Carnegie Mellon University
Silicon Valley

Electrical & Computer ENGINEERING

SMILE:
A Synchronized, Multi-sensor Integrated Learning Environment

Bob Iannucci, Ph.D.
Distinguished Service Professor, ECE
Director, CyLab Mobility Research Center
http://sv.cmu.edu/bob

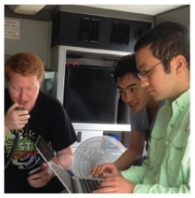
@Stanford, May 29, 2019

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CARNEGIE MELLON UNIVERSITY IN SILICON VALLEY

DEPARTMENTS ON CAMPUS

Electrical and Computer Engineering
Information Networking Institute
Integrated Innovation Institute

CAMPUS EXPERTISE

Software Engineering
Wireless Systems
Internet of Things
Sensors
Computer Architecture
Information Security & Privacy
Product Management
Entrepreneurship

- 400 registered students
- MS and PhD programs
- “Bi-coastal” classes, programs, research projects
- Entrepreneurship sponsored through the VentureBridge program

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Observations

- Wireless technologies can enable economic/societal value in
  - Intelligent transportation systems / smart city initiatives
  - Home automation
  - Improvements in manufacturing
  - Tools for humanitarian assistance and disaster response.
- The value may only be realizable through the integration of
  - dis-similar,
  - separately-built,
  - separately-owned,
  - separately-controlled sensing sub-systems

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Challenges

- The emerging Internet of Things and the evolving world of mobile computing have, at their heart, some (nearly-) impossible engineering challenges
  - High performance computing & communications
  - Tiny form factor
  - The requirement to run at vanishingly low power levels
  - Built with severely constrained on-board energy sources
- In addressing these applications and challenges, we take on interesting new risks

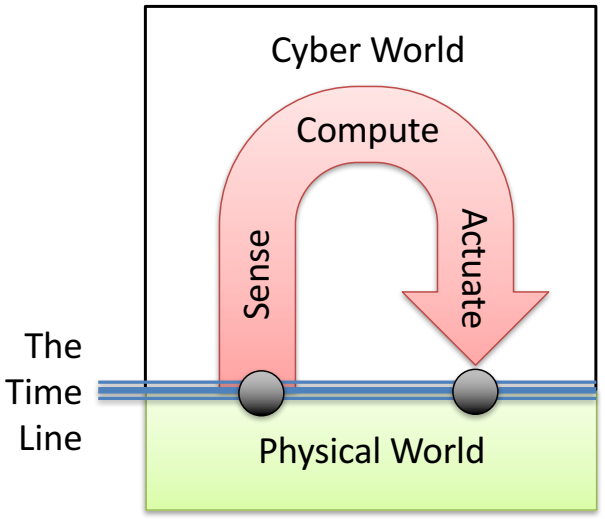
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CONSIDER:
THE VISION OF SMART CITIES

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Adoption Depends on Behaviors and Habits

- Cities, like people, have habits
  - Adoption of new ideas takes time and proof-of-value
  - Smart city concepts are not proven
  - Proof will come from smart city deployments
- Can we make cities smart with a top-down approach?
  - Substantial up-front investment based on faith
  - **Deep suspicion will flourish** in the face of cost, unknown value, “big brother“ concerns, ...
- Is a bottom-up or middle-out approach feasible? Valuable?



Smart cities are inherently **cyber-physical systems**
Gather information, process, take action!

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Some Implicit Criteria for Success

- Devices *anywhere*
  - Unobtrusive
  - Hardened
- City-friendly integration
  - Built into existing infrastructure elements
  - Comparable lifetimes
  - No new procedures for installation, maintenance
- The ability to write city-scale “apps” as easily as we might write a phone app
- Low TCO

Leads to four important technological challenges

Ref: [4]

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SMILE:
PRINCIPLES AND TECHNICAL CHALLENGES

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The OHIO Principle

The state? No.

