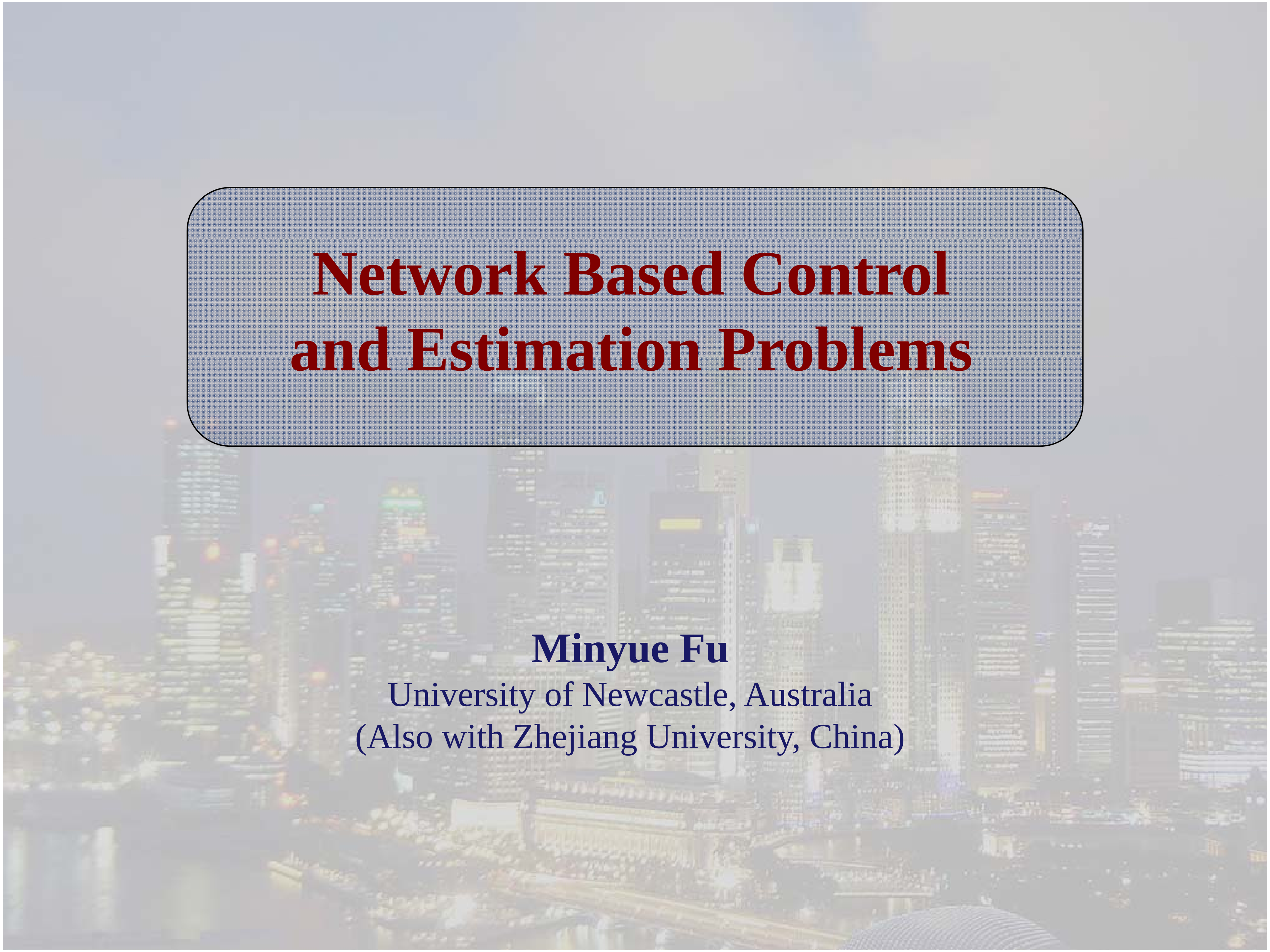

Network Based Control and Estimation Problems

Minyue Fu
University of Newcastle, Australia
(Also with Zhejiang University, China)

Outline

- Introductory Comments on Networked Control Systems
- Examples of Applications
- Research problems in networked control and estimation
- Concluding Remarks

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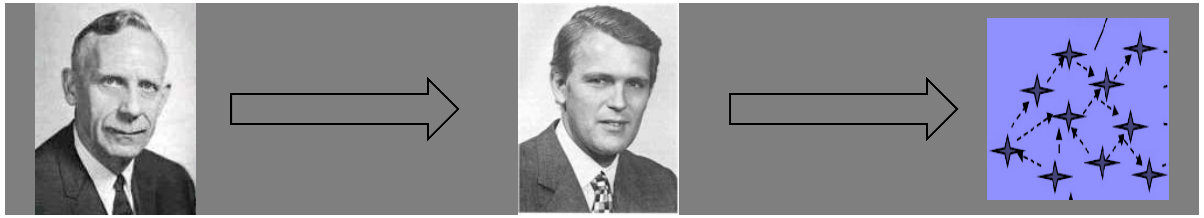
After the eras of classical control theory (frequency domain approach) and modern control theory (state-space approach), we are in the era of *Networked Complex Dynamic Systems*.

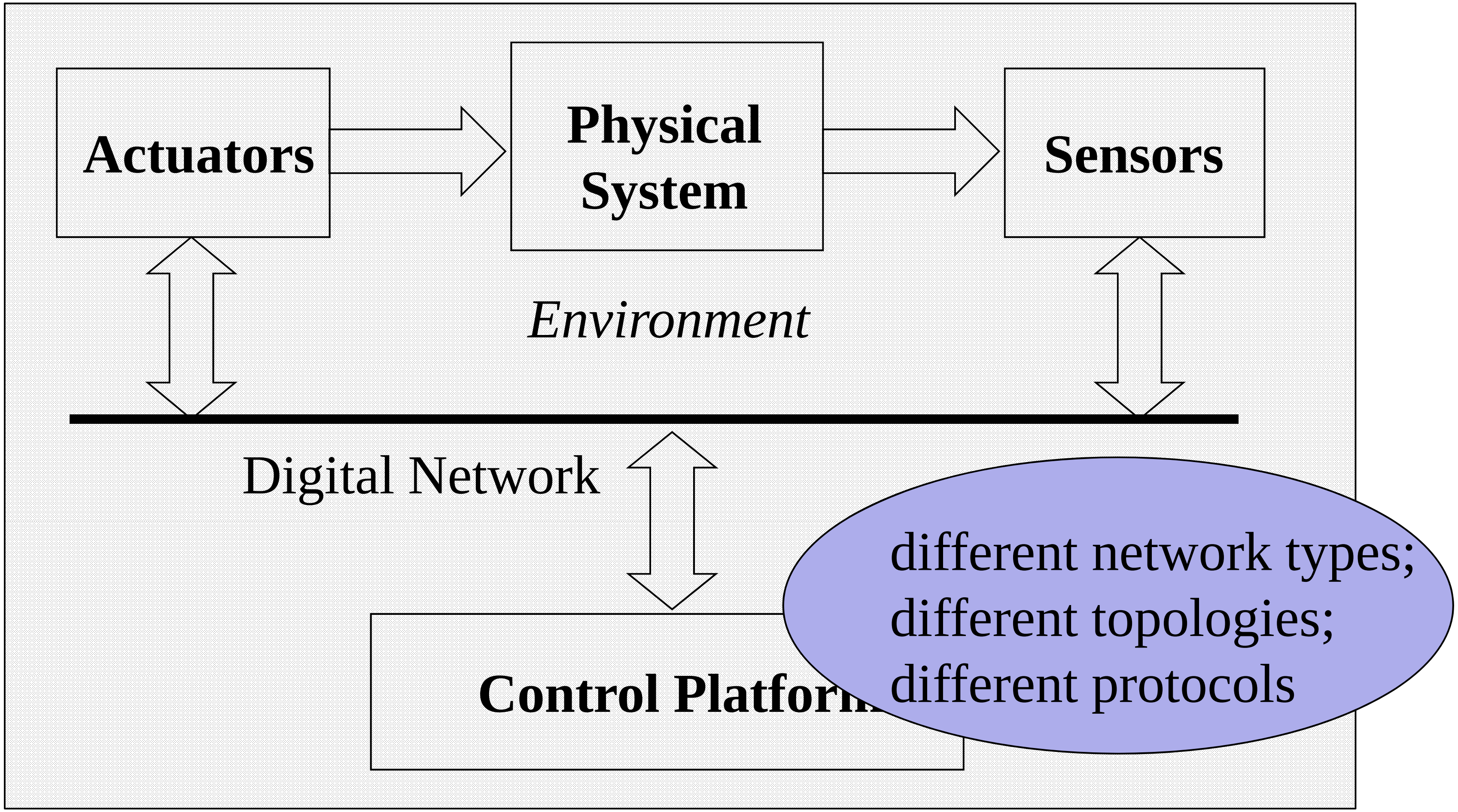


Migration of the Control Field

Single-loop/multi-loop;
Centralised control;
Limited sensing;
Limited computing;
Limited applications

Large interconnected systems;
Distributed processing;
Embedded sensing and actuating;
Communication networks;
Wired and wireless technologies;
Multidisciplinary applications (bio/nano/quantum/energy/environment)

Networked Control Systems



different network types;
different topologies;
different protocols

Outline

- Introductory Comments on Networked Control Systems
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- Concluding Remarks

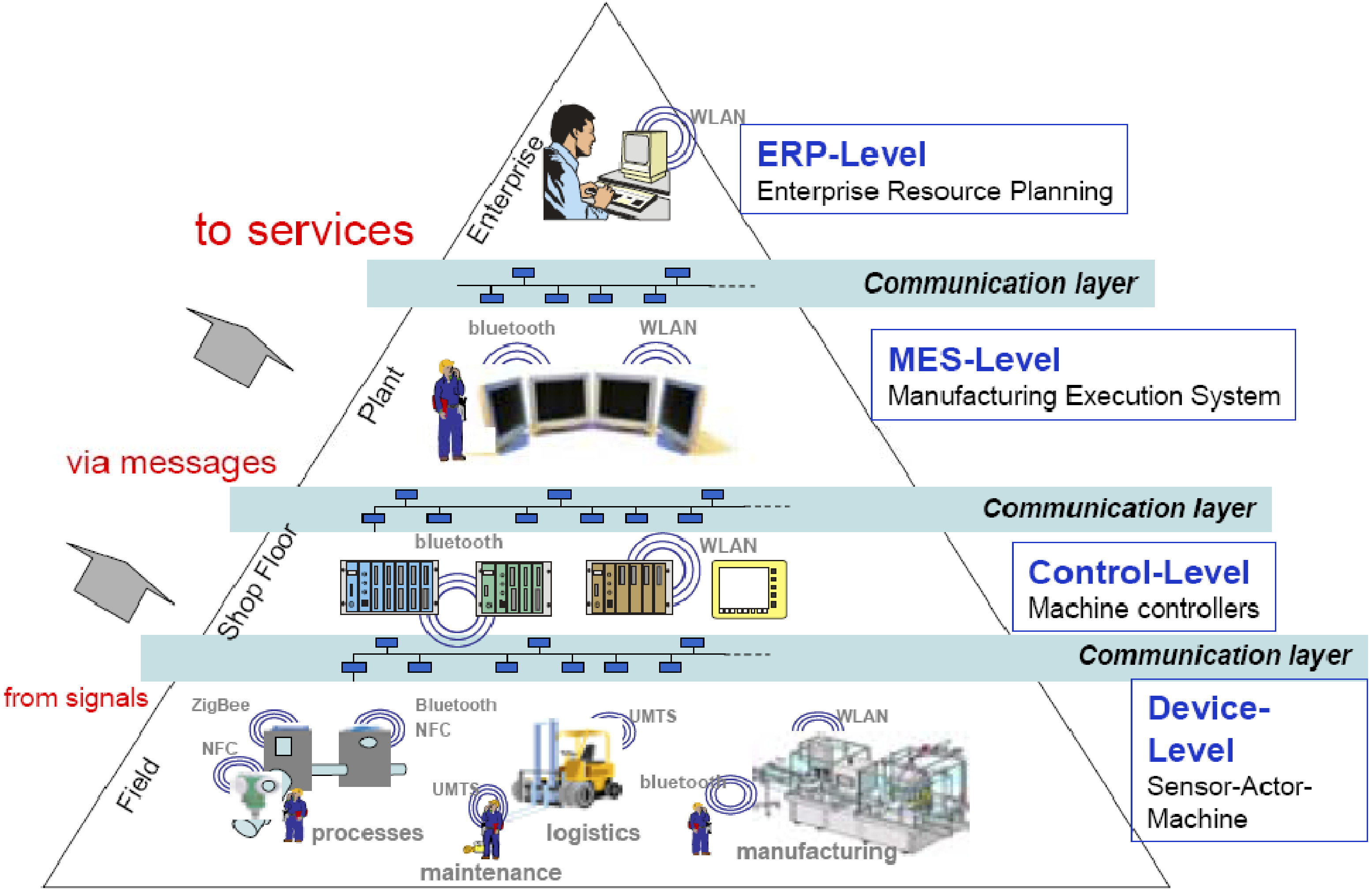
Example 1: Industrial Control Systems

- First Generation: Mechanical systems
  - Mechanical links, Hydraulic links,…
- Second Generation: Electrical systems
  - Electrical wires: point-to-point connections between actuators, sensors and control platform
- **Third Generation: Networked systems**
  - Hierarchical, multi-layer control structure connected via digital networks
  - Different types of networks (DeviceNet, Fieldbus, LAN…)
  - Wireless is a dominant and challenging trend

Remark

Control theory started to study networked control only recently, way after industrial control network systems became commercial, routine and reliable.

