Computer Networking: Internet and Beyond

Hongwei Zhang

hongwei@iastate.edu, 515 294 2143

http://www.ece.iastate.edu/~hongwei

IOWA STATE UNIVERSITY
Electrical and Computer Engineering

Acknowledgement: this lecture is partially based on the slides of Dr. James Kurose, and Dr. Keith Ross

Well-known network applications

E-mail

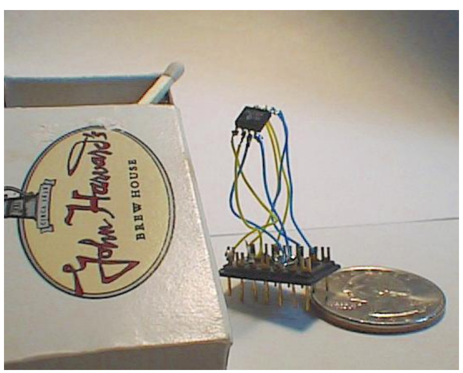
WWW

Video conference

Internet Appliances

IP picture frame
http://www.ceiva.com/

Web-enabled
toaster + weather forecaster



World’s smallest web server
http://www-ccs.cs.umass.edu/~shri/iPic.html

Internet phones

History, Development, and Future

JEOPARDY!
Networking

First Internet application?

First Computer Network?

Outline

- Internet
- From Internet to sensornet/IoT
- From sensornet/IoT to WCPS
- General challenges of WCPS
- Looking into the future

Outline

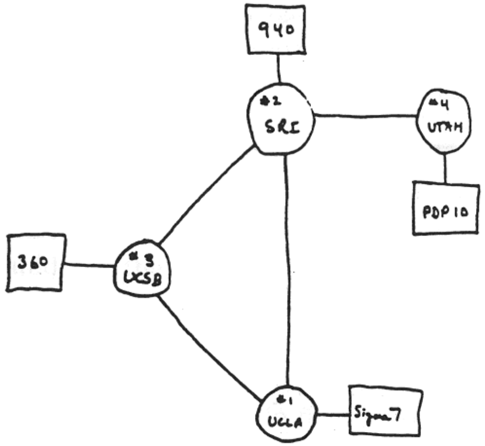
- Internet
- From Internet to sensornet/IoT
- From sensornet/IoT to WCPS
- General challenges of WCPS

Internet History

1961-1972: Early packet-switching principles

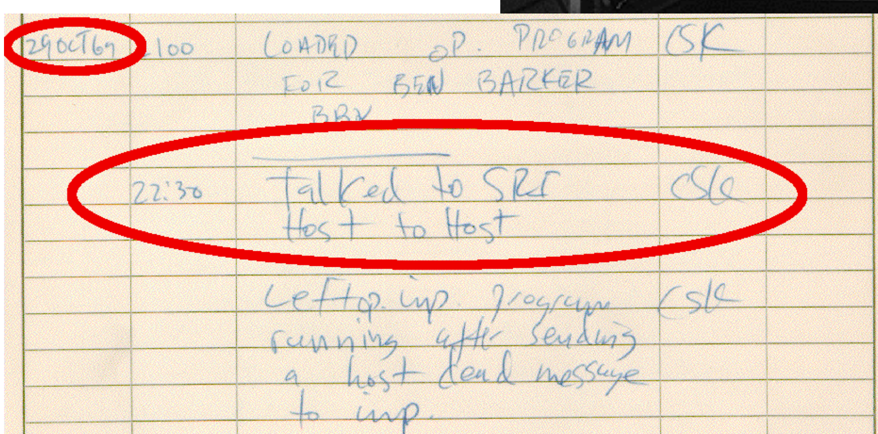
- 1961: Kleinrock - queueing theory shows effectiveness of packet-switching
- 1964: Baran - packet-switching for secure voice over military nets (in real-world systems)
- 1967: ARPAnet conceived by Advanced Research Projects Agency (Kleinrock's colleagues at MIT)
- 1969: first ARPAnet node operational (at UCLA), and three added soon after

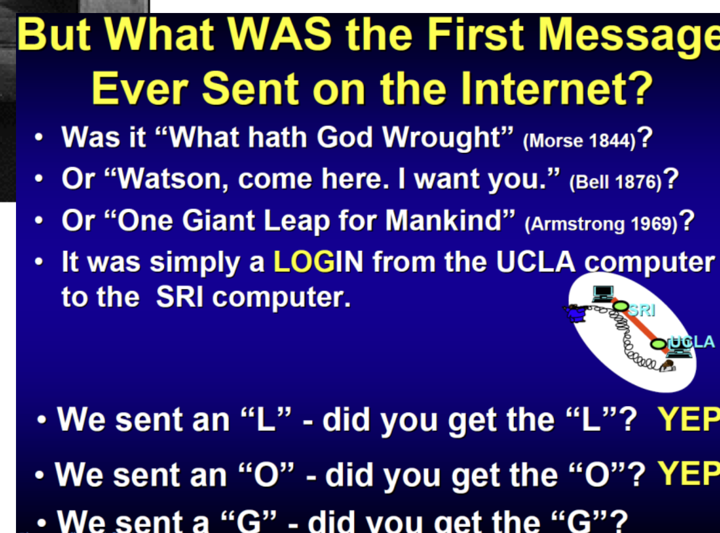
- 1970-1972:
  - NCP (Network Control Protocol): first host-host protocol
  - ARPAnet has 15 nodes; ARPAnet public demonstration;
  - first e-mail program



THE ARPA NETWORK


INTERFACE
MESSAGE
PROCESSOR
Developed for the Advanced Research Projects Agency by Bolt Beranek and Newman Inc.


29 OCT 69
2100
LOADED OP. PROGRAM
FOR BEN BARKER
BBN
CSK
22:30
Talked to SRI
Host to Host
CSK
Left op. imp program
running after sending
a host dead message
to imp.
CSK


But What WAS the First Message Ever Sent on the Internet?
• Was it "What hath God Wrought" (Morse 1844)?
• Or "Watson, come here. I want you." (Bell 1876)?
• Or "One Giant Leap for Mankind" (Armstrong 1969)?
• It was simply a LOGIN from the UCLA computer to the SRI computer.
SRI
UCLA
• We sent an "L" - did you get the "L"? YEP!
• We sent an "O" - did you get the "O"? YEP!
• We sent a "G" - did you get the "G"?
©Leonard Kleinrock 2006

Internet History

1972-1980: Internetworking, new and proprietary nets

- 1970: ALOHAnet satellite network in Hawaii
- 1976: Ethernet at Xerox PARC (for shared broadcast networks)
  - *ACM Turing Award 2009*
- late70's: proprietary architectures: DECnet, SNA (IBM), XNA (Xerox)
- 1974: Cerf and Kahn - architecture for interconnecting networks
  - *ACM Turing Award 2005*
- 1979: ARPAnet has 200 nodes

What about real-time communications needed by AR/VR (e.g., telepresence & telesurgery)?

Cerf and Kahn's internetworking principles:

- minimalism, autonomy - no internal changes required to interconnect networks
- best effort service model
- stateless routers
- decentralized control

defined today's Internet architecture

Internet History

1980-1990: new protocols, a proliferation of networks

- 1983: deployment of TCP/IP (all "Internet" nodes change from NCP to TCP/IP on the same day!)
- 1982: SMTP e-mail protocol defined
- 1983: DNS defined for name-to-IP-address translation
- 1985: FTP protocol defined
- 1988: TCP congestion control

- New national networks: BITnet, CSnet, NSFnet, Minitel (France)
- 100,000 hosts connected to confederation of networks

Internet History

1990, 2000's+: commercialization, the Web, new tech/apps

- Early 1990's: ARPAnet decommissioned; MILNET, Defense Data Networks, etc. (for Department of Defense)
- 1991: NSF lifts restrictions on commercial use of NSFnet; decommissioned in 1995, commercial ISPs
- early 1990s: Web
  - hypertext [Bush 1945, Nelson 1960's]
  - 1989: HTML, HTTP: Berners-Lee
  - 1994: Mosaic, later Netscape
  - late 1990's: commercialization of the Web

Late 1990's – 2000's:

- more killer apps: instant messaging, P2P file sharing
- network security to forefront
- est. 50 million host, 100 million+ users
- backbone links running at Gbps

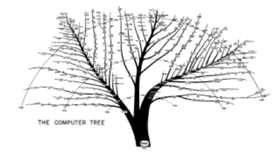
2000+:

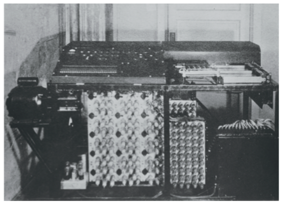
- Social networking
- Wireless sensing and control networking etc

Outline

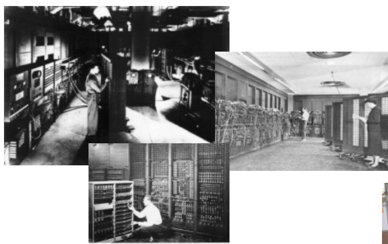
- Internet
- From Internet to sensornet/IoT
- From sensornet/IoT to WCPS
- General challenges of WCPS
- Looking into the future

Retrospect on computing & networking





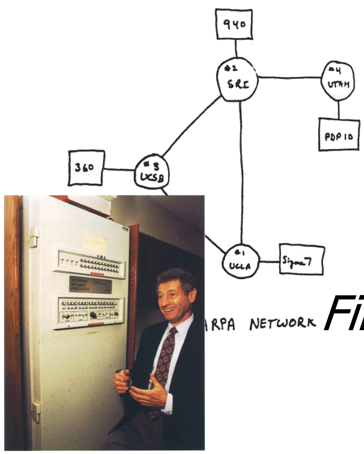
ISU Atanasoff-Berry Computer (1937-1942)



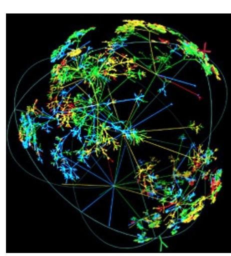
ENIAC: first computer (1945)

Apple II: first successful PC (1977)

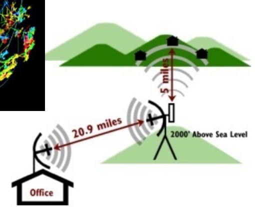
Laptop, PDA … (1979 -)



First computer network (1969)



Internet, wireless …



What if

Ubiquitous Computing & Networking + Sensing & Control ?

