Networked Control Systems: Opportunities and Challenges

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Outline

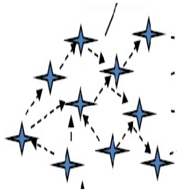
- Introductory Comments on Networked Control Systems
- Examples of Applications
- Wireless Industrial Control Networks
- Challenges in Fundamental Research
- Concluding Remarks

Evolution of Control

- Servomechanism 1940’s – 1970’s:

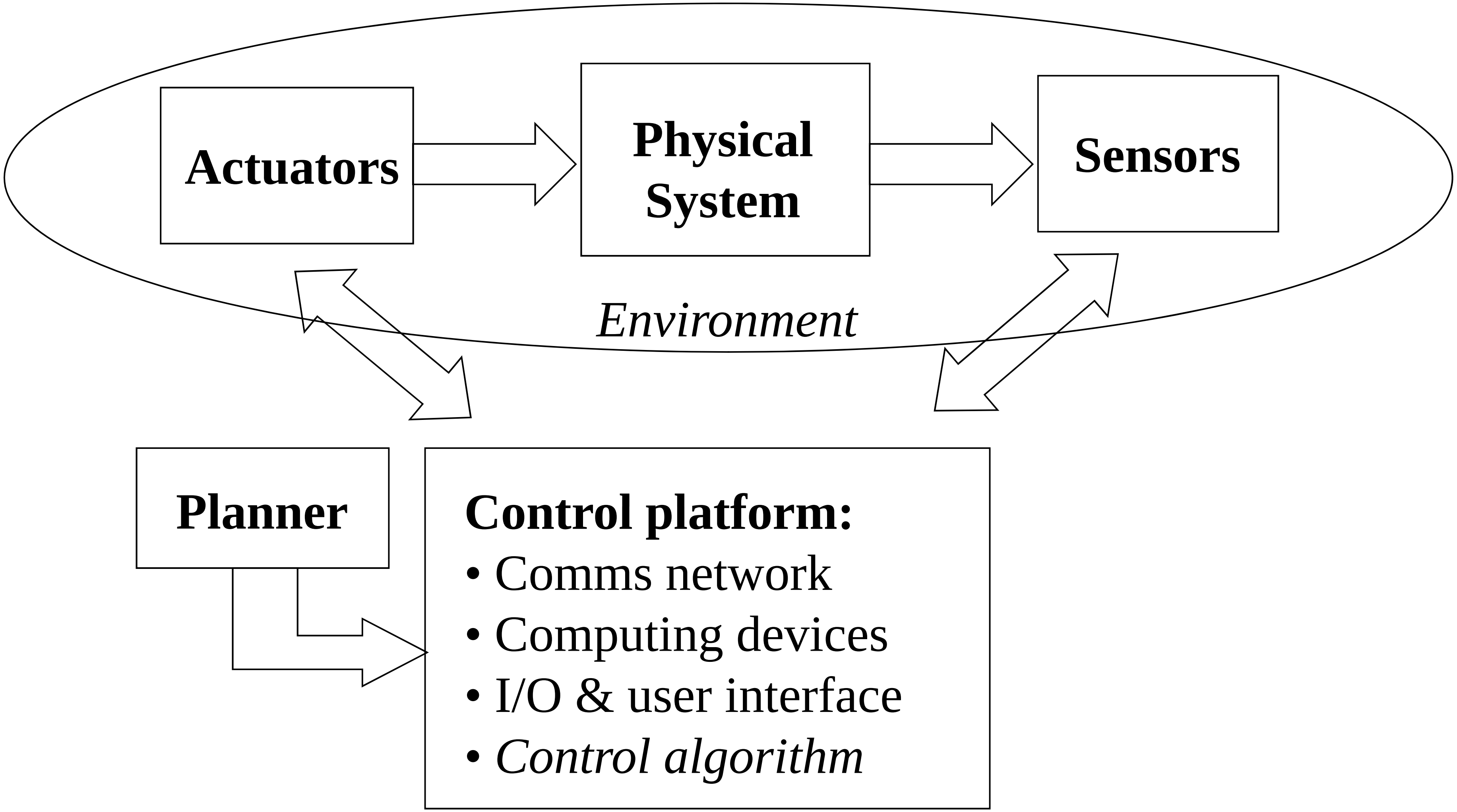
  - Motivations: gun control, radar, navigation, regulation …
  - Approaches: frequency-domain, analog implementation
  - Features: single-loop, primitive theory, application-oriented
- State Space 1960’s-1990’s

  - Motivations: aerospace, space, guidance, automation, robotics…
  - Approaches: state-space, digital implementation, numerical optimization, simulation, visualization
  - Features: advanced theories, serious theory-application gap
- Networked Complex Dynamic Systems 1990’s –



  - Motivations: Networked control, plant-wide control, bio/nano/quantum systems
  - Approaches: Embedded systems, complex dynamics modelling, *interdisciplinary research*, optimization
  - Features: information processing, embedded and *networked*

Real-world Control Systems



Actuators

Physical System

Sensors

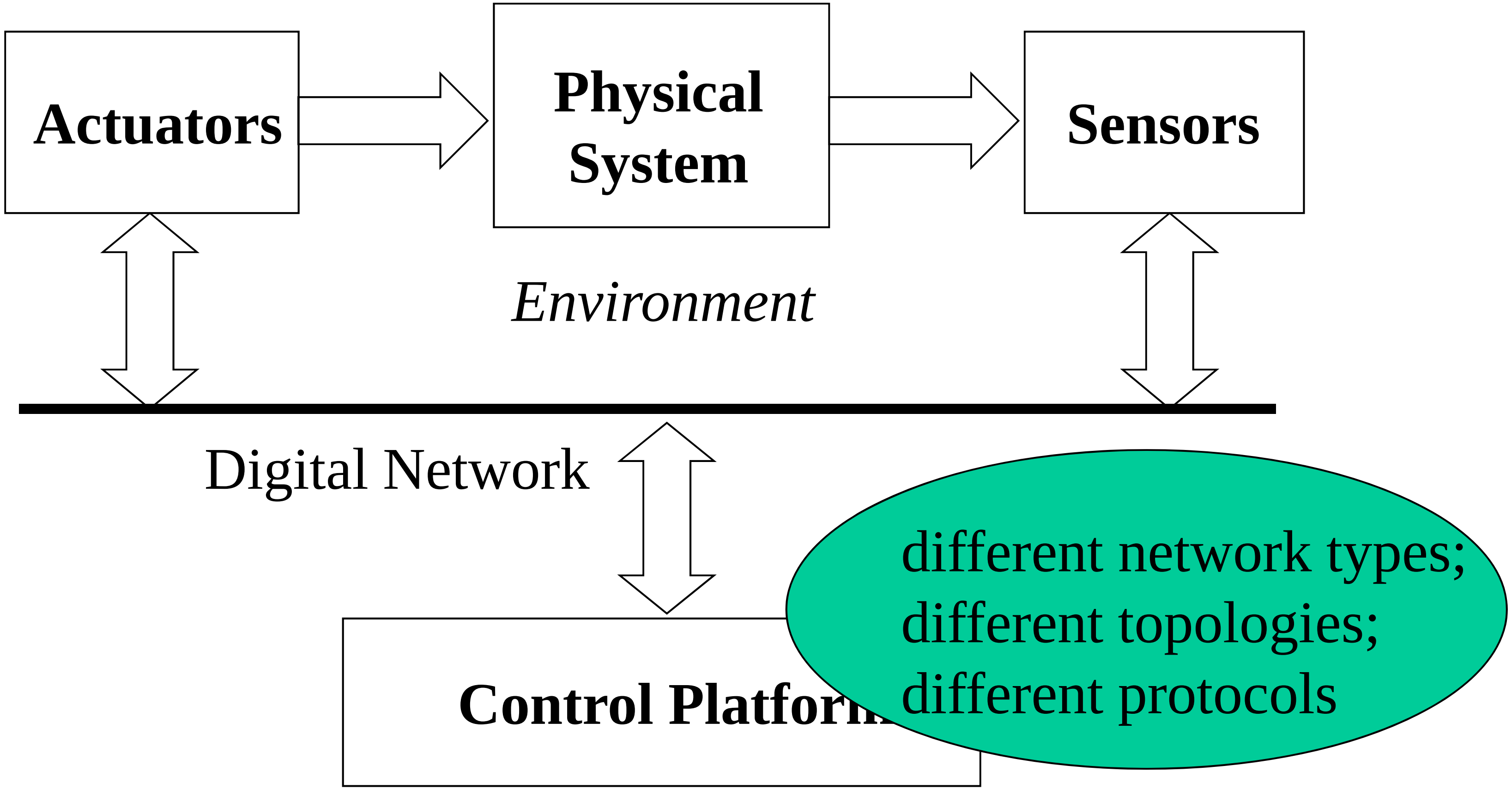
Environment

Planner

Control platform:

