Carnegie Mellon University
Silicon Valley

Toward Platformization of the Internet of Things

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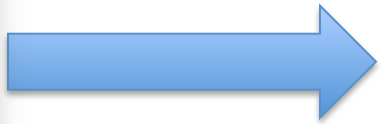
A Young Kid who Thought Asynchrony was the Big Idea



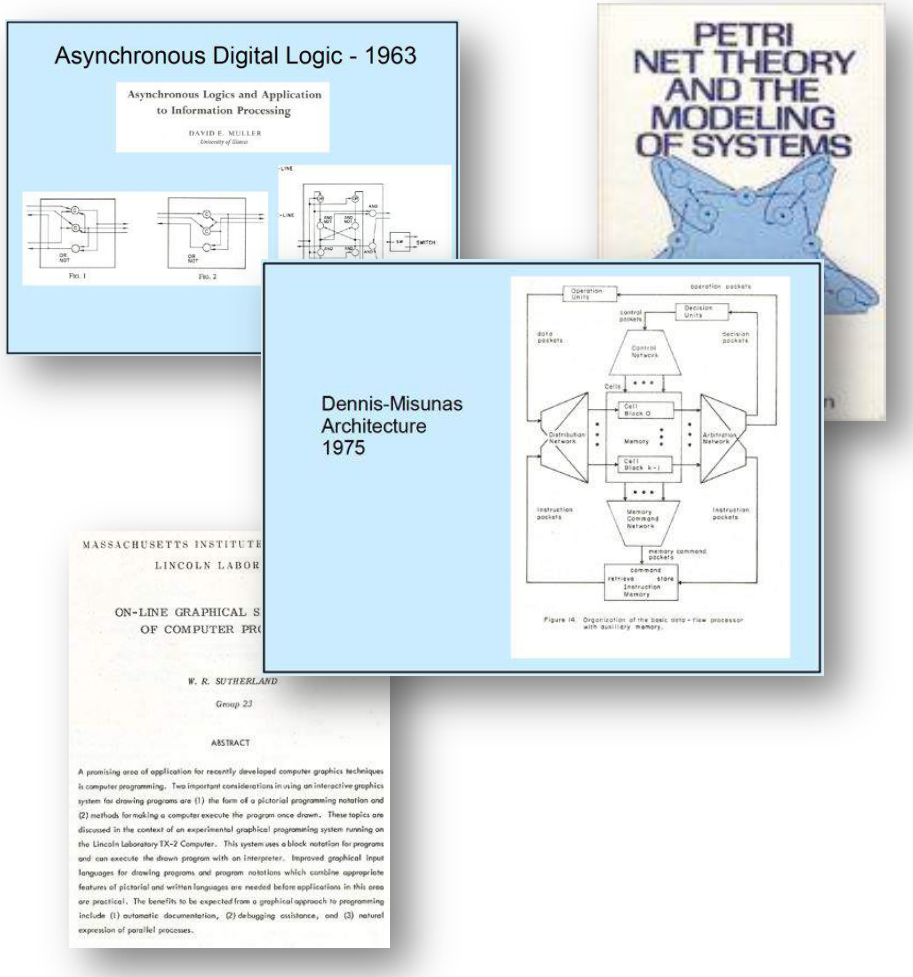


Image Sources:

- Jack Dennis
- Bert Sutherland
- James Peterson
- IBM

But today…

- Different level of asynchrony – federated systems for the Internet of Things

- Platforms – how would I know if I had one?
- Cyber-physically-enabled networks – what?
- A tale of time-awareness
- Federation
- Scalability

Wikipedia says...

A computing platform is, in the most general sense, whatever pre-existing environment a piece of software is designed to run within, obeying its constraints, and making use of its facilities. Typical platforms include a ***hardware architecture****, an* ***operating system*** *(OS), and* ***runtime libraries****.*

Computing Platforms: Past and Present

	Golden Age	Standard Platform	Compatibles	Value Shift to Software	Value Shift to Services
Mainframe	GE, NCR, CONTROL DATA, UNIVAC	IBM	amdahl, Magnuson Computer	CSC	IBM, Andersen Consulting, EDS
Mini	Prime, apollo, digital, Data General	digital	EMC², EMULEX	ORACLE, SAP	EDS
PC	ATARI, Commodore, sinclair	IBM Personal Computer	COMPAQ, DELL, hp	Microsoft	IBM, EDS
Mobile		???			

Hypothesis

The standard platform for cloud-connected computing is a *combination* of

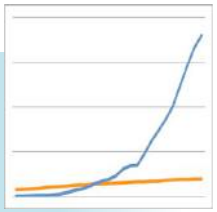
1. A flexible, powerful, programmable mobile device family
2. A flexible, powerful, programmable network

Observation: *#1 exists. #2 does not (**why not?**)*

If true, the evolution of
cloud-connected computing is stalled.

Mobile Networks as a Computing Platform?