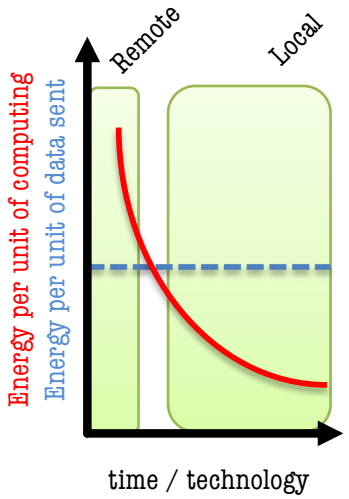
Only
Handle
It
Once

We can ill-afford to send humans out to adjust, tune, re-power or service 100 billion inexpensive sensor devices

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Corollaries to the OHIO Principle

- **Interplanetary travel** design approach
- **Pack your energy** for the mission
  - May harvest a little along the way
- **Distribute intelligently**
  - Local *vs*. remote computing (incl. machine learning)



Where should we draw the line?



Energy concerns push us toward computing LOCALLY (in the sensor)
and only communicating when necessary

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An Hour in the Life of an OHIO Device Designed for a Five-year Mission

The Power Challenge

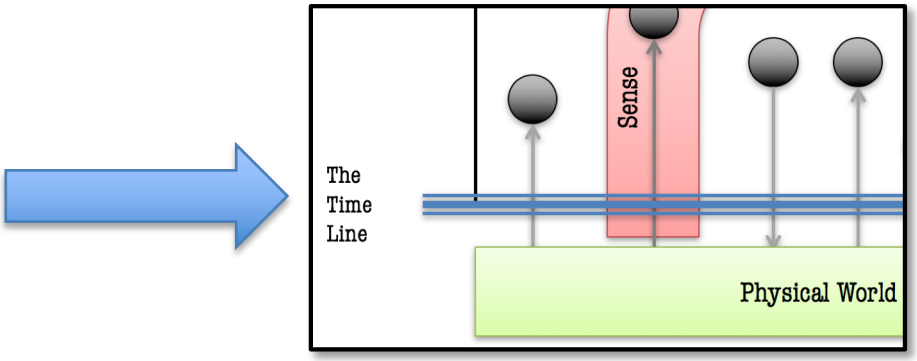
State	Seconds per hour
Sensing & processing	30
Receiving	5
Transmitting	5
Shut off	3560

LiPo prismatic battery
- 3.7V
- 1000mAh
- 2.00" x 1.50" x 0.23"
- < 8% per month self-discharge
- Rechargeable
- -25C..60C
- Idealized analysis

- Asynchronous, and mostly asleep
- **Don't waste Tx / Rx power on network protocol overhead**

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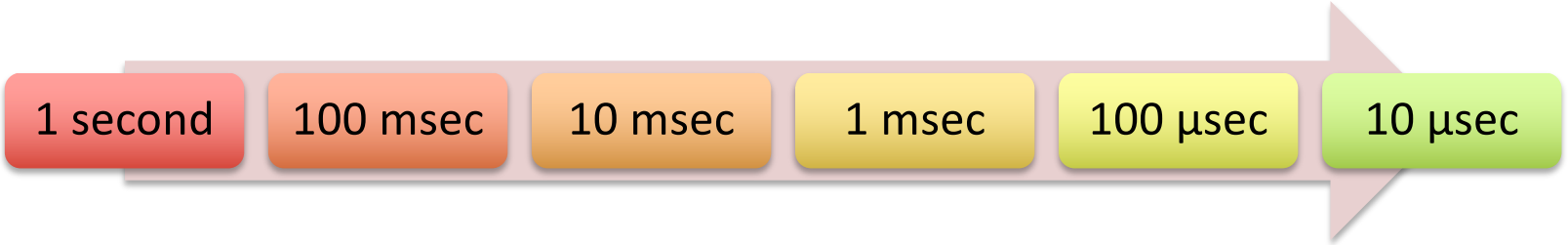
The Time Line

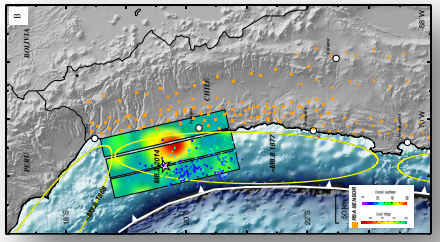


- Below the line: time is real
  - Concurrency, simultaneity, causality
- Above the line: time is meta-data
  - Programmer can manipulate the representation of time
- Crossing cyber to physical?
  - Translate programmer's intent to reality – not always possible
- Crossing physical to cyber?
  - In a distributed world, how do we time-label events in a way that is **correct enough** as to not give rise to subsequent errors? Time-ordering of events?