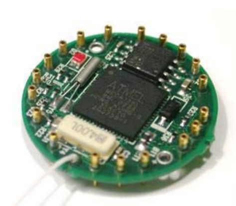
→ *Ubiquitous, fine-grained* sensing & control

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

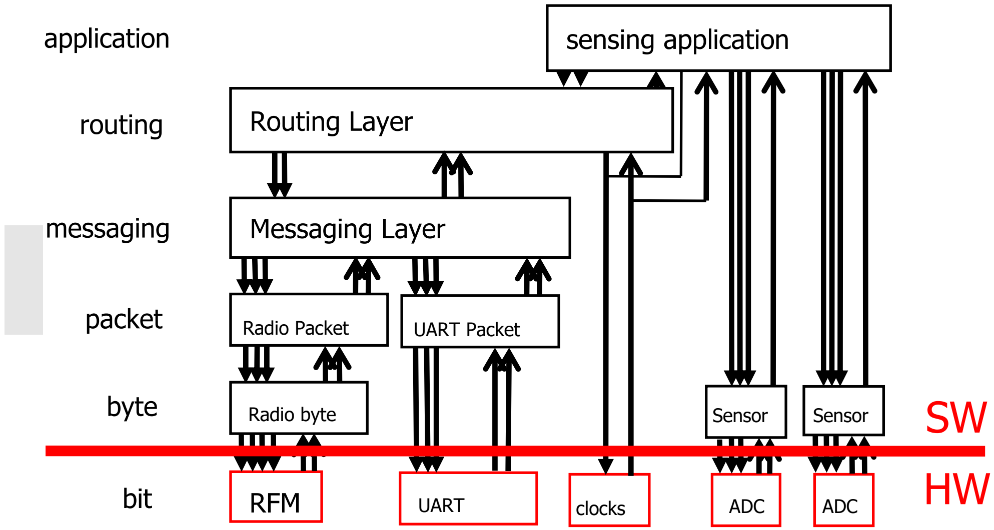
  …

- Many -)






- TinyOS: an open-source OS for WSNs



- Contiki / Contiki-NG

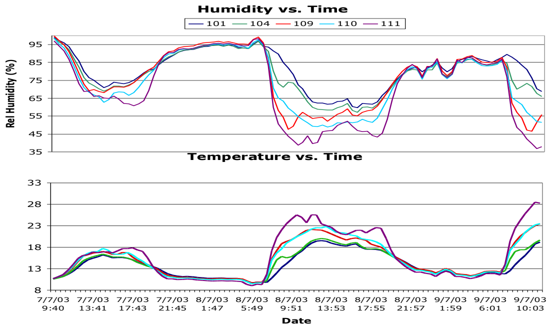
Wireless sensor networks:
innovative ways of interacting with the world …

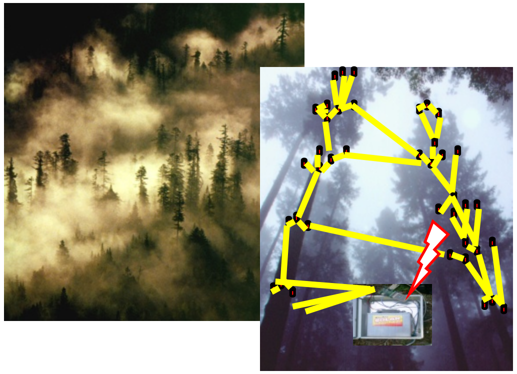
Science: ecology, seismology, oceanography …

Engineering: industrial automation, precision agriculture, structural monitoring …

Daily life: traffic control, health care, home security, disaster recovery, virtual tour …

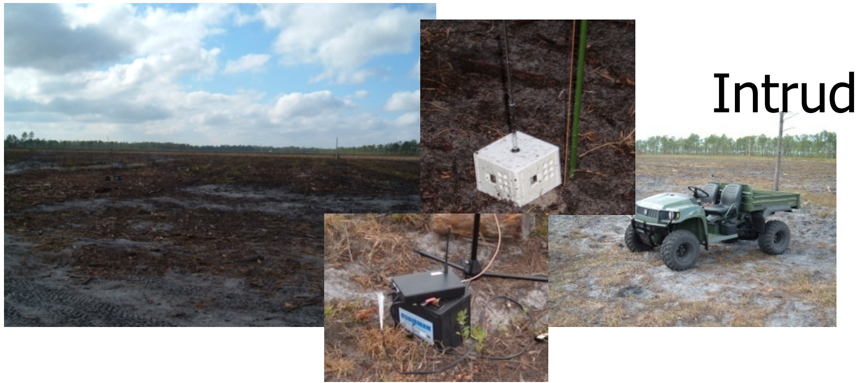
Sensor networks of early days





Redwood ecophysiology

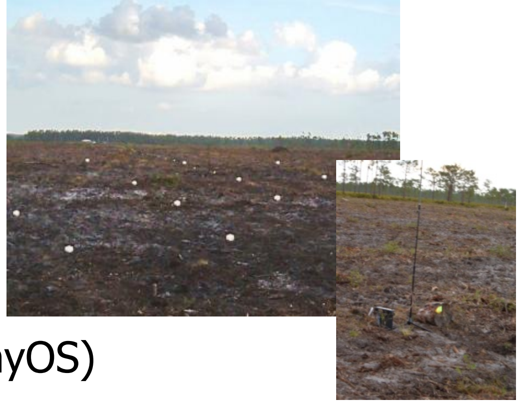
Wind response of Golden Gate Bridge



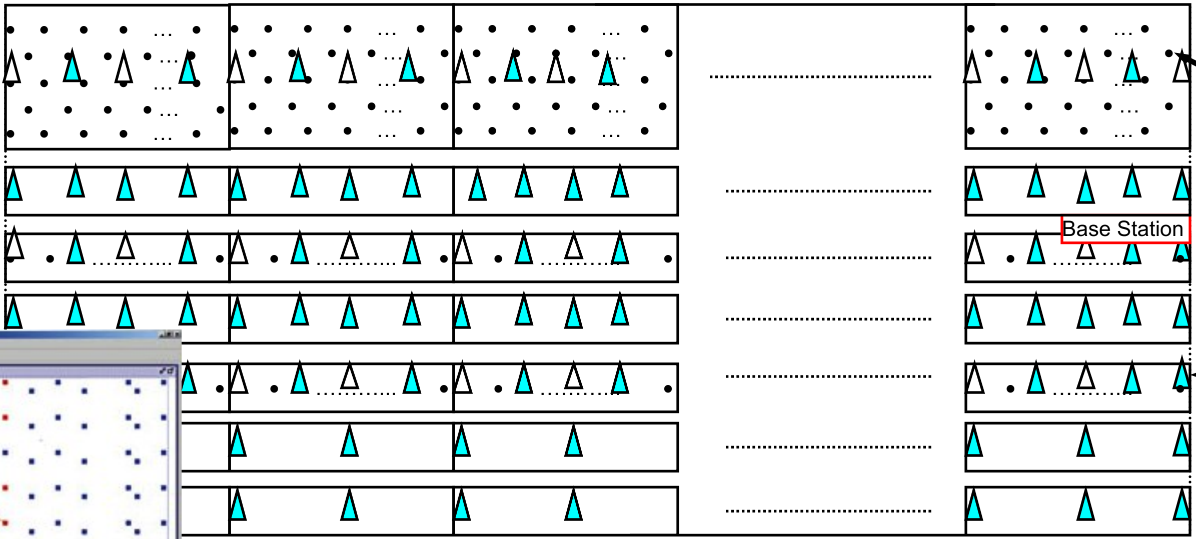
Intruder detection, classification, and tracking