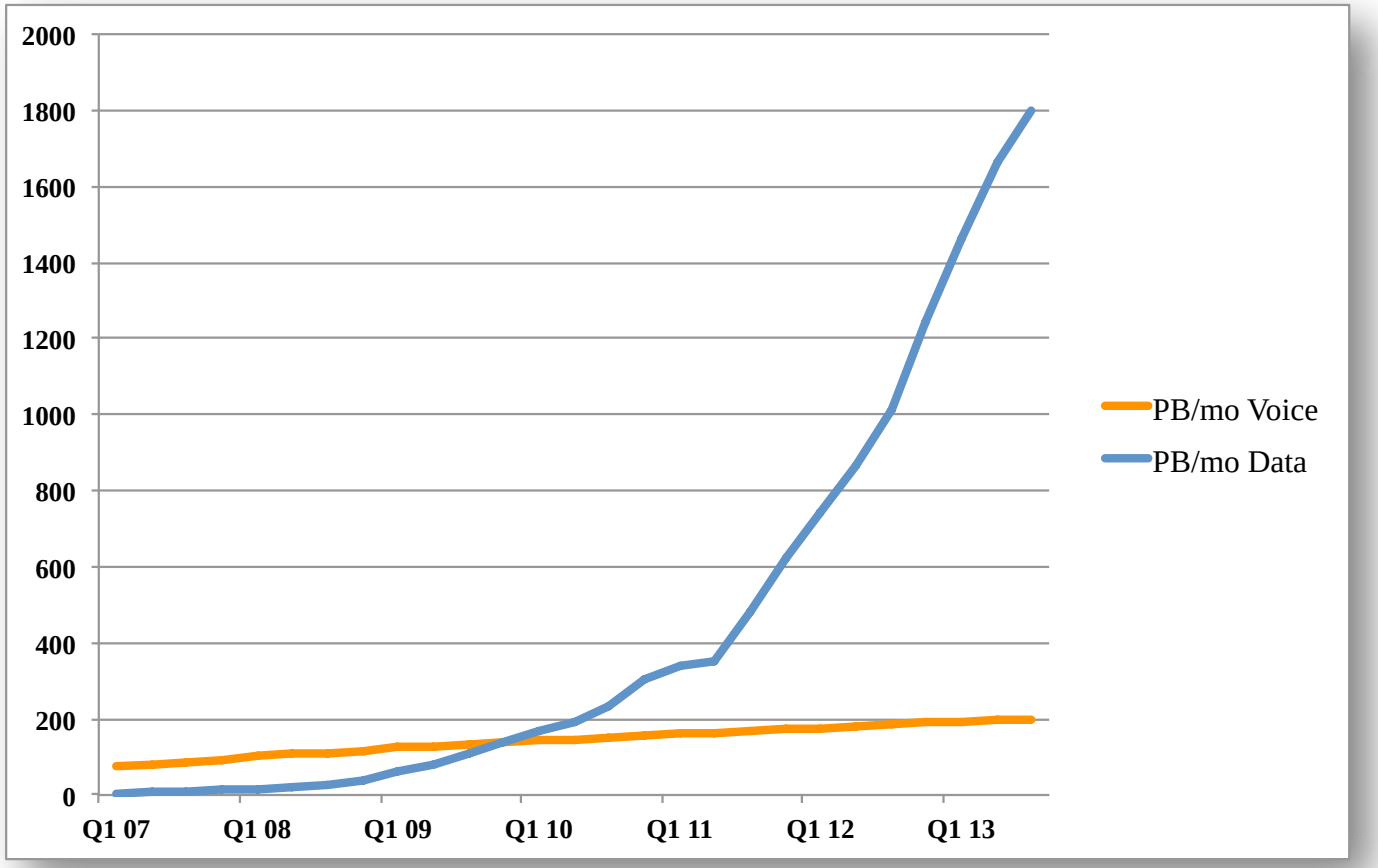
Circuit switching legacy persists…



But then, in 2009, a funny thing happened.

Time	1973-1983	1983-1993	1993-2003	2003-2013
Network Generations	1G – AMPS	2G – GSM, CDMA	3G – UMTS, EV-DO	4G – HSPA, LTE
Radio Technology	NBFM	TDMA/CDMA	WCDMA	OFDM
Voice	Analog CSW	Digital CSW	Digital CSW	Digital CSW → Packet
Data	(none)	19kbps	100kbps	10-100Mbps

In a network designed for CSW Voice traffic, PSW data now dominates



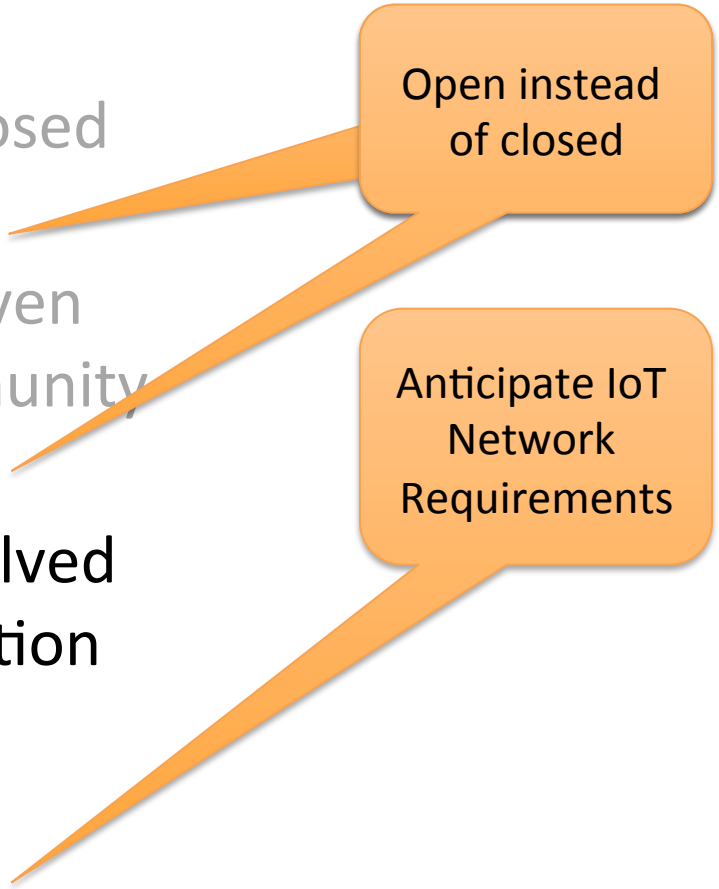
Source: *The State of the Internet.* Technical report, Akamai Technologies, Inc., Cambridge, MA, 3rd Quarter 2013.