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Application-Specific Time Accuracy Requirements





Crowdsourcing using Smartphones[2]

[1] 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



Networked UAV Sensors[1]

[2] 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.

Acoustic Beamforming

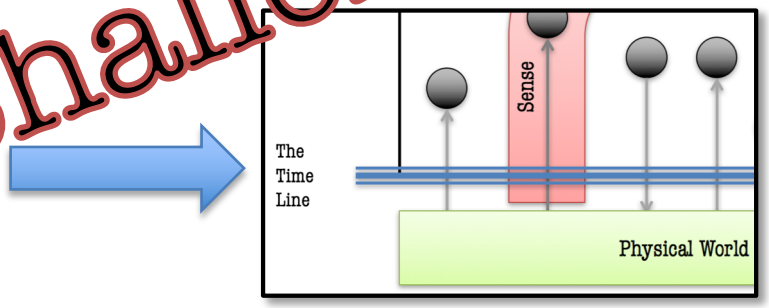
Networked Situated Sensors

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Crossing the Time Line: Essential to the IoT but Difficult

- First and foremost, **consistency** in labeling events crossing the time line
- Time concepts in everyday apps
  - **Concurrency**
  - **Simultaneity**
  - **Time-ordering**
  - **Periodicity**
- Clock consumes power
- Starting / stopping requires sync → power

The Time Challenge



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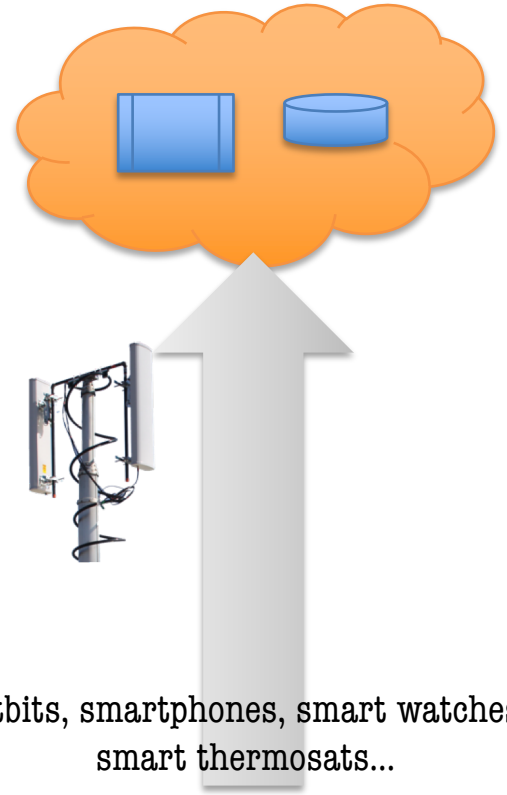
The Value is in Sharing Data

- Imagine the Smart Intersection
- Hazard detection requires sharing of information and fusion across sensor systems
- Sharing?
  - Provenance and data integrity
  - Privacy
  - Value-for-data

The Federation Challenge

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Programing Today's Distributed System



Fitbits, smartphones, smart watches, smart thermosats...

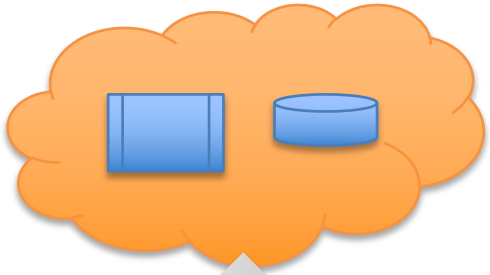
Cloud programming
- Aggregation
- Machine learning
- Visualization

Effectively closed

Embedded programming
- Fixed functionality
- Focused on low-power operation

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Programming in the Cyber-Physical Network



```
USING [ e23, e97 ]
DO [ b1 ]
SYNCHRONIZED TO cl
TOLERANCE x ON
```

Decomposition

Fitbits, smartphones, smart watches, smart thermosats...

