# Sensing and Control with Limited Transmissions

(based on joint work with O.C. Imer)

TAMER BAŞAR

Dept ECE, CAS and CSL, UIUC

tbasar@control.csl.uiuc.edu

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# Outline

- Networks & Control
- Joint sensor-controller design

  -- What/when/how to transmit & control
- Estimation with "Power-Limited Communication"
- Control with "Power-Limited Communication"
- When to measure & when to control
- Other issues / Conclusions

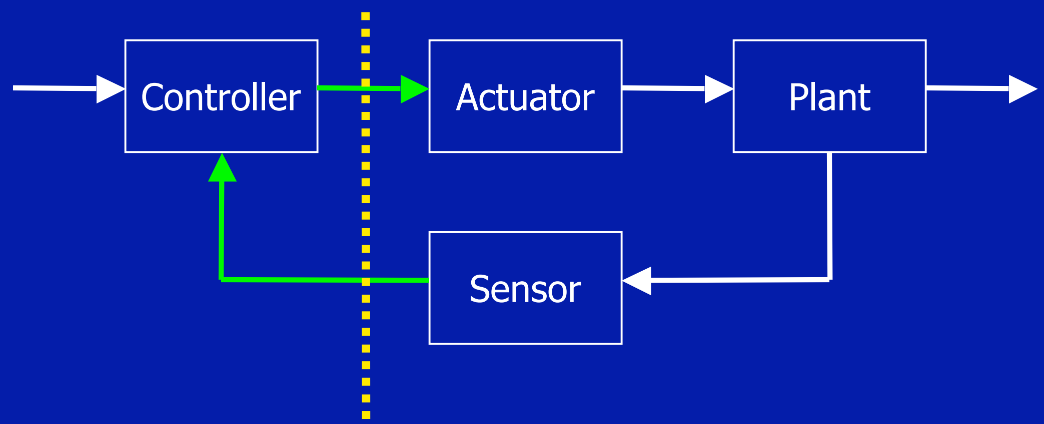
# Networks & Control

- A surge of research interest in using networks for communication in control/monitoring systems
- Advantages: flexibility, reduced wiring, lower installation costs, agility in diagnosis and maintenance, remote operations, ...
- Challenges: synchronization, timing problems, reliability, *communication network and channel constraints*, ...

# Networks & Control

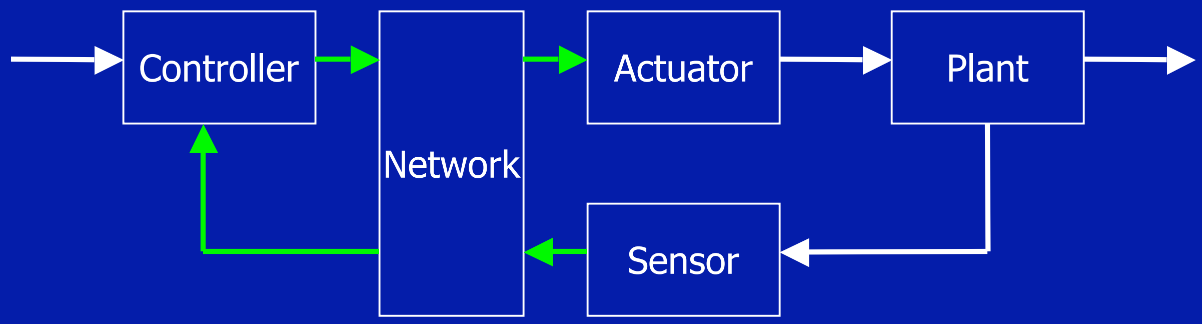
- Traditional Control Systems have dedicated data paths for communication

Controller-Plant Communication

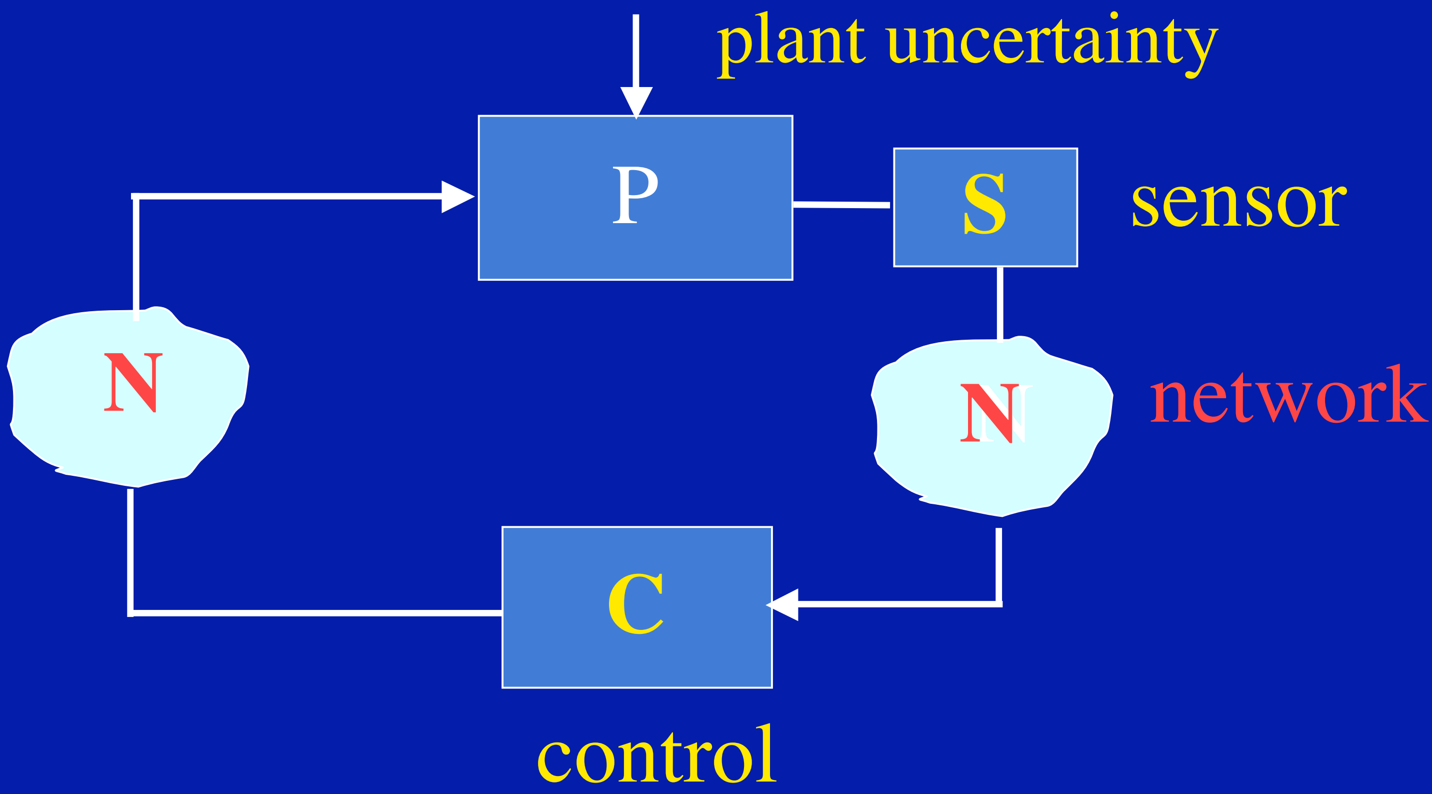


# Networks & Control

- In Networked Control Systems (NCS) controller-plant communication takes place over a network