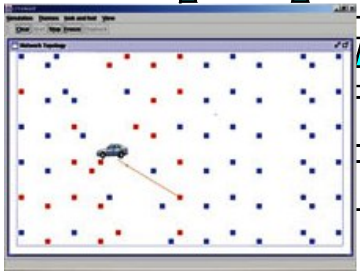
ExScal

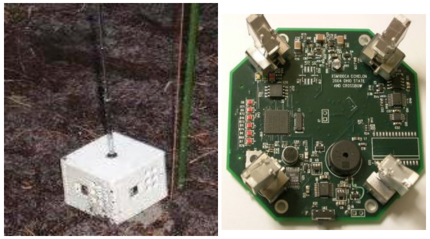
- Field project to study scalability of middleware and applications in sensornets



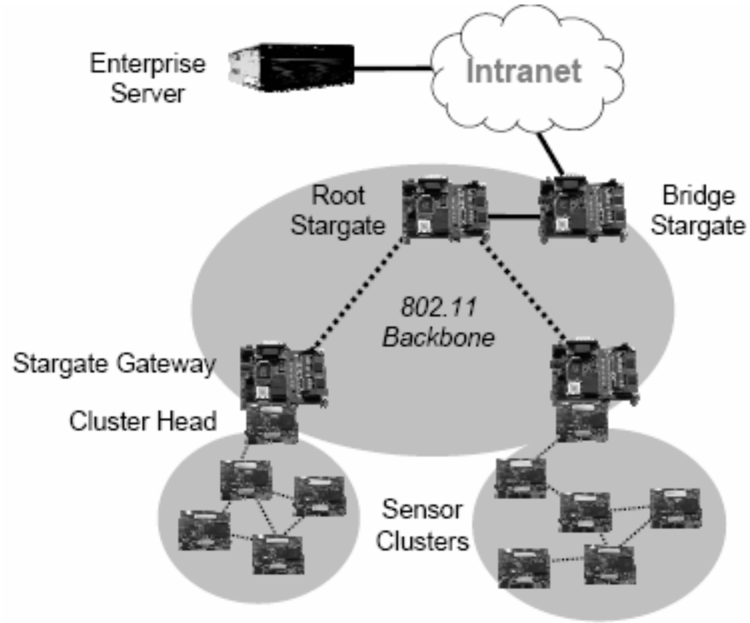
- Deployed in an area of ~1,300m × 300m
- 2-tier architecture
  - Lower tier: ~ 1,000 XSM, ~210 MICA2 sensor nodes (TinyOS)
  - Higher tier: ~ 210 IEEE 802.11b Stargates (Linux)





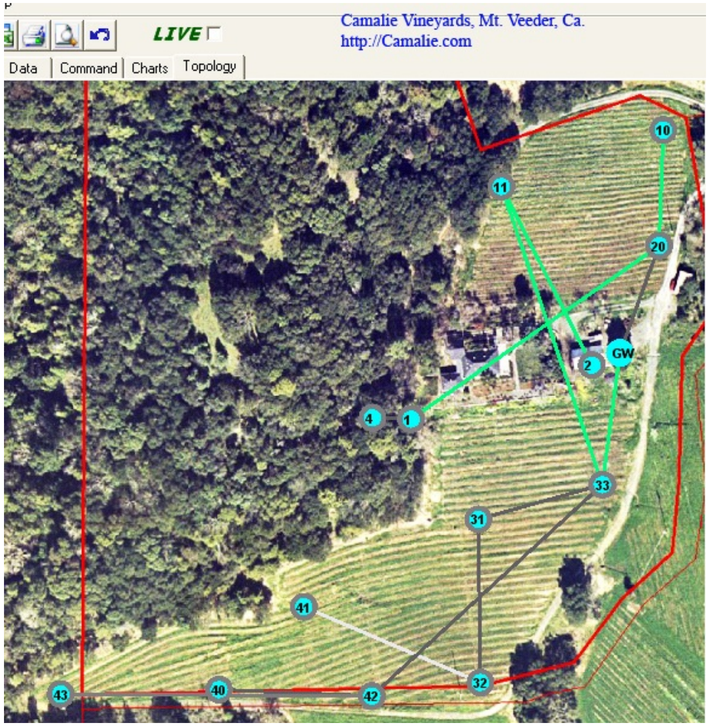


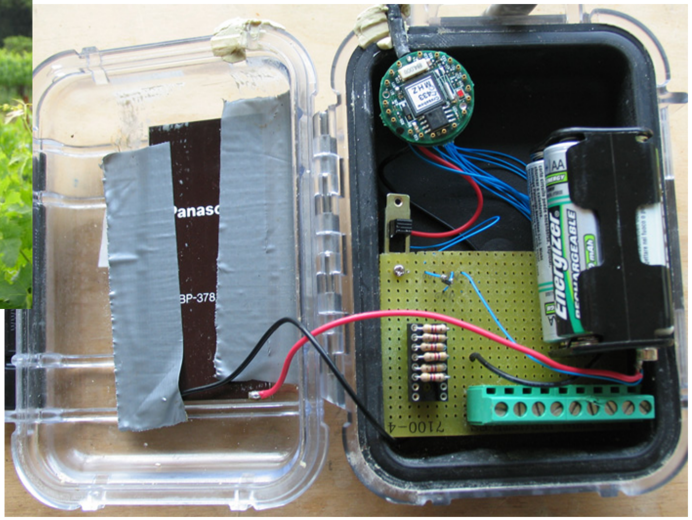
Industrial monitoring:
Intel Semiconductor Factory monitoring …