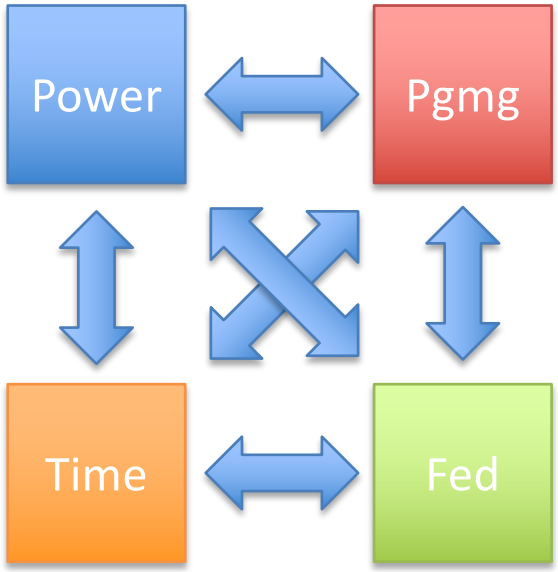
Implications

- One program on multiple devices
- **Multiple programs on one device**

The Programming Challenge

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A Perspective on our Challenges



- The challenge with our Challenges is that they can't be solved in isolation
- We really have a PLATFORM challenge

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SMILE: PLATFORM-ORIENTED APPROACH

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Platformization and Iannucci's Law

In each generation of computing, the emergence of a ***standard platform*** *transforms the industry by shifting value from hardware to software and services.*

Let's engage in a little bit of "marketecture" thinking.

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Computing Platforms: Past and Present

	Golden Age	Standard Platform	Compatibles	Value Shift to Software	Value Shift to Services
Mainframe	GE, NCR, 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, Apple, sinclair	IBM Personal Computer	COMPAQ, DELL, hp	Microsoft	IBM, EDS
Mobile	BlackBerry, NOKIA, Google, SAMSUNG, Apple, htc	Mobile Apps plus cloud services			

What's the next platform?

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Hypothesis: it will be the The Cyber-Physical Network

An *integration* of

1. Flexible, powerful, programmable, open device families
2. Flexible, powerful, programmable, open wired and wireless networks designed for the next 100 billion devices

Observation: *#1 mostly exists.* ***#2 does not exist***

Will it emerge as an evolution of legacy wireless networks?

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Design Parameters of this New Computing Platform

- Distributed, federated, and energy-poor
- Programmed in a way that separates correctness from distribution

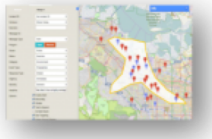
- RAN and applications will separate: RAN-agnostic networks
  - Cellular, WiFi, LP-WAN fully integrated
  - Artificial ties between services and bearers will be eliminated
  - Not your parents' cellular network which is almost, but not quite, entirely unlike a real IP network
- Free transistors and machine learning enable spectrum collaboration
- Time will be a first-order concept in programming
- Edge computing will vanish in favor of *edgeless computing*

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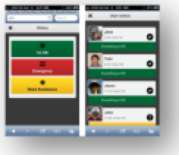
SMILE-RELATED RESEARCH

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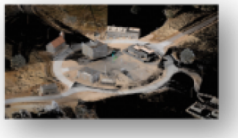
CCSG: Integrating Computing & Communications



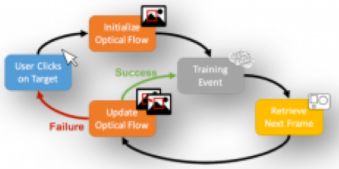
Wireless Emergency Alerts



Survivable Social Network



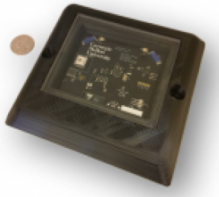
In-situ measurements and physics-based modeling of environments



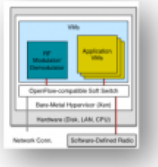
Accelerated Incremental training of CNNs

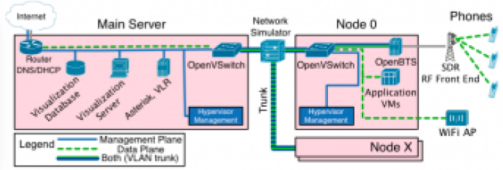


UAS + Cellular: "Holes in the Sky"