# Remote Control Paradigm



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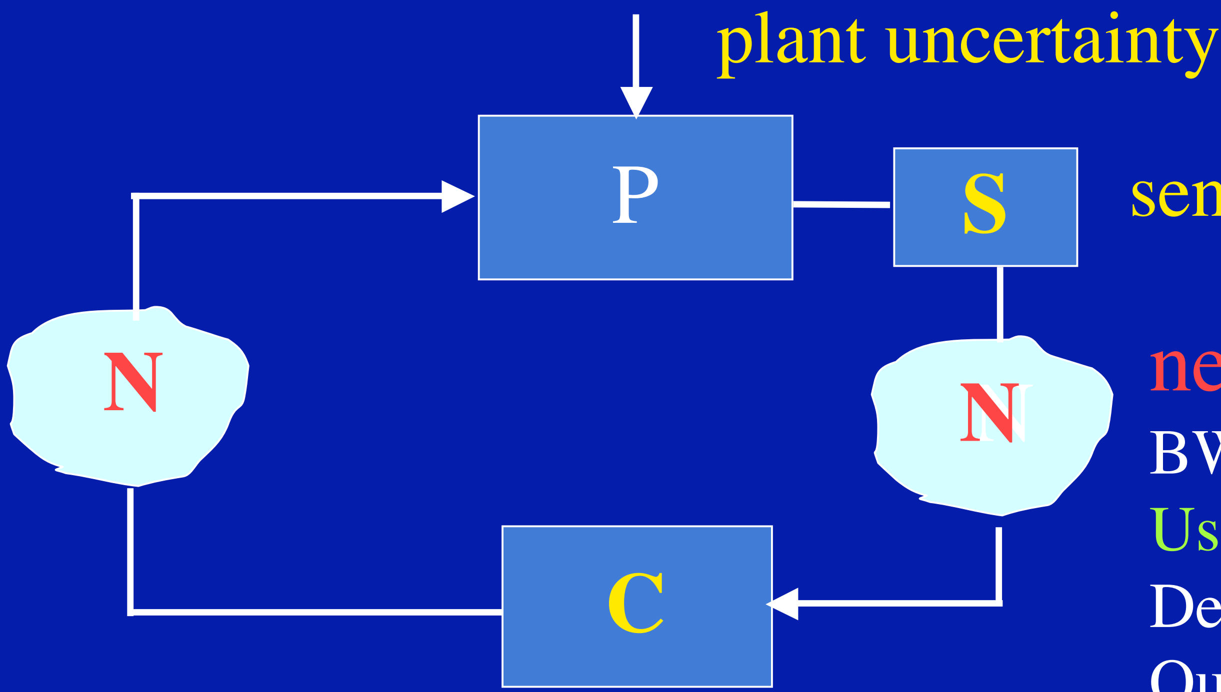
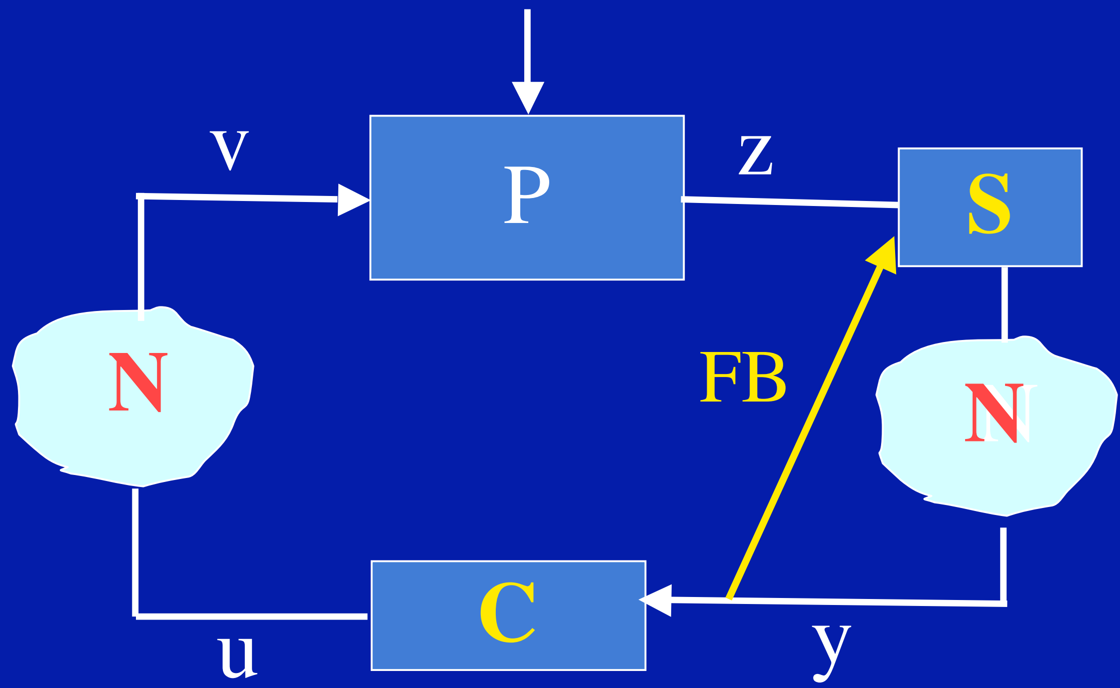



network
BW limitations
Usage limitations
Delay
Quantization (Q)
Link failure

PI (S, Q, C) → optimize

# Remote Control Paradigm

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Non-classical information!

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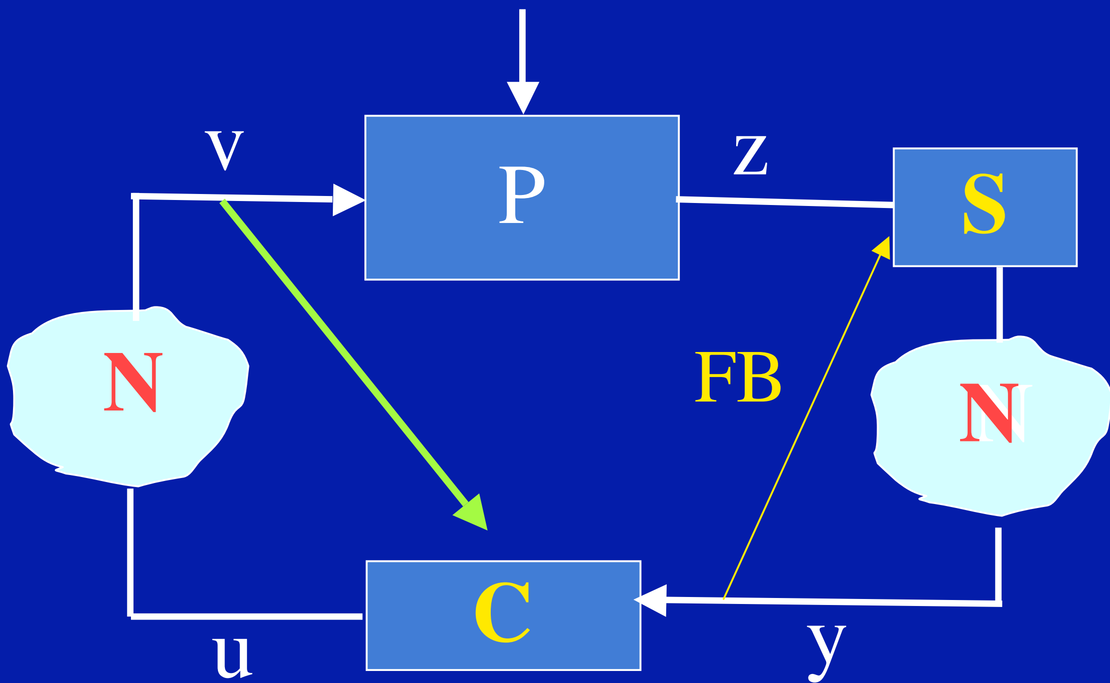


sensor

network

BW limitations

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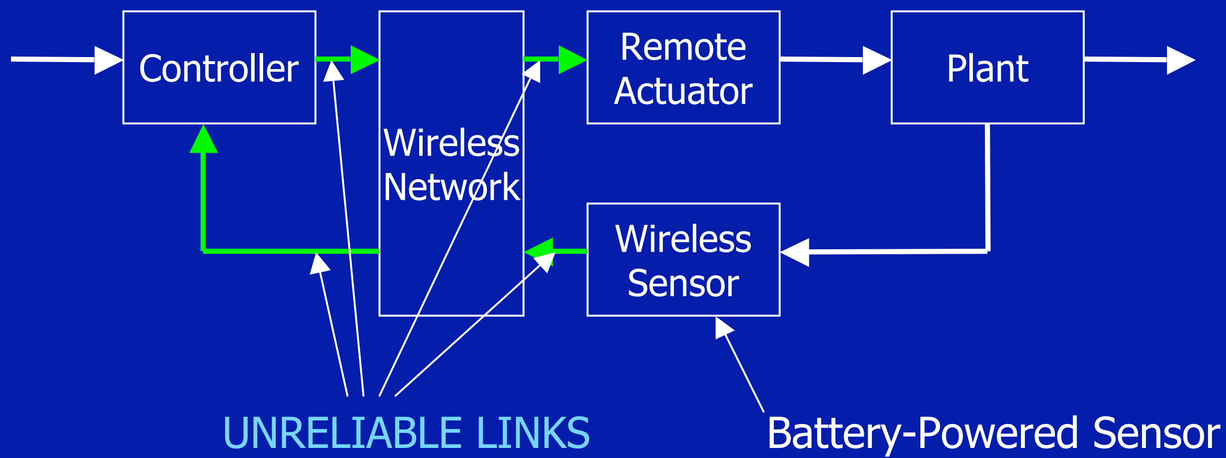
# Wireless Networks & Control

- Estimation & Control when controller-plant communication takes place over a Wireless Network



# Wireless Networks & Control

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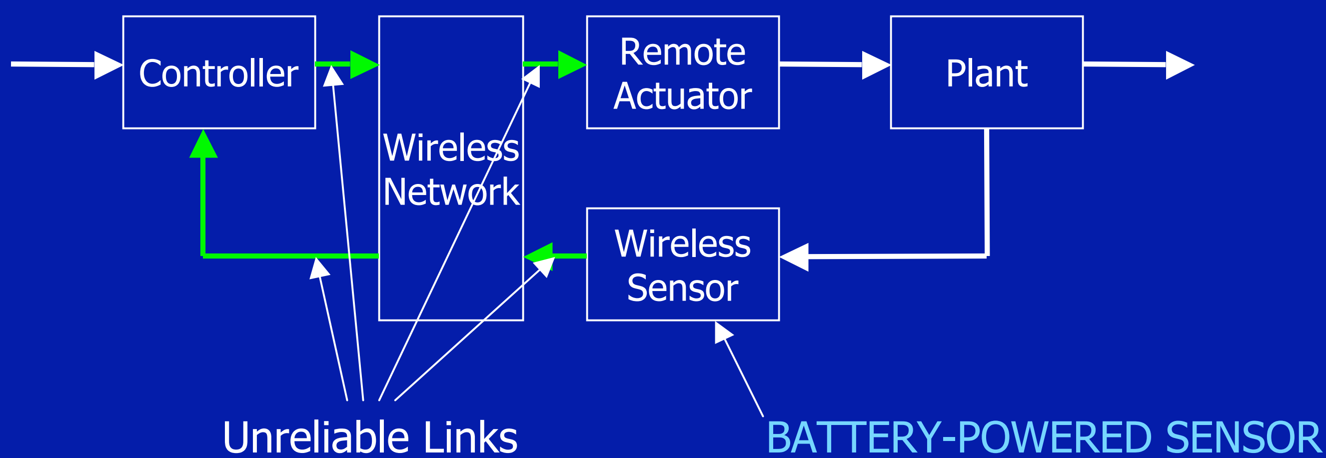

# Limited Usage in Sensing & Control
## Reasons

- To conserve battery power in wireless sensors
  (with RF channels a significant amount of power is consumed to transmit sensor measurements)
- Sharing of bandwidth among several users
  (time allocation limited transmission -- TDM systems)
- Power limitation on controller
- Limits on the frequency of interaction with the plant/system
- CANs -- actuator, controller, sensor connected over a serial bus -- access one at a time

