M2M: System Control via PLC

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烽火台  Beacon Tower
The ancient tower meets radio-tech.

something has changed
No Change... for thousands years

1000 – 2000 years ago

two days ago

Human to Human
M2M or Cyber Physical Systems

- Comm. users for thousands years
- New Users

Conventional Users

M 2 M Communications

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M2M: Old and also very New field of research

- Industrial Machines  Automatic cranes, Robotic arms.
- Robots / Humanoid
- Intelligent Transportation System
- Home/Building/Community
  Energy Management
- Smart Grid and Smart Community
Smart Grids

- Two way flow of Energy and Information
  - Information Collection: Sensor Networks
  - System Control: Control Communications

- Features
  - Scale
    - larger than conventional control/sensor networks
  - Security
    - Information is highly private
  - Reliability and Robustness
    - Error in Communication results in social problem
    - Possibility of Intentional Attacks
  - M2M Communication
Control of distributed machines / plants in a wide area is a key to sustainable society.

* PLC is wireless technology that uses lines!
Control of distributed machines in a wide area is a key to sustainable society.

Wireless* is not Reliable!

Robust Reliable Radio is needed

* PLC is wireless technology that uses lines!
reliable/robustness was important also in traditional wireless communications

Is there any difference?
Measures of Wireless Systems

Wireless Engineers’ Favorites are

- Top (Best Case) Data Rate
- Throughput = Average Data Rate
- Average Bit Error Rate
Averages are the same, but …

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Average/Worst Delay

The data is provided by Prof. Hirayama@NIT

Wireless LAN: 802.11g (64bytes/packet)
Propagation: 10 meters LOS
Transmission: 100packets, 1ms after ACK
Location: Indoor @ University Building (10 x 20 m²)
Guaranteed Quality than Average High Speed

- **Conventional Radio**
  - High Speed & Capacity
  - Focuses on Max Quality and Average Quality

- **Wireless Control**
  - Small Amount of Control Data in particular time delay
  - Focuses on Worst Quality
reliable/robustness was important also in traditional wireless communications

Is there any difference?

**Human**: focus on *Average* and provide *Best Effort*

**M2M**: focus on *Worst Case* and provide *Guaranteed* Just in Time than *Real Time*
Upper Layers of Conventional Systems

- Human Communications
  - Complicated
  - Highly intelligent
  - Difficult to have a math model than Control’s M2M communications
Upper Layers of Control Systems

- Physical System (Machines) are
  - Not so Complicated as human
  - Not so Intelligent as human
  - possible to represent and evaluate with mathematics.

M 2 M Communications
reliable/robustness was important also in traditional wireless communications

Is there any difference?

Evaluation by QoS of upper (control) Layer is possible and necessary

Human: focus on Average and provide Best Effort

M2M: focus on Worst Case and provide Guaranteed

Reliable Robust Radio Control!!
What is Reliable Robust Radio Control?
Control System

Command says “Stop!”

Machine stops with delay.

$s(t)$

$t$

Command (reference signal)

Machine

$v(t)$

$t$

Output (behavior of the machine)

$s(t) ightarrow f(s(t)) ightarrow v(t)$

Error in Control System:

$\varepsilon_M(t) = v(t) - s(t)$
Radio Control System

Error in Wireless Comm:
\[ \varepsilon_{C}(t) = r(t) - s(t) \]

Overall Errors:
\[ \varepsilon_{S}(t) = u(t) - s(t) \]

\[ s(t) \xrightarrow{A/D} s[n] \]

Error Control

\[ \text{ modulation} \]

Radio Channel

\[ \text{ noise} \]

interference

\[ r(t) = g(s(t)) \]

\[ f(s(t)) \rightarrow v(t) \]

\[ s(t) \xrightarrow{g(s(t))} r(t) \]

\[ f(r(t)) \rightarrow u(t) \]
Radio Control System: Probabilistic System

Deterministic System: $s(t)$ determines $v(t)$

Stochastic System: $s(t)$ defines probability of $r(t)$, $u(t)$

In Radio Control System even if input is determined still output is stochastic/random

Measure of Quality based on Stochastic behavior of the system is needed.
Examples of Performance Measures

- **System**
  - Machine: $f(\cdot)$
  - Command: $s(t)$
  - Channel: $\text{Prob}(r(t)|s(t))$

- **Measures** [based on Stochastic behavior of $\varepsilon(t)=u(t)-v(t)$]
  - MSE: $\text{E}[\varepsilon^2(t)]$
  - worst case: $\max|\varepsilon(t)|$
  - outage prob.: $\text{Prob}(\Theta<|\varepsilon(t)|)$
  - delay
What is Reliable Robust Radio Control?