Preventative equipment maintenance: monitoring vibration signals …

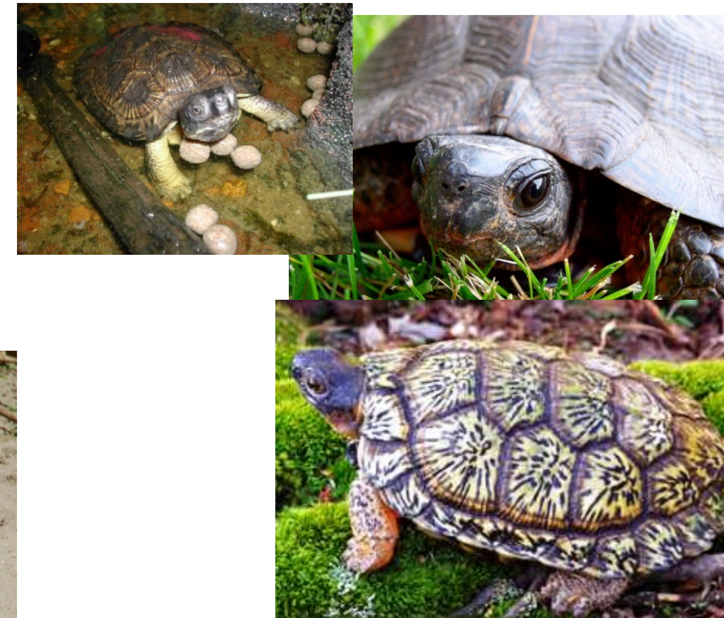
Precision agriculture: smart vineyard

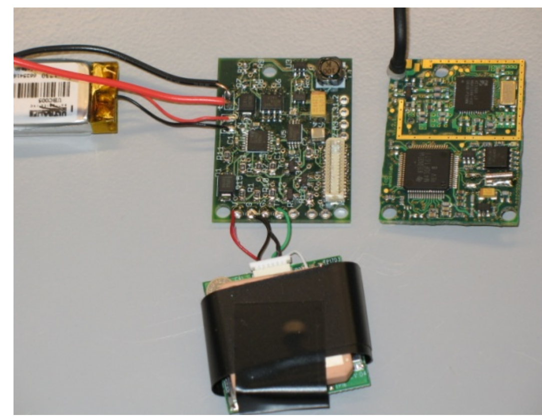


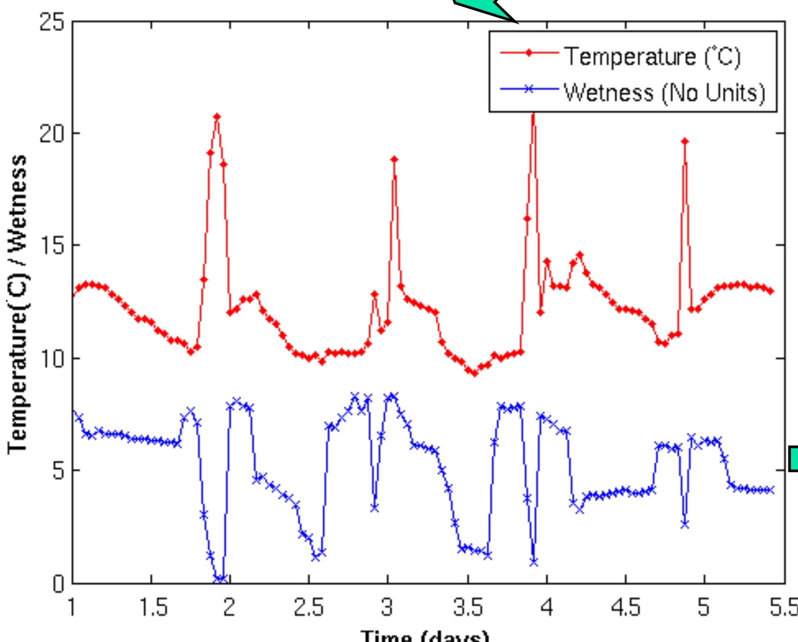


monitor soil humidity, temperature, chemistry …

TurtleNet: track wood-turtles …

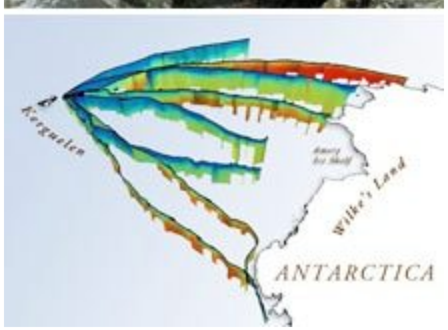






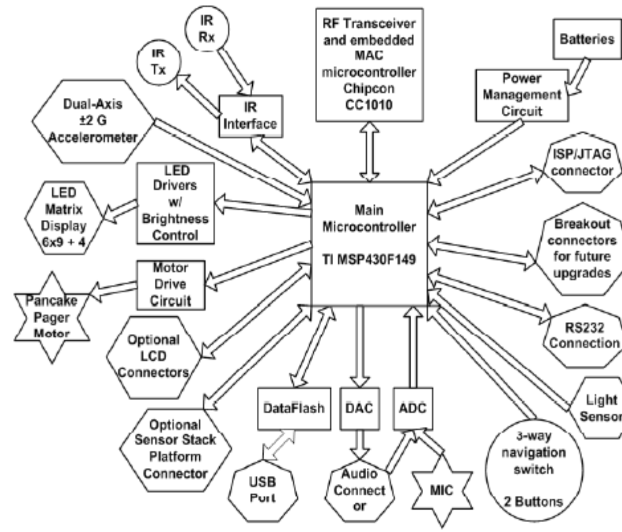
the turtle came out of the water to sun itself for only brief periods and went back into the colder water …

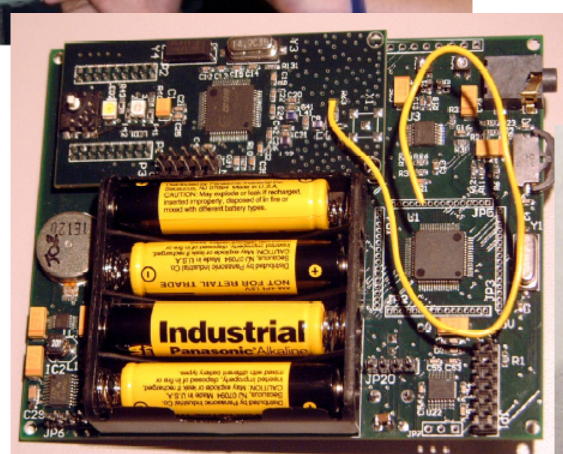
SealNet: use nature to help scientific study

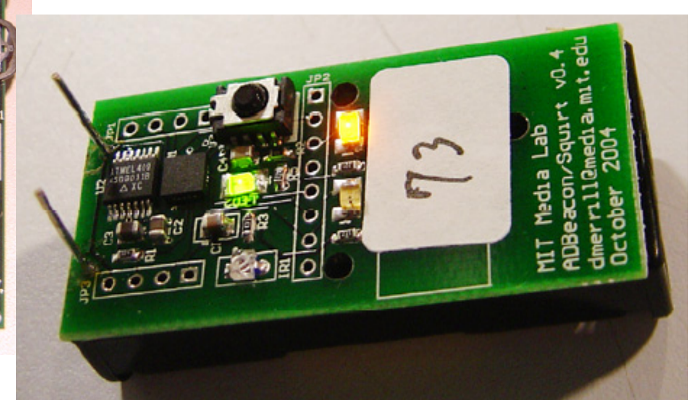


- To measure ocean's *temperature and salinity* levels, as well as the seal's location and depth.
- Sensing data are collected for every dive; Each time the seals resurfaced to breathe, that data was relayed via satellite to certain data centers in US and France
  - As the seals migrated and foraged 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

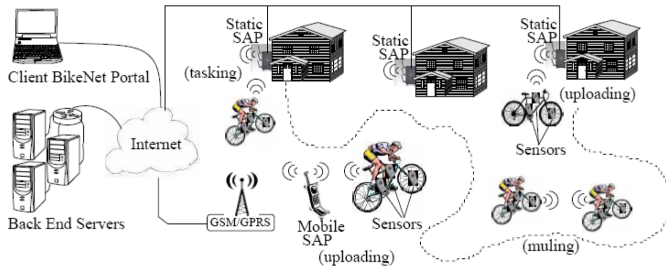
Social dynamics and networking

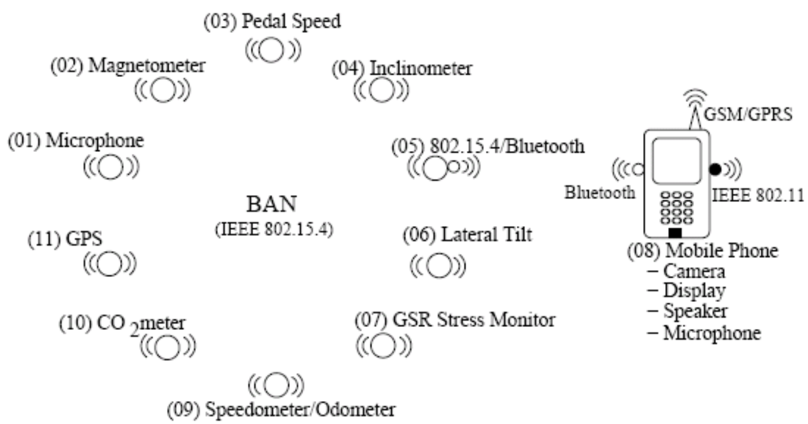






BikeNet: mobile sensing system for cyclist experience mapping





(a) A two-axis magnetometer is attached to a Tmote Invent via its ADC.

(b) An external GPS unit is attached to a Tmote Invent via its UART0 port.

(c) A BikeNet static SAP is a WiFi AP with an Invent inserted in the USB port.

(d) Waterproof OtterBox. Wires are fed through drilled holes that are then filled with silicone sealant. Wires have crimped connectors for easy disconnect.

(e) Ground truth video/sound/photo helmet with four N80s and GPS receiver, only for use in debugging our system and validating our inference techniques.

(f) BikeNet mobile SAP implementation. The Nokia N80 Bluetooth radio associates with a custom-built Bluetooth/802.15.4 gateway.

- Monitor cyclist performance/fitness: speed, distance traveled, calories burned, heart rate, galvanic skin response, etc

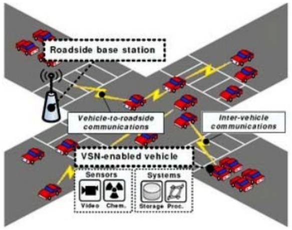
- Collect environmental data: pollution, allergen, noise, and terrain condition monitoring/mapping, etc

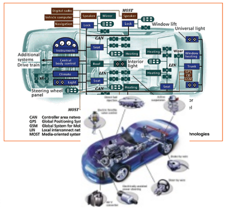
Outline

- Internet
- From Internet to sensornet/IoT
- From sensornet/IoT to WCPS
- General challenges of WCPS
- Looking into the future

From open-loop sensor networks to closed-loop cyber-physical systems (CPS)

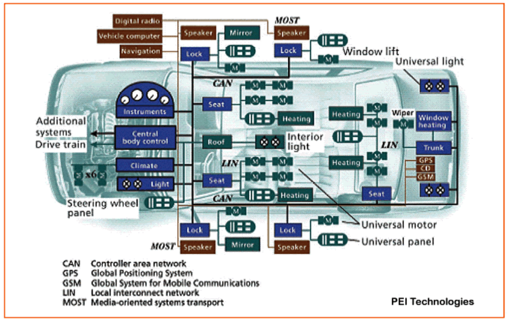
- Sensing, networking, and computing tightly coupled with the control of the physical world
  - Automotive
  - Alternative energy grid
  - Industrial monitoring and control

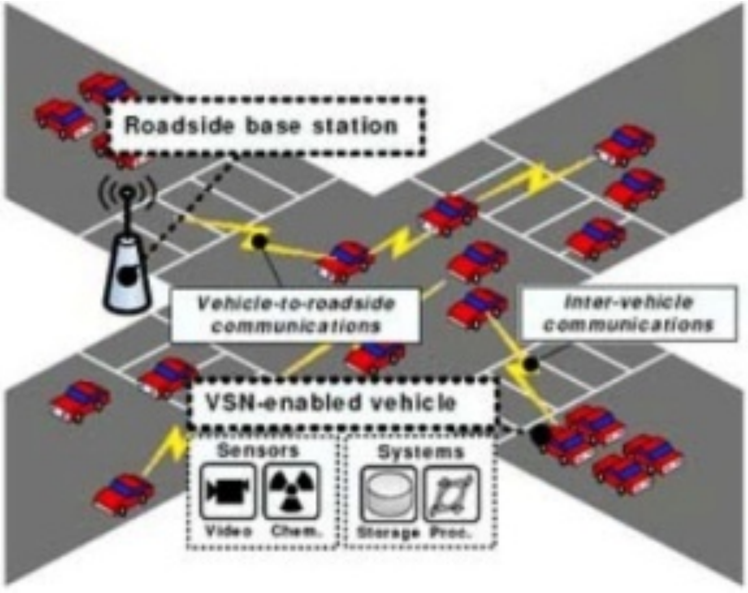




- Wireless networks as carriers of mission-critical sensing and control information
  - Stringent requirements on *predictable* QoS such as reliability and latency