Looking Ahead: Architectural Challenges for the IoT Platform

- **Time-Aware**: time as a first-order concept; logical correctness includes time-accuracy; current network assumptions are leading us away from this
- **Federated**: the ability to fuse information across logical, geographical and political boundaries with the ability to manage security, privacy, precision, and provenance
- **Scalable**: the ability to scale computing capacity as IoT devices are added

How Do We Proceed?

- **Obstacle**: existing networks are closed and are resistant to study
- **Obstacle**: network evolution is driven by a small, closed standards community
  - Contrast to evolution of the internet
- **Obstacle**: current architecture evolved from circuit switching and assumption of "wired last mile"
  - Characteristics of packet wireless are *fundamentally* different
  - Architecture did not anticipate IoT



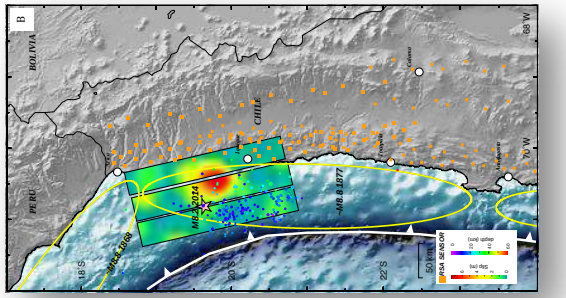
TIME-AWARE

What Does Time Have to Do with IoT?

- Device-to-device and Device-to-cloud
  - Distributed sensing: correlation of physical measurements
  - Distributed actuation: control systems
  - Deadlines have physical consequences – network an issue

Gunfire Detection

Cellular control of UAVs



Earthquake Warning

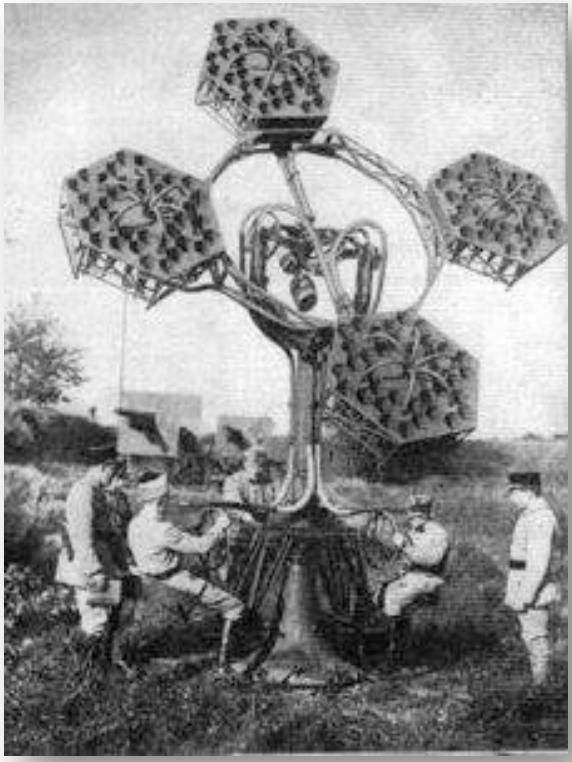
Teng, E., Falcao, J. D., Dominguez, C. R., Mokaya, F., Zhang, P., & Iannucci, B. ***Aerial Sensing and Characterization of Three-Dimensional RF Fields***. In Second International Workshop on Robotic Sensor Networks. Seattle, WA. 2015.

Minson, S. E., Brooks, B. A., Glennie, C. L., Murray, J. R., Langbein, J. O., Owen, S. E., Heaton, T., Iannucci, R. A. and Hauser, D. L. ***Crowdsourced Earthquake Early Warning***. Science Advances, 1(3), 1–7. http://advances.sciencemag.org/content/1/3/e1500036

http://commons.wikimedia.org/wiki/File:Boomerang_3_Gunfire_Acoustic_Detection_System_MOD_45153048.jpg

Example: Acoustic Beamforming

- Time Difference of Arrival
- Sensor-to-sampler
  - Predictable (wires)
  - Variable (wireless)
- Distributed time sync
  - Microsecond accuracy
- Can we count on the network?



http://www.douglas-self.com/MUSEUM/COMMS/ear/ear.htm

Télésitemètre:
Jean Baptiste Perrin's Acoustic Locator

http://www.douglas-self.com/MUSEUM/COMMS/ear/ear.htm

Networks and Time

- Distributing time
  - NTP, IEEE 1588 (PTP), White Rabbit, …
- Respecting time, end-to-end
  - Deadlines
  - Latency
  - Predictability