Automation and Control Pyramid



to services

via messages

from signals

ERP-Level
Enterprise Resource Planning

Communication layer

MES-Level
Manufacturing Execution System

Communication layer

Control-Level
Machine controllers

Communication layer

Device-Level
Sensor-Actor-Machine

Source: *SmartFactory*, Germany

Main Challenges for Wireless

- Reliability & Security
- Premature technology
- Inadequate standards for industrial control
- **Lack of rigorous control design methods**

The current wireless technologies are developed mainly for three types of applications:

- voice communication (mobile phones)
- sensor networks (low data-rate applications, e.g. Zigbee)
- data communication (e.g., wireless LAN)

They typically involve

- large transmission delays (hundreds of milliseconds)
- packet dropouts (serious problem, also related to TX delays)
- transmission errors
- quantization errors (low resolution quantization)

Fundamental Conflict:

Contention-based communication protocols

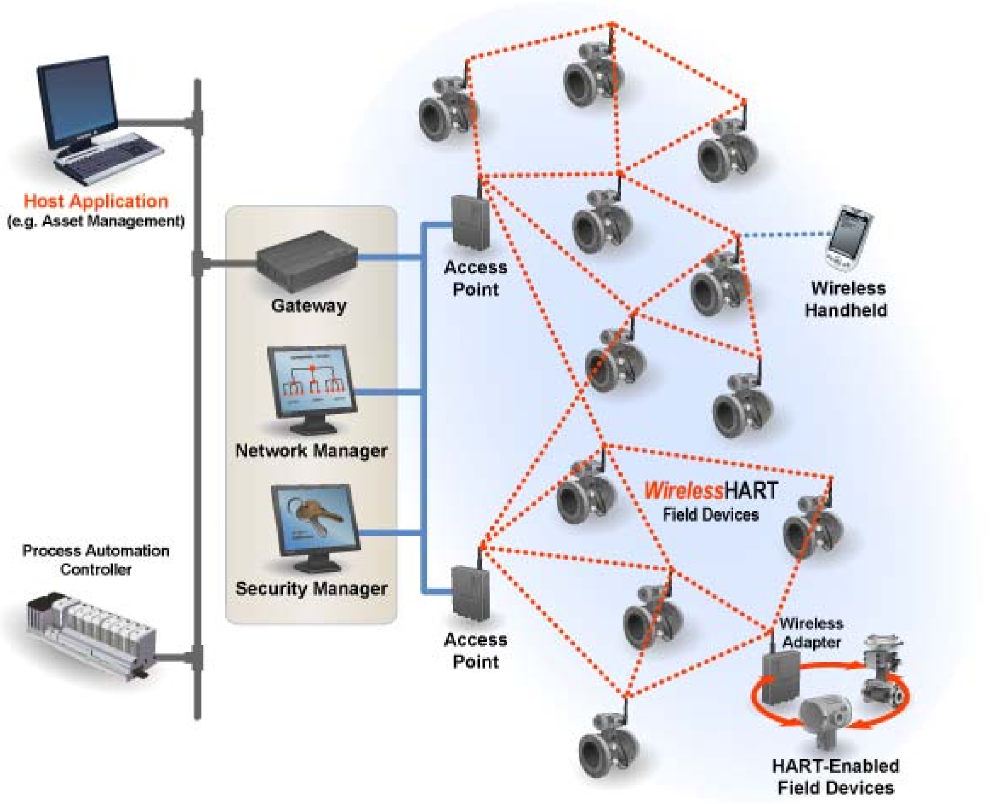
vs.

Time-based control requirements

Wireless HART

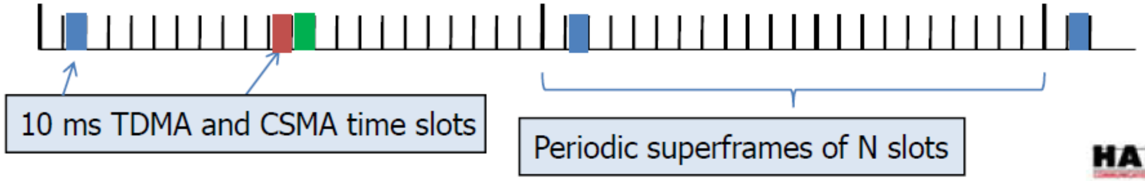
HART COMMUNICATION FOUNDATION

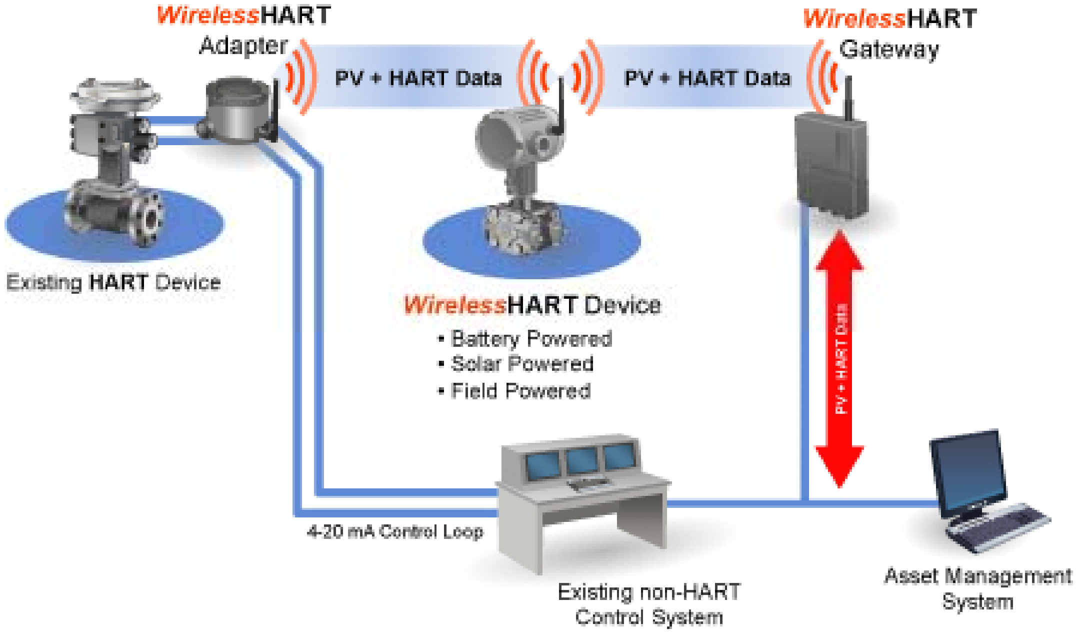
- Developed by HART Communication Foundation in conjunction with Emerson, ABB and Siemens.
- Designed to support the wide range of process industry use cases from simple monitoring to closed loop control



Star-mesh topology

- Protocol: mixed TDMA and CSMA
- Time synchronization: accuracy of 1msec
- Time delay: theoretical max = 20 msec per hop;   average = 30 msec
- Devices: WHART device/adaptor/gateway





Preliminary assessment on 1-sec cycle process control loops with a 3 to 4 hop WirelessHART network:

- The overall control performance of a typical *WirelessHART network is comparable to that of traditional wired field buses.*
- The *WirelessHART protocol allows for secure, highly reliable, low latency control with almost no impact* on the bandwidth and absolutely no impact on process performance.
- *WirelessHART is simple, reliable, and secure.*

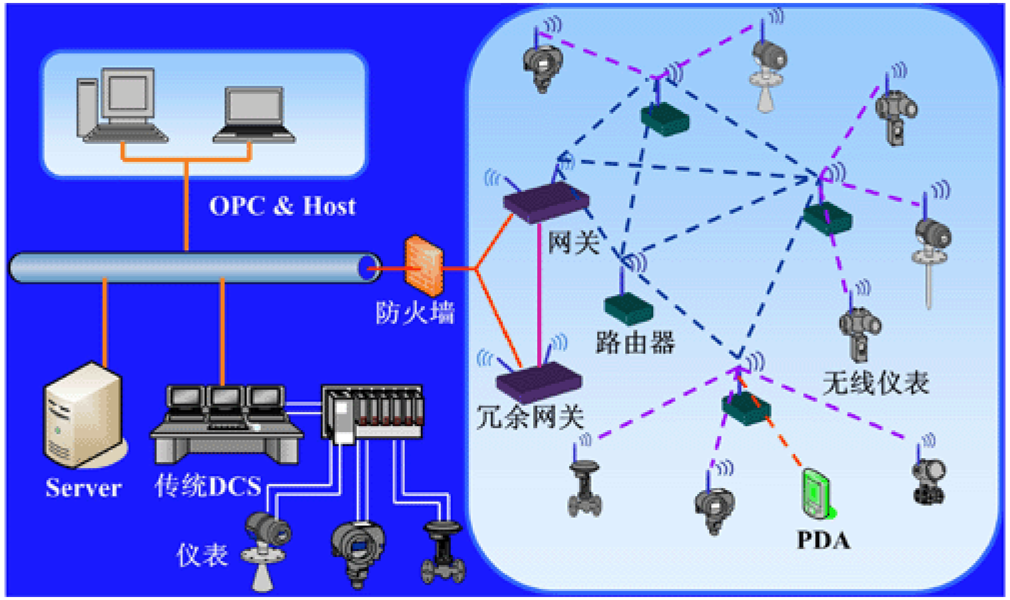
(source: “Control with WirelessHart,” Hart Communications Foundation)

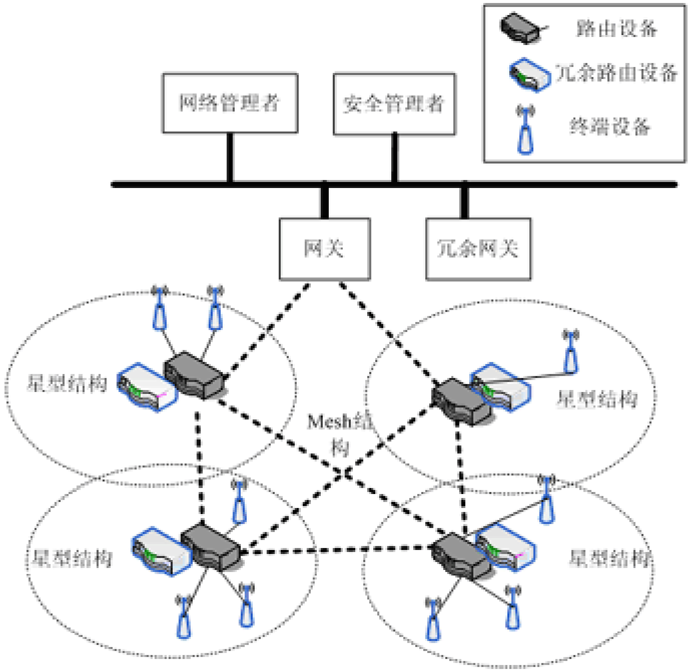
ISA Fellow Greg McMillan conducted a research in early 2009 on commercial bioreactors using WirelessHart PH devices and concluded that *with a comprehensive battery life management approach, exception reporting, and a secure, reliable self-organizing and optimizing network, wireless process control is ready for all but the fastest processes, provided the transmitter resolution settings are right for the application.*

(Source: G. McMillan, “Is wireless process control ready for prime time?” Control Global, May 2009.)

工业无线网络WIA
Industrial Wireless Network WIA

- Developed by Chinese Science Academy (中国科学院沈阳自动化所)
- 工业无线网络WIA技术体系是由中国工业无线联盟推出的具有自主识产权的技术体系，形成了国家标准草案，并与Wireless HART、ISA100并列为主流的工业无线技术体系。
- 于2008年10月被IEC列为一个新的公共可用规范（PAS）进入国际标准化进程; 预计在2011年12月，WIA-PA规范将正式成为IEC国际标准。





WIA-PA Products

Wireless modules, wireless gateways, wireless access points, wireless sensors, …

Successful Applications

- 循环流化床锅炉压力温度传输系统
- 抽油井示功图无线监测系统
- 电机系统能源效率在线监测与能源管理
- 连轧厂连续退火生产线炉棍轴承温度检测系统

Large scale development and applications, rigorous tests of the standard, and comprehensive comparison with WirelessHART are yet to happen.

Example 2: Smart Electricity Grid

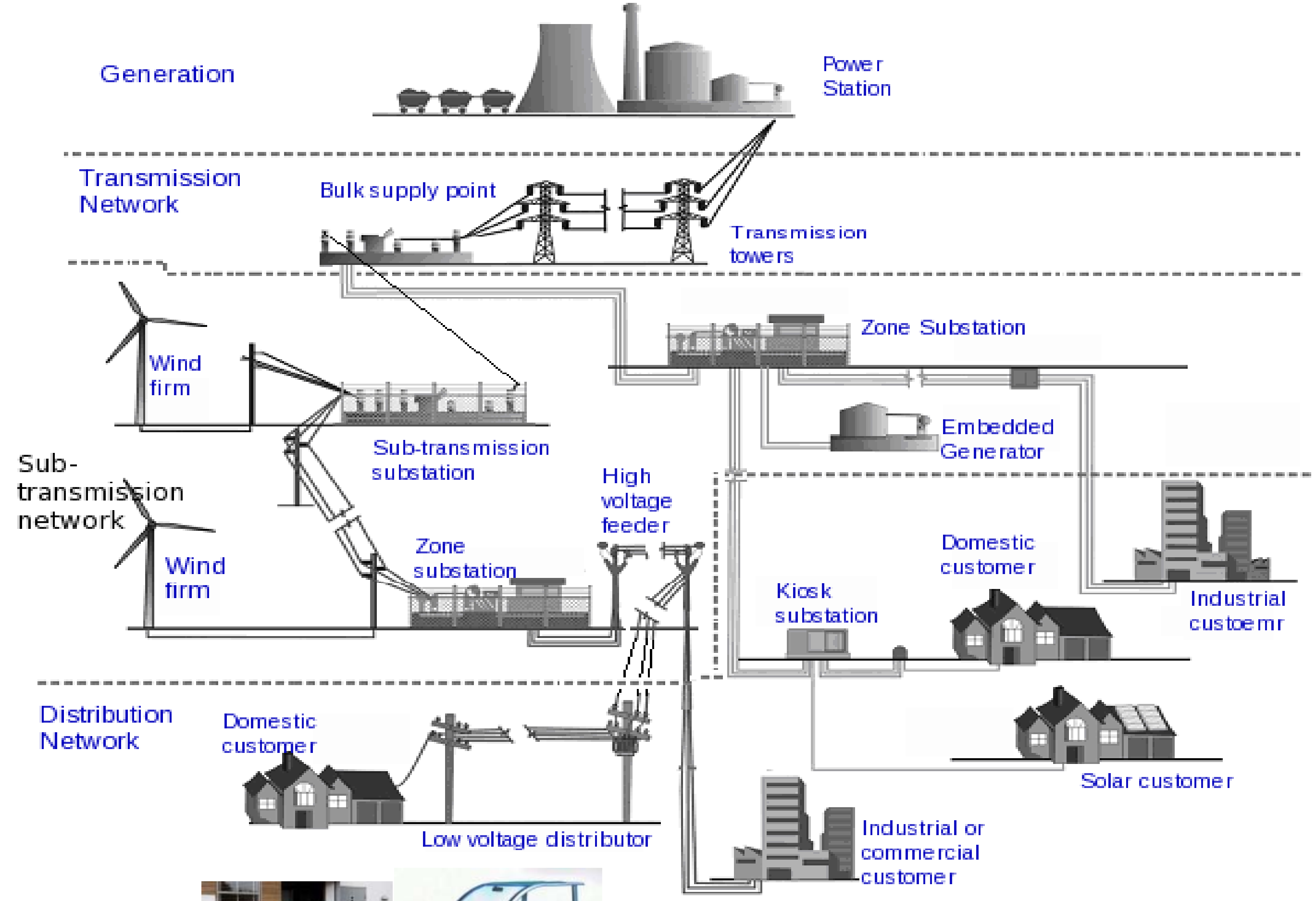
Modern electricity Networks need to be able to cope with