- Comms network
- Computing devices
- I/O & user interface
- *Control algorithm*

Networked Control Systems



Actuators

Physical System

Sensors

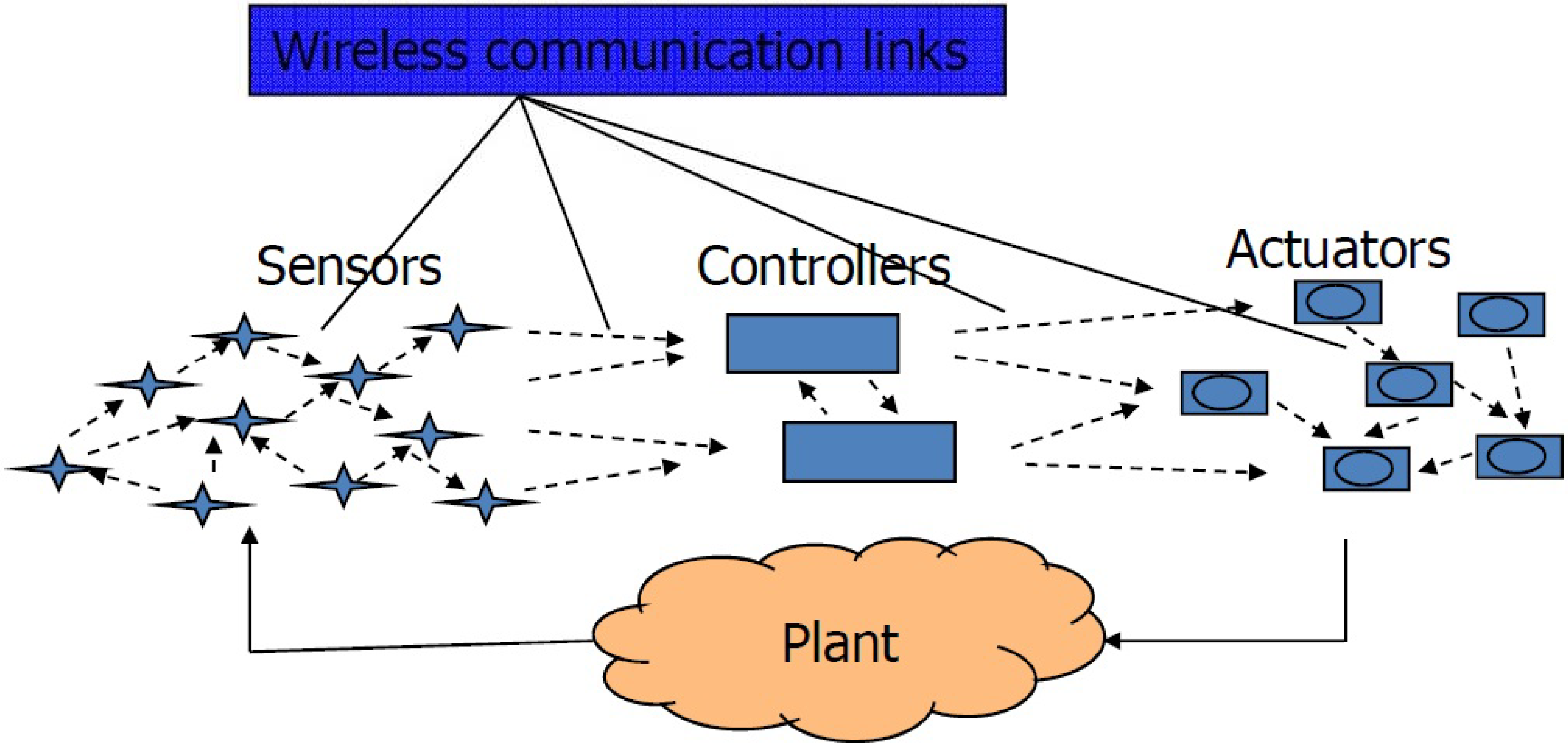
Environment

Digital Network

Control Platform

different network types;
different topologies;
different protocols

Wireless Networked Control Systems



(Source: Karl Johansson)

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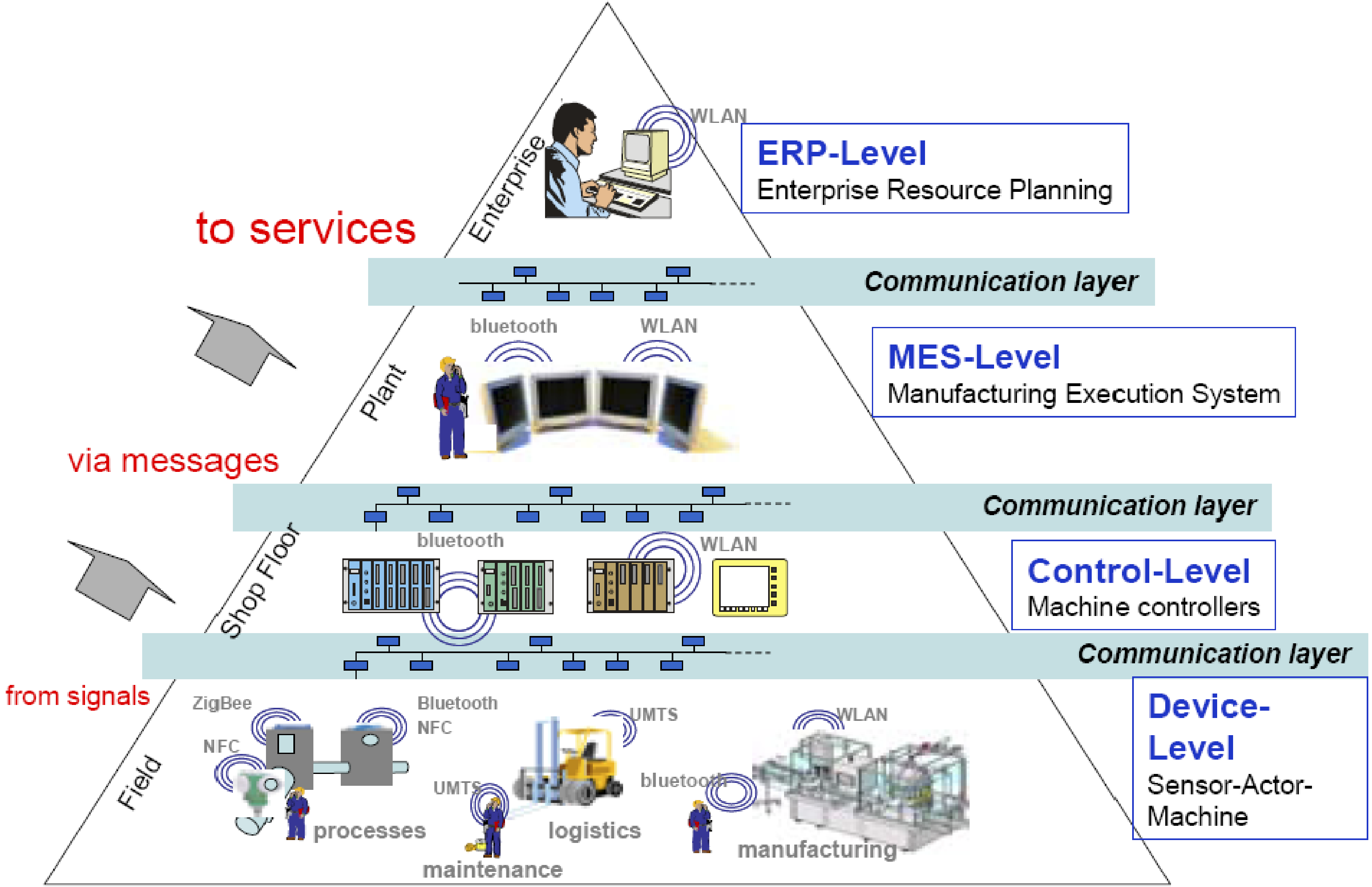
Example 1: Industrial Control Systems

- 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…)
  - PCs and computing units become the main control platform
  - 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