Vehicular CPS





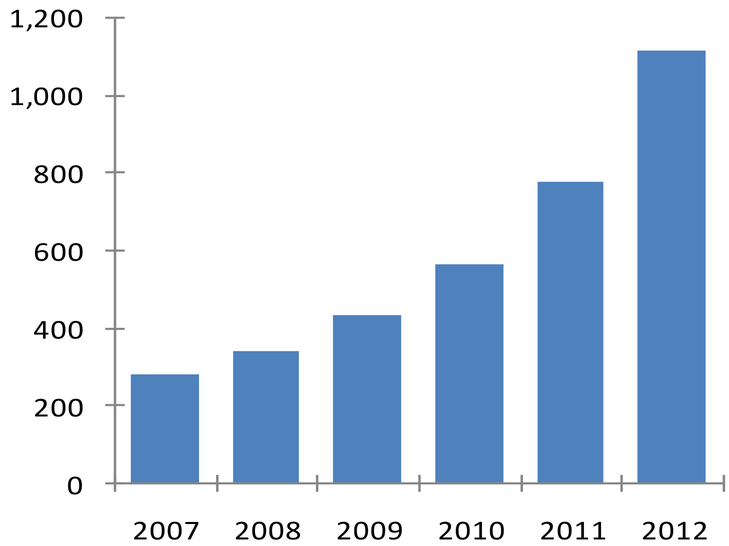
Micro power grid

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

EVs as distributed storage

EVs as controllable load

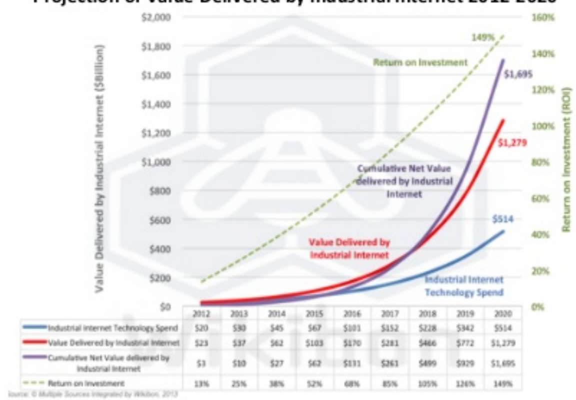
Process Control Industries: Wireless Market Growth



Worldwide Market for Wireless Devices in Process Manufacturing

($Millions) ©2008 ARC Advisory Group

Market Status Industrial Internet



	2012	2013	2014	2015	2016	2017	2018	2019	2020
Industrial Internet Technology Spend	$20	$30	$45	$67	$101	$152	$228	$342	$514
Value Delivered by Industrial Internet	$23	$37	$62	$103	$170	$281	$466	$772	$1,279
Cumulative Net Value delivered by Industrial Internet	$3	$10	$27	$62	$131	$261	$499	$929	$1,695
Return on Investment	13%	25%	38%	52%	68%	85%	105%	126%	149%

Projected value by 2020:

€1.57 Trillion

Current US value:

€57.3 Billion

Source: http://postscapes.com/internet-of-things-market-size, Exchange rate USD-Euro, 0.924, March 9, 2015

industrial internet®
CONSORTIUM

WirelessHART®

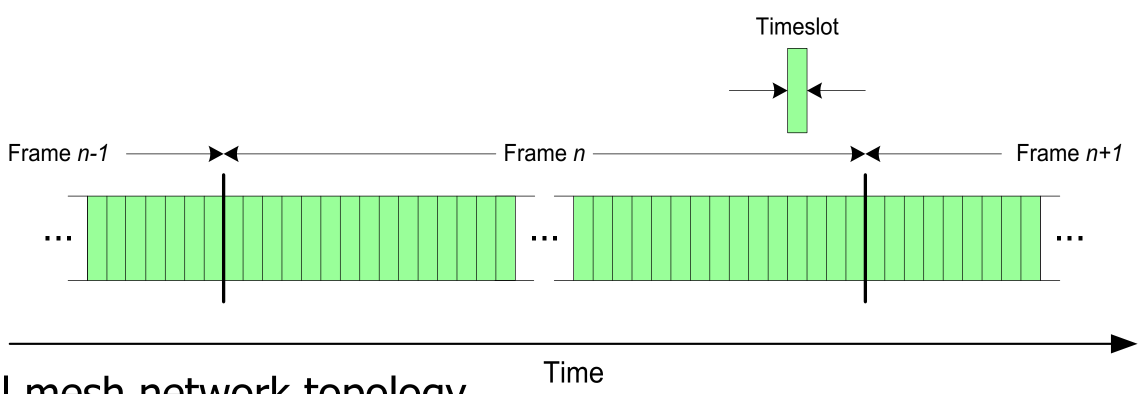
ISA 100
WIRELESS

WIA 工业无线网络WIA
Industrial Wireless Network WIA

6TiSCH

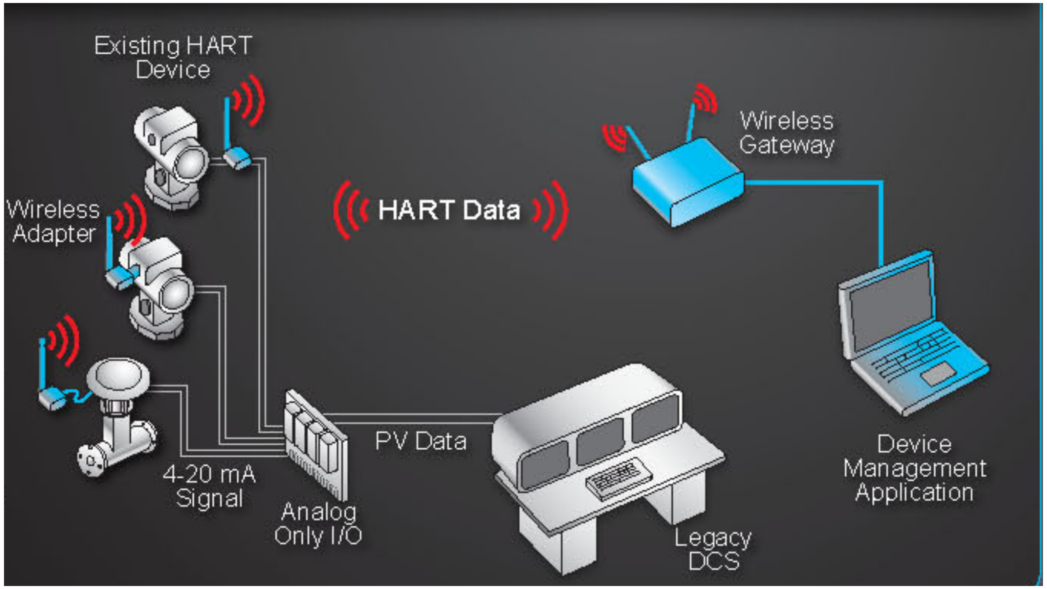
Standardization efforts

- 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)

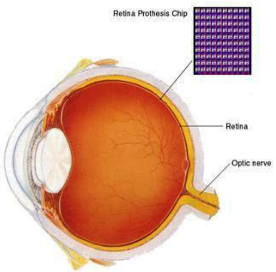
- IETF
  - 6TiSCH
  - RFC 4944 (6LowPAN)
    - IPV6 over 802.15.4
  - ROLL Working Group
    - Began May 2007
    - Routing over low-power lossy nets
    - Application areas:
      - Industrial
      - Home
      - Buildings

      Etc.

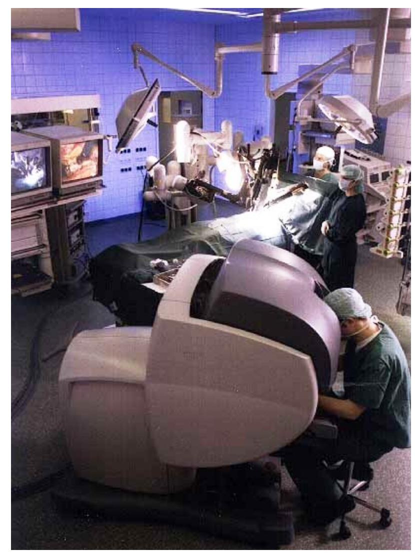
- Others
  - IEEE 802.15.4e: time-synchronized frequency hopping
  - IEEE 802.15.4g: grid smart metering