- Diversified range of energy sources
  - Traditional baseline generation (coal, oil, hydro…)
  - Renewable (wind, solar, tidal, wave, geo-thermal, …)
  - Distributed generation (gas turbines, fuel cells, …)
- Diversified range of loads
  - air-conditioning systems
  - electrical vehicle charging systems
  - bi-directional loads (through micro-grids)

Driving Forces

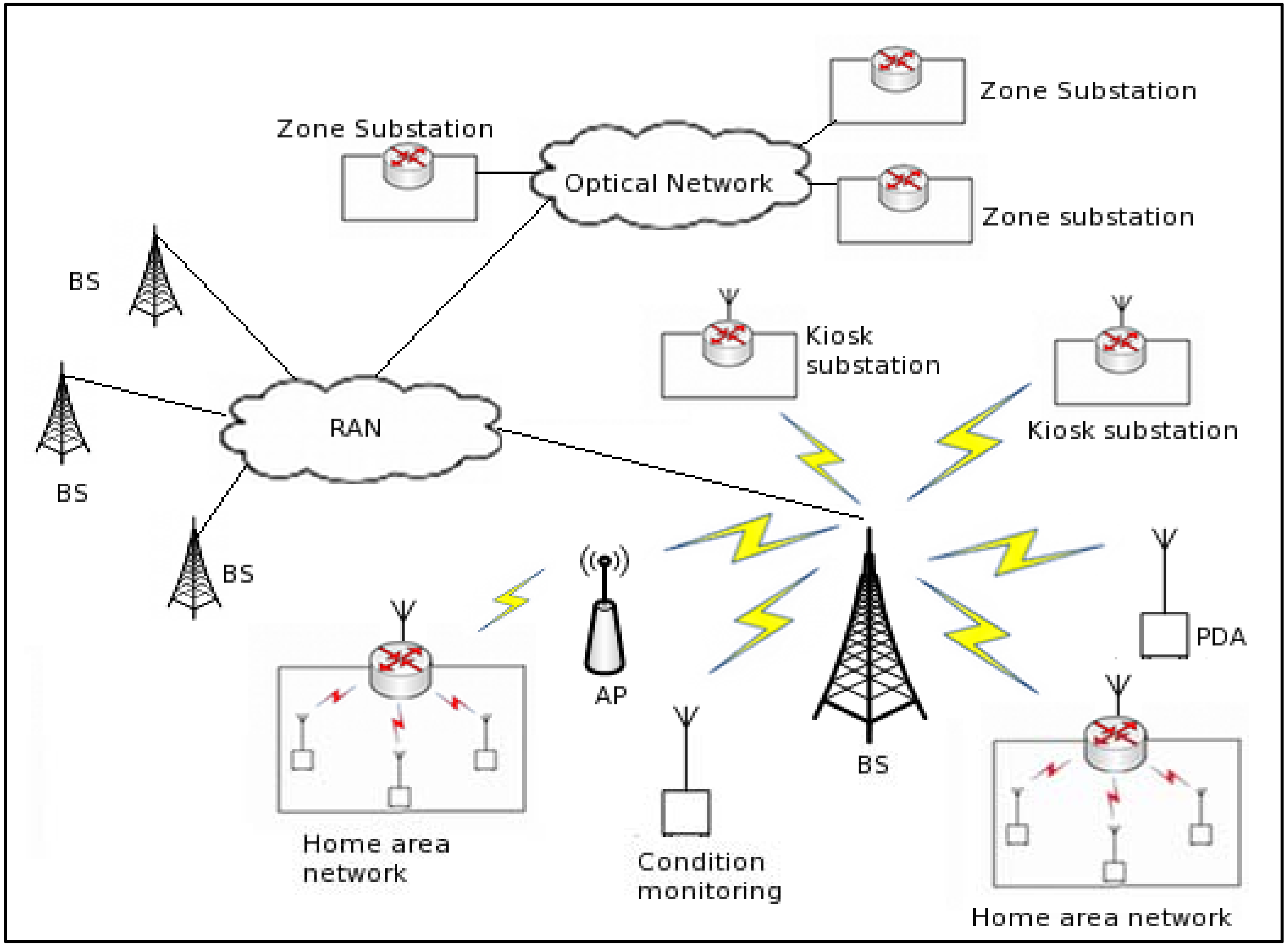
- More efficient energy usage
- Less environmental impact
- Financial means: real-time pricing

Electricity Distribution Network



Courtesy of *EnergyAustralia*

Smart Grid Comms Network: (Designed at University of Newcastle)



Research Problems

- Developing the basic frameworks for the **wireless communications network** infrastructure for an intelligent electricity grid.

- Developing a comprehensive **communications and control network simulation model** to evaluate the performance of the developed smart grid for different applications, demographic and topographic scenarios.

- Developing **network-based control and estimation** strategies for smart grid to ensure stable operations and optimized energy utilization, and to deal with the intermittent, and unpredictable nature of renewable sources.

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Two Approaches

Use sufficient network resources (bandwidth, power, redundancy …) to ensure that wireless transmission is *guaranteed* to be *sufficiently* fast and reliable, i.e., network problems (such as delays, packet losses, data rate limit) become negligible. Wireless networks essentially become wired networks, transparent to the users.

Develop a rigorous networked control theory to deal with network problems so that control performances can still be *sufficiently guaranteed* despite of the network problems.

We will focus on the latter approach.

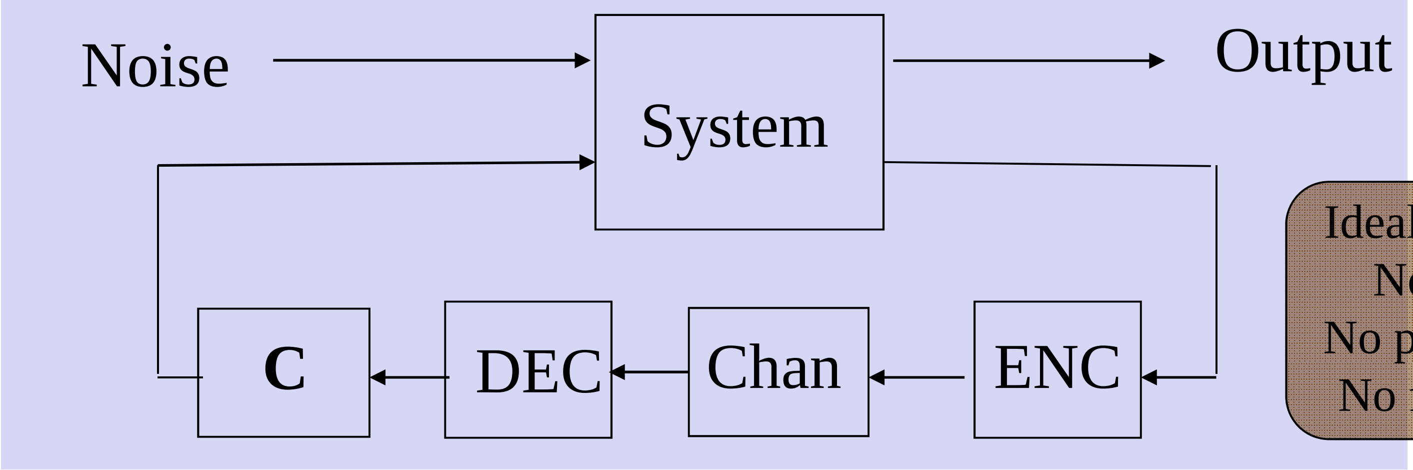
Samples of Research Problems

- Networked Control Problems
- Networked Estimation Problems
- Consensus Problems
- Modeling of Communication Systems

Networked Control Problems

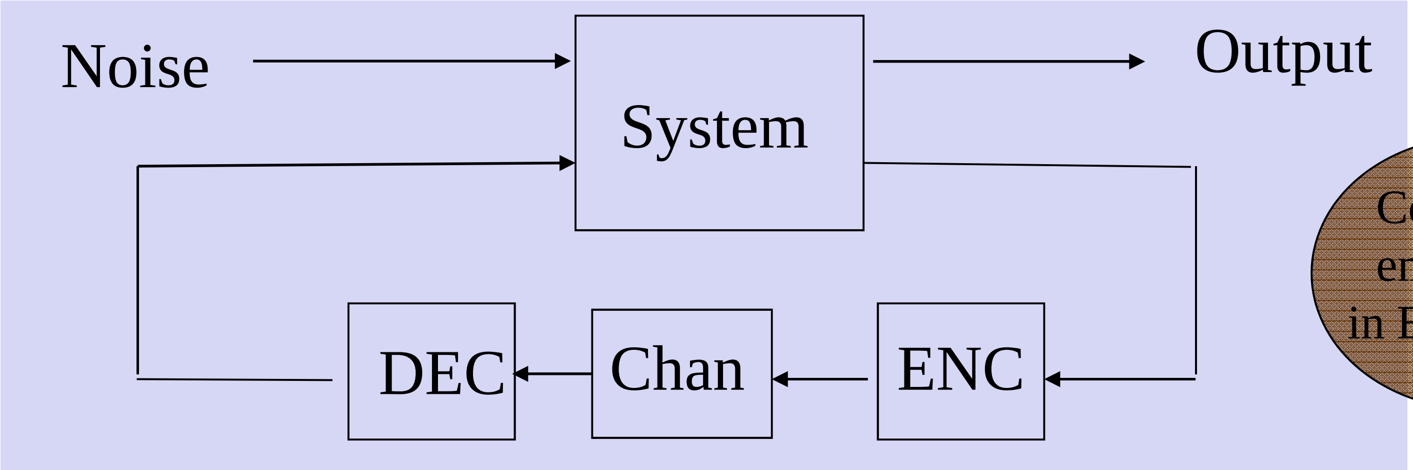
Quantized Feedback Control

Structure for Networked Control:



Ideal Channel:
No delay,
No packet loss
No fading,…

Simplified (and More General) Structure:



Controller
embedded
in ENC/DEC

Some Known Results for Linear Systems

System:
$$x[k+1] = Ax[k] + Bu[k]$$
$$y[k] = Cx[k]$$

Minimum Data Rate for Stabilization

(Nair&Evans, System &Control Letters, 2000)

If the quantizer is allowed to have memory (or dynamic), then the minimum data rate for feedback stabilization is

$$R > \log_2 \prod_i \lambda_i^u(A)$$

unstable eigenvalues

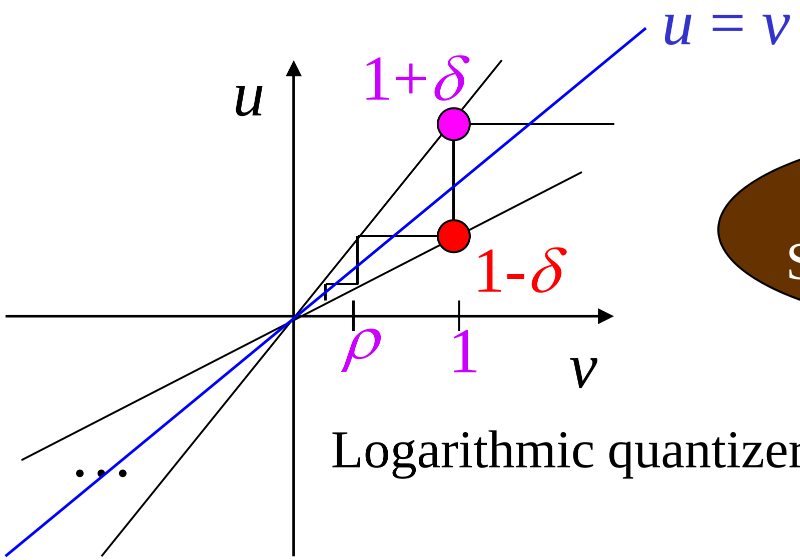
Various generalisations : stochastic, MIMO, nonlinear, …

Minimum Quantization Density

(Elia&Mitter , *IEE-TAC* 2001, Fu&Xie, *IEEE-TAC* 2005)

If the quantizer must be static and quadratic stability is of concern, then the optimal structure is logarithmic and the minimum quantization density for stabilization is

$$\rho > \frac{1-\delta}{1+\delta}, \qquad \delta^{-1} = \prod_i |\lambda_i^u(A)|$$



Logarithmic quantizer

Also known as the Sector Bound Approach

Other Related Results:

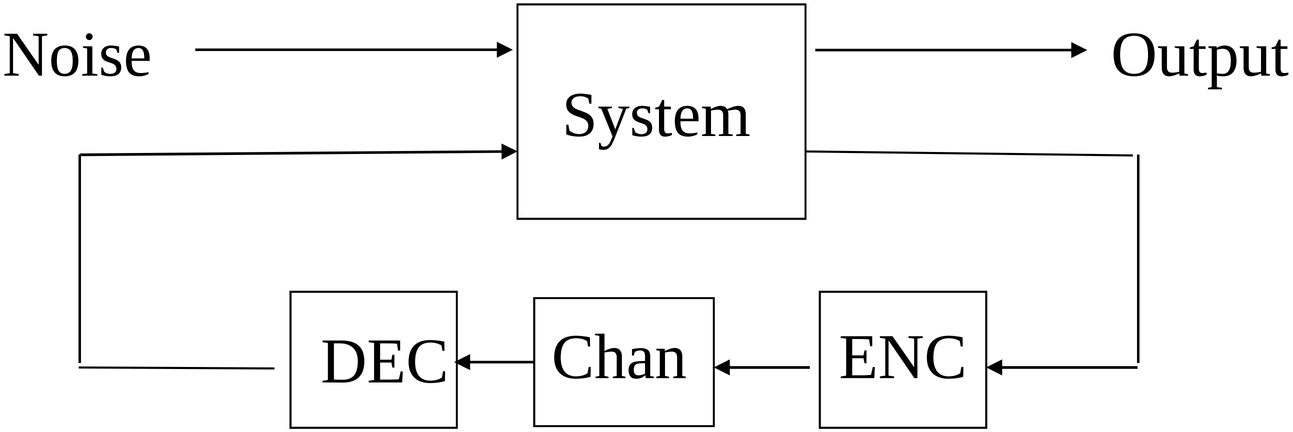
Relationship between logarithmic quantizer and dynamic quantizer (Fu, Su, You and Xie, *Automatica* 2010):
The minimum data rate for stabilization can be achieved using a variable-rate logarithmic quantizer.