When Time Got Respect

- In the beginning, time was revered
- The network *was* the time authority
  - Initially Mabel (or Ernestine) at Central, then
  - Human speaking clock, then
  - Mary Moore and Jane Barbe

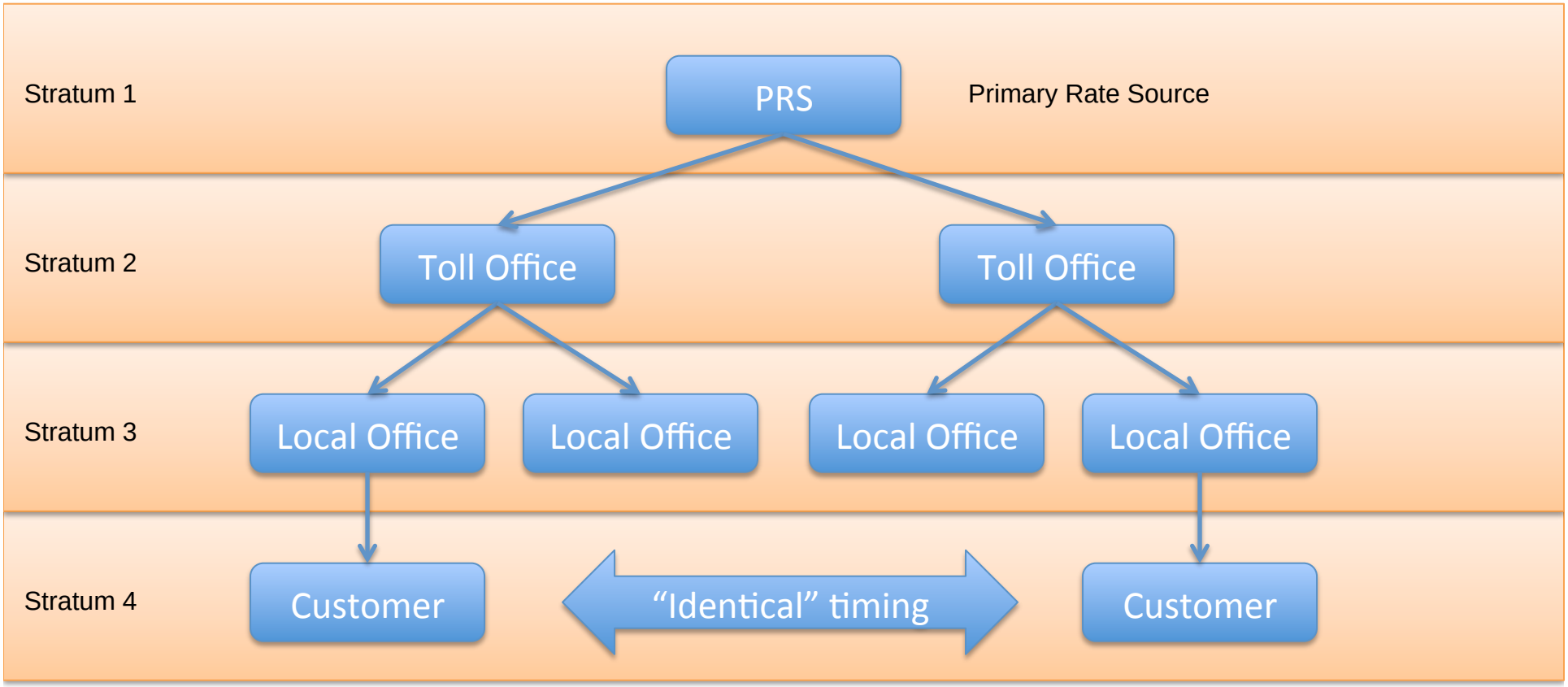
NIST: *"The audio portions of the WWV and WWVH broadcasts can also be heard by telephone. The time announcements are normally delayed by less than 30 ms when using land lines from within the continental United States, and the stability (delay variation) is generally < 1 ms"*

Source: http://www.nist.gov/pml/div688/grp40/ttds.cfm

Then Digital Happened

- Initially, time gets more respect
- A synchronous NA "T1" network
  - 1.544 Mbps (~648 nsec/bit)
- With a master clock
  - "Primary Reference Source"
- Dedicated digital circuits from/ to anywhere; bit timing under control
  - Jitter tolerated with a modicum of protocol and buffering
  - No such thing as "wander"

