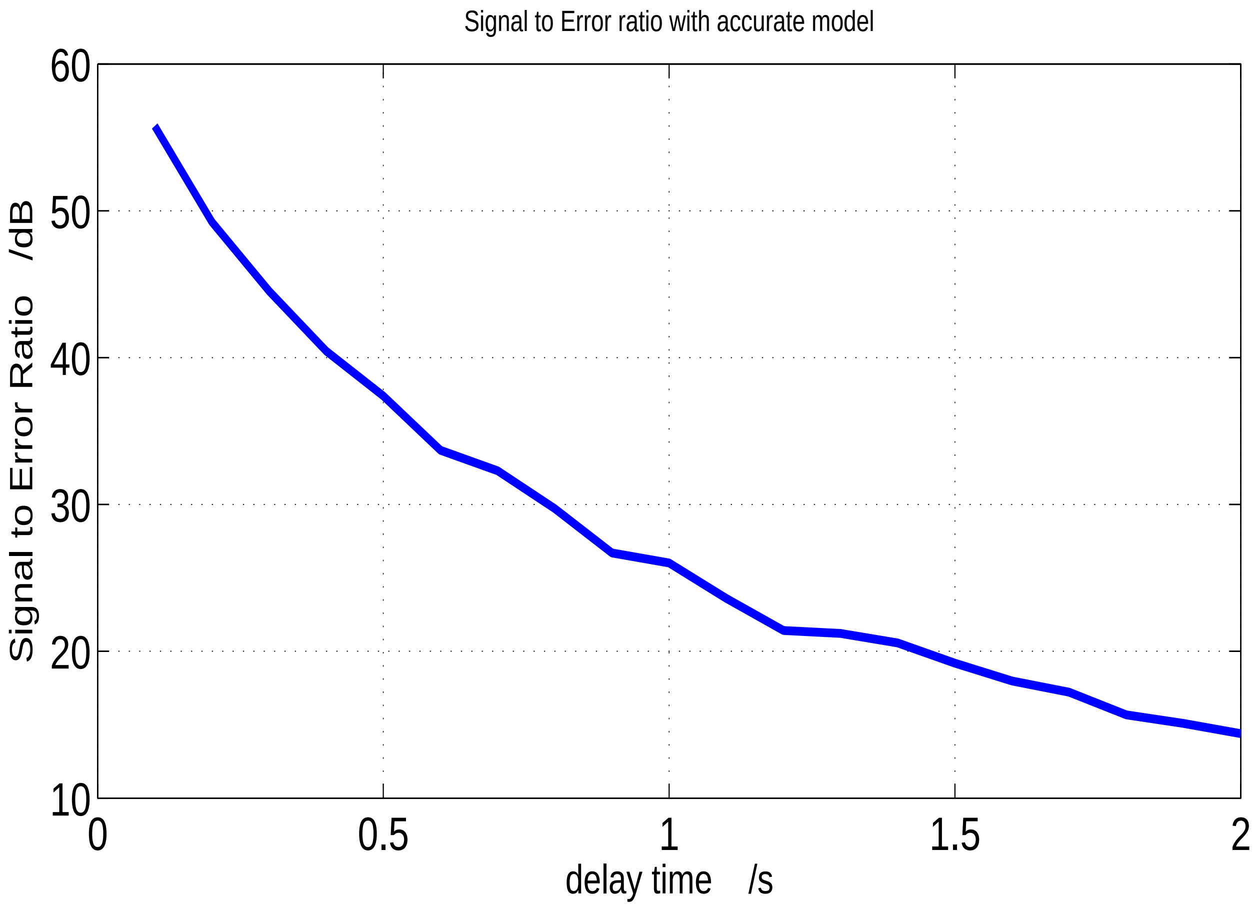


Electro-mechanical system example:

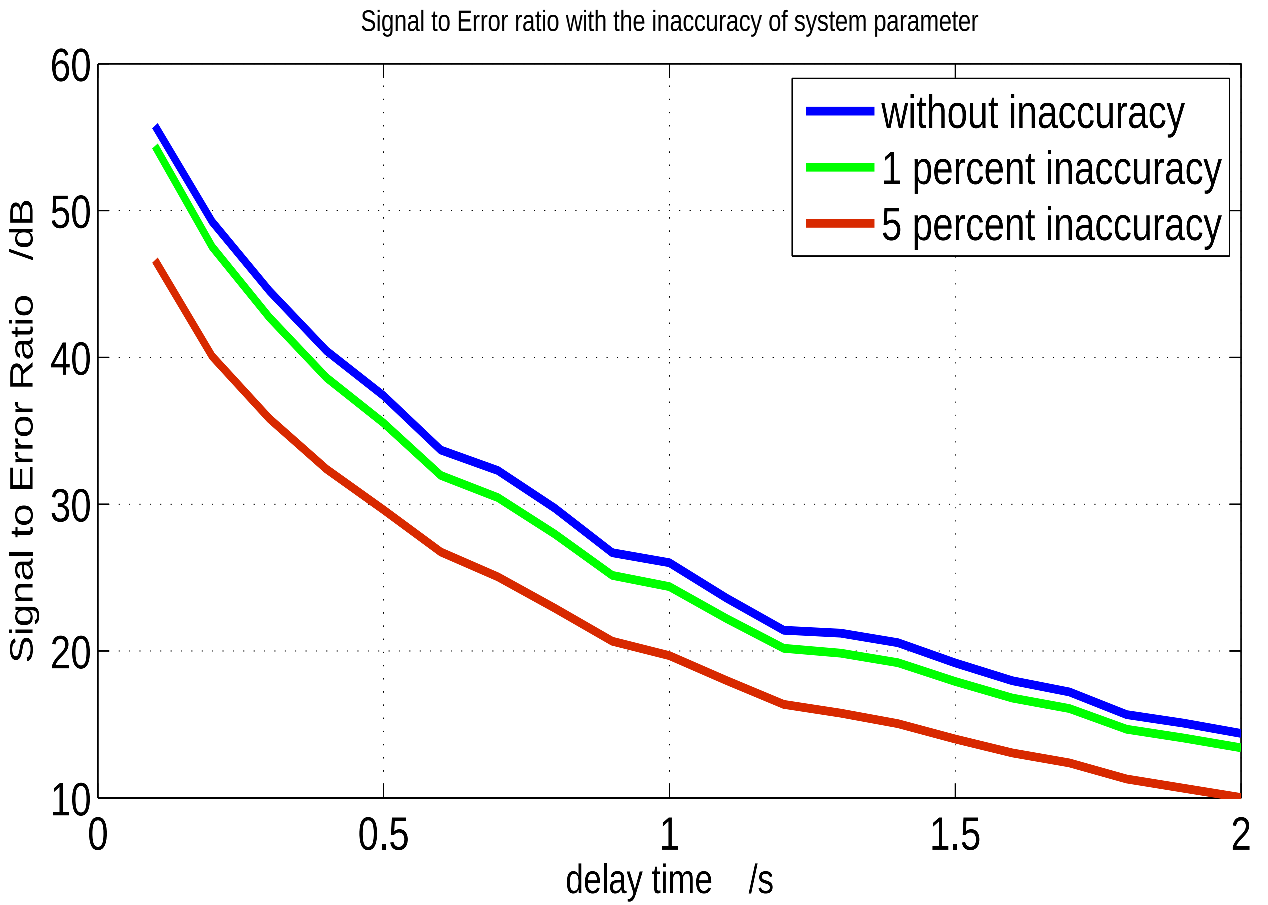
$$A = \begin{pmatrix} -7.037 & -12.38 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \quad , \qquad \mathsf{eig}\,(A) = \{\, 0\,,\, 0\,,\, -3.5185 \pm j0.0126 \,\}$$

$$B = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad , \qquad C = 10^3 * [\,0.022 \quad 0.389 \quad 2.01 \quad 13.14\,]$$

DELAY-MITIGATING CONTROL – electro-mechanical example



DELAY-MITIGATING CONTROL – electro-mechanical example



DELAY-MITIGATING CONTROL – summary

- Delay-mitigation transmutes delay into increased estimation error.
- Decrease in signal to estimation-error ratio is almost linear in Δ_c .
- Added noise in the loop results in a shift of the “SNR vs. delay” curve.
- Inaccuracies in system parameters also translate into increased estimation error.

CONCLUDING REMARKS

- Our networked estimation/control scheme allows us to transform communication delay into increased estimation error, largely avoiding the destabilizing effects of such a delay.
- We have explored the feasibility of networked estimation with multirate distributed sensing. Our model for networked estimation subsumes some previous models (e.g., Bernoulli packet drop) as special cases.
- Time-stamping of transmitted measurement data facilitates “delay-insensitive” estimation in the presence of communication delay. For instance, we can transmute delay into an increase in state estimation error.
- Similarly, time-stamping of transmitted state estimates makes it possible to overcome very long delays in the estimation-control loop, while avoiding adverse effects on the stability of the closed-loop system.