Minimum data rate for stabilization under packet loss (You and Xie, *Automatica* 2010): The minimum data rate for stabilization subject to i.i.d. packet arrival rate λ is precisely determined.

Optimal tracking control subject to logarithmic quantization (Qi & Su, *ICARCV* 2008, ASCC 2009): Generalisation of quantized stabilization to optimal tracking control is made.

Quantized Linear Quadratic Gaussian (LQG) Control

(Nair et.al., Proc. IEEE 2007; Fu, CDC 2008)



Problem
Standard LQG problem, but subject to bit rate constraint

Known results

1) Separation Principle fails in general;
2) When the bit rate is not too small,
   Separation Principle holds approximately.

How to *best* design quantizer and controller is still open.

Process Control Problems

At Control/Device Levels

- Feedback stabilization
- PID Control
- LQG Control
- Model Predictive Control (MPC)
- State Estimation and Fault Diagnosis

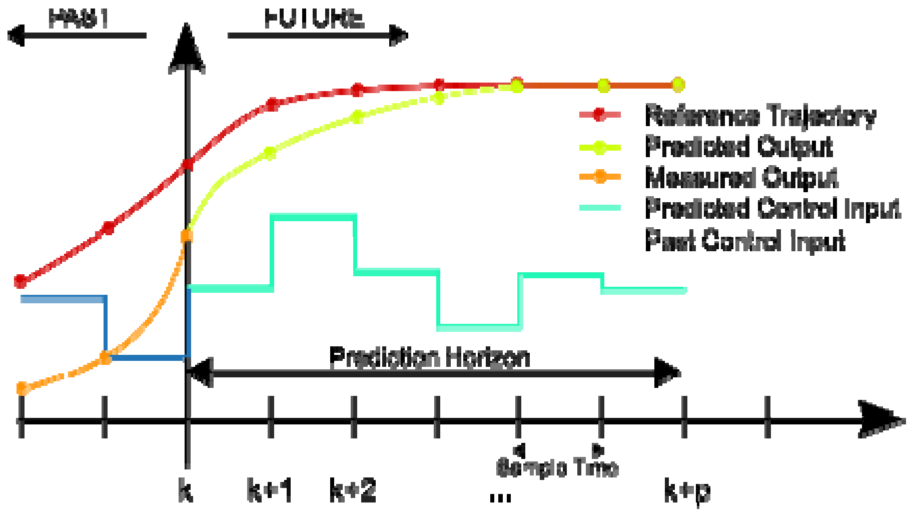
At Manufacturing/ERP Levels

- Scheduling
- Resource allocation and optimization

Key Questions

- How to solve these problems in the presence of wireless?
- Can wireless do as well as wired solutions?
- When and where to use wireless?

MPC Design with Network Constraints



on-line design

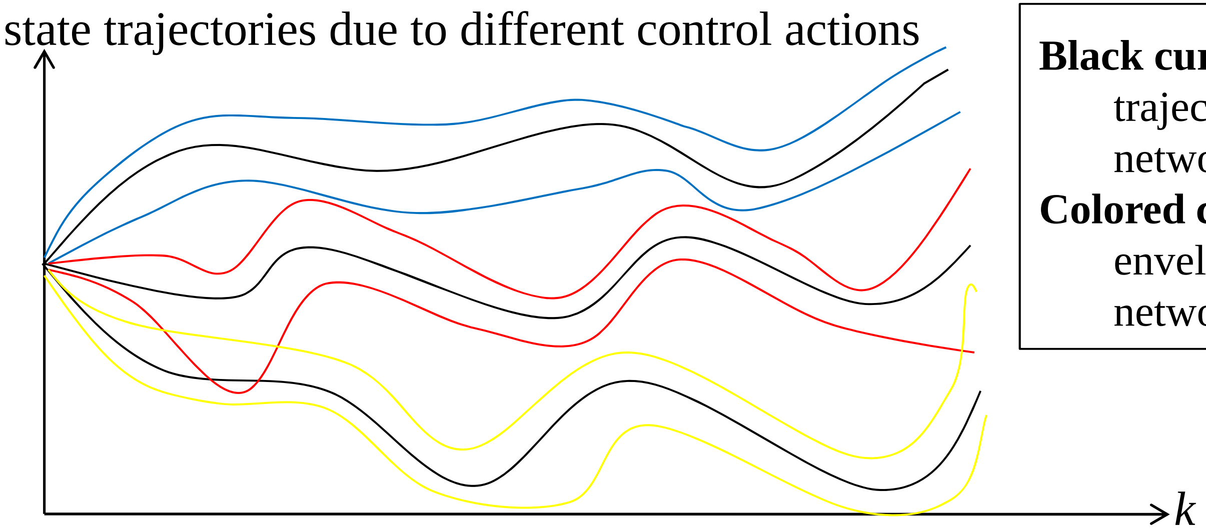
Minimize:

$$J = \sum_{i=1}^{N} w_i (r_i - x_i)^2 + v_i \Delta u_i^2$$

deterministic setting

Key Problem: How to minimize *J* now, over a given distributions for packet loss, time delays and finite alphabets?

Smart ideas are needed to avoid computational complexities.



Black curves: possible trajectories without network constraints

Colored curves: trajectory envelopes due to network constraints

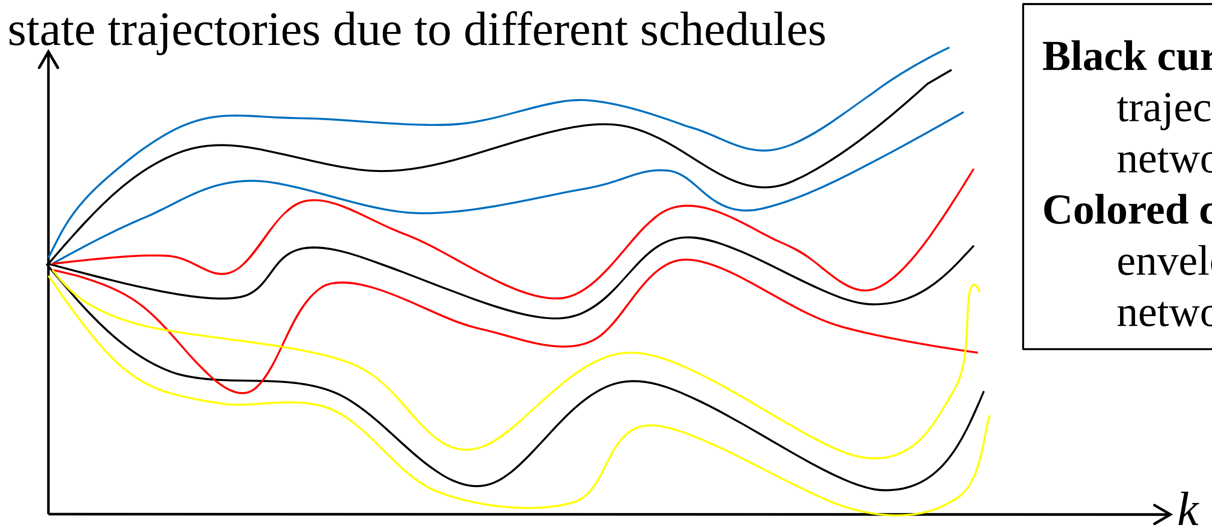
Problem 1: How to minimize $E[J]$?

$$\min\ E[J] = E\left[\sum_{i=1}^{N} w_i (r_i - x_i)^2 + v_i \Delta u_i^2\right] \qquad \text{(stochastic)}$$

Problem 2: How to guarantee that $J < B$ for a given bound B with probability, say, at least 99%.

(This is a harder yet more important problem. It is closely related to *randomized control design* theory.)

Optimal Scheduling with Network Constraints



Black curves: possible trajectories without network constraints

Colored curves: trajectory envelopes due to network constraints

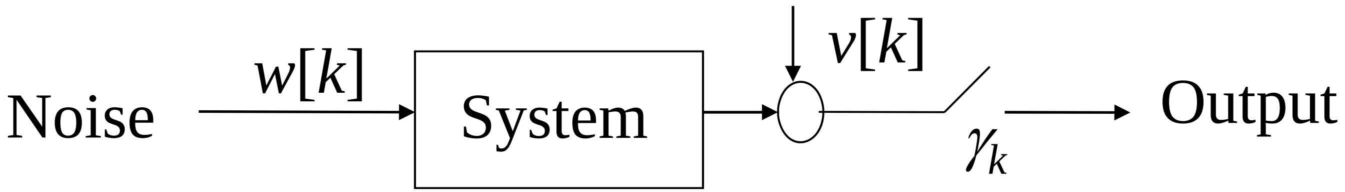
Problem 1: How to design optimal schedule in an average sense?

Problem 2: How to optimize the schedule to guarantee a given performance bound with probability, say, at least 99%.

Problem 3: What wireless network resources are needed to guarantee a given performance bound (with probability of 99%)?

Networked Estimation Problems

State Estimation with Packet Dropouts



System: $$x[k+1] = Ax[k] + w[k]$$
$$y[k] = \gamma_k (Cx[k] + v[k])$$

Packet loss: $$P(\gamma_k = 0) = p; \qquad P(\gamma_k = 1) = 1 - p$$

Optimal estimator = Kalman filter with missing data, i.e.,

$$\hat{x}[k+1] = A\hat{x}[k] + L_k \gamma_k (y[k] - C\hat{x}[k])$$

Anderson&Moore, *Optimal Filtering*, 1979

Estimation error covariance:

$$P_{k+1} = \begin{cases} AP_k A^T - AP_k (C^T P_k C + R)^{-1} P_k A^T, & \text{if } \gamma_k = 1 \\ AP_k A^T, & \text{if } \gamma_k = 0 \end{cases}$$

Key Problem: How to analyse the stochastic behaviour of P_k

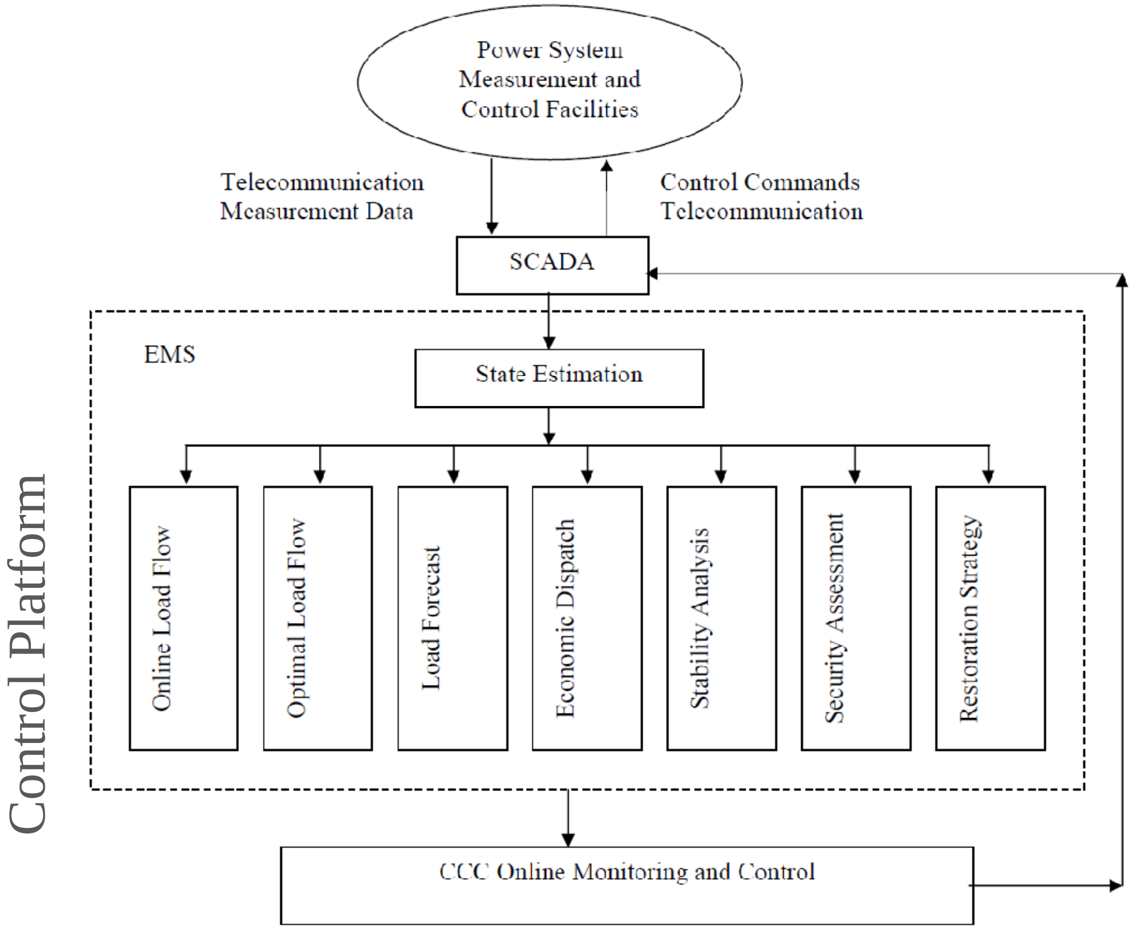
Abundant results are available on state estimation with packet dropouts:

- [Sinopoli, et.al., IEEE-TAC 2004] studied state estimation with intermittent observations using an i.i.d. packet dropout model.
- [Schenato, Proc. IEEE 2007] studied the stability of state estimators with intermittent observations.
- Shi, Epstein and Murray, "Kalman Filtering Over A Packet-dropping Network: A Probabilistic Perspective", *IEEE-TAC,* 2010.
- Characterization of necessary and/or sufficient conditions to guarantee the mean square stability of Kalman filters [Huang & Dey, Automatica07], [Mo & Sinopoli, CDC2008], [You, Fu,Xie, IFAC WC 2011 (submitted)].
- Error covariance distribution for Kalman filters with packet dropouts [Rohr, Marelli & Fu, in *Discrete Time Systems,* 2010];
  [Rohr, Marelli & Fu, CDC 2010; IFAC WC 2011 (submitted)];
- Related result: Gupta, Hassibi, Murray, IEEE-TAC 2007, LQG with packet dropout.