Time as an integral element of network: Globally Synchronous

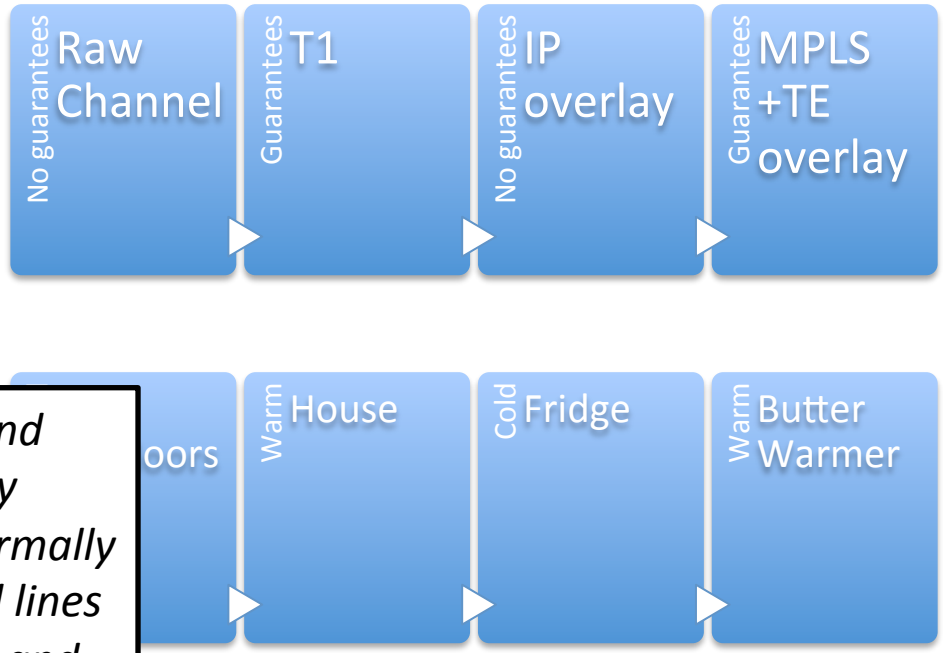


But Then Times Changed

- AT&T Divestiture and economics drove a (de-)evolution
  - Installed plant was lots of raw copper circuits
  - Overlaid digital coding to get nailed-up, dedicated T1's: synchronous
  - Carved up and shared the T1's statically: Frame Relay
  - Supported multiple carriers / clocks: plesiochronous
  - Statistically shared but bandwidth-guaranteed: ATM (isochronous)
  - Dynamically shared with no guarantees: IP (asynchronous)
- Time did not govern the network; network could not convey time
- Buffering went through the roof; QoS went down

IP-based Networks and QoS

- Contention-based channel access (Ethernet, 802.11)
- Best Efforts routing
  - "I'd tell a joke about UDP… but I don't know if you'll get it"
- Bufferbloat



NIST: "The audio portions of the WWV and WWVH broadcasts can also be heard by telephone. The time announcements are normally delayed by less than 30 ms when using land lines from within the continental United States, and the stability (delay variation) is generally < 1 ms. ***When mobile phones or voice over IP networks are used, the delays can be as large as 150 ms****."*

There is **no substitute** for real timing guarantees in telecommunications networks

Can Networks Support Time-Based IoT?

- 2G: things were rather orderly: GSM / TDMA (*the 217 Hz Buzz*)
  - Core network used circuit switching
- 3G: switch to CDMA
- 3.9G(LTE)/802.11: OFDM, requiring more accurate time and frequency
  - Frequency errors manifest as inter-carrier-interference (ICI)
  - Bandwidth is spent synchronizing and estimating channel
    - *e.g.*, 802.11 maxes out at 12 MHz of usable bandwidth in a 20 MHz channel
    - Can better local time reduce lost bandwidth?
- 4G and beyond: OFDMA (channel access) adds further need for accurate time
  - Statistical multiplexing – core network is IP!

Can Devices Support Time-Based IoT?

Scheme	Time accuracy	Frequency Accuracy
HF Radio	1-10 milliseconds	down to 5 parts per 10^{12}
Omega nav and VLF	2-10 microseconds	several parts per 10^{11}
LORAN-C	several microseconds	1 part per 10^{11}
Portable cesium clock	microsecond	2 parts per 10^{12}
GPS	100-500 nanoseconds (SA)	Comparable to LORAN-C

GPS only works outdoors (we spend 80% of our time indoors)

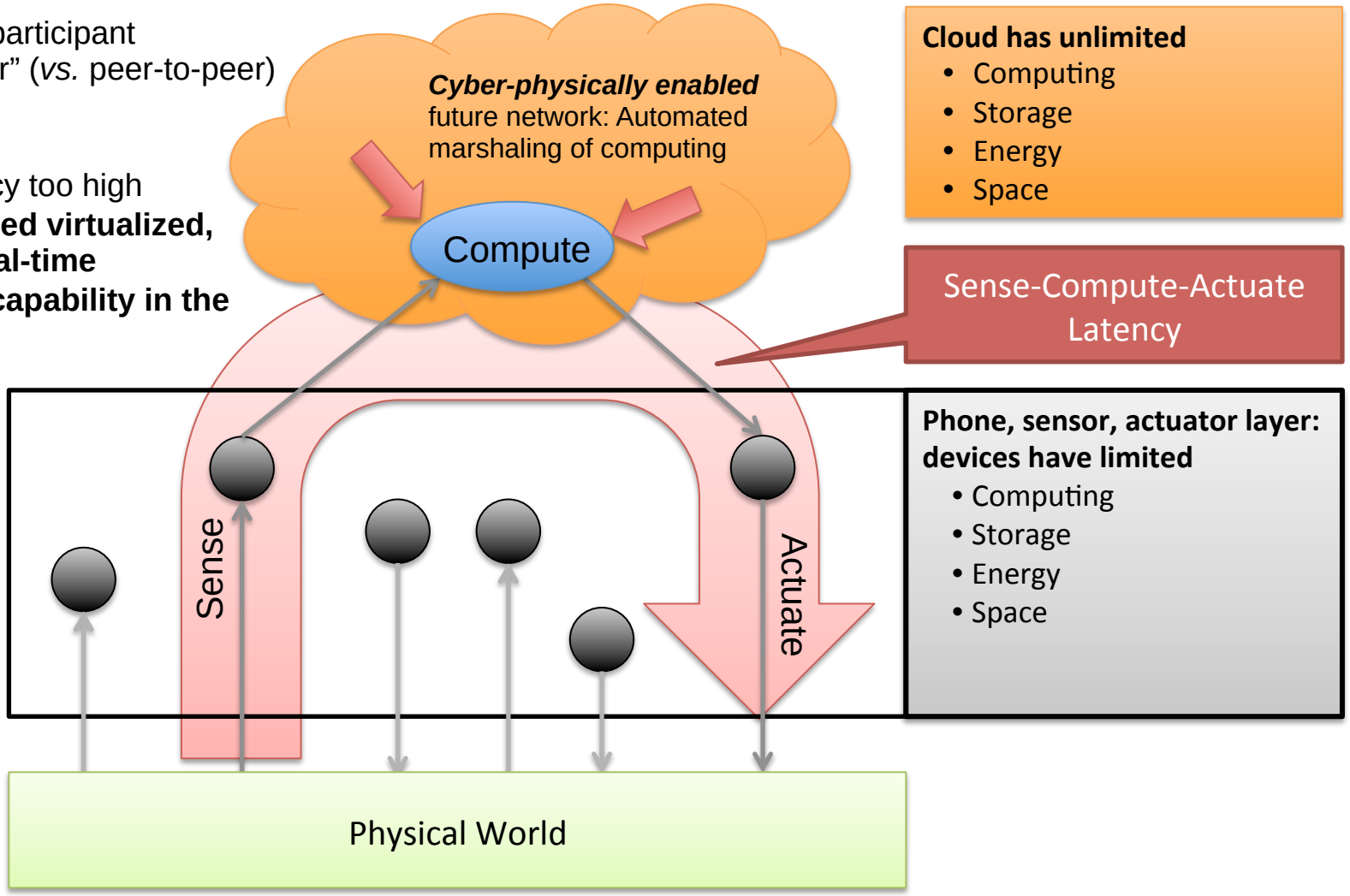
Current GPS solutions are very power hungry