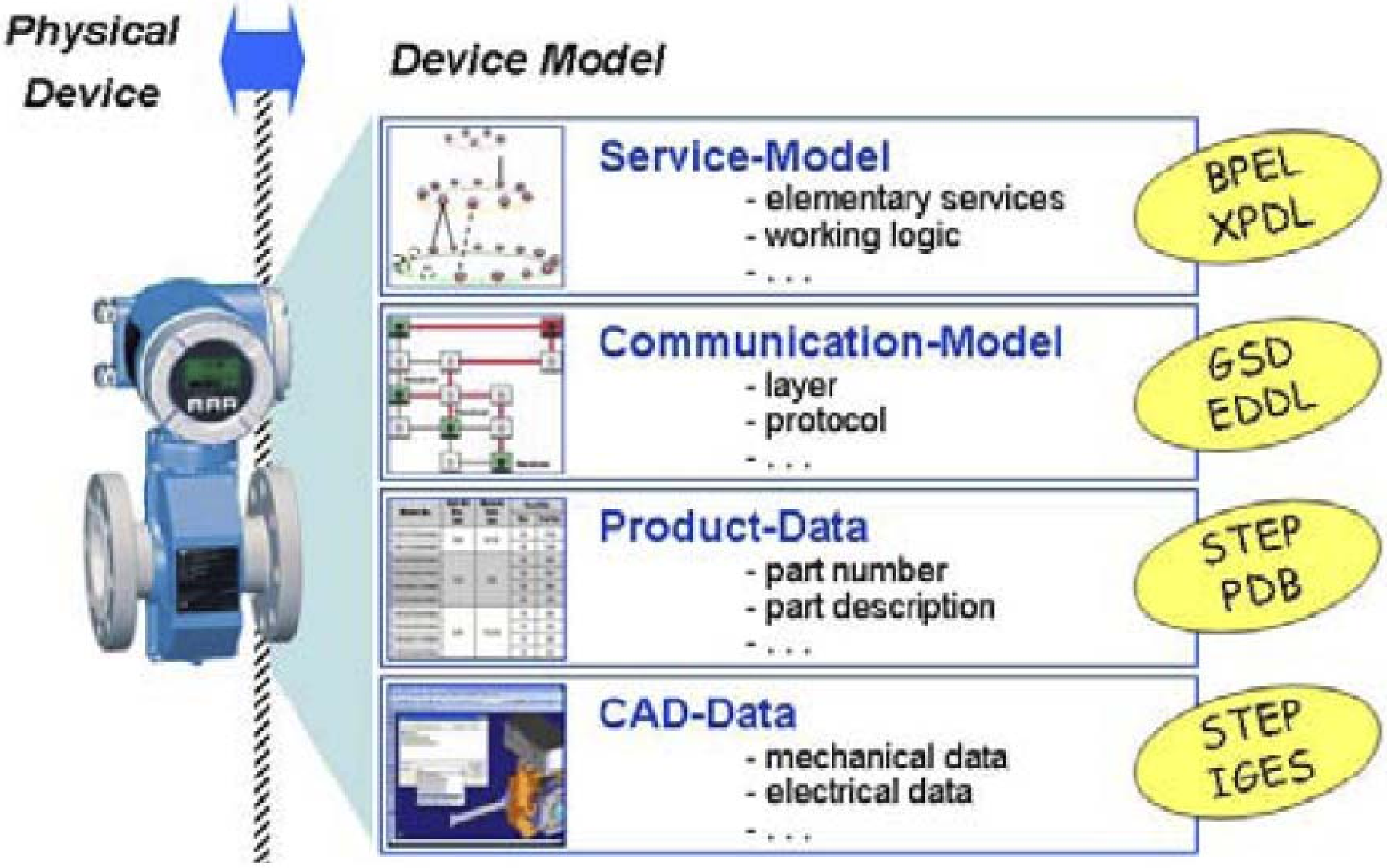
Communication layer

Control-Level
Machine controllers

Communication layer

Device-Level
Sensor-Actor-Machine

Wireless Embedded Devices:



Physical Device

Device Model

Service-Model
- elementary services
- working logic
- . . .

BPEL
XPDL

Communication-Model
- layer
- protocol
- . . .

GSD
EDDL

Product-Data
- part number
- part description
- . . .

STEP
PDB

CAD-Data
- mechanical data
- electrical data
- . . .

STEP
IGES

Main Challenges for Wireless

- Reliability
- Security
- Premature technology
- Inadequate standards for industrial control purposes
- **Control design methods: virtually non-existent!**

Fundamental Conflict:

Contention-based communication protocols

vs.

time-based control requirements

packet dropouts (serious problem, also related to TX delays)

- transmission errors
- quantization errors (low resolution quantization)

Example 2: Electricity Smart Grid

Modern electricity Networks need to be able to cope with

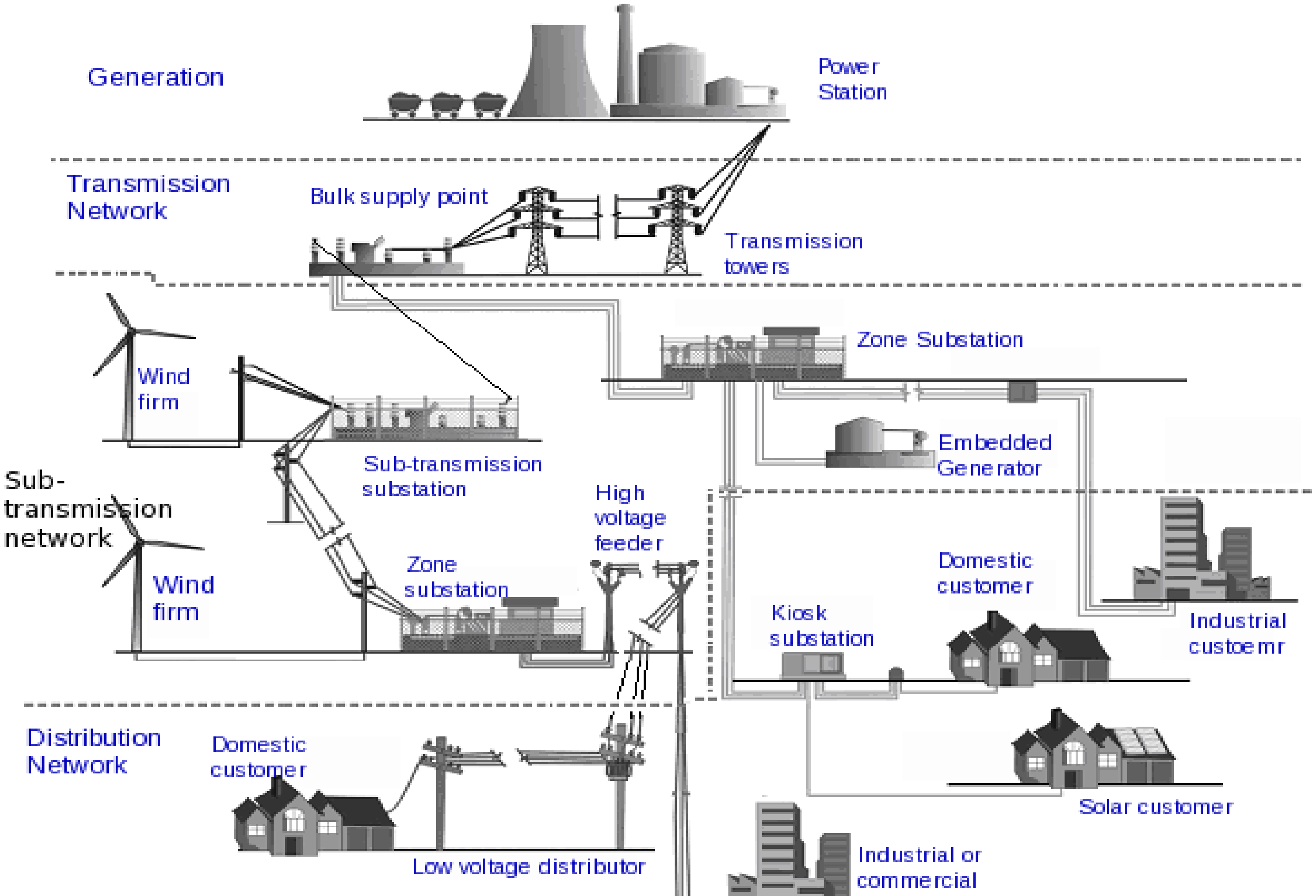
- Diversified range of energy sources
  - Traditional baseline generation (coal, oil, hydro…)
  - Renewable (wind, solar, tidal, wave, geo-thermal, …)
  - Distributed generation (gas turbines, fuel cells, …)

- Diversified range of loads
  - air-conditioning systems
  - electrical vehicle charging systems
  - bi-directional loads (through micro-grids)

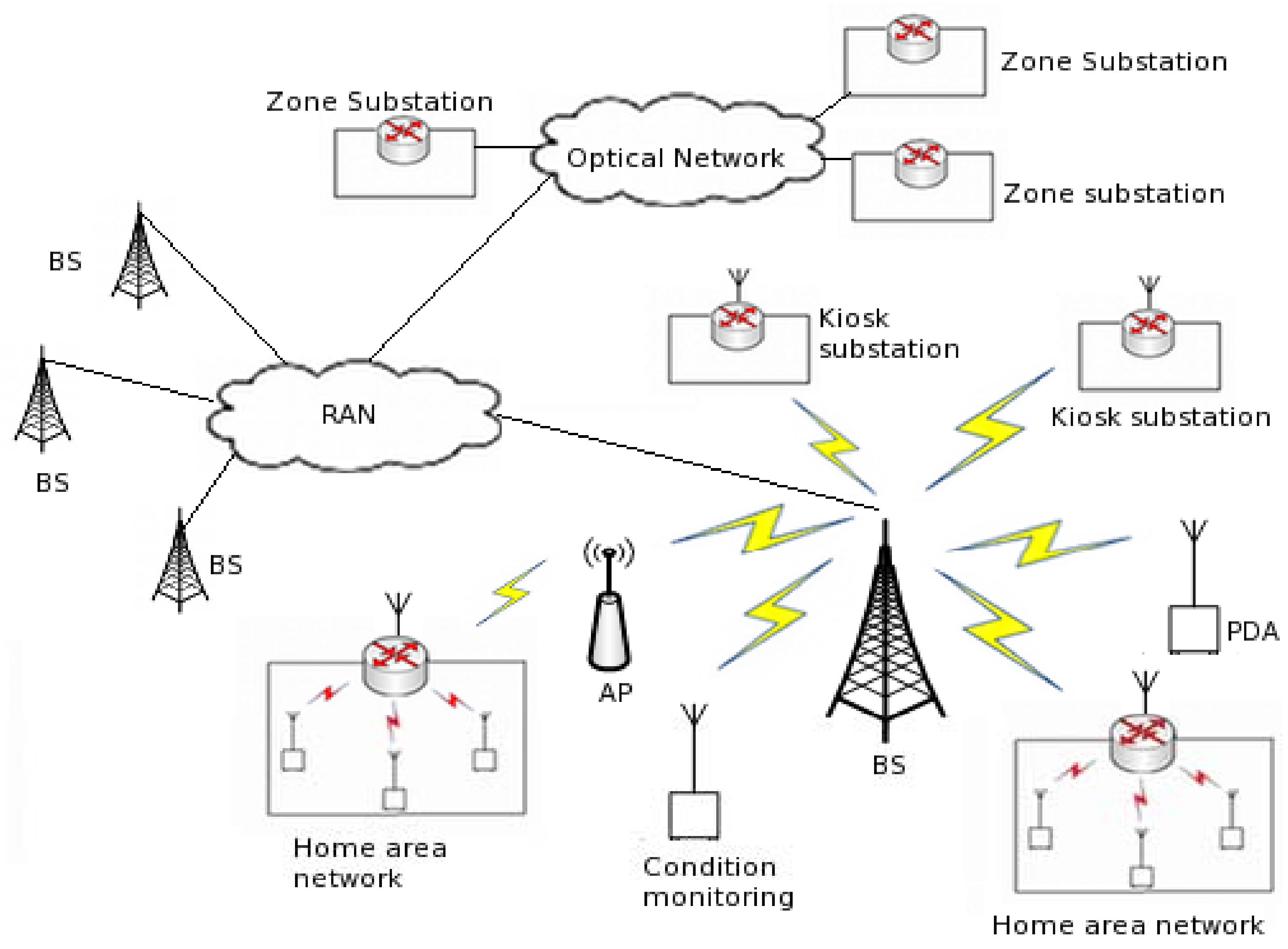
Driving Forces

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

Electricity Distribution Network



Smart Grid Comms Network:



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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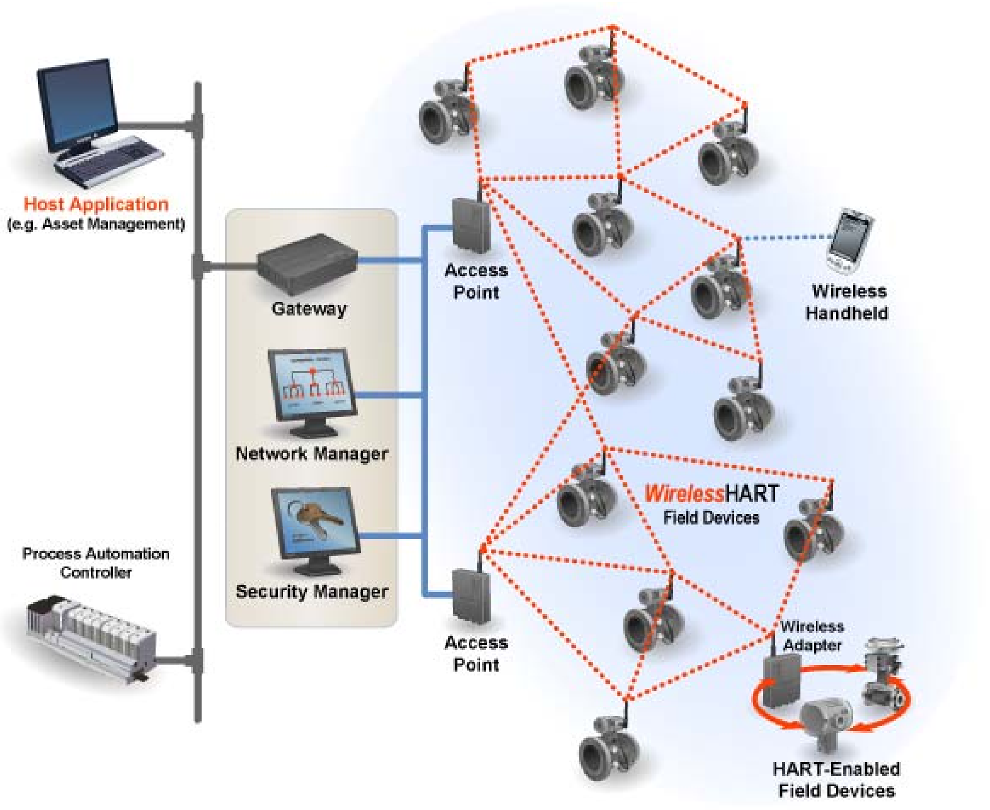
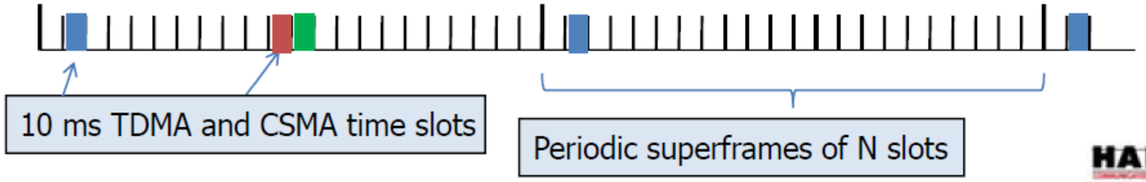
Wireless HART

- 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



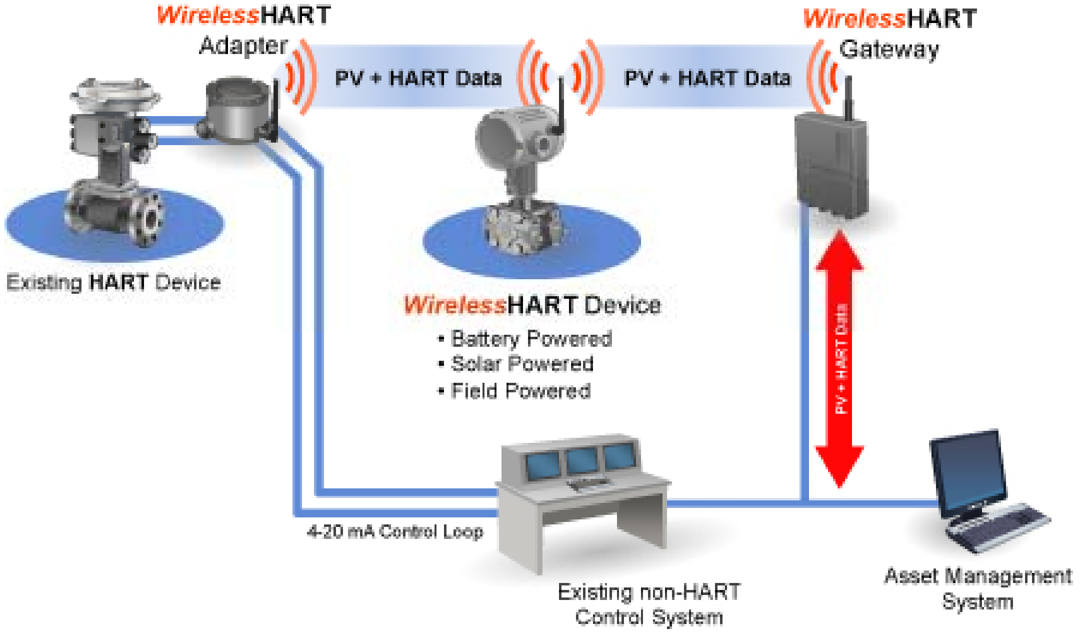
Star-mesh topology

- 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



10 ms TDMA and CSMA time slots

Periodic superframes of N slots



- 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.*

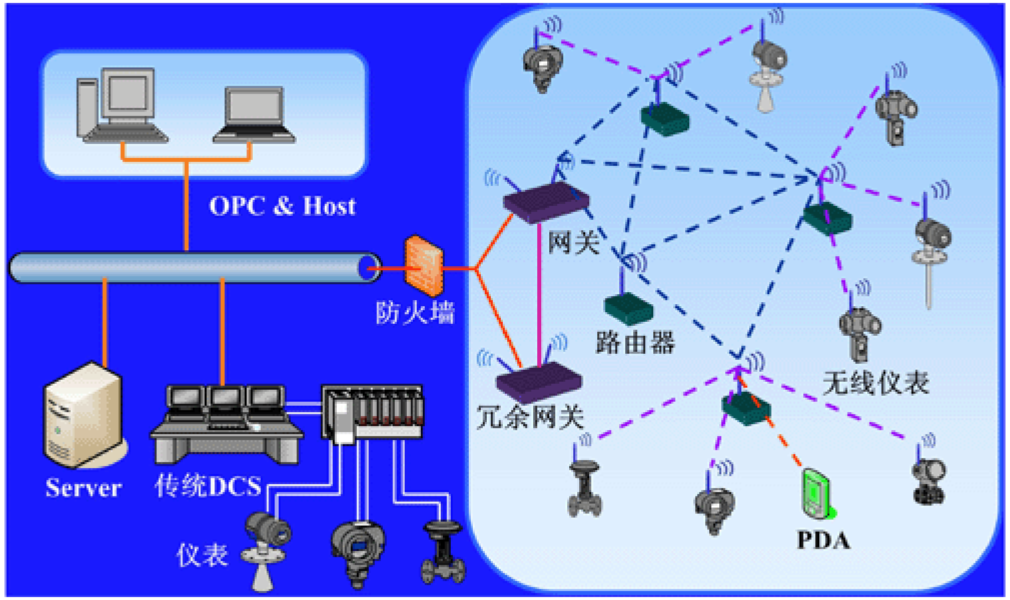
  (source: "Control with WirelessHart," Hart Communications Foundation)

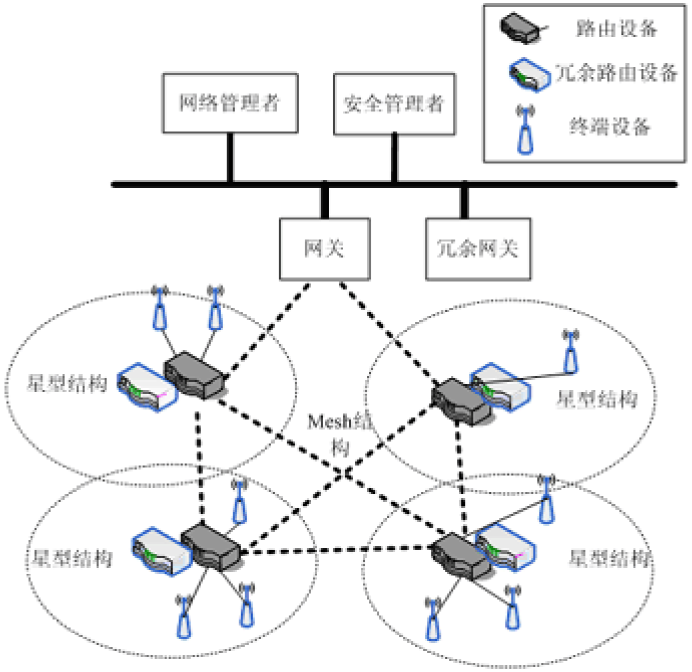
- ISA Fellow Greg McMillan conducted a research in early 2009 on commercial bioreactors using WirelessHart PH devices and concluded that *with a comprehensive battery life management approach, exception reporting, and a secure, reliable self-organizing and optimizing network, wireless process control 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.)