Dynamic State Estimation for Power Networks

(Tai, Marelli & Fu, 2010)

Role of State Estimation in power network control system:



Control Platform

Power System Measurement and Control Facilities

Telecommunication Measurement Data

Control Commands Telecommunication

SCADA

EMS

State Estimation

Online Load Flow

Optimal Load Flow

Load Forecast

Economic Dispatch

Stability Analysis

Security Assessment

Restoration Strategy

CCC Online Monitoring and Control

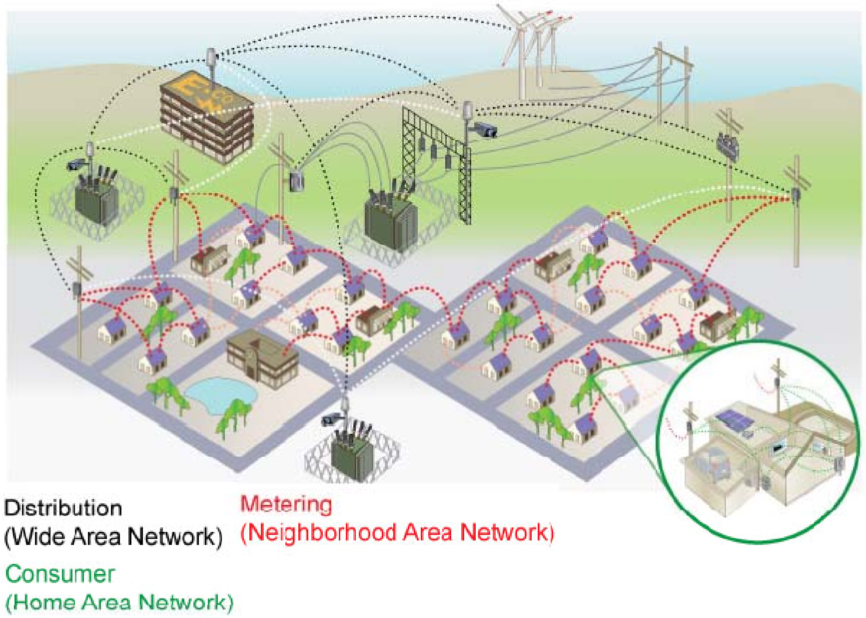
State estimation is vital for all control functions

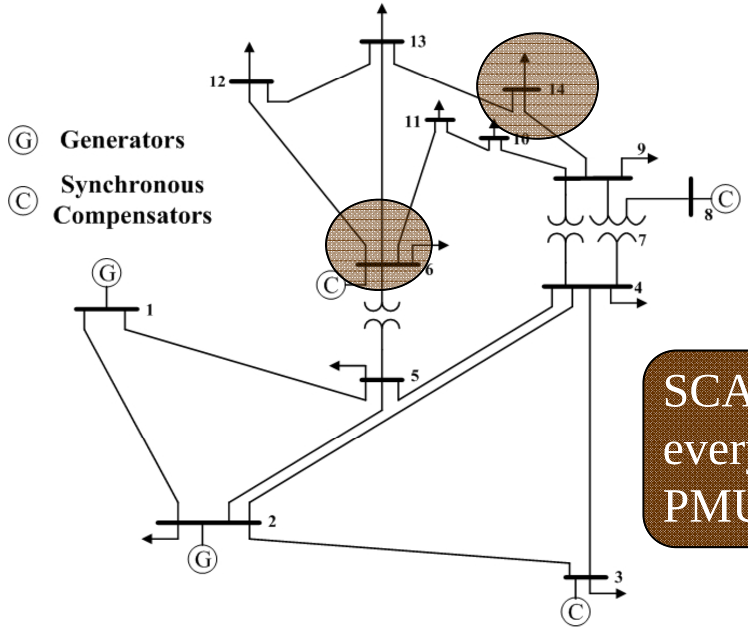
SCADA system: simple, yet slow (not suitable for smart grids)

Phasor Measurement Unit (PMU): fast and linear but expensive

Key research problem in smart metering

How to do dynamic state estimation when both SCADA and PMU measurements are available and they are subject to random transmission delays and packet losses?





IEEE 14-Bus System

SCADA at every bus; PMUs only

Power system model

$$X_{k+1} = AX_k + B\bar{X} + \omega_k$$

$$Y_k = h\left(X_k\right) + \nu_k$$

$$Z_k = \Upsilon_k Y_k.$$

packet loss

Kalman filter

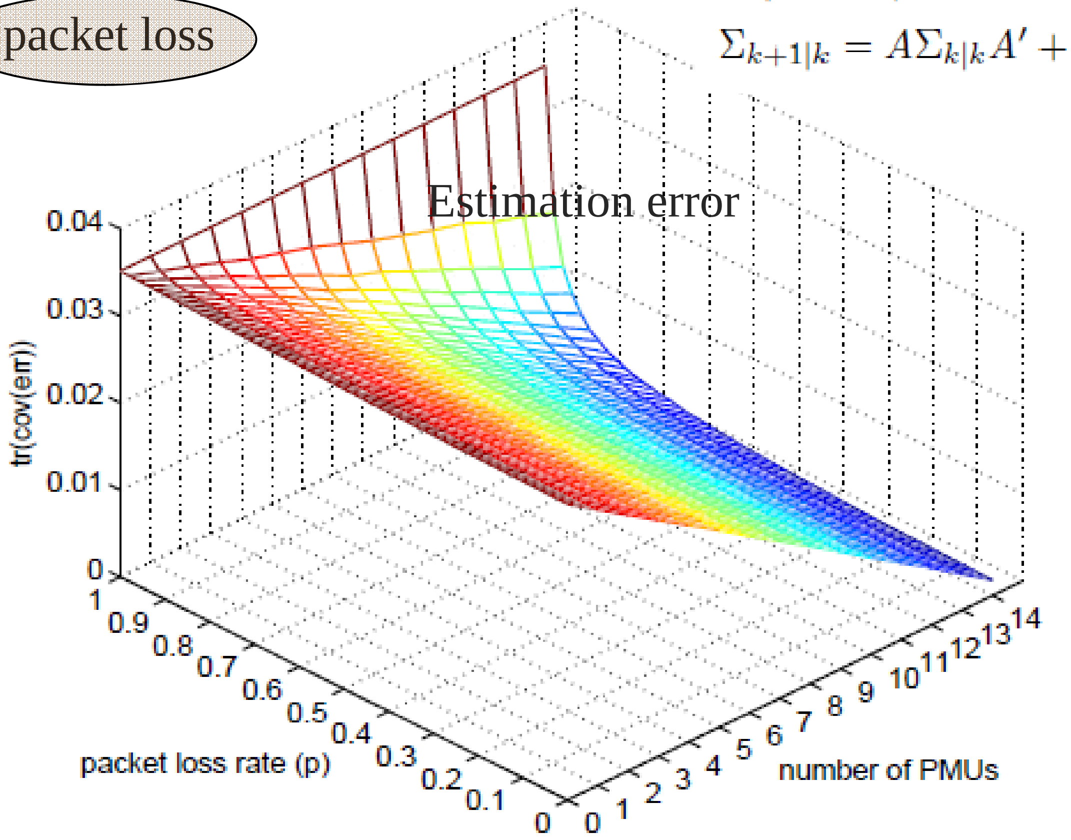
$$\hat{X}_{k|k} = \hat{X}_{k|k-1} + G_k\left[Z_k - \Upsilon_k h\left(\hat{X}_{k|k-1}\right)\right]$$

$$\hat{X}_{k+1|k} = A\hat{X}_{k|k} + B\bar{X}$$

$$G_k = \Sigma_{k|k-1} H_k' \Upsilon_k' \left(\Upsilon_k H_k \Sigma_{k|k-1} H_k' \Upsilon_k' + \Upsilon_k \Sigma_\nu \Upsilon_k'\right)^{-1}$$

$$\Sigma_{k|k} = \Sigma_{k|k-1} - G_k \Upsilon_k H_k \Sigma_{k|k-1}$$

$$\Sigma_{k+1|k} = A\Sigma_{k|k} A' + \Sigma_\omega,$$

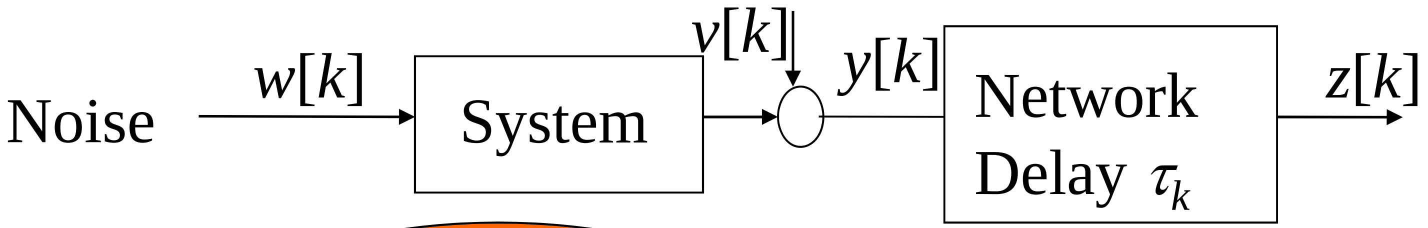


Estimation error

Applications

- Control
- Power quality analysis
- System simulation
- Power network design
- Communication network design

Quantized Estimation with Random Time Delays



System: $[k] + w[k]$

$v[k]$

Wrong delay model:

$$z[k] = y[k - \tau_k]$$

Excellent work by Schenato, *IEEE-TAC* 2008.

Delay i randomly.

Packets received at time k:

k-N	…….		k-1	k
1	1	0	0	1

Problem: Too much packet loss

$z[k] = y[k-1]$ (delayed)

$z[k+1] = y[k+1]$ (no delay)

$y[k]$ is lost!

Opti issing data

Key Probl stochastic behavior of P_{k+1}

System Identification & Parameter Estimation

Traditionally, system identification and parameter estimation are typically based on “*sufficient excitation*”. System model or parameters can be estimated from the given measurements.

Questions (in the presence of network problems)**:**

1) How to determine the “sufficient excitation” conditions?

2) How to estimate system model or parameters?

3) How to analyse the performance (consistency, convergence rate, computational complexity)?

4) What network properties are required to guarantee performance?

Identification of ARMA Models using Intermittent and Quantized Output Observations

You, Marelli & Fu (submitted to ICASSP 2011)

Research Problems

- To study the joint effects of quantization and packet dropouts on system identification.
- To derive effective system identification algorithms to cope with both quantization and packet dropouts
- To jointly design quantizer and parameter estimator for system identification.

ARMA Model:

$$\begin{aligned} x(t) &= \frac{B(q)}{A(q)} u(t) \\ y(t) &= x(t) + w(t) \\ z(t) &= \gamma_t \mathcal{Q}_t(y(t)), \end{aligned}$$

Parameterized denominator and numerator: $A(q,\theta)$ and $B(q,\theta)$

Quantizer: $\mathcal{Q}_t$ has *K* levels, possibly time-varying

Packet dropout Model: γ_t is a packet dropout parameter, a sequence of i.i.d. Bernolli random variables with

$$\mathrm{P}(\gamma_t = 1) = \lambda, \quad \mathrm{P}(\gamma_t = 0) = 1 - \lambda$$

Problem: for each time step *N*, find the maximum likelihood estimate $\hat{\theta}_N$ of the true ARMA parameters θ_* .

Quantizer Design:

$$\mathcal{Q}_t : \mathbb{R} \to \{v_{t,1}, \cdots, v_{t,K}\},\ t \in \mathbb{Z}$$

Quantization intervals: $[b_{t,k-1}, b_{t,k}] = \mathcal{Q}^{-1}[v_{t,k}],\ k = 1, \cdots, K$

with $b_{t,0} = -\infty$ and $b_{t,K} = \infty$

Proposed quantization: $$b_{t,k} = \tilde{b}_k + x(t, \hat{\theta}_{t-1}).$$

Optimal quantization for w_k

Predicted value of $x(t,\theta)$

Recursive Parameter Estimation:

1) Use expectation maximization (EM) method for small N;
2) Switch to Newton gradient search when $\hat{\theta}_N$ gets close to θ_* .

Key Result:

Let

$$\Phi = \lim_{N \to \infty} \frac{1}{N} \sum_{t=1}^{N} \psi(t, \theta_\star) \psi^T(t, \theta_\star)$$

measure of persistent excitation

$$\mu = \frac{\bar{\sigma}^2}{\sigma^2}$$

where

$$\bar{\sigma}^2 = \mathcal{E}\left\{ \tilde{\mathcal{Q}}^2 \left[w(t) \right] \right\}$$

$$\psi(t, \theta) \quad = \quad \frac{\partial}{\partial \tilde{\theta}} x(t, \tilde{\theta}) \bigg|_{\theta}$$

Then, $\sqrt{N} \left(\hat{\theta}_N - \theta_\star \right) \to \mathcal{N}(0, C)$ *in distribution*

$$\boxed{C = \frac{\sigma^2}{\lambda \mu} \Phi^{-1}}$$

Note: λ is due to packet dropout
μ is due to quantization

Fault Detection and Diagnosis

Many system model-based fault detection and diagnosis methods are widely used.

They rely on a key assumption: Measurements are available without delays and errors.