- Optimization of QoS at Control (Application) Layer
- QoS measures considering its stochastic behavior
Chronological Review of our works on Reliable Robust Wireless Control

Papers are at
http://www.katayama.nuee.nagoya-u.ac.jp/dbase/search-e.php
Proposal: Radio Control as a new research topic (1999)

Radio for Control… Improvement of Systems
- Propagation measurement[ focusing on worst cases]
- Space Diversity with Repeater-Cloud

Evaluation by QoS of Control
- Trade-off between Control Rate and Error Rate (2006～)

Inverted Rotary Pendulum as an Example (2008～)

Control of Multiple Machines and their Synchronization (2010～)

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List of our Works on RRRC [2010- ]

- Control of Multiple Machines and their Synchronization (2010～)
- Reduction of Control Data for Frequency Efficiency (2011.3～)
- Control through non-stationary channels (2011～)
- Error Control for Control Communications (2011～)

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Ex. Evaluation by QoS at Control Layer

- Trade-off between Data Transmission Rate and Data Loss Rate
- Optimum Data Transmission Rate

R. Uchida: Reliable Wireless Communications for Control/Sensing based on Diversity Concepts

R. Uchida, H. Okada, T. Yamazato, M. Katayama:
Influence of Characteristics of Wireless Channels on Quality of Wireless Control Systems,
Control Commands are sent through radio channel.
In order to achieve good control performance...
- Decrease Data Loss Rate
- Increase Data Transmission Rate

Both require increase of Transmission Power
Loss Rate & Transmission Rate

Loss Rate: Low
Trans. Rate: Low

Loss Rate: High
Trans. Rate: High

Which gives better Control Quality??
System Model (Radio Part)

- Reference: \( x(t) = \sin(2\pi f_m t + \phi) \), \( f_m = 1/4 \) [Hz]
- Trans. Rate: \( 1/T_s \) [packets/s]
- Packet Size: 512 [bits]
- Modulation: BPSK
- Rayleigh Fading (Doppler Freq. \( 10f_m \) [Hz])
- D/C: 0th order hold (if a packet is lost, its previous held sample is used.)
1st order feedback system: \( K_s = \pi \) (cutoff: 1/2 [Hz])

(ideal) stationary state: \( x(t) \equiv \hat{x}(t) \equiv \hat{o}(t) = o(t) \)

(\( o(t) \): ideal output with enough high trans. rate and low loss rate)
Control Performance can be Improved by the improvement of both $\frac{E_b}{N_0}$ (Error Rate), $\frac{1}{T_s}$ (Trans. Rate).

$E[|\hat{o}_1(t) - o(t)|^2]$
Performance of a Control System

There are optimum transmission rates.
The optimum rates depend on total transmission power.
There is an optimum transmission rate.

The optimum rate does not depend on total transmission power.

Throughput (Comm) optimum does not ensure MSE (Control) optimum

Throughput:
\[
\frac{1}{T_s} - \text{Average Packet Loss Rate}
\]
Rotary Inverted Pendulum
Trade-off between the packet transmission rate and the packet loss rate [1]

Feedback Control through PLC Cyclic Channel


Feedback system that employs a power line as its feedback loop

controller

channel

controlled object

control information

state information

System model

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### Pendulum’s physical parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pendulum’s mass</td>
<td>0.004 [kg]</td>
</tr>
<tr>
<td>Pendulum rod’s mass</td>
<td>0.025 [kg]</td>
</tr>
<tr>
<td>Pendulum rod’s length</td>
<td>0.241 [m]</td>
</tr>
<tr>
<td>Arm’s length</td>
<td>0.152 [m]</td>
</tr>
<tr>
<td>Arm’s moment of inertia</td>
<td>0.00121 [kgm^2]</td>
</tr>
<tr>
<td>Gravitational acceleration</td>
<td>9.81 [m/s^2]</td>
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### Simulation parameters

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<td>Packet length</td>
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<td>Digital sampling rate</td>
<td>1024 Hz</td>
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<tr>
<td>Mains voltage frequency</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Simulation duration</td>
<td>100 s</td>
</tr>
<tr>
<td>Number of simulation trials</td>
<td>100 and 1000 times</td>
</tr>
<tr>
<td>Pendulum angle target value</td>
<td>0 [rad]</td>
</tr>
<tr>
<td>Period of arm motion</td>
<td>10 s</td>
</tr>
<tr>
<td>Arm target value</td>
<td>0⇔π</td>
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<td>Upright region</td>
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Evaluation of the average SNR vs the control quality

The cyclostationary noise case shows a better performance at the lower SNR region.
Packet loss rate behavior

SNR $\gamma = 4$ dB
packet length: 40 bits
modulation scheme: BPSK

Cyclostationary noise case
Stationary noise case
Evaluation of the average SNR vs the control quality

however, the stationary noise case shows a slightly better performance at the higher SNR region
Packet loss rate behavior

SNR $\gamma = 6$ dB

packet length: 40 bits
modulation scheme: BPSK

SNR $\gamma = 6$ dB
Feedback Control with PLC

- Time variant (Cyclo-stationary) Channel
  - Example of the system where
    - average and worst error rates (comm. quality measures) are not good measure of control quality, and
    - the cyclic “good-states” dominate overall control quality.
Synchronous Move of Multiple Plants

(Allow me skip contents and focus on the main idea)


The concert with 10 minutes delay and the music is great!
The concert with 1 second of random delay of each player confirms central limit theorem.
Synchronization is often more important than latency.
Importance of Radio/PLC Control is increasing
- Control of Smart Grid --- Typical Cyber-Physical System

Radio/PLC Control is interesting for Control People
- Behavior of systems become stochastic
- Control of multiple distributed plants
Invitation to M2M Research

- Radio/PLC Control is new and interesting application for Communication People
  - Conventional measures of quality are not sufficient.
  - Total optimization including application layer is possible/necessary.
  - There exists new concepts/viewpoints such as synchronous move and common clock delivery.
- meanings of bits change: needs new theory

In Classic Comm. Theory
Bits can be canned or stored/compressed taking time

In Control Communications
Bits have to be fresh!