Overview of Wireless Networked Cyber-Physical Systems

Hongwei Zhang

http://www.cs.wayne.edu/~hzhang
Outline

- From Internet to sensornet
- From sensornet to WCPS
- General challenges of WCPS
- Challenges to wireless networking
Outline

- From Internet to sensornet
- From sensornet to WCPS
- General challenges of WCPS
- Challenges to wireless networking
Retrospect on computing & networking

ENIAC: first computer (1945)

Apple II: first successful PC (1977)

Laptop, PDA … (1979 -)

First computer network (1969)

Internet, wireless …
What if Ubiquitous Computing & Networking + Sensing & Control?

→ *Ubiquitous, fine-grained* sensing & control
Sensor nodes

- A XSM sensor node (2004)
  - 8MHz CPU, 4KB RAM, 128KB ROM
  - Chipcon CC1000 radio: 19.2 kbps
  - Infrared, acoustic, and magnetic sensors
  - Sounder
  ...

- Many more (2001 - )
TinyOS: an open-source OS for WSNs
Wireless sensor networks: *innovative ways of interacting with the world …*

**Science:** ecology, seismology, oceanography …

**Engineering:** industrial automation, precision agriculture, structural monitoring …

**Daily life:** traffic control, health care, home security, disaster recovery, virtual tour …
Sensor networks of today

Redwood ecophysiology

Wind response of Golden Gate Bridge

Intruder detection, classification, and tracking
ExScal

- Field project to study scalability of middleware and applications in sensornets
- Deployed in an area of \( \sim 1,300 \text{m} \times 300 \text{m} \)
- 2-tier architecture
  - Lower tier: \( \sim 1,000 \) XSM, \( \sim 210 \) MICA2 sensor nodes (TinyOS)
  - Higher tier: \( \sim 210 \) IEEE 802.11b Stargates (Linux)
Industrial monitoring:
Intel Semiconductor Factory monitoring …

Preventative equipment maintenance:
monitoring vibration signals …
Precision agriculture: smart vineyard

monitor soil humidity, temperature, chemistry …
TurtleNet: track wood-turtles ...

The turtle came out of the water to sun itself for only brief periods and went back into the colder water ...
SealNet: use nature to help scientific study

- To measure ocean’s temperature and salinity levels, as well as the seal’s location and depth.
- Sensing data are collected for every dive; Each time the seals resurfaced to breathe, that data was relayed via satellite to certain data centers in US and France
  - As the seals migrated and foraged for food during their winter journey, they circumnavigated the Antarctic continent and its continental shelf, diving down to 2,000 feet more than 60 times a day
Social dynamics and networking
BikeNet: mobile sensing system for cyclist experience mapping

- Monitor cyclist performance/fitness: speed, distance traveled, calories burned, heart rate, galvanic skin response, etc
- Collect environmental data: pollution, allergen, noise, and terrain condition monitoring/mapping, etc
Outline

- From Internet to sensornet
- From sensornet to WCPS
- General challenges of WCPS
- Challenges to wireless networking
From open-loop sensor networks to closed-loop cyber-physical systems (CPS)

- Sensing, networking, and computing tightly coupled with the control of the physical world
  - Automotive
  - Alternative energy grid
  - Industrial monitoring and control

- Wireless networks as carriers of mission-critical sensing and control information
  - Stringent requirements on predictable QoS such as reliability and latency
Vehicular CPS
Smart energy grid CPS

An example smart grid CPS
with heterogeneous distributed-energy-resources (DER)
Micro power grid

Coordination among distributed energy sources, controllable loads, energy storage, etc.

EVS as controllable load

EVS as distributed storage
Process Control Industries: Wireless Market Growth


($Millions) ©2008 ARC Advisory Group

Figure 5.11 Germany Industrial Internet Market Revenue Forecast 2015-2025 ($ billions, AGR%)
Standardization efforts

- **WirelessHART**
  - Part of HART Field Communication Specification, Revision 7.0
    - Ratified September 2007
    - Allows for wireless transmission of HART protocol
  - Based on IEEE 802.15.4 PHY with modified MAC Layer
    - Adaptive frequency hopping
    - Time-division multiple access (TDMA)
  - Full mesh network topology
Network Manager
- Makes all decisions
- Devices can be “dumb”