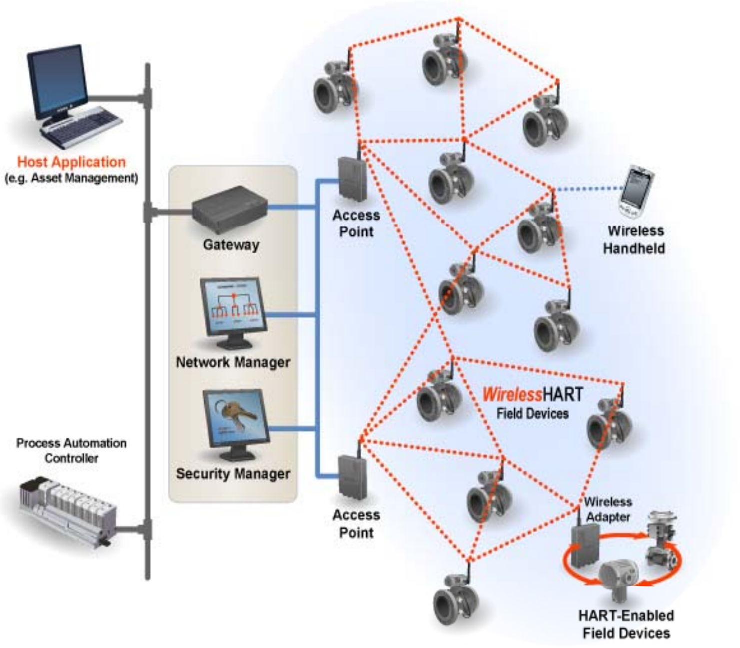
Questions (in the presence of network problems)**:**

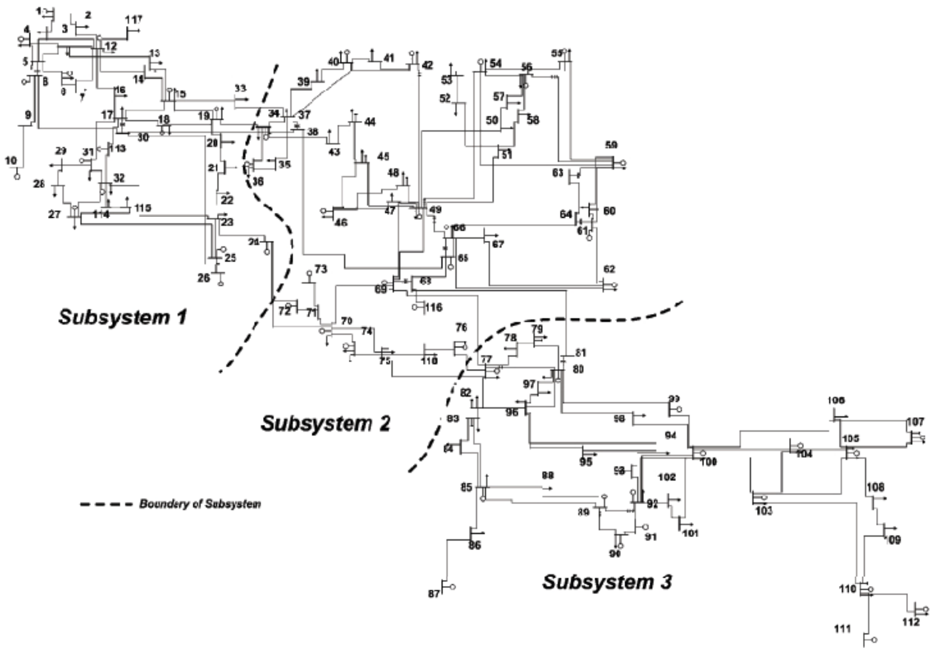
1) How to avoid false alarms?

2) How to *robustify* fault detection/diagnosis algorithms?

3) What network properties are required to guarantee performance?

Distributed Estimation and Control





Constraints: Limited data rate & computing power

Need hierarchical, multi-timescale structures.

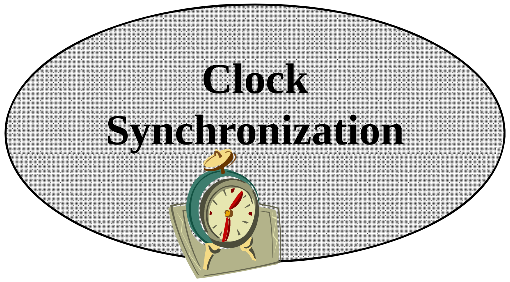
Consensus Problems

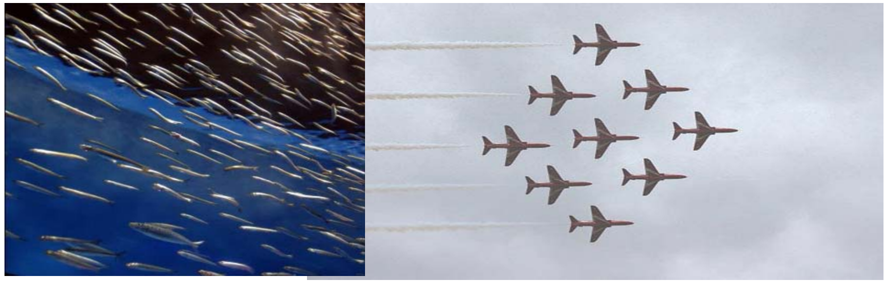
Consensus Control for Multi-agent Systems

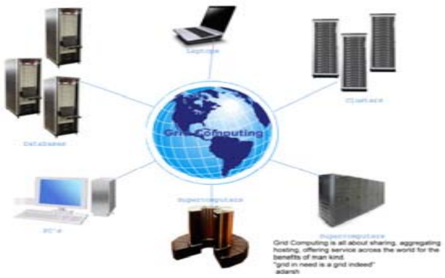
T. Li, M. Fu, L. Xie & J. Zhang,
ASCC 2009, *IEEE-TAC* 2010.

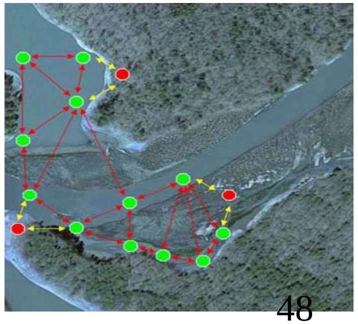
- Formation control
- Distributed estimation
- Multi-sensor data fusion
- Distributed computing

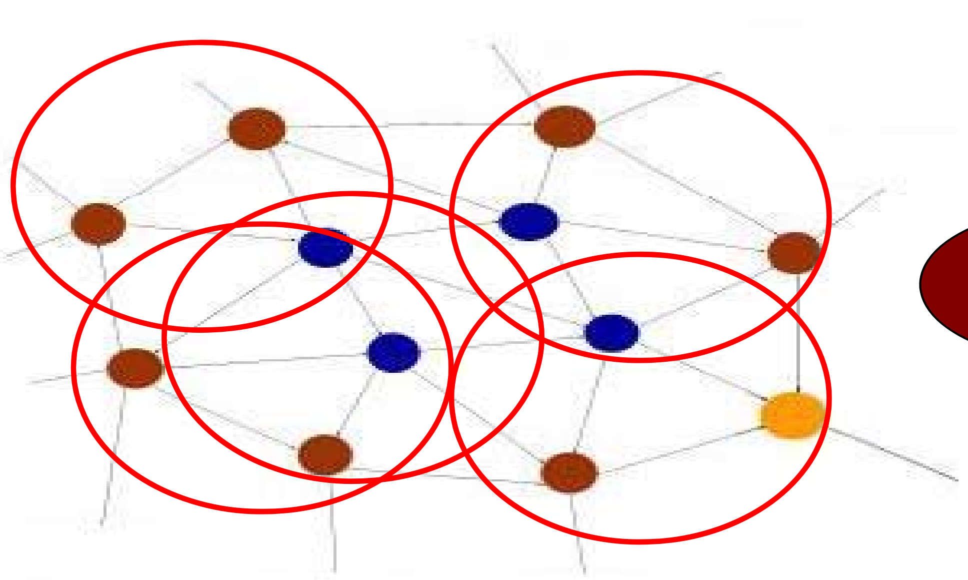
Distributed average consensus control


Clock Synchronization









N nodes

Distributed consensus: to achieve agreement by distributed information exchange

$$x_i(t) \to \frac{1}{N}\sum_{j=1}^{N} x_j(0), \qquad t \to \infty$$

average consensus

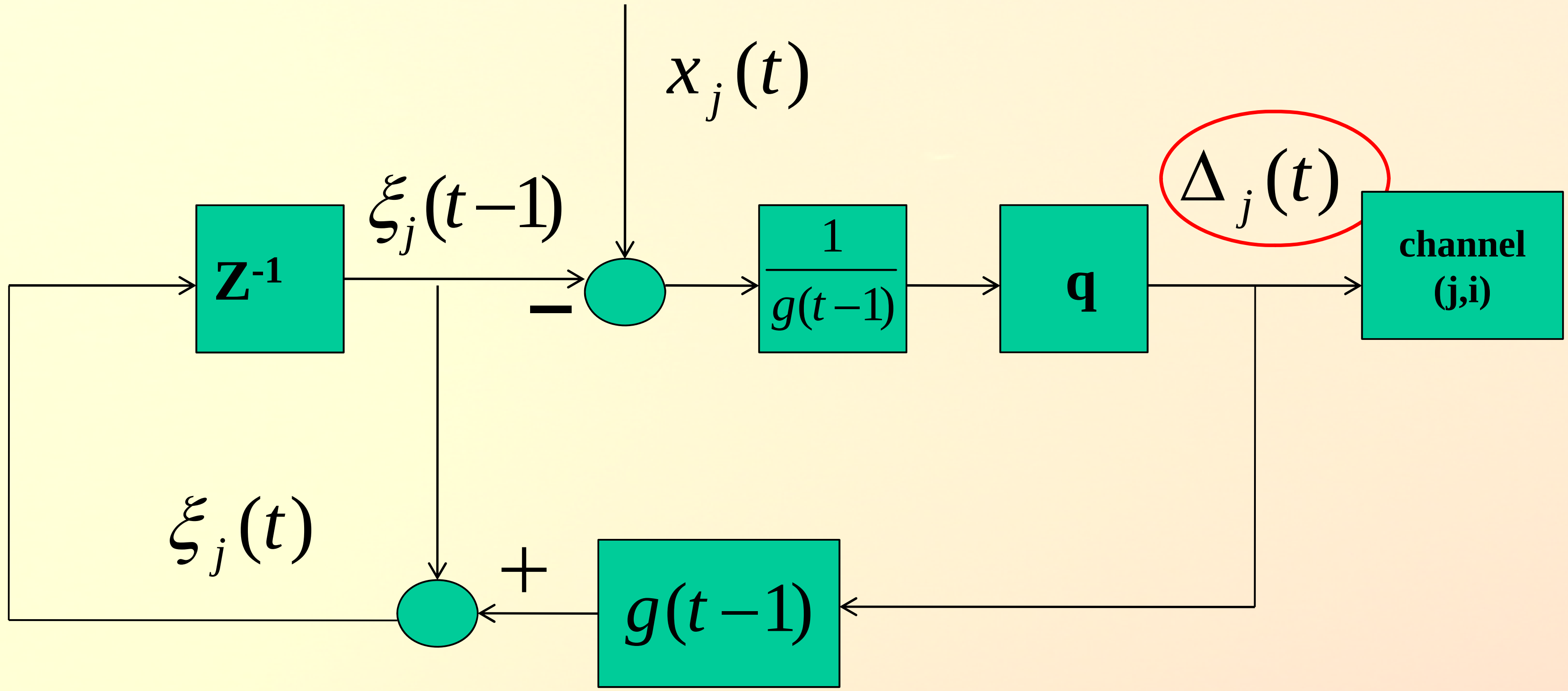
Problem 1

How many bits does each pair of neighbors need to exchange at each time step to achieve consensus of the whole network?

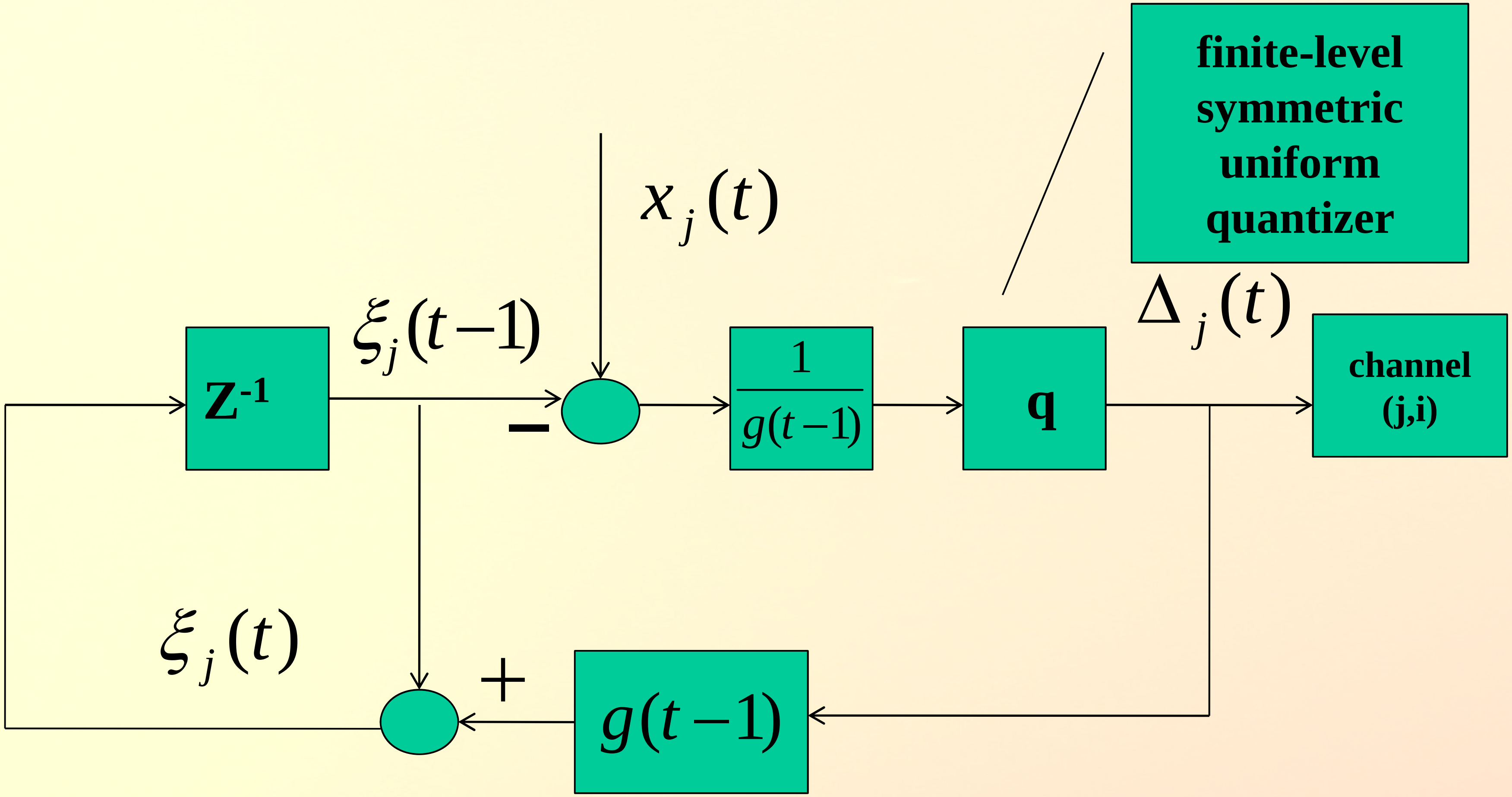
Problem 2

What is the relationship between the consensus convergence rate and the number of quantization levels?