# Limited Usage in Sensing & Control

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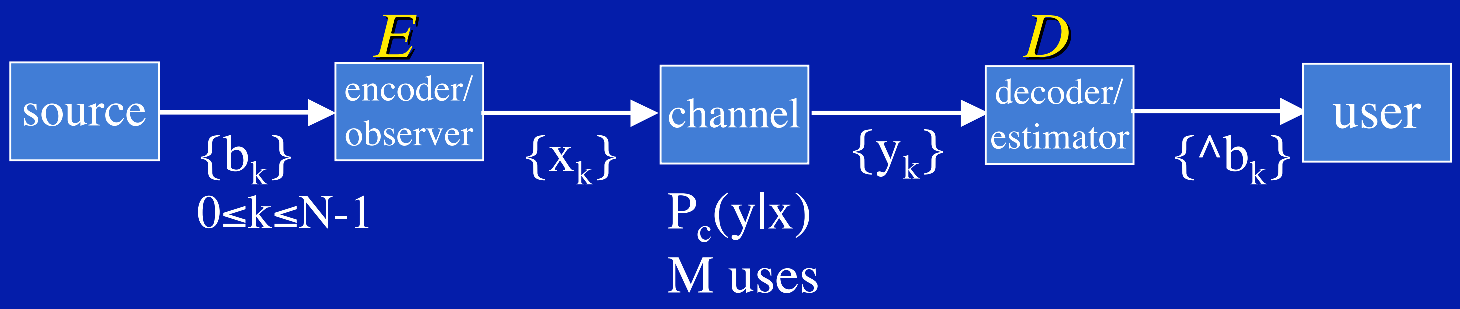
**Sensing and Control are Expensive !**

# PROBLEM CLASS I

## Optimal Estimation over a Limited-Use Channel

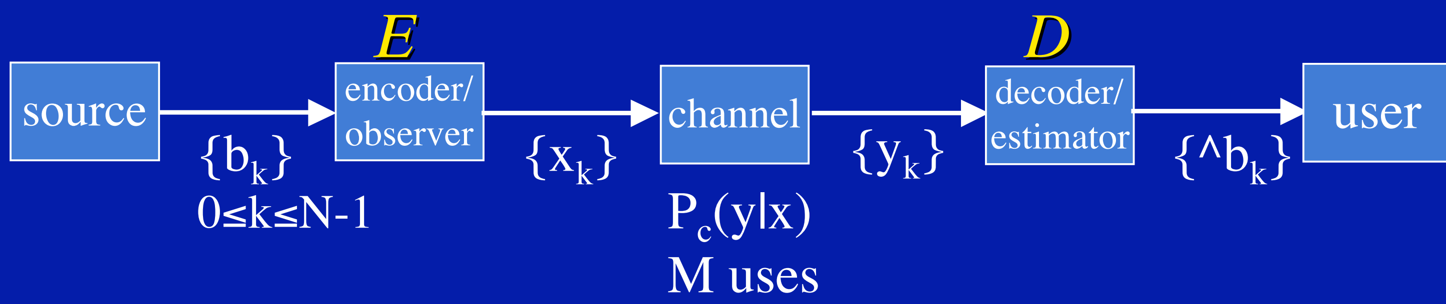



$x_k = E(z_k)$ $x \in X$ $y \in Y$

$z_k = b_k + v_k$ $M < N$

*Given a "source" and a "memoryless channel", for a given message length N, and number of channel uses M, what is the minimum attainable value of the average distortion $D_{(M,N)}$ and a corresponding* ***E & D*** *pair?*

# Optimal Estimation over a Limited-Use Channel

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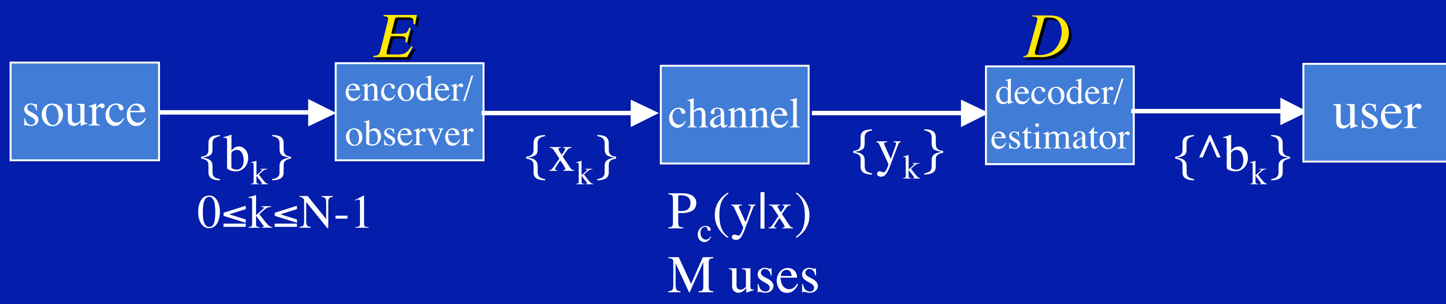
e.g. $D_{(M,N)} = E\{(1/N) \sum_0^{N-1} (b_k - \hat{b}_k)^2\}$ $\qquad$ MSE

or the probability of error measure

# Optimal Estimation over a Limited-Use Channel



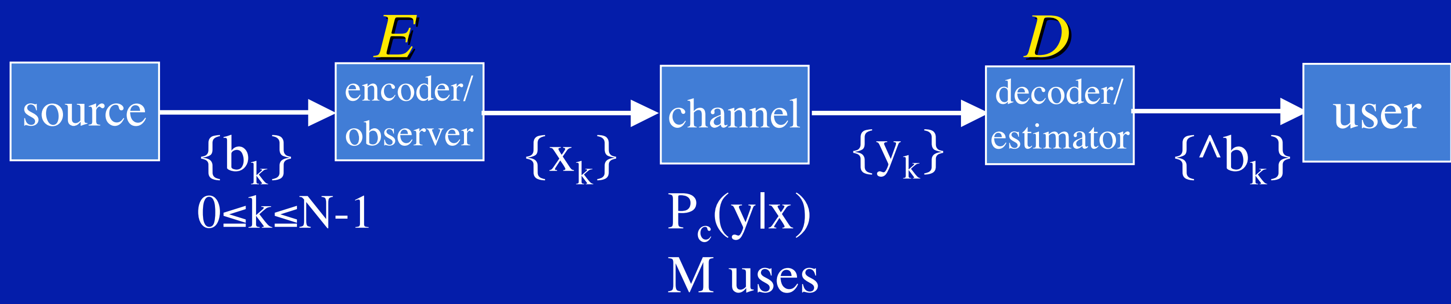

$x_k = \mathcal{E}(z_k)$ $\qquad x \in \mathcal{X}$ $\qquad y \in \mathcal{Y}$

$z_k = b_k + v_k$ $\qquad M < N$

**Order of actions at time k:**

1. $b_k$ (or $z_k$) becomes available to the sensor
2. Sensor makes a decision: transmit/shape or not
3. Estimator acts by generating $\hat{b}_k$
4. Estimation error is incurred and we move to k+1

# Optimal Estimation over a Limited-Use Channel




$x_k = E(z_k)$

$z_k = b_k + v_k$

$x \in X \quad y \in Y$

$M < N$

**Dynamic & Non-classical**

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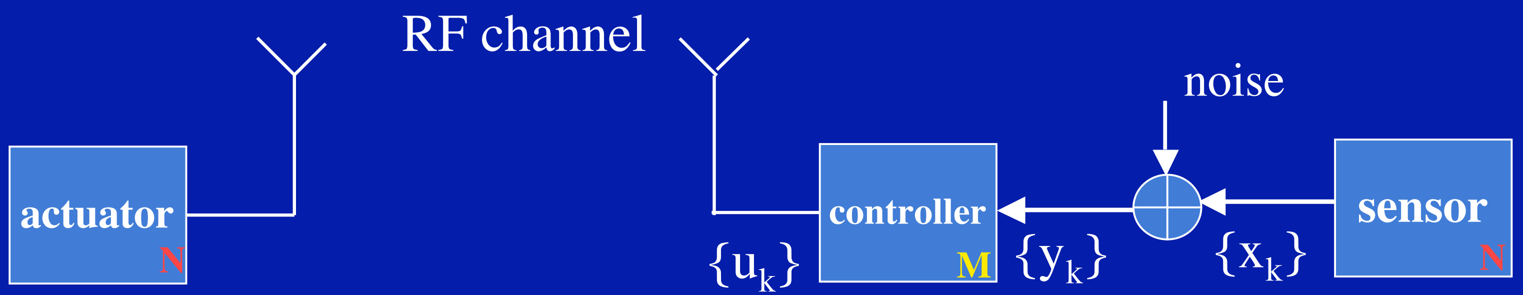
# PROBLEM CLASS II