  - IEEE 802.15.4a: UWB/CSS physical layer
  - IEEE 802.11s: mesh networking

Healthcare CPS



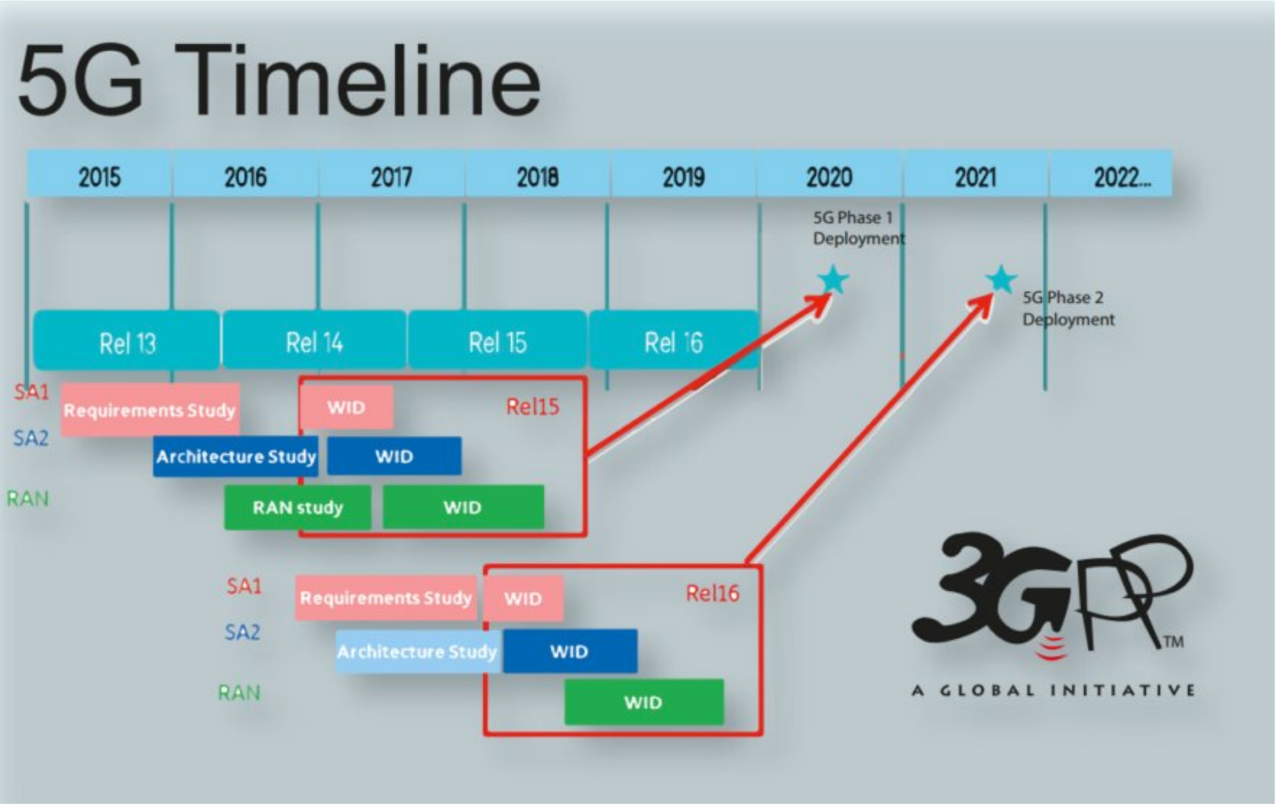
Medical implant: artificial retina …



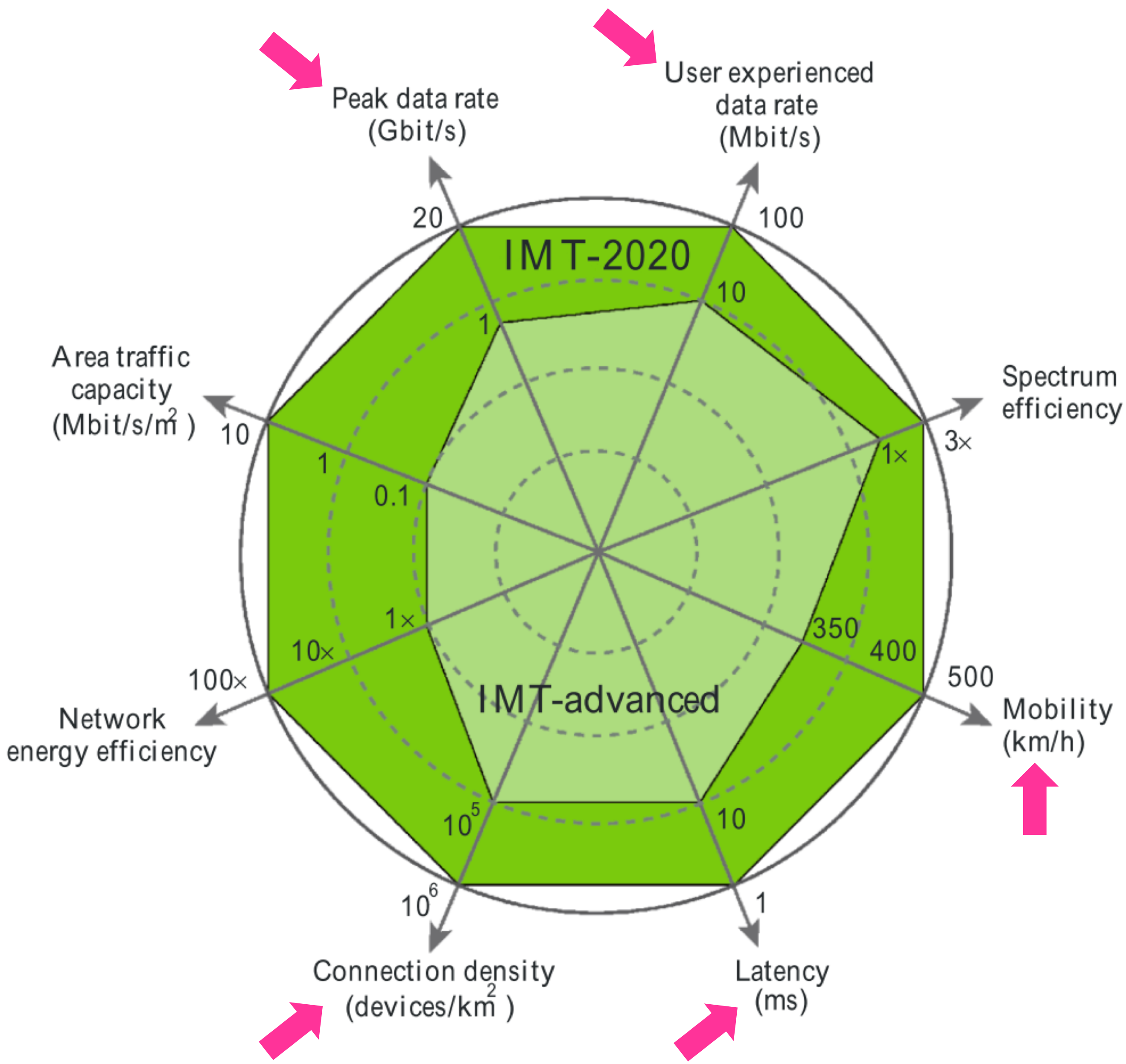
Remote, robotic surgery

Assisted living: health monitoring & coordination …

Cellular: 5G



5G Timeline
2015
2016
2017
2018
2019
2020
2021
2022...
5G Phase 1 Deployment
5G Phase 2 Deployment
Rel 13
Rel 14
Rel 15
Rel 16
SA1
Requirements Study
WID
Rel15
SA2
Architecture Study
WID
RAN
RAN study
WID
SA1
Requirements Study
WID
Rel16
SA2
Architecture Study
WID
RAN
WID
A GLOBAL INITIATIVE