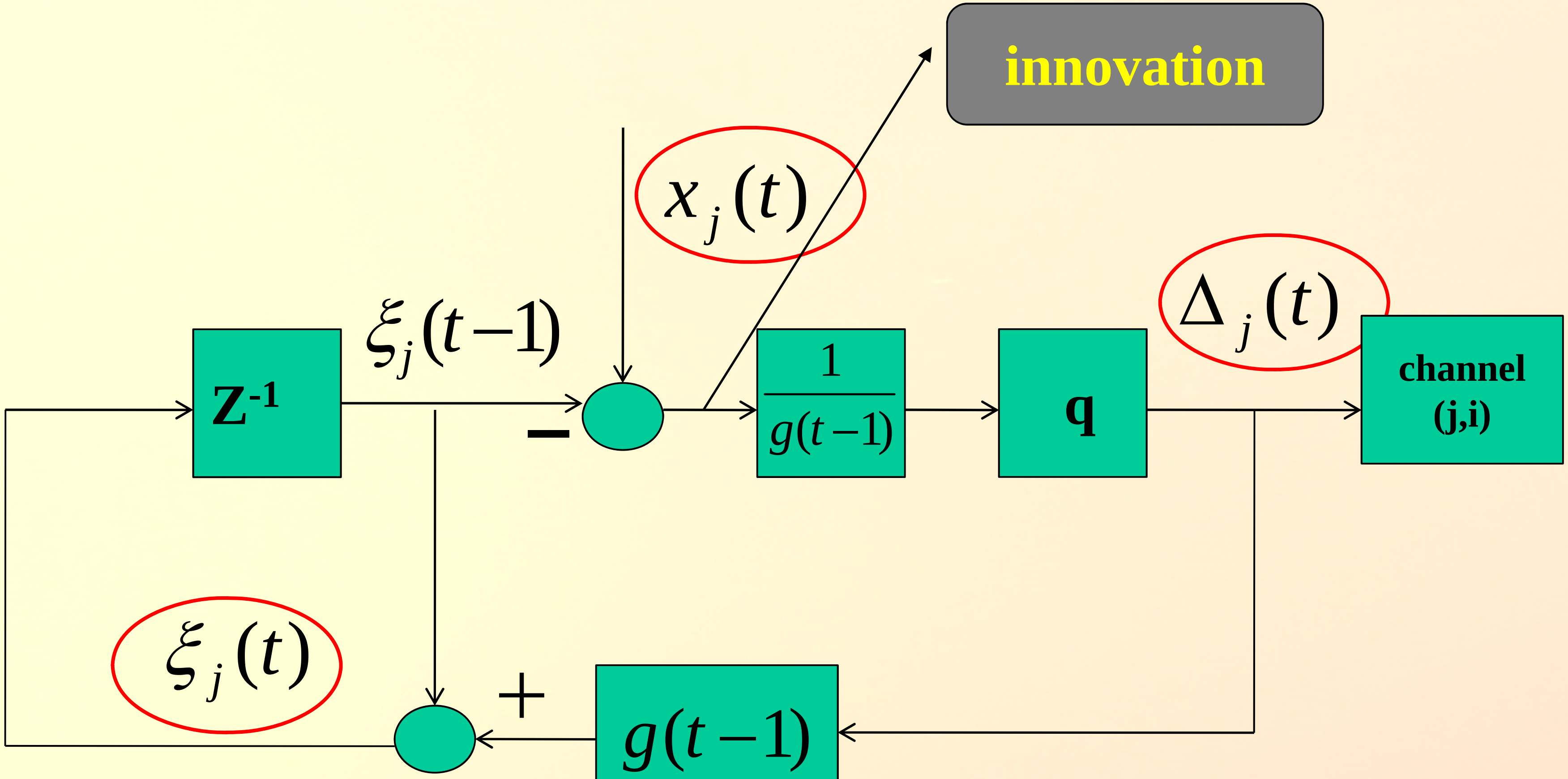
Distributed protocol for quantization



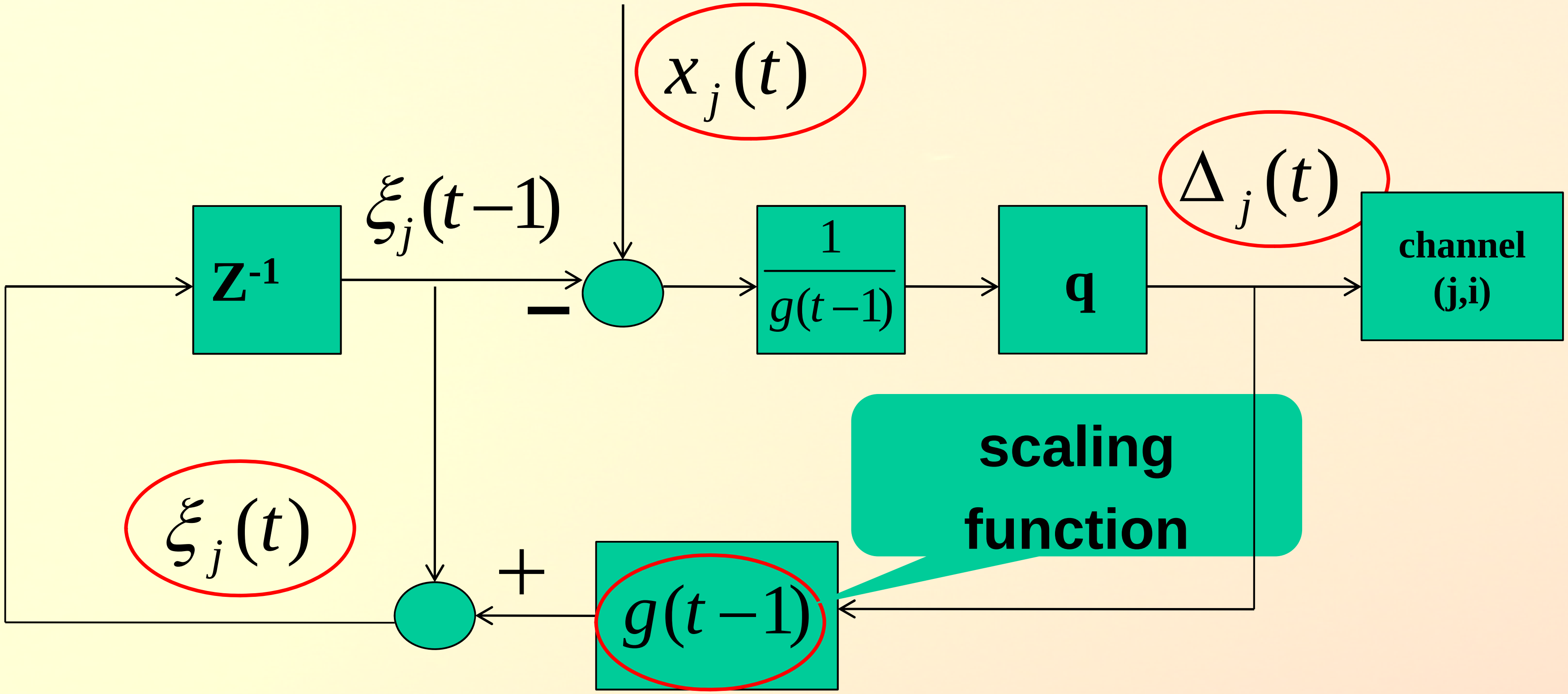
Distributed protocol for quantization



Distributed protocol for quantization



Distributed protocol for quantization



For a connected network, average-consensus can be achieved
with exponential convergence rate
base on a single-bit exchange
between each pair of neighbors
at each time step

The highest asymptotic convergence rate **increases** as the **number of quantization levels** and the **synchronizability increase**, and **decreases** as the network **expands**

Convergence rate:

$$\inf \gamma \approx \exp\left\{-\frac{KQ_N^2}{2\sqrt{N}}\right\}$$

where K = # of quantization levels and

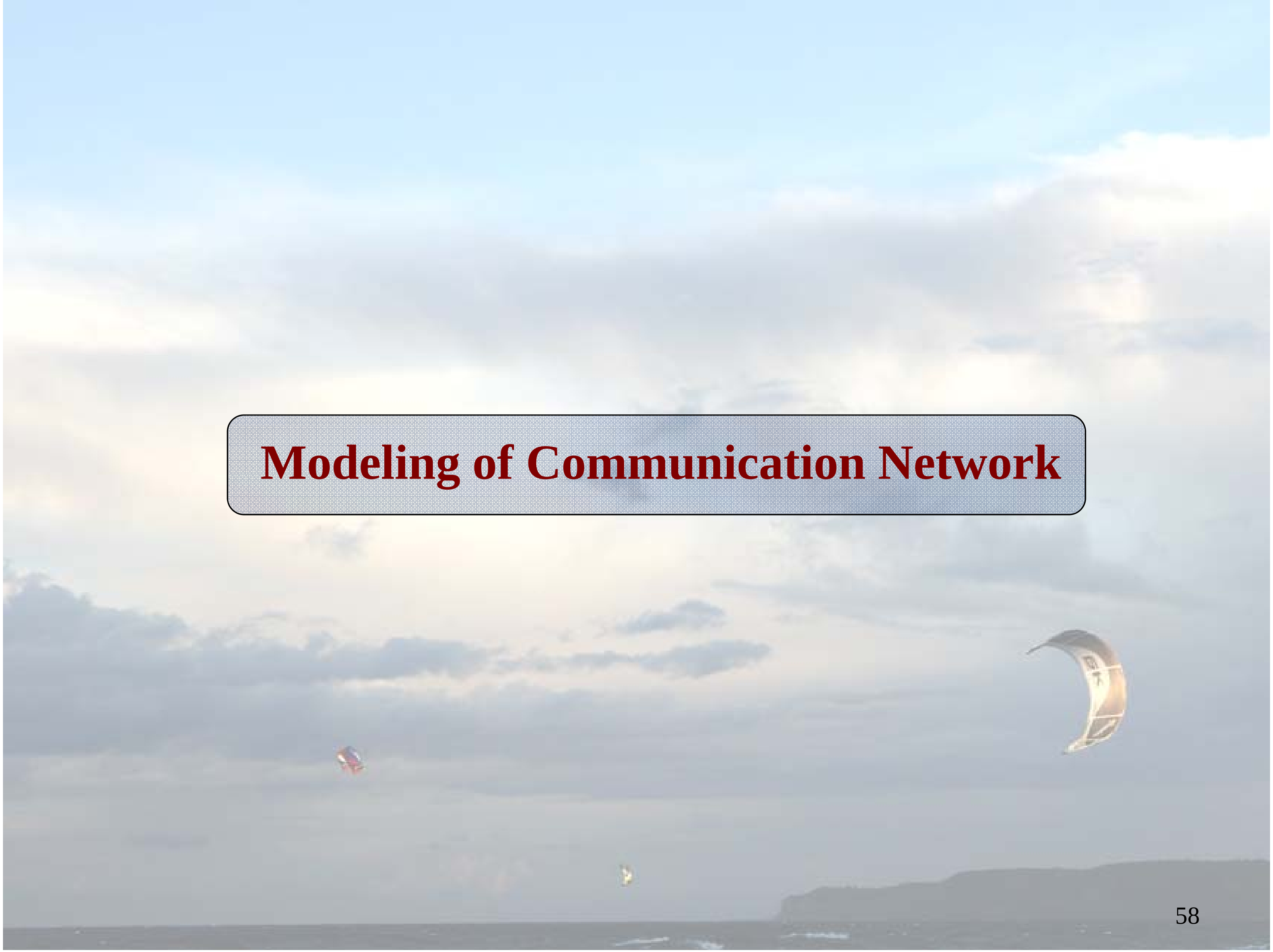
$$Q_N^2 = \frac{\lambda_2}{\lambda_N}$$

Synchronizability

Barahona & Pecora
PRL 2002
Donetti et al.
PRL 2005

More General Problems:

1) **More general consensus problems?**
2) **Better control protocols?**
3) **Consideration of network constraints:**
    - **communication protocols;**
    - **packet loss;**
    - **time delays;**
    - **quantization constraints.**