## Control over a Limited-Use Channel



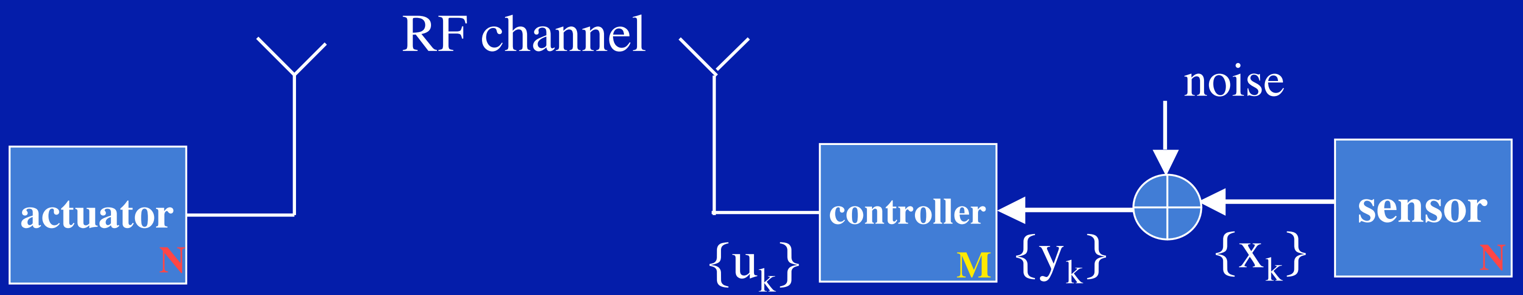

$x_{k+1} = f(x_k, u_k, w_k)$ $\qquad x_k \in X_k$ , $u_k \in U_k$ , $y \in Y_k$

$y_k = h_k(x_k) + v_k$ $\qquad M < N$

$u_k = \mu_k(I_k)$, $I_k := \{y_{[0,k]}, u_{[0,k-1]}\}$, $\mu_k \rightarrow U_k$ only M times

*Given a horizon of N units, and with controller allowed to transmit for only M < N times, what is the minimum attainable value of a performance index J, and a corresponding controller?*

# Control over a Limited-Use Channel

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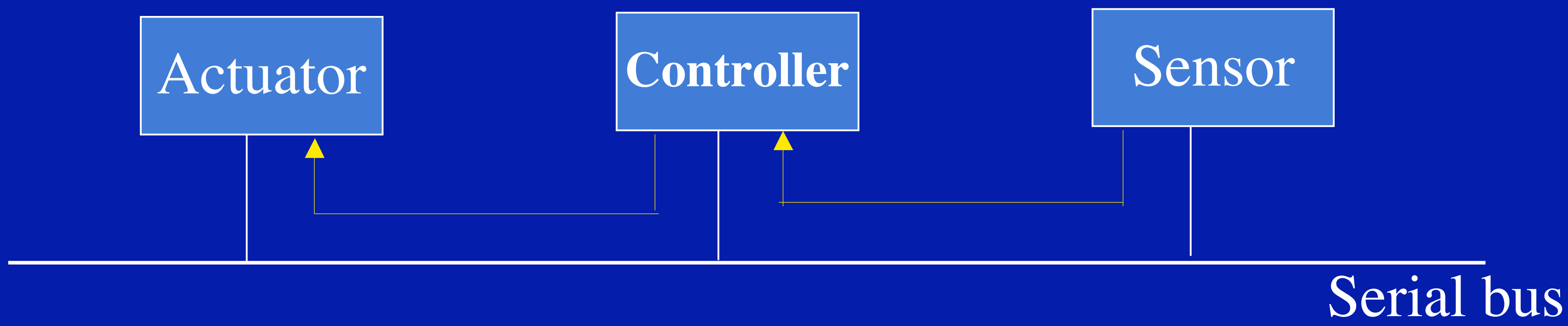
*Given a horizon of N units, and with control allowed to transmit for only M < N times, what is the minimum attainable value of a performance index J, and a corresponding controller?*

e.g. $\qquad J = E\{q(x_N) + \sum_0^{N-1} g(x_k,u_k)\}$

# PROBLEM CLASS III

## Scheduled Measurements & Controls




$$x_{k+1} = A\, x_k + a_k\, u_k + w_k\ ,\quad k = 0, \ldots, N-1$$

$a_k$ is 0 or 1

$$y_k = (1 - a_k)\, x_k\ ,\ k = 0, \ldots, N-1$$ measurement

Controller cannot receive and send simultaneously

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# PROBLEM CLASS I

# OPTIMAL ESTIMATION

# Estimation: A Special Case

N=2, M=1, $b_0$, $b_1$ i.i.d. Gaussian, 0-mean, variance $\sigma^2$

Perfect channel, no noise

Estimation error: $e = E\left\{(b_0 - \hat{b}_0)^2 + (b_1 - \hat{b}_1)^2\right\}$

**Open-loop sensor policy:**

Arbitrarily picks transmission time ==> $e_{OL} = \sigma^2$

**Closed-loop sensor policy:**

Transmit $b_0$ if it lies outside $[\alpha, \beta]$, $\alpha < 0 < \beta$; otherwise $b_1$

Minimization problem faced by sensor:

$$e_{(\alpha,\beta)} = \int_{\alpha}^{\beta} (b - E[b \mid b \in [\alpha, \beta]])^2 f(b)\, db + \sigma^2 P\{b_0 \notin [\alpha, \beta]\}$$

# Special Case: Solution

$(\alpha^*, \beta^*) = (- \sigma, \sigma)$

$\Rightarrow$

$$e_{CL}^* = e_{(\alpha^*, \beta^*)} = [1 - \sqrt{(2 / \pi e)}]\, \sigma^2$$
$$\approx 0.52\, \sigma^2$$

$\Rightarrow$

**48% improvement over the OL policy**

# Special Case: Solution

$(\alpha^*, \beta^*) = (-\sigma, \sigma)$

$\Rightarrow$

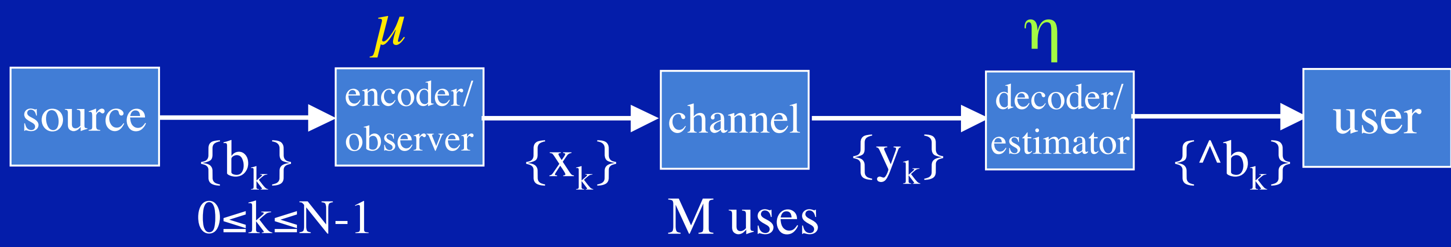
**The knowledge of no action is useful information !!**

$\Rightarrow$

**48% improvement over the OL policy**

# Optimal Estimation over a Limited-Use Channel

## -- i.i.d. case, perfect channel --




$x_k = \mu_k(I^e_k)$ $\quad\quad$ $\hat{b}_k = \eta_k(I^d_k)$ $\quad\quad\quad\quad$ $z_k = b_k + v_k$

$s_k$ : # channel uses left at time k

$t_k$ : # decision slots left at time k

$I^e_k = \{(s_k, t_k); z_{[0,k]}, x_{[0,k-1]}\}$, $1 \le k \le N-1$; $I^e_0 = \{(s_0, t_0); z_0\}$

$I^d_k = \{(s_k, t_k); y_{[0,k]}\}$, $\quad 0 \le k \le N-1$

$\rho_k$ : 0-1 quantity; 1 if sensor transmits

$s_{k+1} = s_k - \rho_k$ , $s_0 = M$ $\quad\quad$ s-*dynamics*

# Optimal Estimation over a Limited-Use Channel

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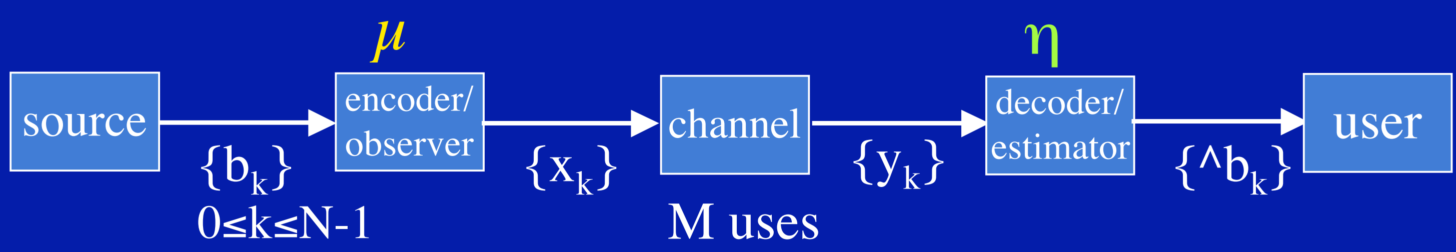


$x_k = \mu_k(I^e_k)$ $\hat{b}_k = \eta_k(I^d_k)$ $z_k = b_k + v_k$

**Find $\mu_{[0, N-1]}$ and $\eta_{[0, N-1]}$ that minimize a given PI: MSE or Probability of error**

$I^d_k = \{(s_k, t_k); y_{[0,k]}\}, \quad 0 \leq k \leq N-1$

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# Optimal Estimation over a Limited-Use Channel

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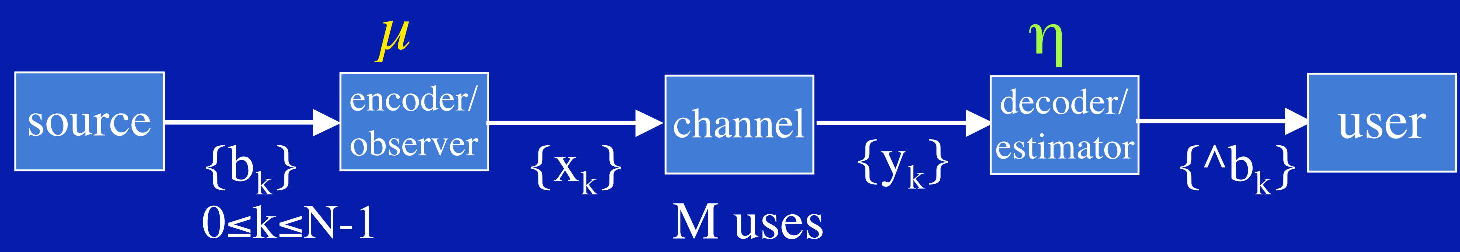