WIA 工业无线网络WIA
Industrial Wireless Network WIA

- Developed by 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系列产品

无线模块、无线设备、无线网关、。。。

成功案例

- 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.

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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?

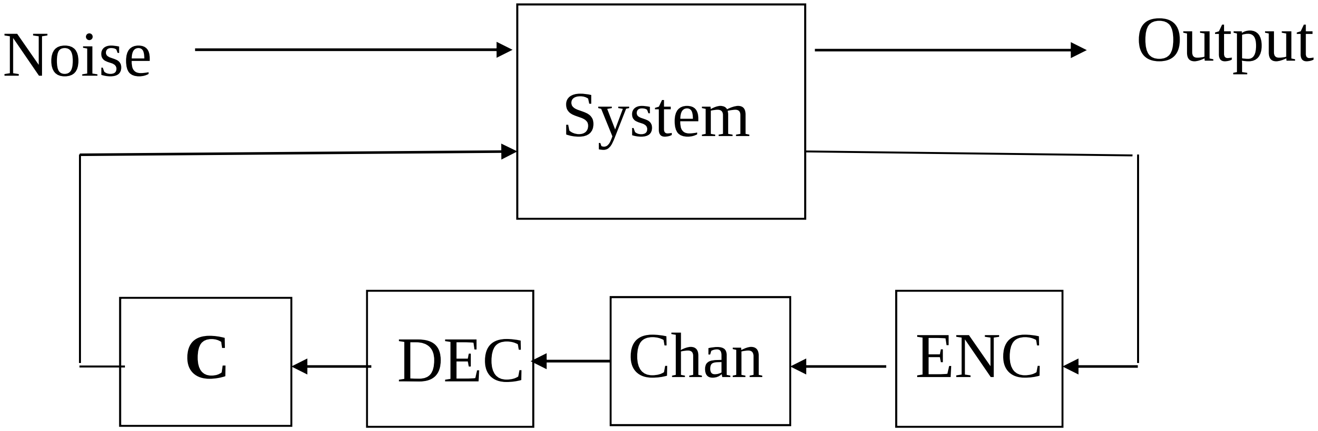
Two Approaches

1) Use sufficient network resources (bandwidth, power, redundancy …) to ensure that wireless transmission is *guaranteed* to be *sufficiently* fast and reliable. That is, network problems (such as time delays, packet losses, data rate limit) become negligible. Wireless networks essentially become wired networks, transparent to the users.
2) 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.

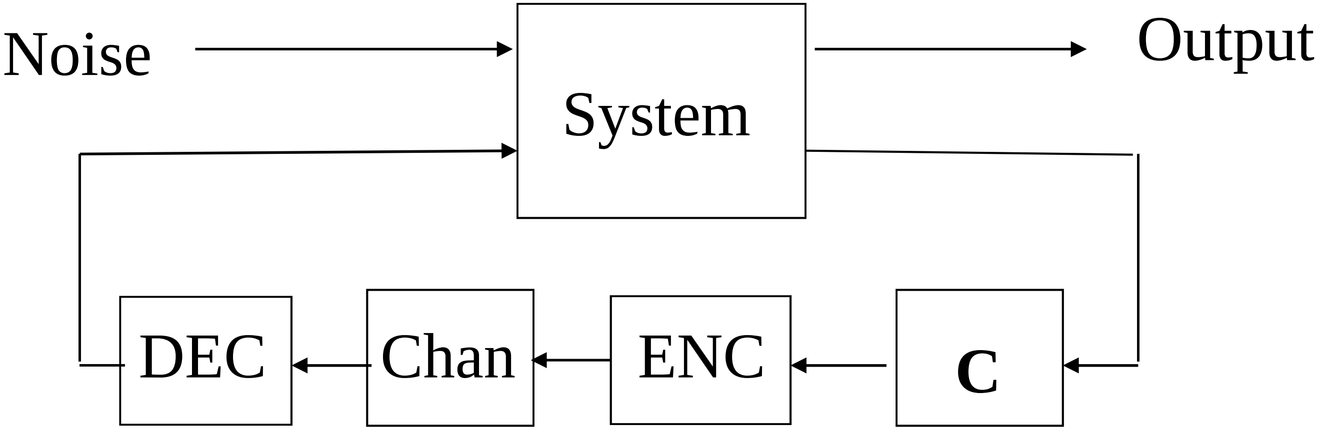
We will focus on the latter approach.

Quantized Feedback Control

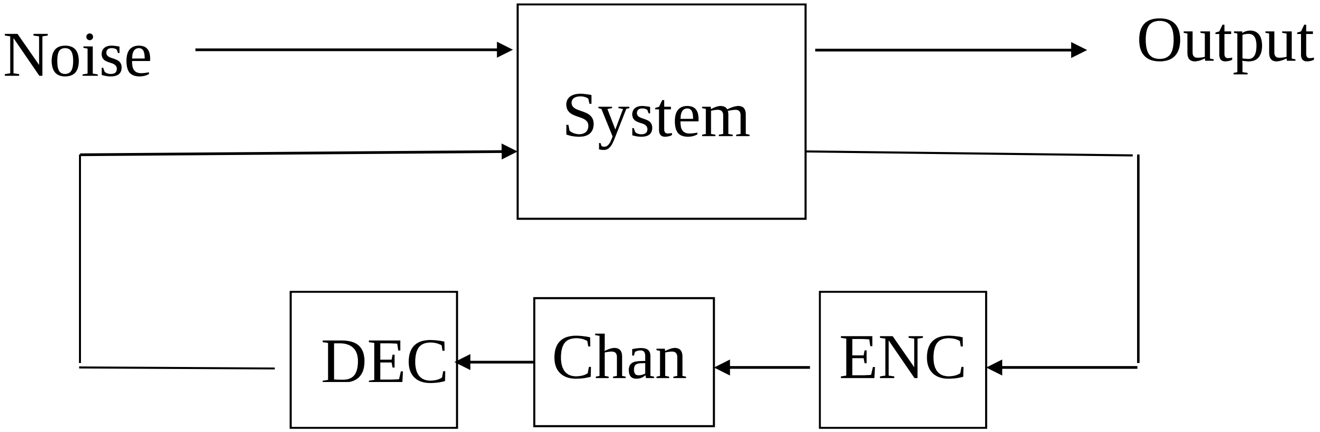
Structure for Networked Control:



Alternative Formulation:



Simplified (and More General) Structure:



- Encoder is allowed to “pre-process” the input data
- Decoder is allowed to “post-process” the output data

Ideal Channel Assumption: No delay, error-free, memoryless

Under this assumption: Networked control = quantized control

Some Known Results for Linear Systems:

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

Problem Setting: Stabilization of SISO system (noise free).

Result 1:

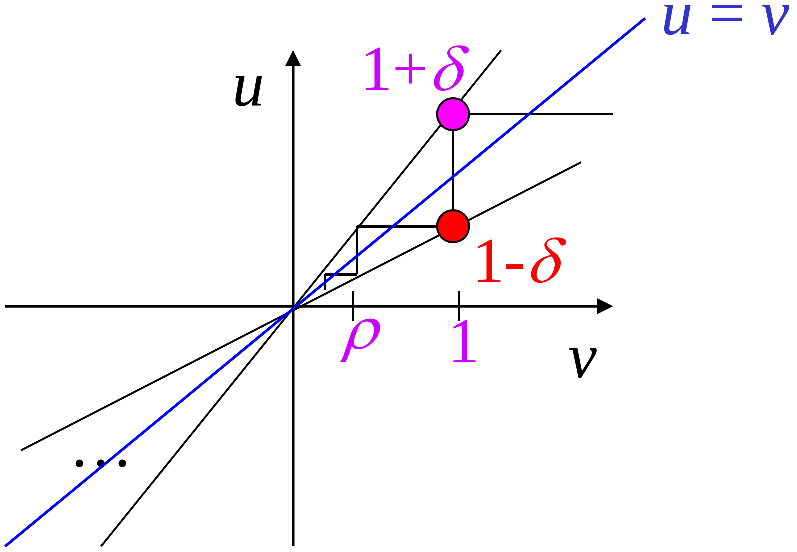
If the quantizer is allowed to have memory (or dynamic), then the minimum data rate for feedback stabilization is

$$R > \log_2 \prod_i \lambda_i^u(A)$$ (product of unstable eigenvalues)

Result 2:

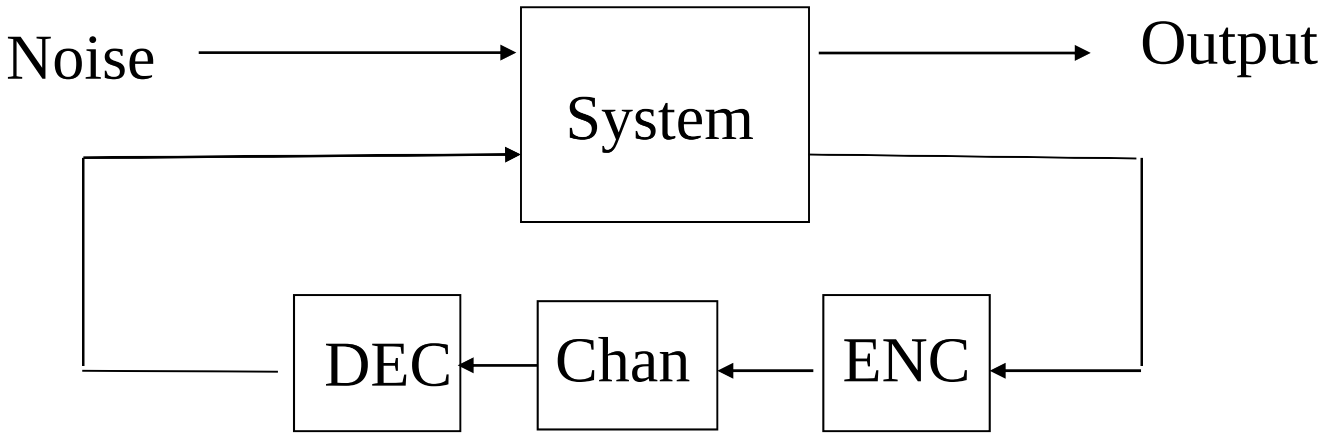
If the quantizer must be static, then the optimal structure is logarithmic and the minimum quantization density for feedback stabilization is

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



Key Problem: Quantized feedback control for performance

Quantized Linear Quadratic Gaussian (LQG) Control



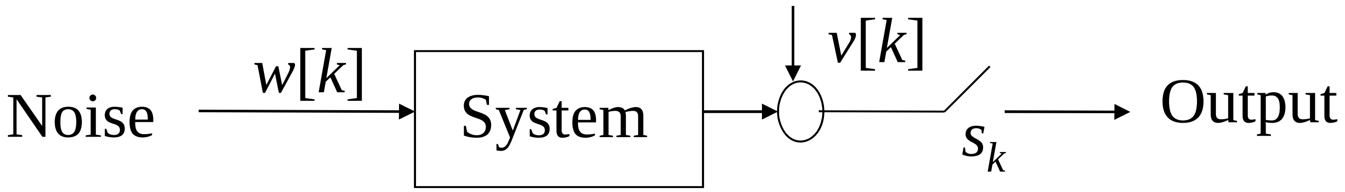
Problem: Standard LQG problem, but subject to a quantization constraint (i.e., bit rate constraint)

Some known results:

1. Separation principle fails in general
2. When the bit rate is not too small, the separation principle holds approximately.

How to best design quantizer and controller is still open.

State Estimation with Packet Dropouts



Noise $w[k]$ System $v[k]$ s_k Output

System: $$x[k+1] = Ax[k] + w[k]$$

$$y[k] = s_k (Cx[k] + v[k])$$

$$P(s_k = 0) = p; \qquad P(s_k = 1) = 1 - p$$

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

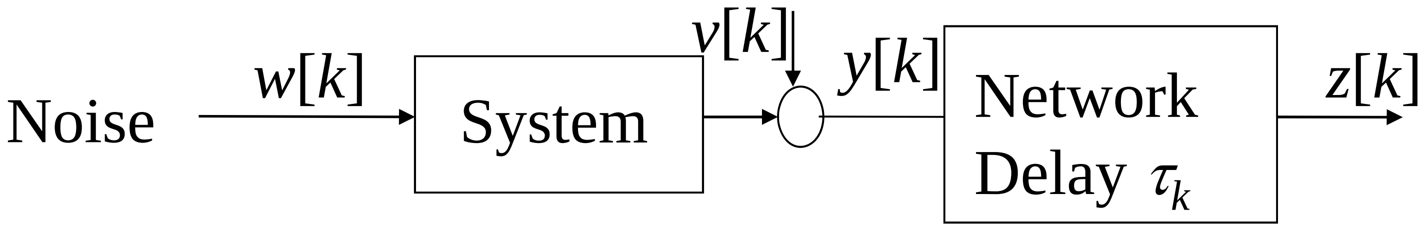
$$\hat{x}[k+1] = A\hat{x}[k] + L_k s_k (y[k] - C\hat{x}[k])$$

Estimation error covariance:

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

Key Problem: How to analyze the stochastic behavior of P_{k+1}

State Estimation with Random Time Delays



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

Delay model: $\tau[k] = 0, 1, \ldots, N$ randomly.

Packets received at time k:

			k-N	…….		k-1	k
1	1	……	1	1	0	0	1

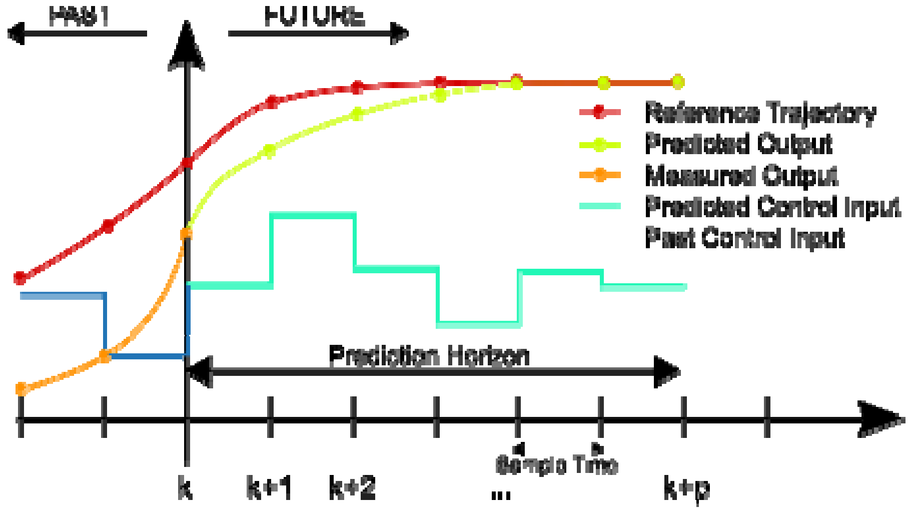
Optimal estimator = Kalman filter with missing data

Key Problem: How to analyze the stochastic behavior of P_{k+1}

Quantized Estimation with Packet Dropout and/or Random Time Delays:

How to do state estimation when the bit rate is also limited?

MPC Design with Network Constraints



On-line design

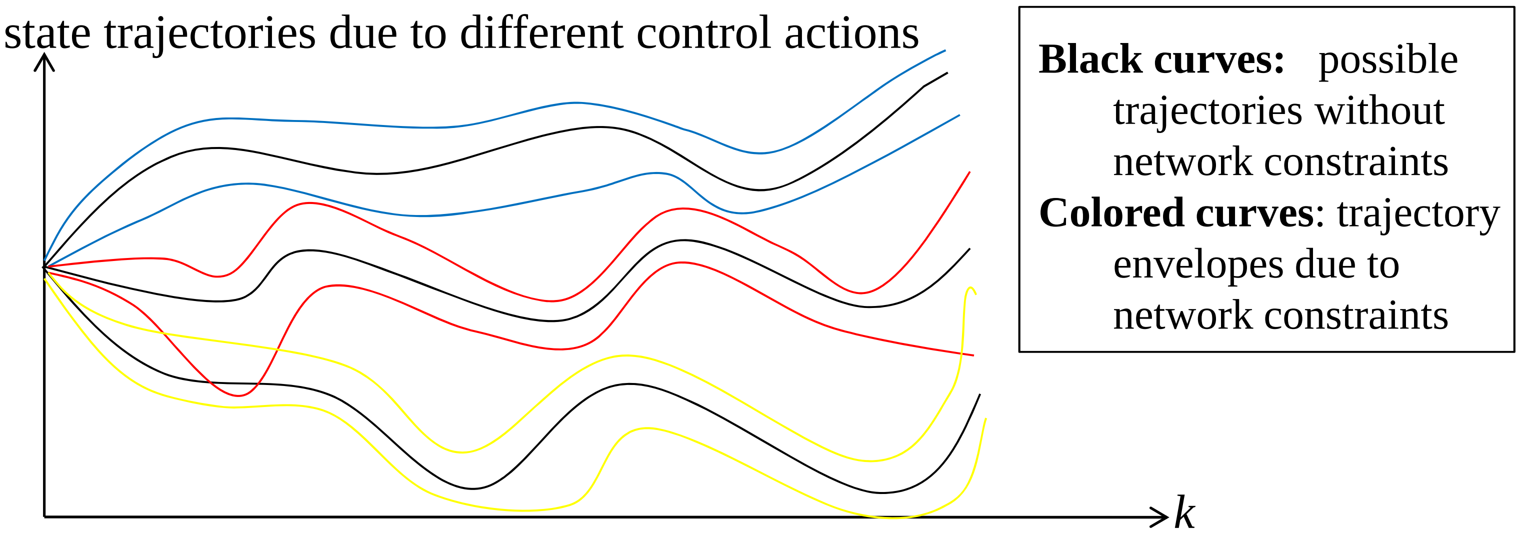
Minimize:

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

(deterministic)

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

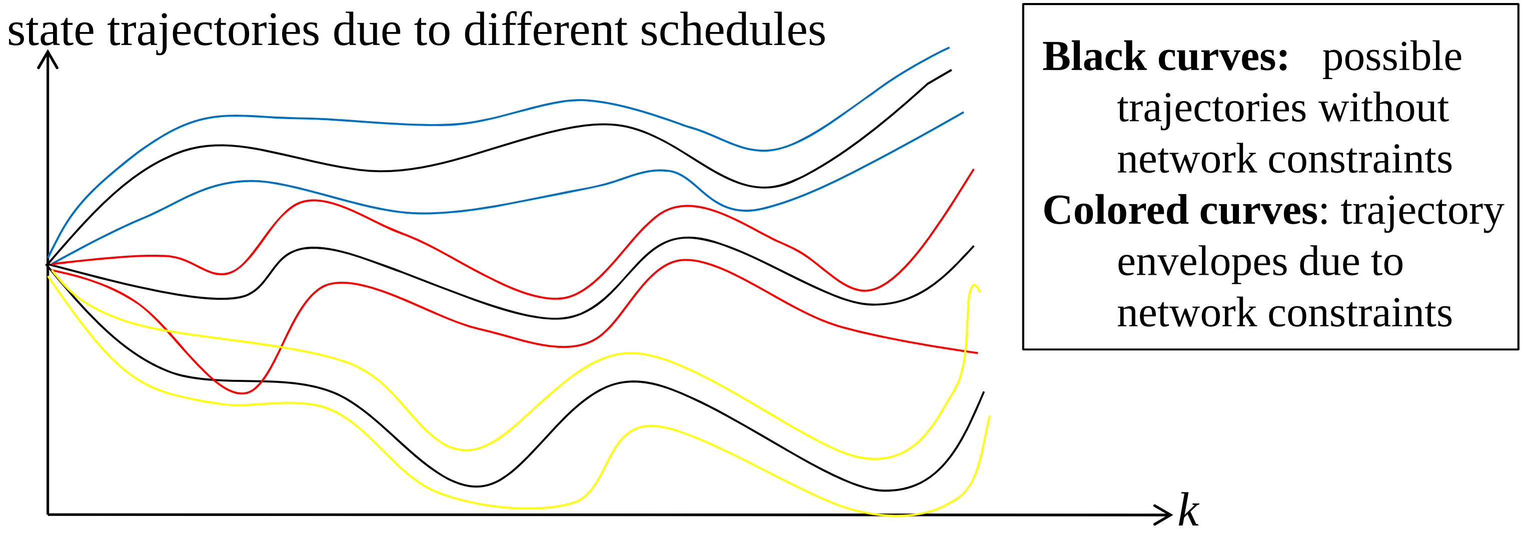
Problem 1: How to minimize $E[J]$?

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

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%)?

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?

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.

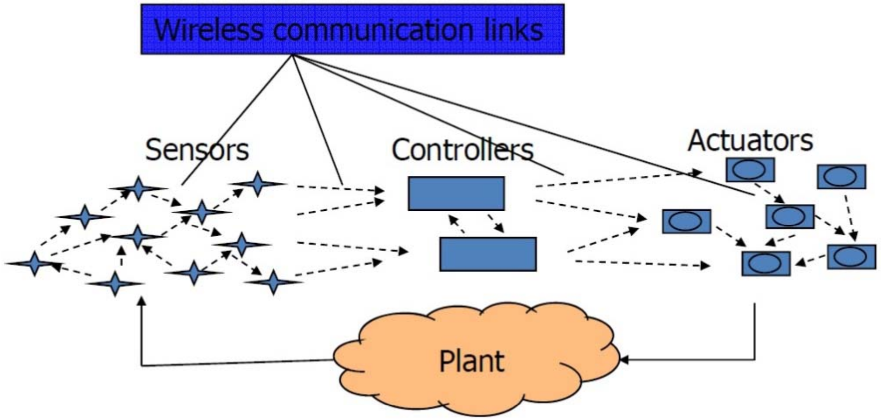
Questions (in the presence of network problems)**:**

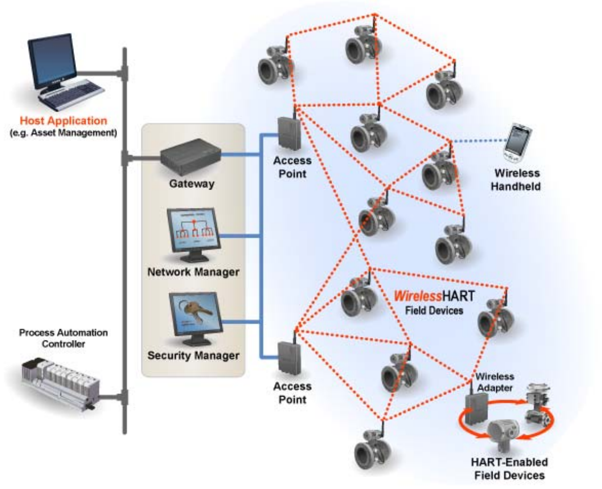
1) How to avoid false alarms?

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

3) What network properties are required to guarantee performance?

Distributed Estimation and Control





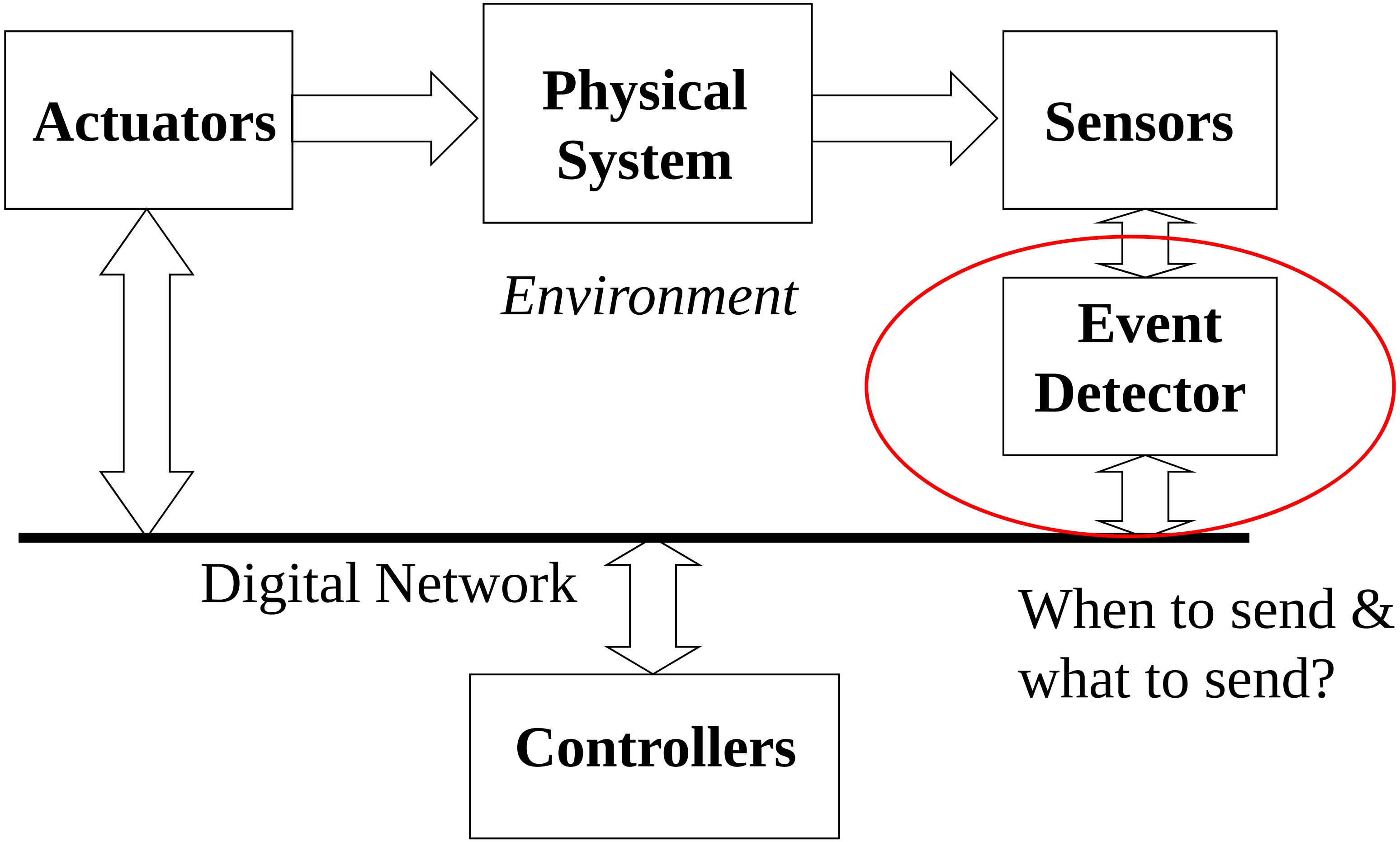
A key problem with networked control is data overloading:
(*Data Rich Information Poor* syndrome)

Question: How to do estimation and control in a distributed fashion?

Main constraint: communication data rate limit.

Need hierarchical, multi-timescale structures.