Presently mainly supported by “Dust Networks Inc.”
- SoC and module products
ISA SP100.11a

- ISA: Instrumentation, Systems, and Automation Society
- ISA develops standards for ANSI
  - ISA SP100 scope includes all types of manufacturing
  - ISA 100.11a is first standard for wireless industrial monitoring and control

- WIA-PA (China-led effort)
IETF

- 6TiSCH
- RFC 4944 (6LowPAN)
  - IPv6 over 802.15.4
- ROLL Working Group
  - Began May 2007
  - Routing over low-power lossy nets
- Application areas:
  - Industrial
  - Home
  - Buildings
  - Etc.
- Others
  - IEEE 802.15.4e: time-synchronized frequency hopping
  - IEEE 802.15.4g: grid smart metering
  - IEEE 802.15.4a: UWB/CSS physical layer
  - IEEE 802.11s: mesh networking
Healthcare CPS

Medical implant: artificial retina …

Remote, robotic surgery

Assisted living: health monitoring & coordination …
Outline

- From Internet to sensornet
- From sensornet to WCPS
- General challenges of WCPS
- Challenges to wireless networking
Complex systems

- Design, analysis, and implementation of complex, integrated sensing, communication, computing, control, and physical systems
  - Complex interactions among potentially conflicting actuations
    - E.g., in vehicular CPS, numerous safety features, such as adaptive cruise control, forward/rear crash avoidance, and curve speed control, may desire to apply varying amounts of braking torque at various rates under various, potentially overlapping conditions
  - Continuous & discrete dynamics + discrete control
  - Dynamics and uncertainties in all aspects of CPS: cyber and physical
Real-time, networked control

- Communication requirements
  - Large delay implies reduced stability region (e.g., in proportional-integral control), longer settling time, larger maximum overshoot in control [3]
    - Low latency is even more important than information accuracy, since control systems are usually robust to information inaccuracy
  - Many control techniques have been developed for systems with constant time delay; variable time delays can be much more difficult to compensate for, especially if delay jitter is large [1].
    - Large jitter in messaging latency also increases max. end-to-end latency (see next slide).
  - To stabilize a system that is open-loop unstable, we need certain minimum rate of quantized feedback information which depends on the open-loop poles [2]
End-to-end real-time scheduling in networked, distributed systems

- Large jitter in job completion time increases the maximum end-to-end completion time and reduces schedulability of end-to-end tasks [5]
  - Implication: large jitter in messaging latency increases max. end-to-end latency

Implications

- Low delay and delay jitter in network data delivery
- Necessary data rate/throughput, even though small in some cases
- Jitter control in priority-based network real-time scheduling
Outline

- From Internet to sensornet
- From sensornet to WCPS
- General challenges of WCPS
- Challenges to wireless networking
Dynamics and uncertainties in WCPS

- **Within system**
  - Complex spatial and temporal dynamics in wireless communication
  - Potentially unpredictable network traffic dynamics
  - Dynamic application properties (e.g., QoS requirements and INP methods) across applications and over time

- **From environment**
  - Dynamic environments: human/object movement, temperature, etc.
  - Dynamic, interfering co-existing networks
  - Malicious attacks (e.g., jamming)
Mote testbed

- We use Mica2 motes that are deployed in a $14 \times 7$ grid
- Focus on links of the middle row
- Interferers randomly distributed in the rest 6 rows, with 7 motes on each row on average; interfering traffic is controlled by the probability $d$ of generating a packet at an arbitrary time
Complex properties of wireless links

Link estimation becomes a basic element of routing in wireless networks.
Traffic pattern affects link ETX

Unicast ETX in different traffic/interference scenarios
Interactions among dynamics

- Traffic pattern $\Rightarrow$ co-channel interference $\Rightarrow$ link properties $\Rightarrow$ link est. & routing

- Co-existing network $\Rightarrow$ cognitive channel hopping & routing $\Rightarrow$ traffic pattern
Challenges for predictable wireless communication

- How to *model* systems and environmental dynamics, uncertainties, and their impacts?
  How to use these models in *capacity planning and admission control*?

- How to effectively *address* these dynamics, uncertainties and their interactions?
  - Implications for MAC, routing, transport control?

- How to *evaluate* protocols in realistic settings of systems and environmental dynamics?
References