$x_k = \mu_k(I^e_k)$ $\hat{b}_k = \eta_k(I^d_k)$ $z_k = b_k + v_k$

Find $\mu_{[0, N-1]}$ and $\eta_{[0, N-1]}$ that minimize a given PI: MSE or Probability of error

- Best choice for $\eta_k$ is $E[b_k \mid (s_k,t_k); x_k]$ or MAP
- Sufficient statistics for optimum $\mu_k$ is

  $S^e_k := \{(s_k,t_k); z_k\}$

# Solution

Best sensor policy is of the form:

At time k transmit $z_k$ if it is in a measurable set ¥($s_k$,$t_k$), otherwise do not

¥(s,t) obtained offline as the minimizer in a recursive equation satisfied by accumulated optimum error, $e^*(s,t)$, at each point (s,t):

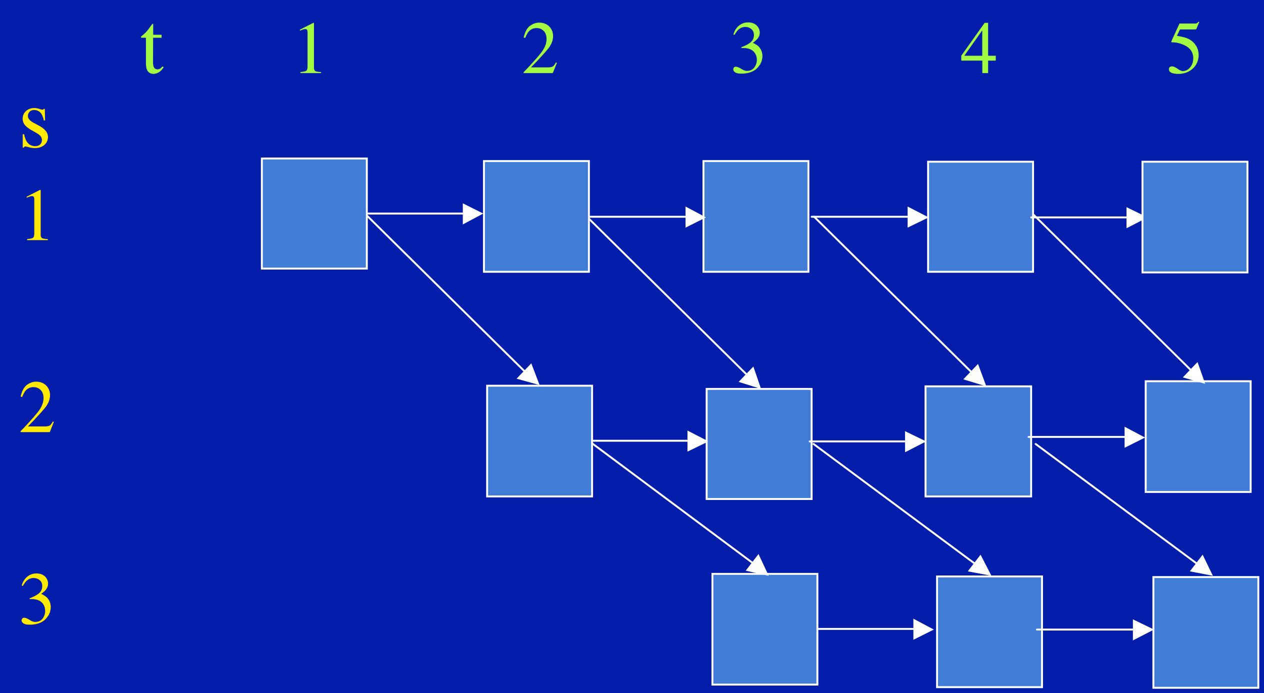
$$e^*(s,t) = \min_{¥(s,t)} \{e^*(s-1, t-1)\ \text{Prob}(z \in ¥) + e^*(s, t-1)\ \text{Prob}(z \notin ¥) + \text{average error at } (s,t) \text{ due to decision at } (s,t)\}$$

$e^*(t,t) = 0$, $e^*(0,t) = t\ \text{var}(b)$

Specific structure of ¥(s,t) depends on the pdf/pmf and PI.

# Offline Computations

The recursion can be solved offline, and the optimal sets ¥(s,t) tabulated starting with small values of (s,t)



# Explicit Solution in a Special Case

Continuous distribution f for b, f(-b) = f(b)

No noise v (from source to sensor) --n.l.o.g

==> $¥^c(s,t) = [-\beta_{(s,t)}, \beta_{(s,t)}]$

$$\beta_{(s,t)} = \sqrt{\ } \{e^*(s-1, t-1) - e^*(s, t-1)\}$$

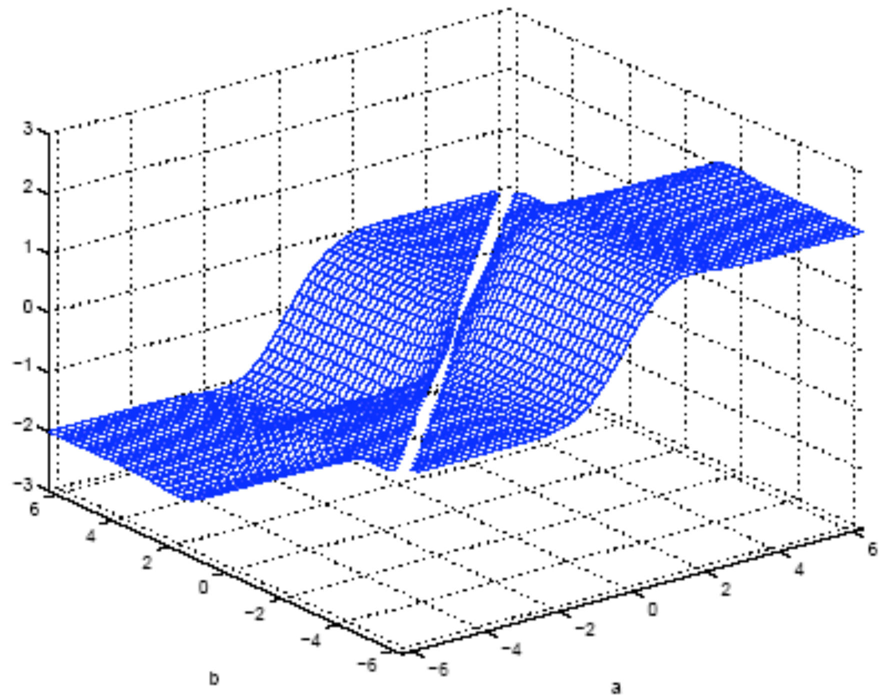
Gaussian: $\varepsilon_{(s,t)} := e^*(s,t) / \mathrm{var}(b)$

$$\varepsilon_{(s,t)} = \varepsilon_{(s-1,t-1)} - [(\beta_{(s,t)})^2 - 1][2\Phi(\beta_{(s,t)}) - 1] - (2/\sqrt{2\pi})\, \beta_{(s,t)} \exp((\beta_{(s,t)})^2 / 2)$$

$$\varepsilon_{(t,t)} = 0, \quad \varepsilon_{(0,t)} = t$$

# The Best Interval in Gaussian Case

Finding the optimal interval




Plot of the objective function in the Gaussian case with $\mathcal{T}_{(s,t)} = [a, b]$ when $\sigma_x^2 = 1$, $e^*_{(s-1,t-1)} = 3$, $e^*_{(s,t-1)} = 1$

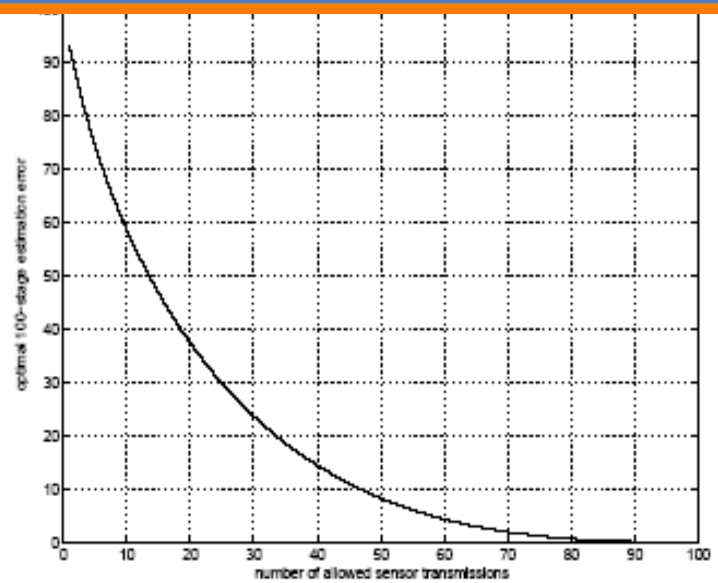
# An Illustrative Example

Problem: Given a time-horizon of length N=100, estimate the state of a zero-mean *i.i.d.* Gaussian process with unit variance

Design Criterion: The cumulative estimation error should not exceed 20.