Denial of Service → Denial of Position → **Denial of Time attacks**

The Cyber-Physically Enabled Network

Network-as-participant
"Near to Near" (*vs.* peer-to-peer)

Today: latency too high
Future: embed virtualized, movable, real-time computing capability in the network



Clean-Sheet Design
If we knew then what we know now…

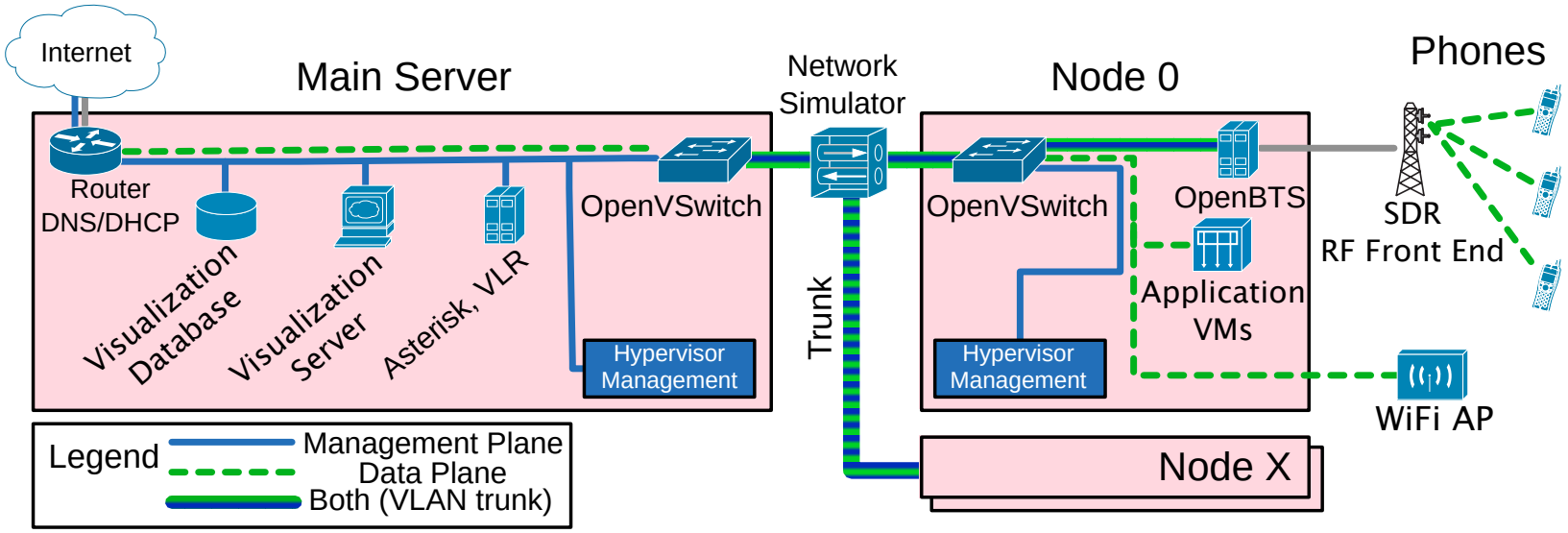
Start with the assumption of building the network side of the IoT computing platform!

- Integrated computing
- Open, compositional structure
- Application- and Service-specific resource allocation
  - What is an IoT “app” ??