Event-based Control

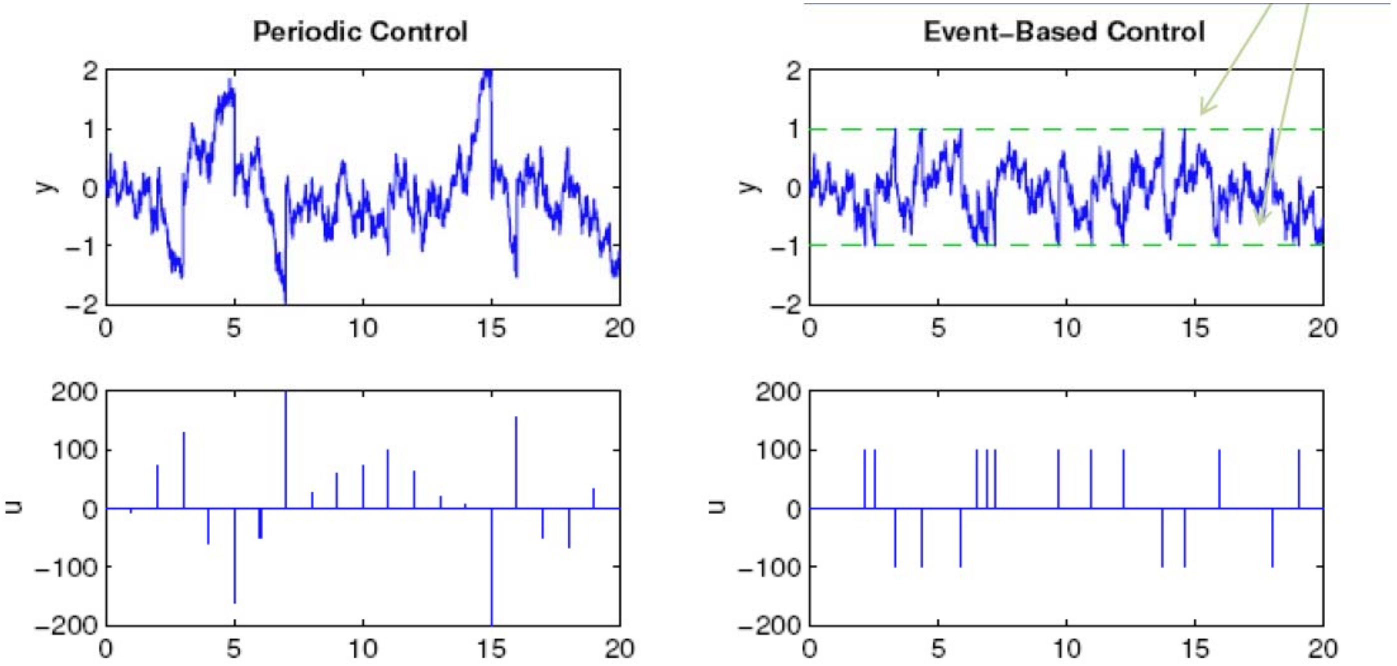


When to send & what to send?

Idea: To minimize the required network resources, i.e., transmit measurement only when necessary.

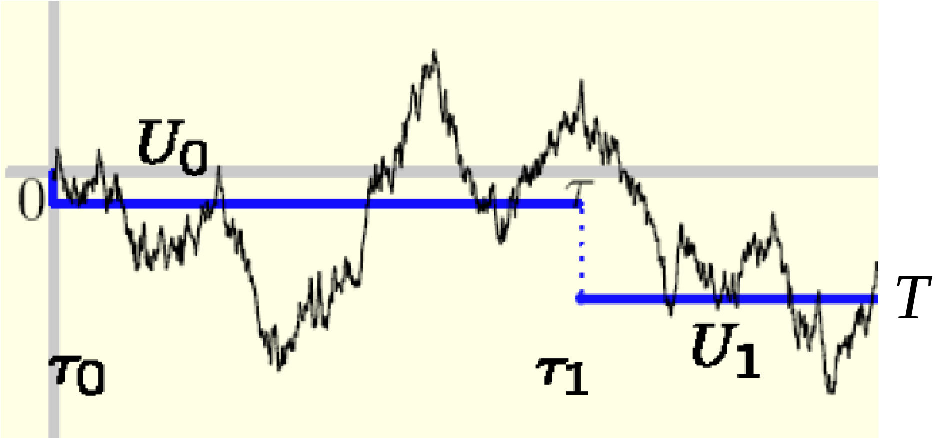
Example 1: Fixed threshold with impulse control

- Control problem: standard LQG problem
- Event detector: Use a fixed threshold, i.e., transmit when the measurement exceeds a given threshold in magnitude.
- Comparison with traditional periodic sampling



(Source: Karl Johansson)

Example 2: Control of a random walk



$$dx_t = u_t dt + dw_t$$

$$x_0 = 0,\ \tau_0 = 0,\ U_0 = 0$$

Question: how to choose τ_1 and U_1 to minimize

$$J = E\left\{\int_0^T x_t^2 dt\right\}$$

Answers:

- If τ_1 is independent of w_t, $\tau_1 = T/2$;
- If τ_1 can depend on w_t, $\tau_1 = \inf\{t : x_t^2 \geq \sqrt{3}(T-t)\}$
- The latter gives much smaller cost.

(Source: Karl Johansson)

General Research questions:

- How to design event detectors for a general system?
- How to design event detectors in a distributed fashion?
- How to deal with packet losses, time delays and quantization problems?

Fundamental Difficulty:

Conflict between *time-triggered* traditional control theory and *event-triggered* network design.

Consensus Control for Multi-agent Systems

- What is consensus? Achieving consensus is a process that all agents begin with multiple states and end with a mutually agreed state.
- Consensus seeking is everywhere: from animal behavior to engineering, e.g., flocking, schooling, swarming, synchronization, formation control, distributed computation…

Clock synchronization

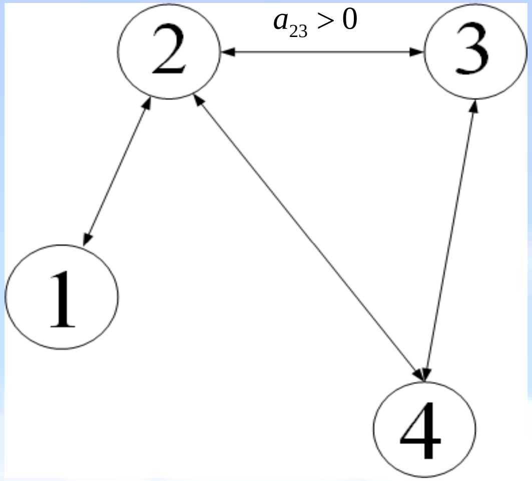
▲ Small fish schooling

▲ Formation of platoon of vehicles

Key features of the consensus problem:

- ✓ Networked agents.
- ✓ Each agent can only interact with its neighboring agents.
- ✓ Information may propagate across the network from one or more agents.
- ✓ Directed or undirected graph $G = \{V, E, A\}$ described using an adjacency matrix $A = [a_{ij}]$ and the edge set *E*:

$$(i, j) \in E \Leftrightarrow a_{ij} > 0$$



Problem Formulation:

- Linear discrete-time agent dynamic:

  $$X_i(k+1) = AX_i(k) + Bu_i(k), k = 0,1,\ldots\cdots (1)$$

- Distributed control p local states

  $$u_i(k) = K\sum^{N}$$

- (Co under the gain K su

- Prob on the graph G systems consensusab

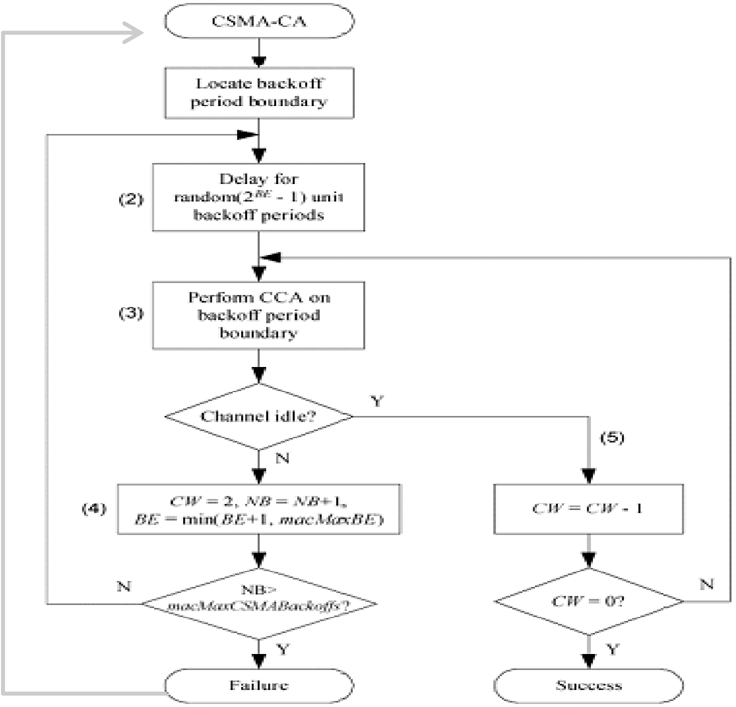
General Problems:

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

Wireless Network 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



Research Problems:

1) For a given topology, how to choose the parameters to optimize packet loss rate, time delays, and energy consumptions?
2) How to do joint optimization of control and network parameters?

Source: 浙大自控系曹向辉

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

此领域（包括工业无线网和基于网络的控制理论）在国内外都是一个空白。对我国自动化学科来讲，当今是一个极好的良机。抓住这个良机，联合起来扎实地研究**3-5** 年，对推动我国自动化学科的发展和对自动化工程核心技术的掌握将有着重要的作用。