**Solution I:** Make 80 sensor transmissions picked at arbitrary times

**Solution II:** Use the optimal sensor transmission and estimation policies



# An Illustrative Example (cont.)

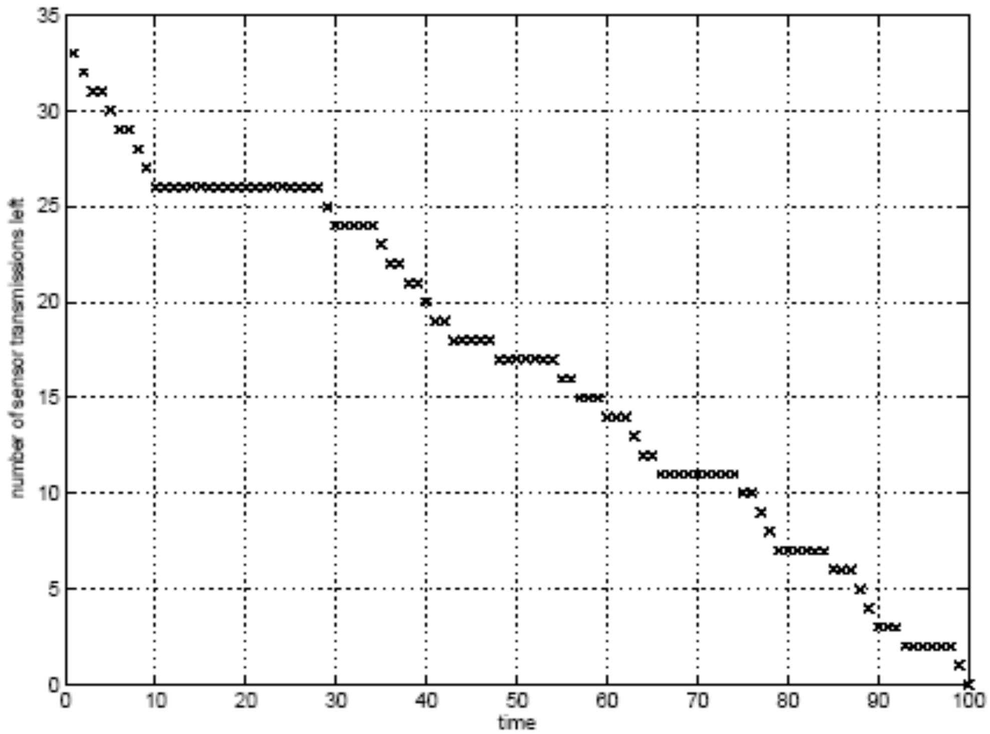
Estimation error of 20 can be achieved with 34 transmissions!

This is approximately 58% improvement --- considerable savings in battery power (if sensor is power-limited) or transmission slots (if the sensor is time-slot limited.

**Design Verification:**

1. Plot of optimal sample paths of the number of sensor transmissions left, starting with (N,M) = (100, 34)
2. Comparison of the sample path cumulative estimation errors between the optimal and an arbitrary policy

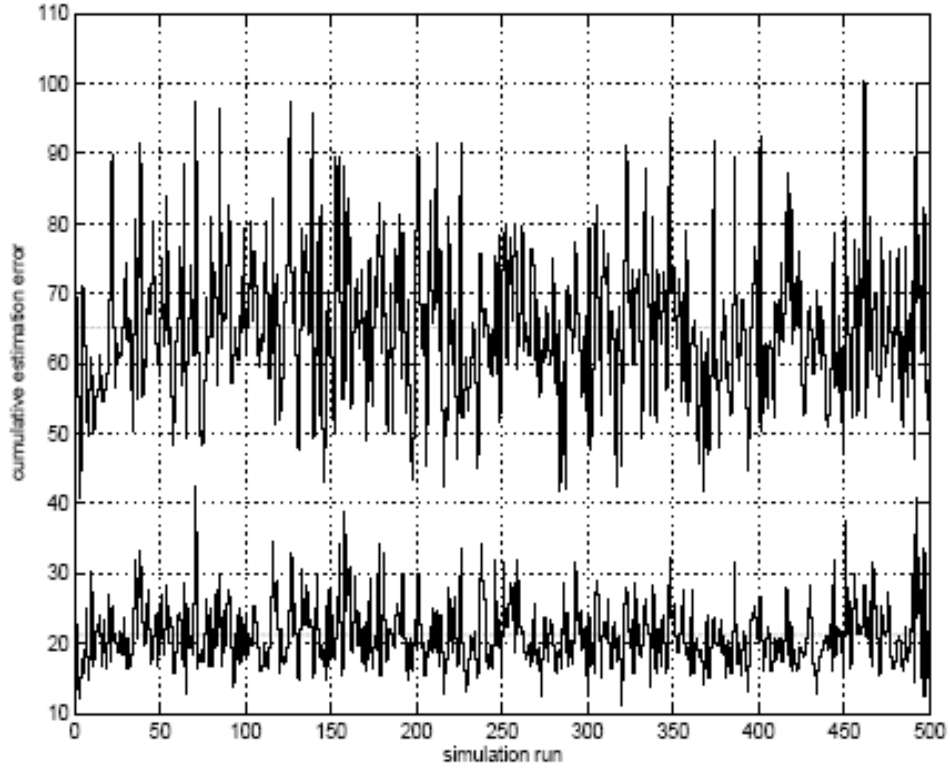
# An Illustrative Example (cont.)




Typical sample path of the number of sensor transmissions left under the optimal transmission policy of the sensor

$$(N, M) = (100, 34)$$

# An Illustrative Example (cont.)




Comparison of the sample path cumulative estimation errors between the optimal and an arbitrary transmission policy

$$(N, M) = (100, 34)$$

# Source as a Markov Process

$b_{k+1} = A\, b_k + w_k \qquad \{w_k\}$ GWN

Optimum sensor policy: keeps track of 3 variables $(r_k, s_k, t_k)$

$r_k$ : # time units passed since last transmission

At time k transmit $b_k$ if it is in a measurable set ¥$(r_k, s_k, t_k)$, otherwise do not

¥(r,s,t) obtained offline as the minimizer in a recursive equation satisfied by accumulated optimum error, $e^*(r,s,t)$, at each (r,s,t):

$$e^*(r,s,t) = \min_{¥(r,s,t)} \{ e^*(1,s-1,t-1)\, \mathrm{Prob}(b_{N-t} \in ¥) + e^*(r+1,s,t-1)\, \mathrm{Prob}(b_{N-t} \notin ¥) + \text{average error at } (r,s,t) \text{ due to decision at } (r,s,t) \}$$

# Again an interval solution

$¥^c(r,s,t) = [\alpha_{(r,s,t)}, \beta_{(r,s,t)}]$

$\beta_{(r,s,t)} = A^r b_{N-t-r} + \sqrt{\{e^*(1,s-1, t-1) - e^*(r+1,s, t-1)\}}$

$\alpha_{(r,s,t)} = A^r b_{N-t-r} - \sqrt{\{e^*(1,s-1, t-1) - e^*(r+1,s, t-1)\}}$

$\varepsilon_{(r,s,t)} := e^*(r,s,t) / \sum_{k=1}^{r} A^{2(k-1)} var(b_0)$

$$\varepsilon_{(r,s,t)} = \varepsilon_{(1,s-1,t-1)} - [(\nu_{(r,s,t)})^2 - 1][2\Phi(\nu_{(r,s,t)}) - 1] - (2/\sqrt{2\pi})\, \nu_{(r,s,t)} \exp((\nu_{(r,s,t)})^2 / 2)$$

$\nu_{(r,s,t)} := \sqrt{\{e^*(1,s-1, t-1) - e^*(r+1,s, t-1)\}}$

# Recap: Smart Sensing

Input parameters:

1. Planning horizon: Desired length of time the sensor will be in operation (N)
2. Battery size: Size of the power source installed into the sensor (M)
3. Process model (data): This is application specific, and can be gathered from a variety of sources including, measurement/historic data, modeling, etc. (Source Statistics)
4. Performance criterion: (Distortion Measure)

# Smart Sensing

## How?

- Given the input parameters and the channel compute the optimum transmission and decoding policies for the wireless sensor & the receiver
- The computation is "power aware" (M), and "planning-horizon aware" (N)
- Minimal online computational complexity (lookup table, binary comparisons,…)
- Offline computational complexity will depend on the source and channel models

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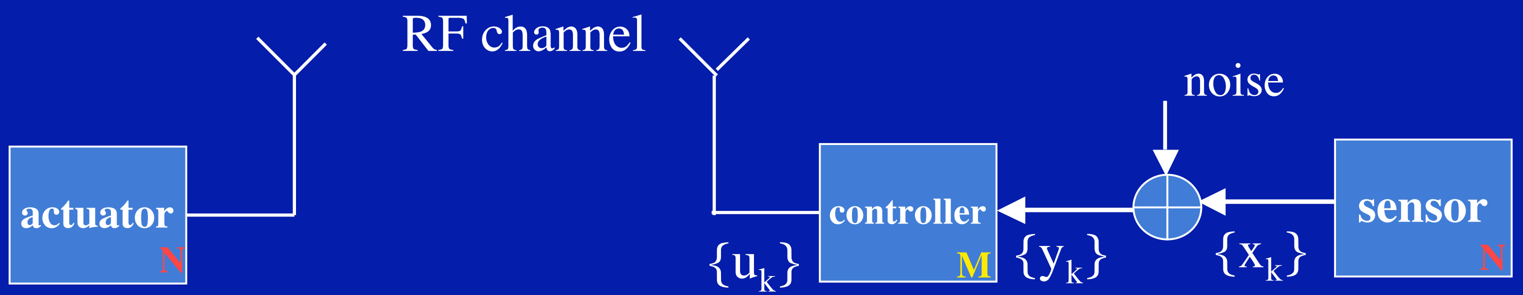
# PROBLEM CLASS II