CROSSMobile: Research Approach

- CROSSMobile testbed – for mobile platform research
  - Enough (opt-in) users to generate interesting data sets
  - Supporting research on many aspects
- IoT integration
  - Out-of-building sensor applications
- Working group of core researchers
  - Regular meetings
- Industrial consortium

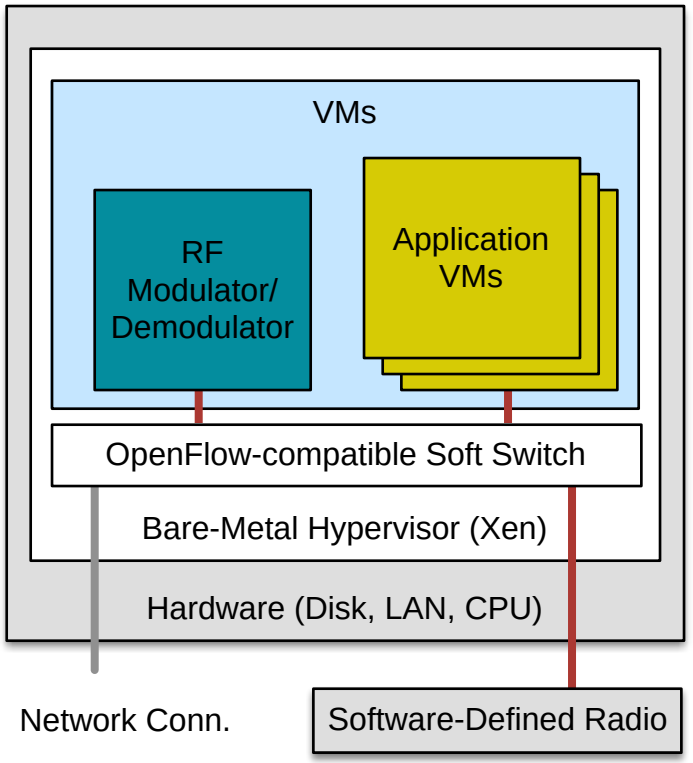
Testbed Network Structure



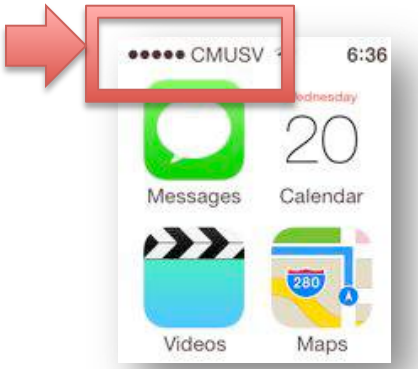
- Voice (SIP based), SMS, data
- Multiple radio bearers with common instrumentation
- Central transaction database
- Full PSTN integration (dial-in, dial-out, CLID)

Testbed Node Structure

- RF modem (OpenBTS) and applications run as VMs under OpenStack
- USRP SDR
- Custom RF front end (duplexer, filter, attenuator, power amp)
- Frequency agile

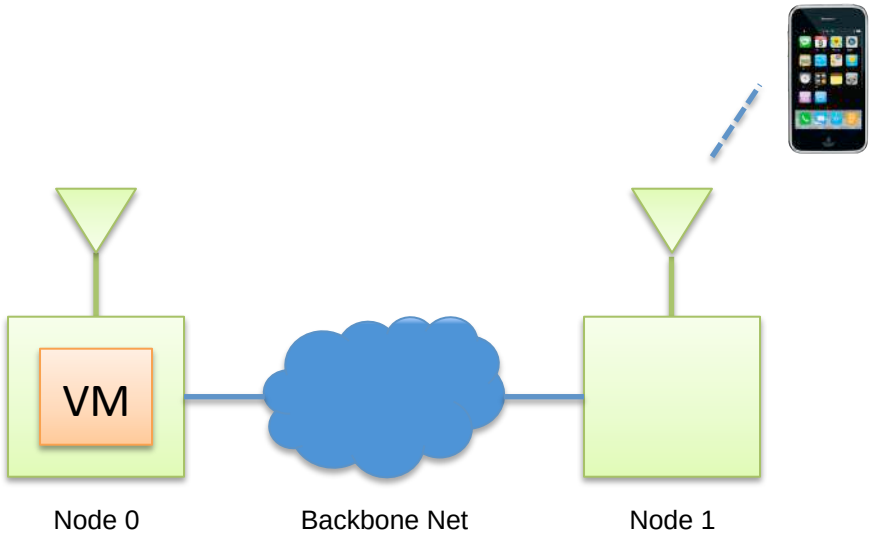


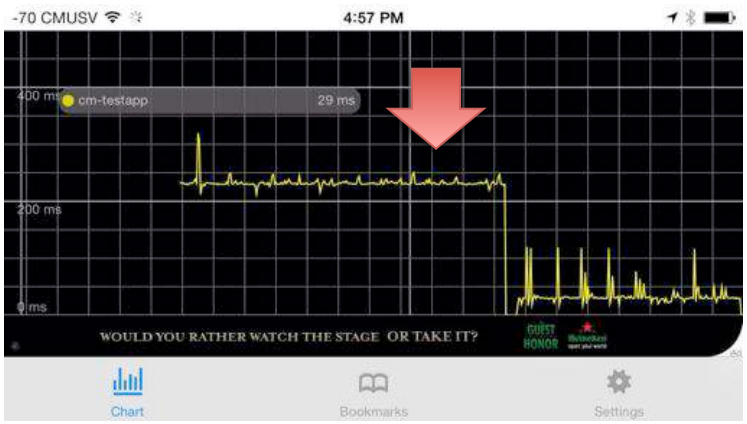
The Testbed is Live



- Four-year FCC licenses: CMU-SV campus, Palo Alto, Unmodified (but unlocked) iPhones and Android
- CROSSMobile SIM
- Campus and Palo Alto nodes operate in GSM900 band