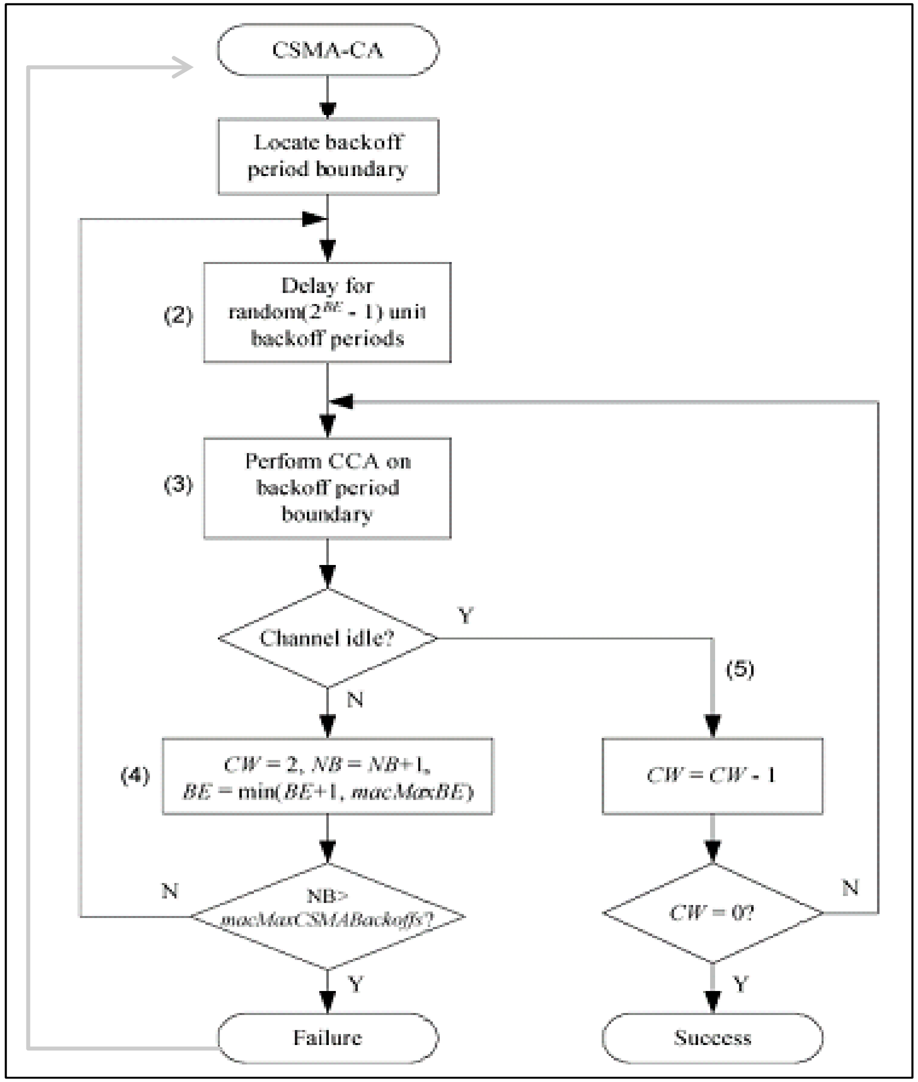


Modeling of Communication Network

Wireless Network Modeling and Optimization

MAC layer model (CSMA/CA)

- IEEE 802.15.4 slotted CSMA/CA
- Time is divided into tiny backoff slots. 0.32ms (20 symbols).
- Transmission is initiated only after two successive successful CCA (clear channel assessment).
- BE (backoff exponent) increases from macMinBE to macMaxBE.
- Key parameters:
  - macMinBE
  - macMaxBE
  - macMaxCSMABackoffs
  - Transmission power

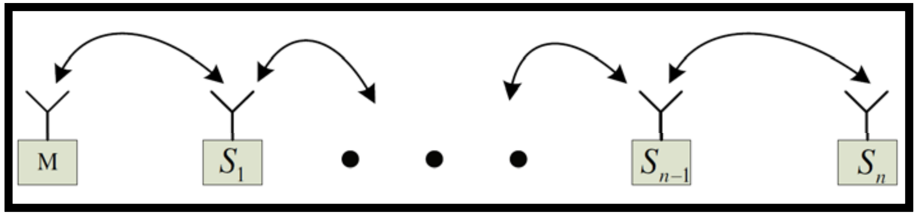


Source: Xianghui Cao

Research Problems

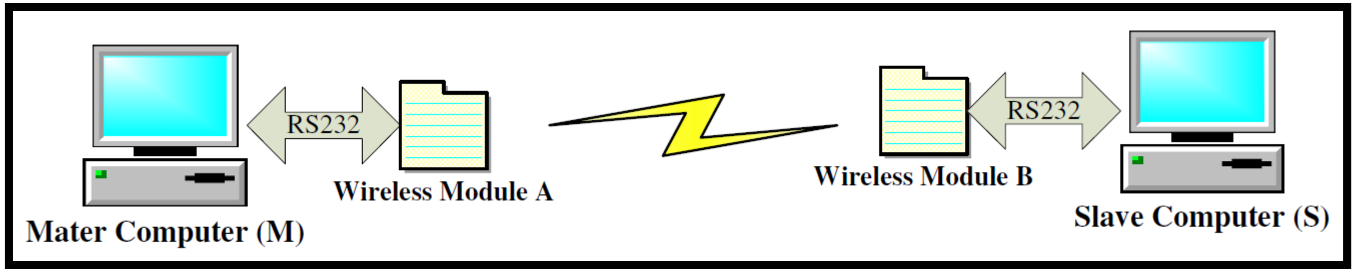
- For a given topology, how to find a suitable model for random transmission time delays?
- For a given topology, how to choose the parameters to optimize packet loss rate, time delays, energy consumptions?
- How to do joint optimization of control and network parameters?

Test bed at Zhejiang University, China



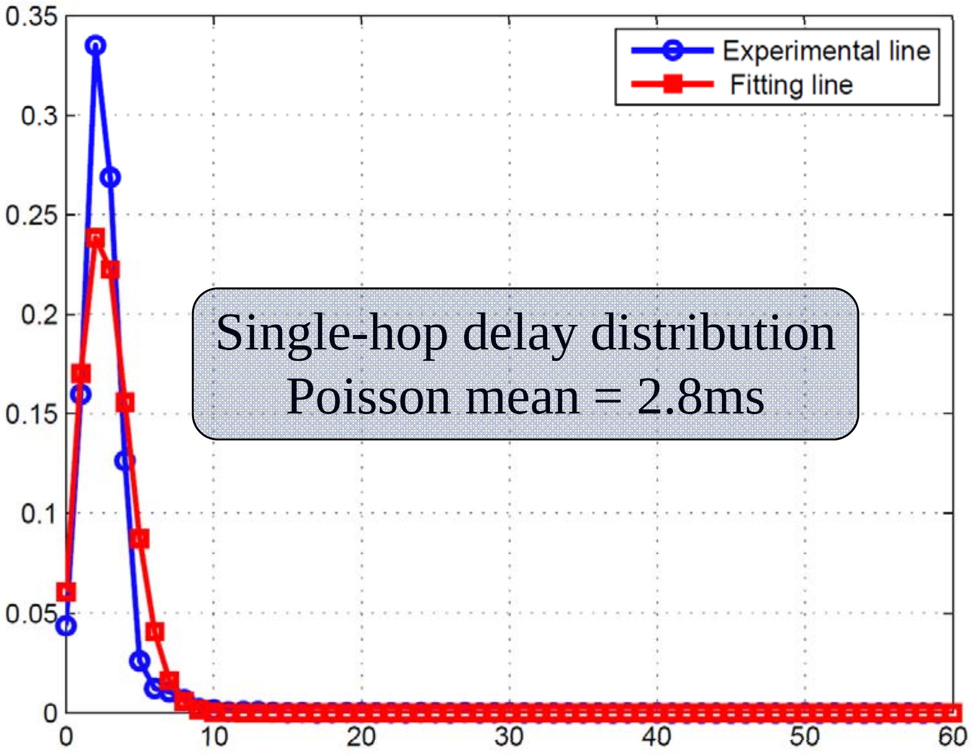
Multi-hop wireless communication system

Wireless module



Research Problems

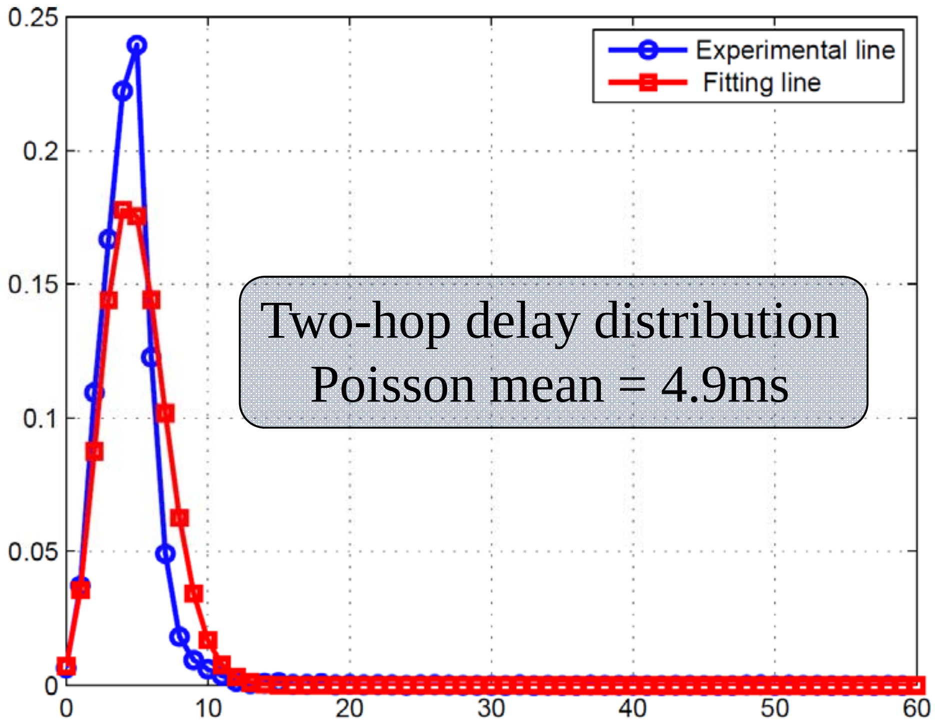
- To find a suitable model for random transmission time delays
- To test the validity of the model in state estimation



Single-hop delay distribution
Poisson mean = 2.8ms

Key Finding

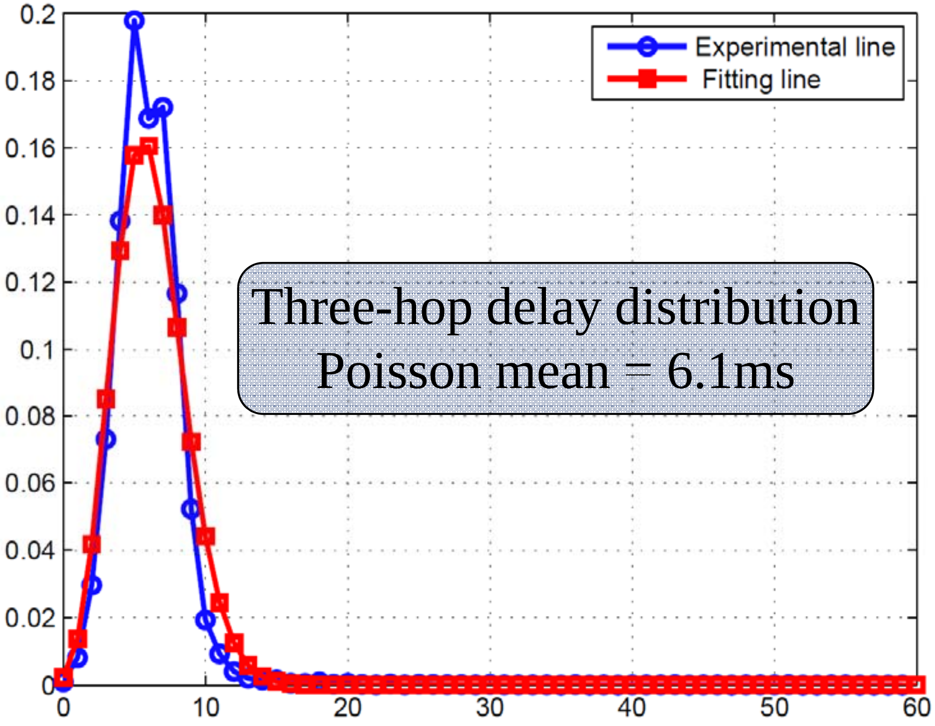
The random time delays introduced in a multi-hop system can be adequately approximated by a Poisson distribution, with its mean value depending on the number of hops.



Two-hop delay distribution
Poisson mean = 4.9ms

Key Finding

The random time delays introduced in a multi-hop system can be adequately approximated by a Poisson distribution, with its mean value depending on the number of hops.



Three-hop delay distribution
Poisson mean = 6.1ms

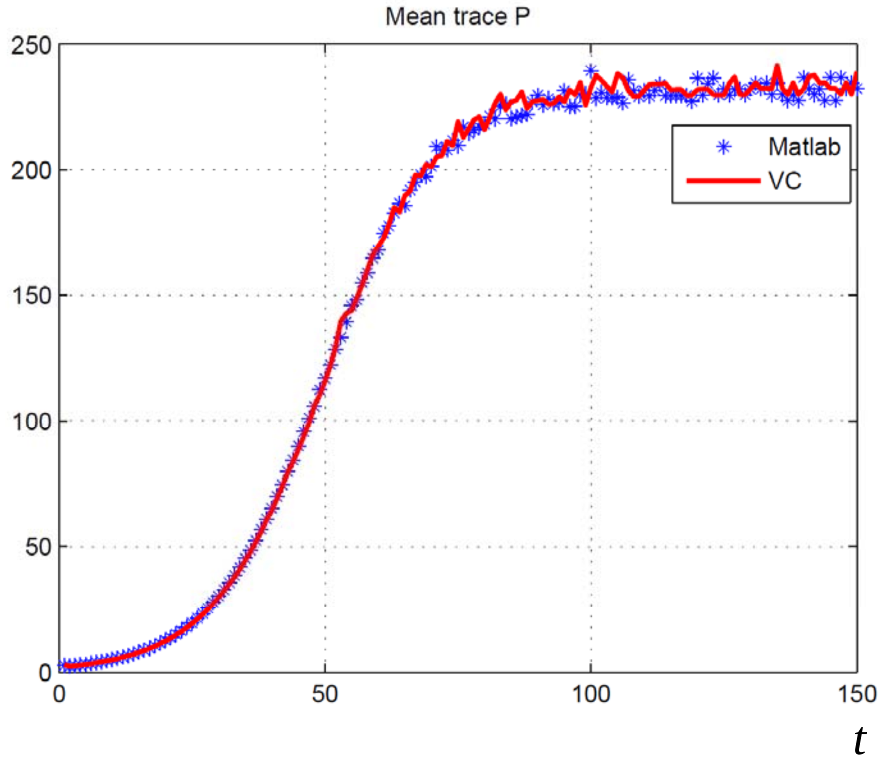
Key Finding

The random time delays introduced in a multi-hop system can be adequately approximated by a Poisson distribution, with its mean value depending on the number of hops.

Verification of Poisson model
on Dynamic State Estimation Error:

* Simulation using Poisson model

\- Result from the test bed



Key Finding

The random time delays introduced in a multi-hop system can be adequately approximated by a Poisson distribution, with its mean value depending on the number of hops.

Concluding Remarks

- Great opportunities for new control theory and applications
- *Many* exciting and challenging research problems
- Urgency about real, relevant and applicable research
- Multidisciplinary research:
  - Wireless device design:

    smart sensors, actuators, embedded systems
  - Communication network design
  - Distributed sensing, sensor fusion and estimation
  - Network-based control paradigms and algorithms