# OPTIMAL CONTROL

# Control over a Limited-Use Channel




$x_{k+1} = Ax_k + u_k + w_k$ $\qquad$ $x_k \in R$ , $u_k \in R$ , $y \in R$

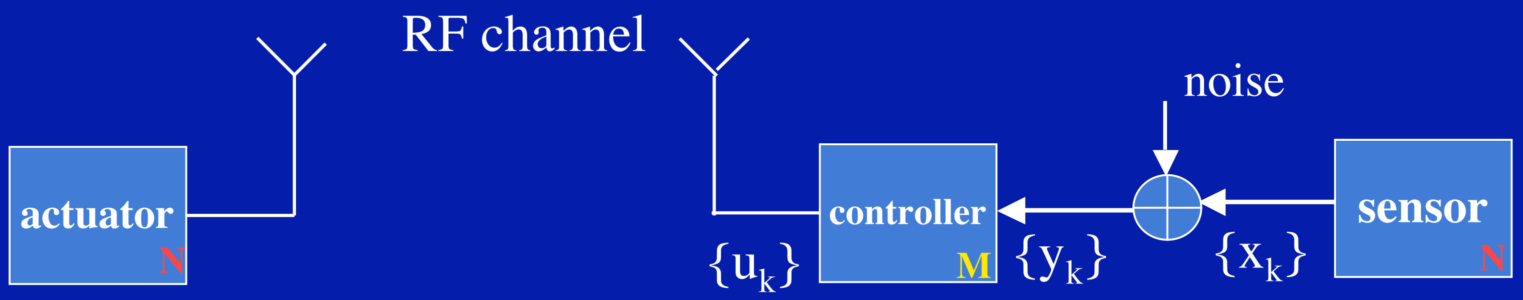
$y_k = x_k + v_k$ $\qquad$ $M < N$

$u_k = \mu_k (I_k)$, $I_k := \{y_{[0,k]}, u_{[0,k-1]}\}$, $\mu_k \to R$ only M times

*Given a horizon of N units, and with control allowed to transmit for only M < N times, what is the minimum attainable value of a performance index J, and a corresponding controller?*

$$J = E\{ (x_N)^2 + \sum_0^{N-1} (x_k)^2\}$$

# Control over a Limited-Use Channel




"Open-loop controller schedule": Determine *a priori* M time slots (out of N) when to apply control, and find the best such M slots as a result of combinatorial optimization.

**Result:** $u_k = -A\,E[x_k \mid I_k]$ for $0 \le k \le M-1$

$= 0$ for $M \le k \le N$

# Closed-Loop Controller Schedule

Scheduling of control is on-line/*a posteriori*

- s : # control actions left (a total of M)
- t : # decision instances left (a total of N)
- Given (M,N), in retrograde time, t : 1 --> N

$$\max\{0, M-(N-t)\} \leq s \leq \min\{t, M\}$$

- With t fixed, the maximum interval for t is [0, t]
- Approach is DP, moving forward in t

  (s,t) can lead to either (s-1, t-1) or (s, t-1)

# Closed-Loop Controller Schedule (continued)

## Online Computation

- For every k, $x_k$ - $E[x_k \mid I_k]$ is independent of control
- If, at k, decision is to control, the optimum choice is

$$u_k = -A\, E[x_k \mid I_k]$$

  where $E[x_k \mid I_k]$ is generated by Kalman filter.
- Decision is to control, if $\mid E[x_k \mid I_k] \mid$ exceeds a certain threshold, $\tau(s_k, t_k)$

  ==> $s_{k+1} = s_k - 1$; $t_{k+1} = t_k - 1$

# Closed-Loop Controller Schedule (continued)

## **Offline Computation**

- $\tau(s_k, t_k)$ is a function of N, $s_k$, $t_k$, $\sigma^2_{k|k-1}$
- Compute optimum cost-to-go's at (s,t), based on whether a control was applied, $J_{(s,t)}^{(1)}$, or not, $J_{(s,t)}^{(0)}$
- $\Delta_{(s,t)} := J_{(s,t)}^{(0)} - J_{(s,t)}^{(1)} = 0$ determines the threshold (it has two roots -- one positive and one negative)

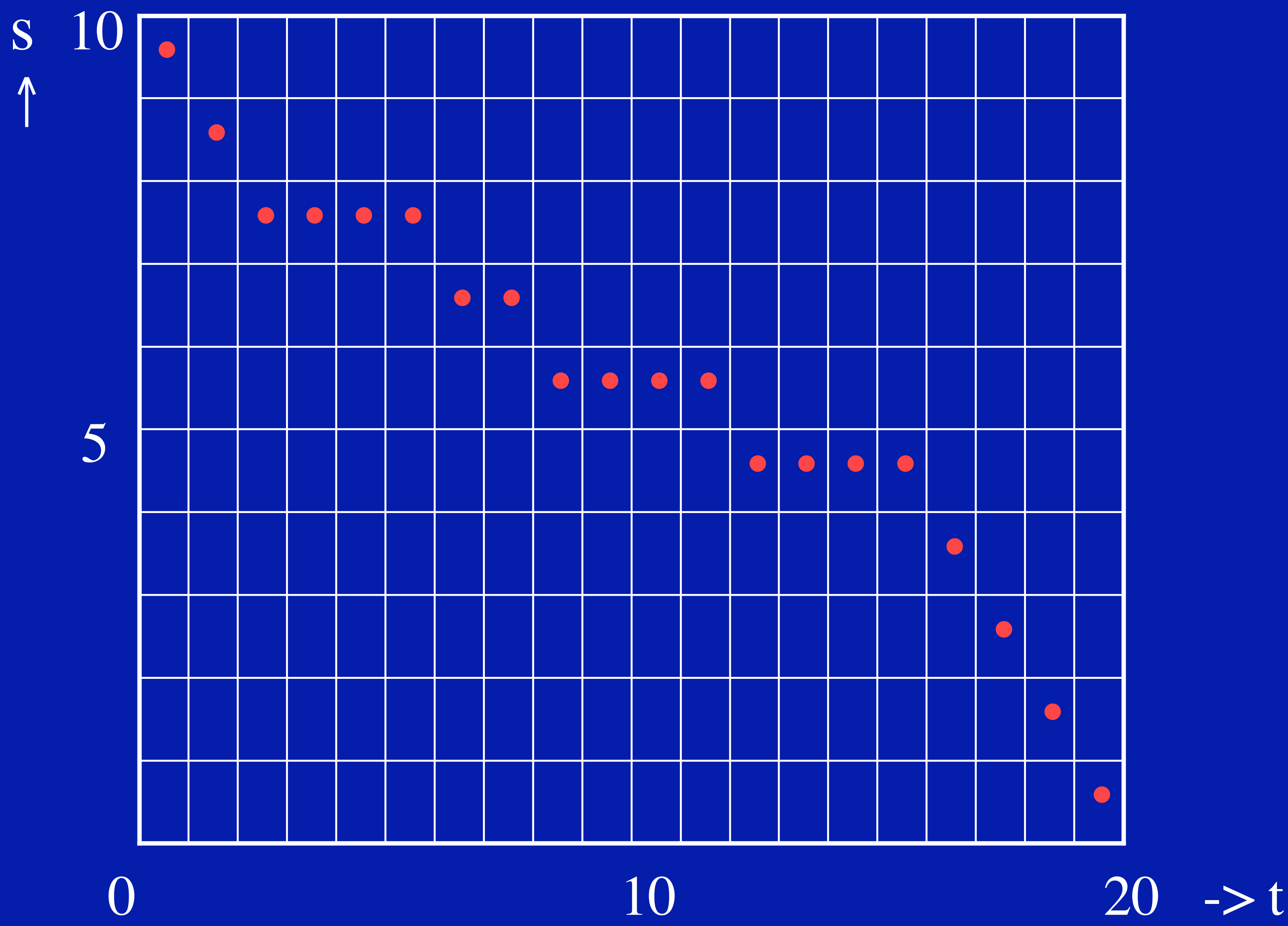
$$\Delta_{(s,t)}(\,\tau(s,t)\,) = \Delta_{(s,t)}(\,-\tau(s,t)\,) = 0$$

# Numerical Solutions

**Numerical integration was used to compute the recursions $\Delta_{(s,t)}$ , which led to thresholds $\tau(s, t)$**

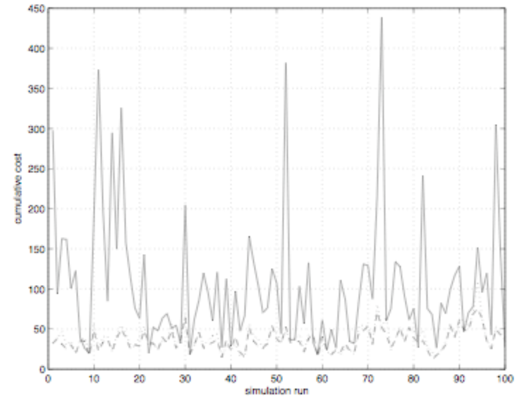
**Implemented the optimal control with M actions for an N-stage problem (N=20). Computed $J_{(M,N)}^*$ based on sample paths, and for different M values**

Times of control action ==>


s
10
5
0
10
20
-> t

# Numerical Solutions (continued)

**$N = 20, A = 1, \sigma_w^2 = \sigma_v^2 = 1$**




Sample path N-stage costs, for M = 1, 10, 20
100 simulation runs

| M | $J^*_{(M,N)}$ | % |
|---|---|---|
| 1 | 96.4266 | 203.9327 |
| 2 | 68.1907 | 114.9343 |
| 3 | 47.2060 | 48.7914 |
| 4 | 44.0160 | 38.7366 |
| 5 | 39.8642 | 25.6503 |
| 6 | 37.1557 | 17.1132 |
| 7 | 35.6168 | 12.2627 |
| 8 | 34.1551 | 7.6555 |
| 9 | 33.6935 | 6.2005 |
| 10 | 33.6913 | 6.1936 |

| M | $J^*_{(M,N)}$ | % |
|---|---|---|
| 11 | 33.2445 | 4.7853 |
| 12 | 32.9262 | 3.7820 |
| 13 | 32.8267 | 3.4684 |
| 14 | 32.4936 | 2.3249 |
| 15 | 32.1082 | 1.2037 |
| 16 | 31.9824 | 0.8072 |
| 17 | 31.8822 | 0.4914 |
| 18 | 31.8417 | 0.3637 |
| 19 | 31.7337 | 0.0233 |
| 20 | 31.7263 | 0 |