Testbed Supports Cloudlets / Fog Computing with Dynamic Migration





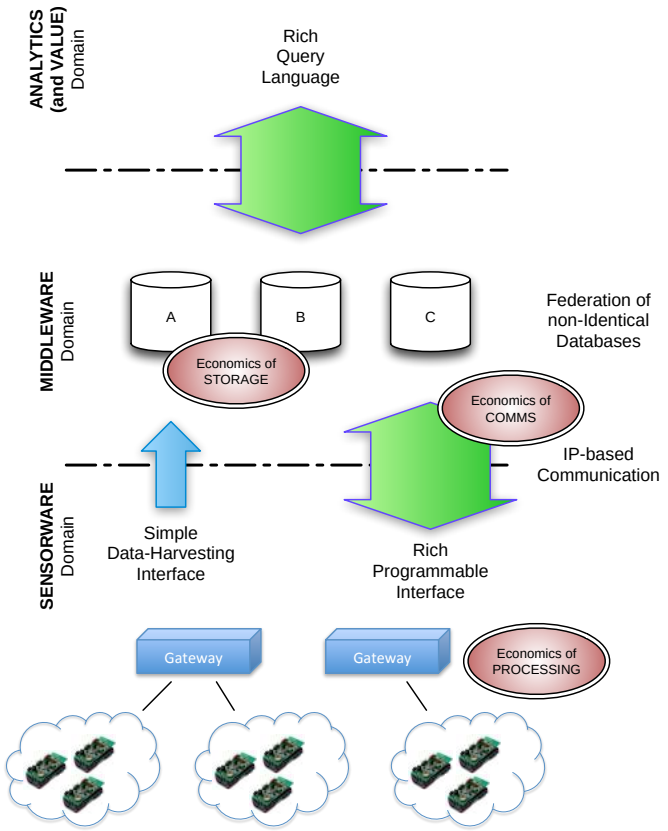
Round-trip time (msec)

- OpenStack-based VM migration today
- Moving to Docker or other lightweight containers
  - Lighter-weight than VM
  - Only move what can't be pre-cached (OS, app code, …)

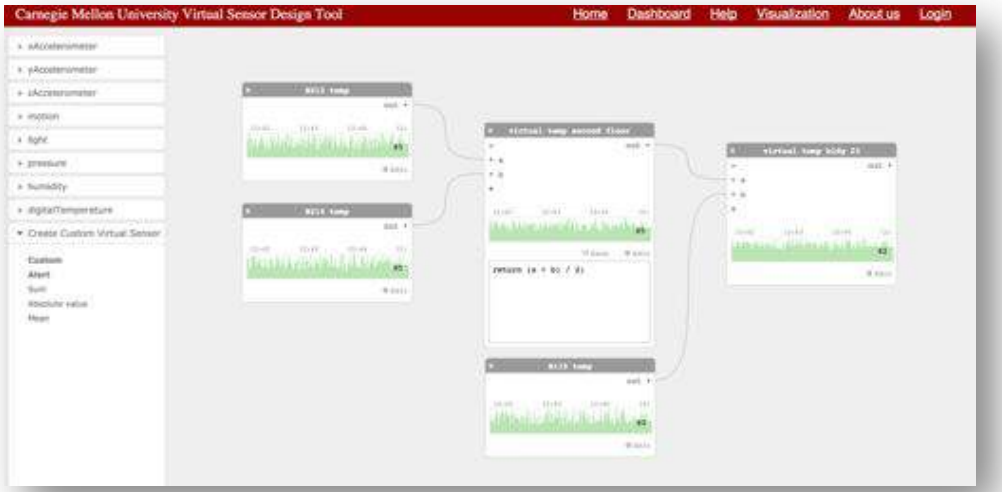
FEDERATED

Federation

- Valuable: build your own vertical application with sensors, actuators and processing
- More valuable: build "apps" on top of verticals created by others
- *"The great thing about standards is that everyone can have his own..."*



Virtual Sensors



- Programs pushed into the network
- Stream-to-stream functions
  - Lazy or Eager evaluation
  - Memoization
- Contributes to the provenance problem!

Zhang, J., Li, Z., Sandoval, O., Xin, N., Ren, Y., Martin, R. A., Iannucci, B., Griss, M., Rosenberg, S. Cao, J. and Rowe, A. ***Supporting Personalizable Virtual Internet of Things*.** In 2013 IEEE 10th International Conference on Ubiquitous Intelligence & Computing (UIC 2013). Sorrento Peninsula, Italy. 2013.

Challenges and Conclusions

- Rotten to the Core: Retro networking is needed for time
  - Time and Network Protocols must come back together.
- Devices are time-challenged – GPS is great… 20% of the time
  - We've only heard the first stories of GPS hijacking
- Somehow, we have to agree on how to federate
  - Open, rather than closed
  - Successful deployments will lead the way
- Scaling endpoints and cloud together is not enough
  - Computational support in the network can and should help

THANK YOU

More info: sv.cmu.edu/bob