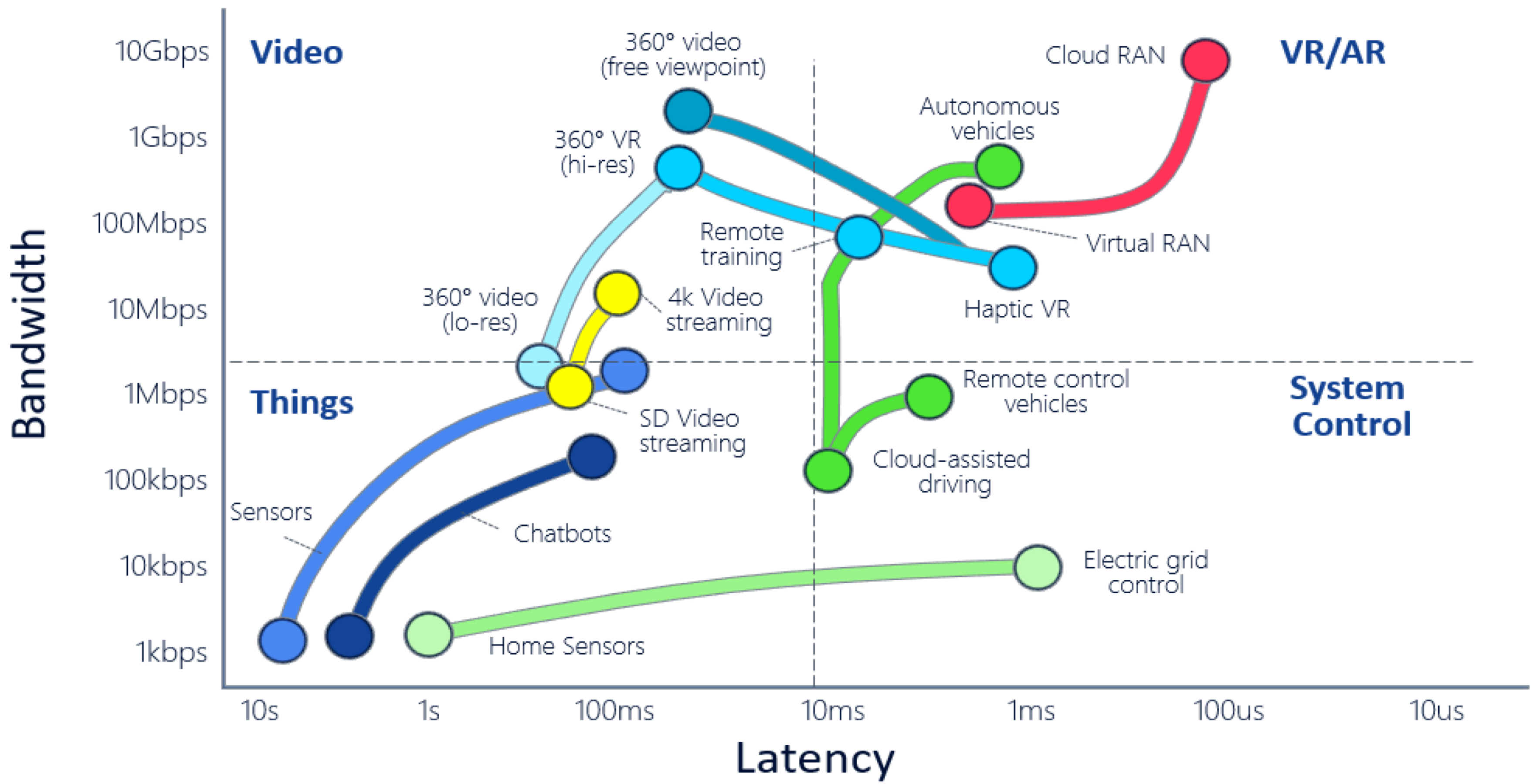


Peak data rate
(Gbit/s)
User experienced
data rate
(Mbit/s)
Area traffic
capacity
(Mbit/s/m2)
Spectrum
efficiency
Network
energy efficiency
Mobility
(km/h)
Connection density
(devices/km2)
Latency
(ms)
IMT-2020
IMT-advanced
20
1
100
10
10
1
0.1
3×
1×
100×
10×
1×
500
400
350
10^6
10^5
1
10

Two Extremes of Advanced Wireless

- *Critical* wireless
  - Gbps+ bandwidth
  - <1ms latency
  - 99.999%+ reliability
- *Massive* wireless
  - 1,000,000 devices / km^2
  - Battery-powered or battery-less
  - (low data rate)

Wide Range of Applications

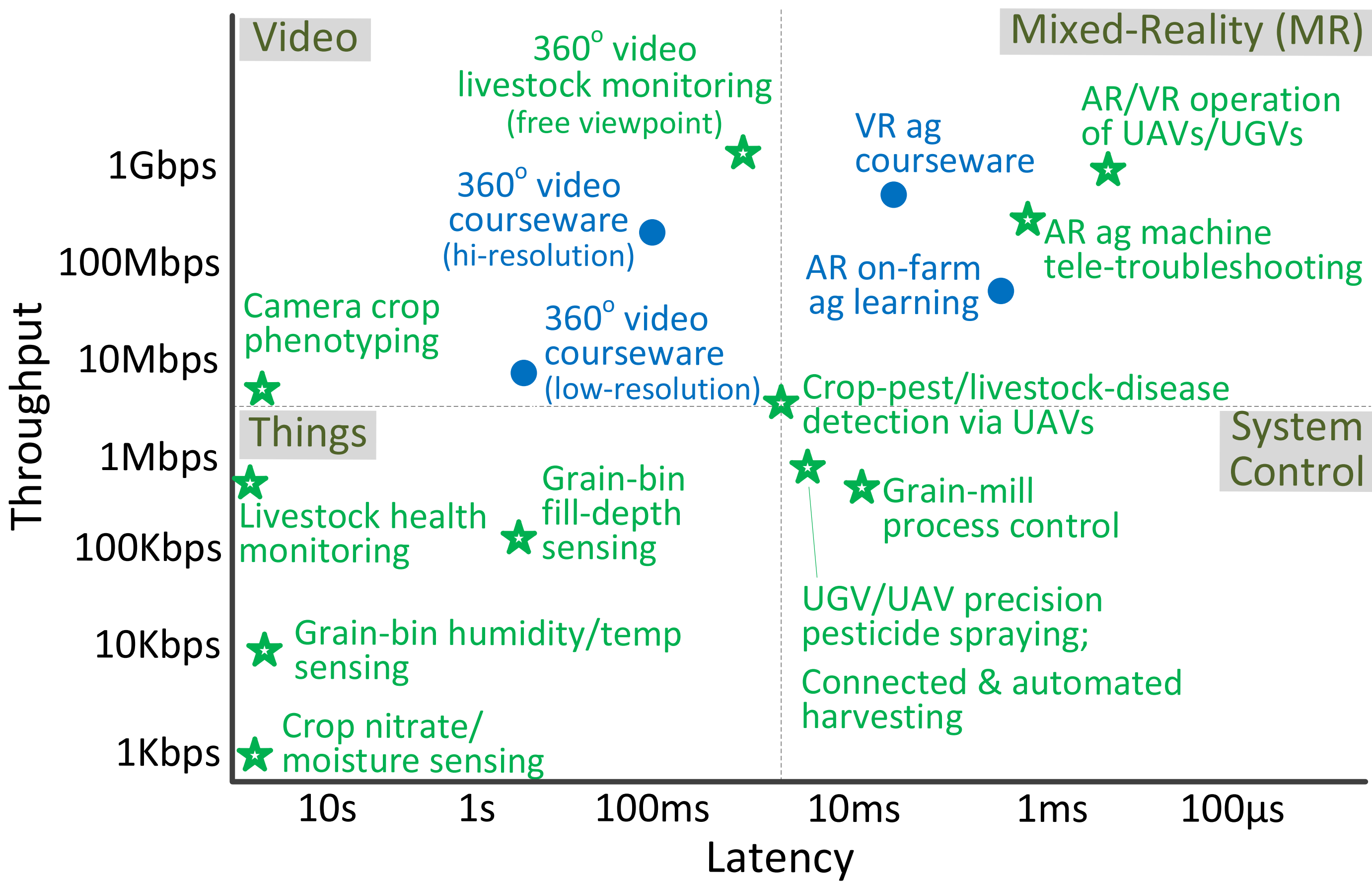


	Use case	Latency (ms)	Reliability (PLR)	Update time (ms)	Data size (bytes)	Device density	Communication range (m)	Mobility (km/h)
A	**Factory automation**	0.25 to 10	10^{-9}	0.5 to 50	10 to 300	0.33 to 3 devices/m^2	50 to 100	< 30
A1	Manufacturing cell	5	10^{-9}	50	< 16	0.33 to 3 devices/m^2	50 to 100	< 30
A2	Machine tools	0.25	10^{-9}	0.5	50	0.33 to 3 devices/m^2	50 to 100	< 30
A3	Printing machines	1	10^{-9}	2	30	0.33 to 3 devices/m^2	50 to 100	< 30
A4	Packaging machines	2.5	10^{-9}	5	15	0.33 to 3 devices/m^2	50 to 100	< 30
B	**Process automation**	50 to 100	10^{-3} to 10^{-4}	100 to 5000	40 to 100	10,000 devices/plant	100 to 500	< 5
C	**Smart grids**	3 to 20	10^{-6}	10 to 100	80 to 1000	10 to 2000 devices/km^2	A few m to km	0
D	**ITS**							
D1	Road safety urban	10 to 100	10^{-3} to 10^{-5}	100	< 500	3000 /km^2	500	< 100
D2	Road safety highway	10 to 100	10^{-3} to 10^{-5}	100	< 500	500 /km^2	2000	< 500
D3	Urban intersection	< 100	10^{-5}	1000	1M / car	3000/km^2	200	< 50
D4	Traffic efficiency	< 100	10^{-3}	1000	1k	3000/km^2	2000	< 500
E	**Professional audio**	2	10^{-6}	0.01 to 0.5	3 to 1000	up to 1/m^2	100	< 5

Table 1. Communication requirements of latency critical IoT applications [1–3]. Please note that *update time* only applies to periodic traffic. The application use cases may also include sporadic or event-based traffic, but the traffic arrival distributions are not mentioned in the table.

Σχηυλζ, Π., Ματτηε, Μ., Κλεσσιγ, Η., Σιμσεκ, Μ., Φεττωεισ, Γ., Ανσαρι, ϑ., … Ωινδισχη, Μ. (2017). Λατενχψ Χριτιχαλ IoT Αππλιχατιονσ ιν 5Γ: Περσπεχτιωε ον τηε Δεσιγν οφ Ραδιο Ιντερφαχε ανδ Νετωορκ Αρχηιτεχτυρε. *IEEE Χομμυνιχατιονσ Μαγαζινε*, *55*(2), 70–78.