# Outline

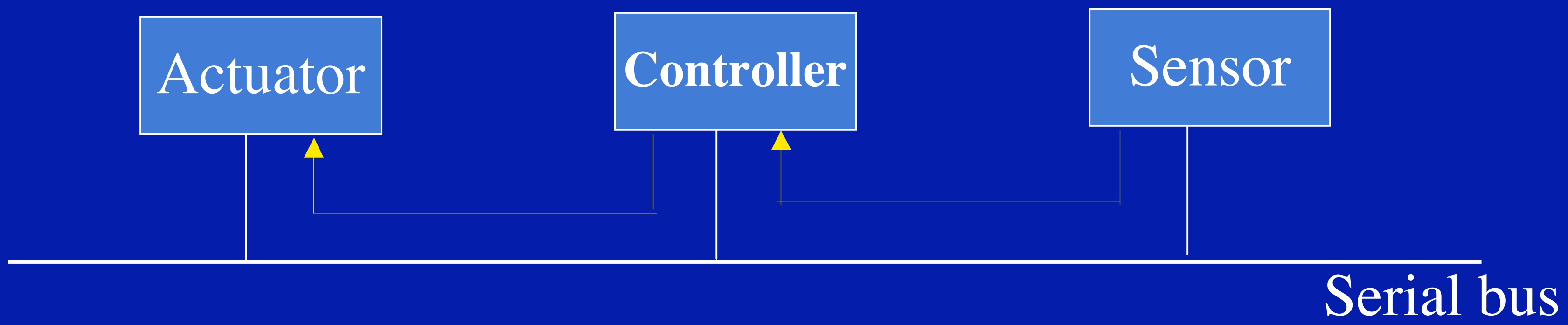
- Networks & Control
- Joint sensor-controller design

  -- What/when/how to transmit & control
- Estimation with "Power-Limited Communication"
- Control with "Power-Limited Communication"
- **When to measure & when to control**
- Other issues / Conclusions

# PROBLEM CLASS III

# OPTIMAL MEASUREMENT AND CONTROL

# Scheduled Measurements & Controls



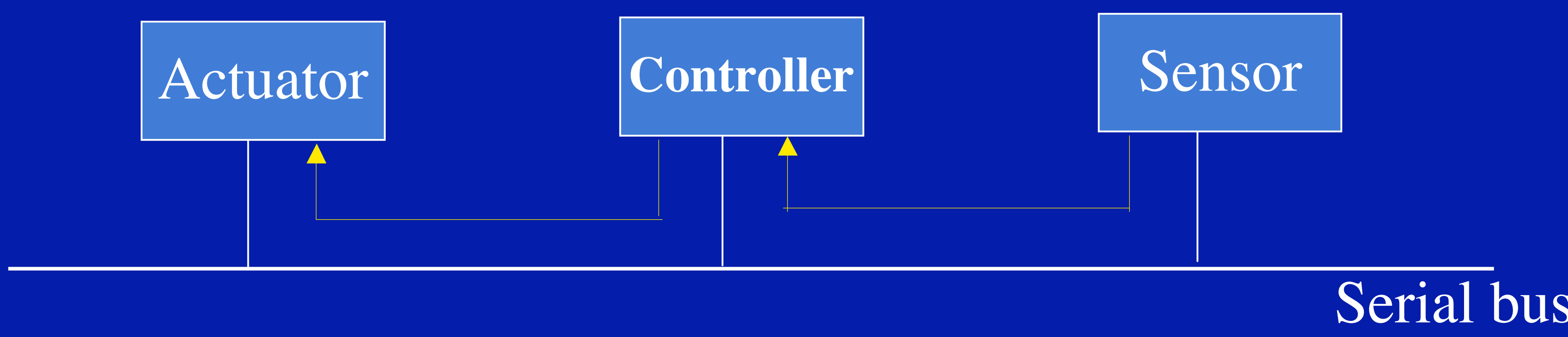

$$x_{k+1} = A\,x_k + a_k\,u_k + w_k\,, \quad k = 0,\ldots, N\text{-}1$$

$a_k$ is 0 or 1

$$y_k = (1 - a_k)\,x_k\,,\ k = 0,\ldots, N\text{-}1$$

measurement

# Scheduled Measurements & Controls

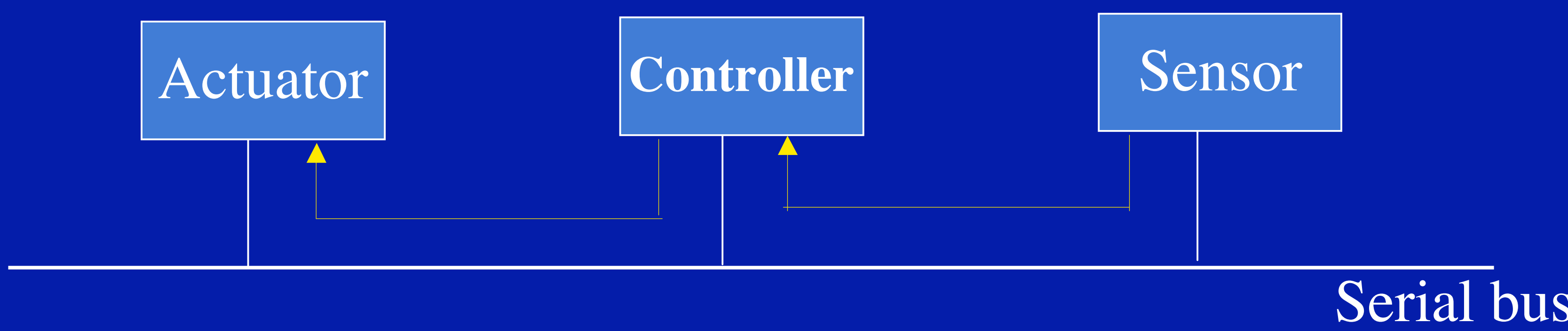



$$x_{k+1} = A\, x_k + a_k\, u_k + w_k\ ,\quad k = 0, \ldots, N-1$$

**Policies:** $(\alpha_k(I_k), \mu_k(I_k)) \dashrightarrow (0, 0)$ or $(1, u_k)$

$$I_k = \{\, y_{[0,\, k-1]},\, u_{[0,\, k-1]} \,\},\quad k = 1, \ldots, N-1$$

# Scheduled Measurements & Controls




$$x_{k+1} = A\, x_k + a_k\, u_k + w_k\ ,\quad k = 0,\ldots, N\text{-}1$$

**Find** $\pi = \{(\alpha_k\,(I_k), \mu_k(I_k)),\ k=1,\ \ldots,\ N\text{-}1\}$

minimizing $J_\pi = E\{\ x_N^{\ 2} + \sum_0^{N-1}\ x_k^{\ 2}\ \}$

# Optimal open-loop scheduled policy:

Optimal open-loop scheduled policy:

**M C M C M C M C M C M C M C**

Optimal open-loop scheduled policy:

**M C M C M C M C M C M C M C**

$$u_k = -A^2 x_k$$

Optimum OL average cost (infinite horizon)

$$\mathbf{J^*_{OL}} = \left(1 + A^2 + (1/2)\,A^4\right) \mathrm{var}(w)$$

## Optimal closed-loop scheduled policy:

A threshold policy (as in the previous case)

Propagate cost-to-go's $J_k^{(0)}$ and $J_k^{(1)}$

This leads to offline computation of the difference $\Delta_k(\tau)$, whose positive root is the optimal threshold at time k.

# Optimal closed-loop scheduled policy (continued)

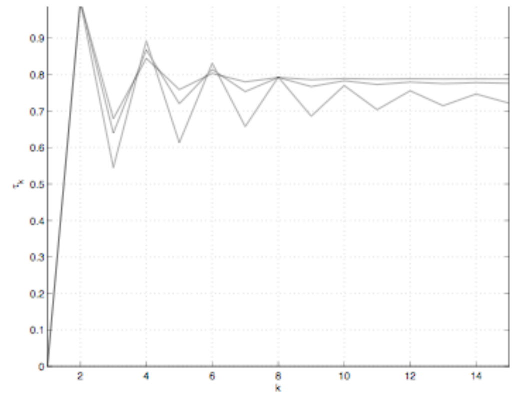
Online implementation:

At k=0, start by measuring (M). For other k:

$$
\begin{aligned}
(\mathbf{a}_{\mathbf{k+1}}, \mathbf{u}_{\mathbf{k+1}}) &= (0,0) && \text{if } a_k = 0,\ |x_k| \le \tau_k \\
&= (1, -A^2 x_k) && \text{if } a_k = 0,\ |x_k| > \tau_k \\
&= (0,0) && \text{if } a_k = 1
\end{aligned}
$$

# Numerical Study

Convergence of $\tau_k$ as $k \to \infty$



**var(w) = 1, A=1, $\tau_k$ converges: 0.7767**

**Does not show much sensitivity to A**

**Rate is sample-path dependent**

# Other Settings

- Noisy measurements (KF with uncertain observations)
- Multi-dimensional case (conceptually similar)
- Cost on control (no longer linear)
- Unreliable/failure prone links for sensing and control transmission
- Multiple agents with infrequent exchange of information and decision
- Nonlinear systems

# Recap

- Networks & Control
- Joint sensor-controller design

  -- What//when/how to transmit & control
- Estimation with "Power-Limited Communication"
- Control with "Power-Limited Communication"
- When to measure & when to control

**Literature:** OCI-TB CDC'05; ACC'06 (2)