Applications in Smart Ag and Rural Education

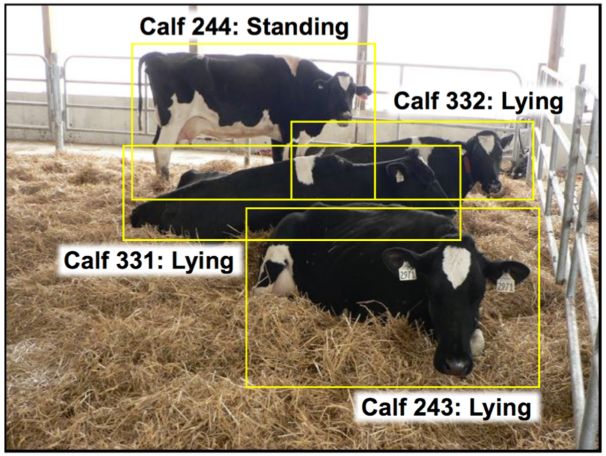


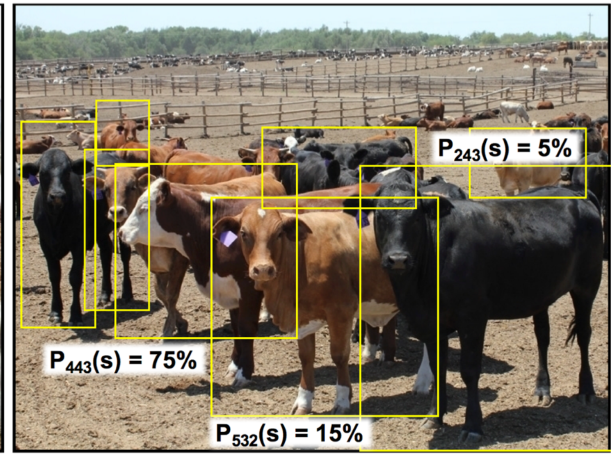
ISU: Crop Sensing & Control

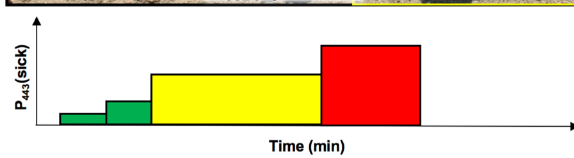
PSI: 1,000+ cameras for phenotyping

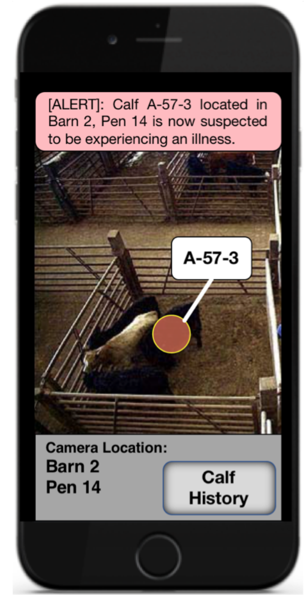
Γενετιχ ςαριατιον φορ Δεϖελοπμενταλ Ροτατιον

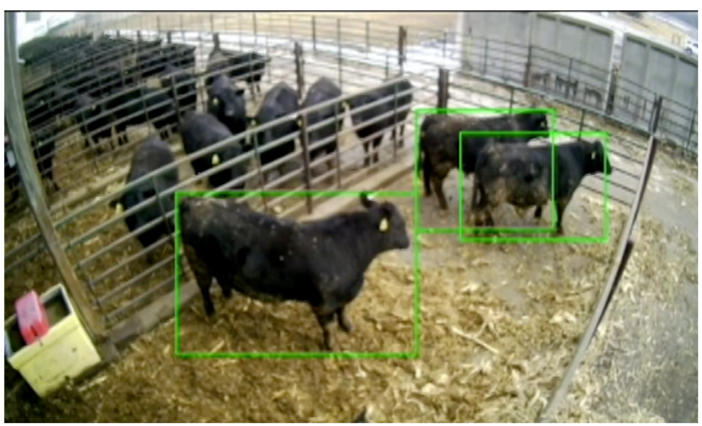
ISU: Livestock Sensing & Control

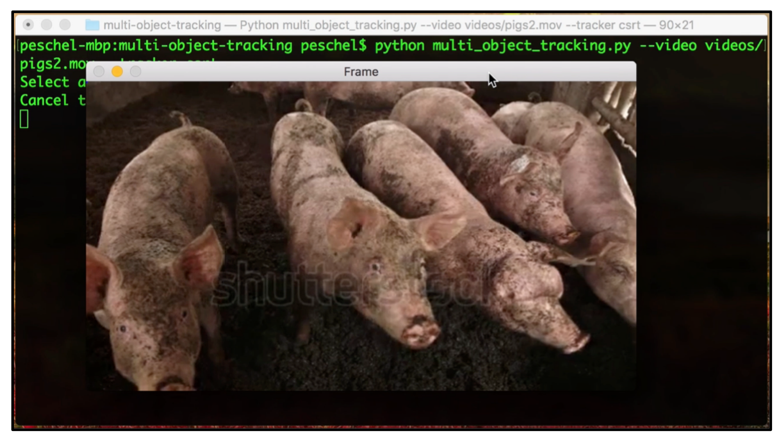


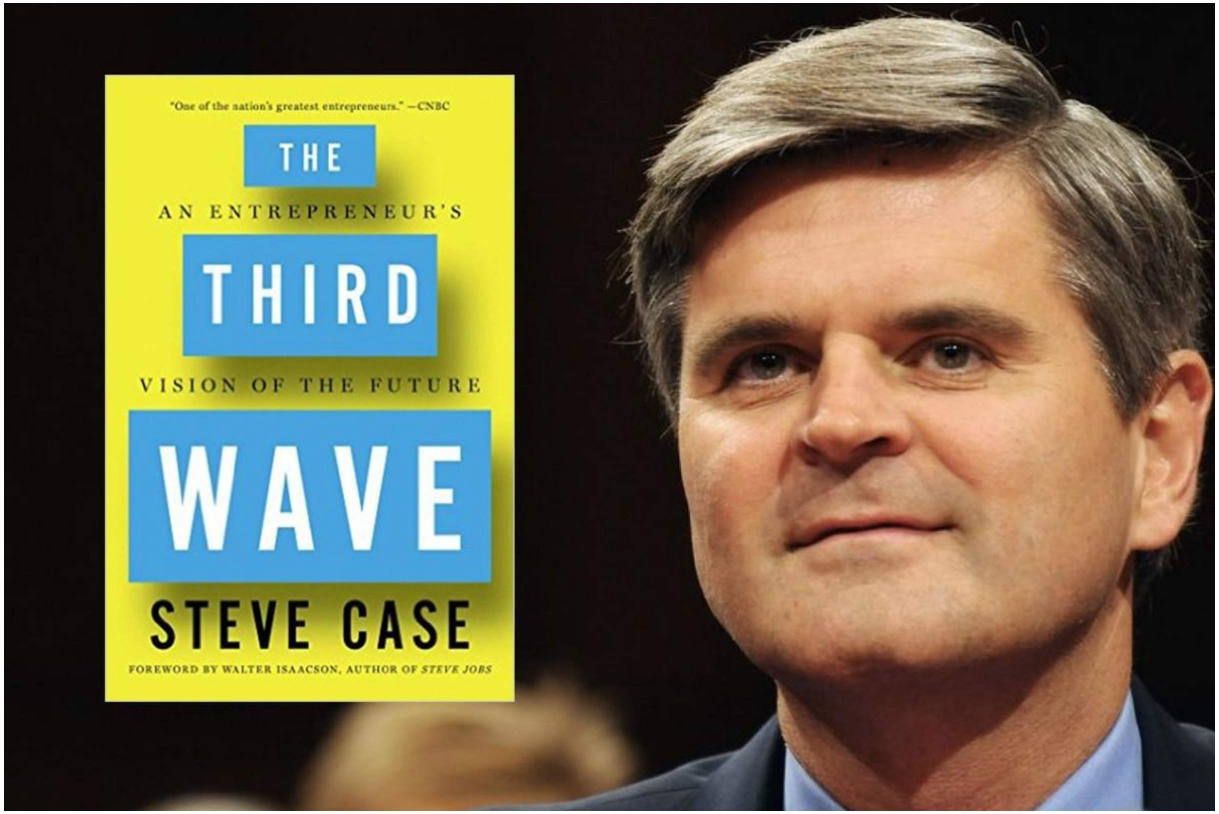












Internet of Things (IoT)

Cyber-Physical-Human (CPH) Systems

Outline

- Internet
- From Internet to sensornet/IoT
- From sensornet/IoT to WCPS
- General challenges of WCPS
- Looking into the future

Complex systems

- 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
    - 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;

    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

- 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
    - Implication to communication: large jitter in messaging latency increases max. end-to-end latency
- Implications
  - Low delay and delay jitter in network data delivery
    - Jitter control in priority-based network real-time scheduling
  - Necessary data rate/throughput, even though small in some cases
  - Control-networking co-design requires *predictability*

Outline

- Internet
- From Internet to sensornet/IoT
- From sensornet/IoT to WCPS
- General challenges of WCPS
- Looking into the future

New network technologies, applications and startups keep emerging …

"The only thing that does not change is change."

How to realize and evolve the vision?

- To understand the underlying principles of computer networking (which do not change as often as technologies)
- To apply and potentially evolve these principles when building new technologies and systems
- We are here to help
  - CPR E 489, CPR E 537, CPR E 543, CPR E 548, research groups …