Crowdsourced Smart Cities™



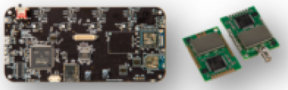


The CROSSMobile™ Wireless Testbed





Adaptation and Cooperation



IoT: Low Power Computing & Comms



Indoor Positioning



The Mobile Node

http://ccsg.ece.cmu.edu

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Projects

- Low-power sync and computing: LongShoT & PowerDué
- Integrating ML into sensing: Autonomous Curiosity
- Federated ML in sensing: SWATT
- (new project) Language framework: TickTalk

- Applications: Crowdsourced Traffic Calming

  USGS Environmental Sensing

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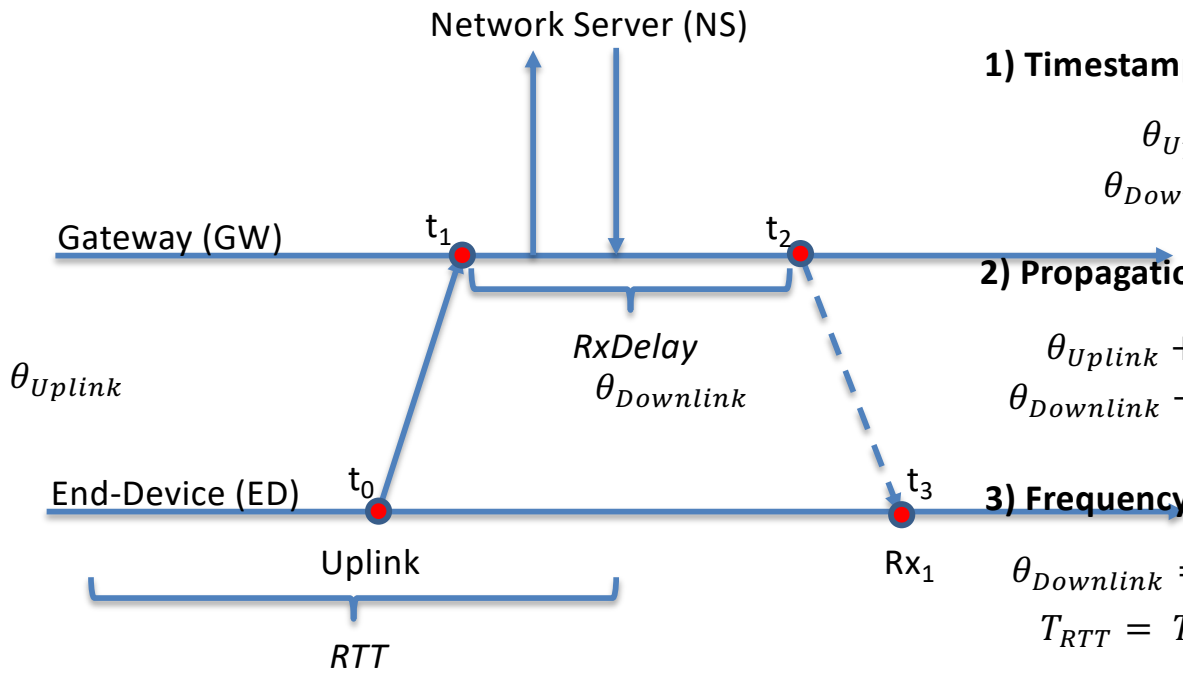
LongShoT: Long-Range Synchronization of Time

Cef Ramirez, Anton Sergeyev, Assya Dyussenova, Bob Iannucci

Can we achieve microsecond-level synchronization over LoRaWAN while maintaining its long-range and low-power attributes?

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Main Challenges



1) Timestamp precision:

$$\theta_{Uplink} = t_1 - t_0$$
$$\theta_{Downlink} = t_2 - t_3$$

2) Propagation Delay @ Range>=1km,

$$\theta_{Uplink} + T_{prop} = t_1 - t_0$$
$$\theta_{Downlink} - T_{prop} = t_2 - t_3$$

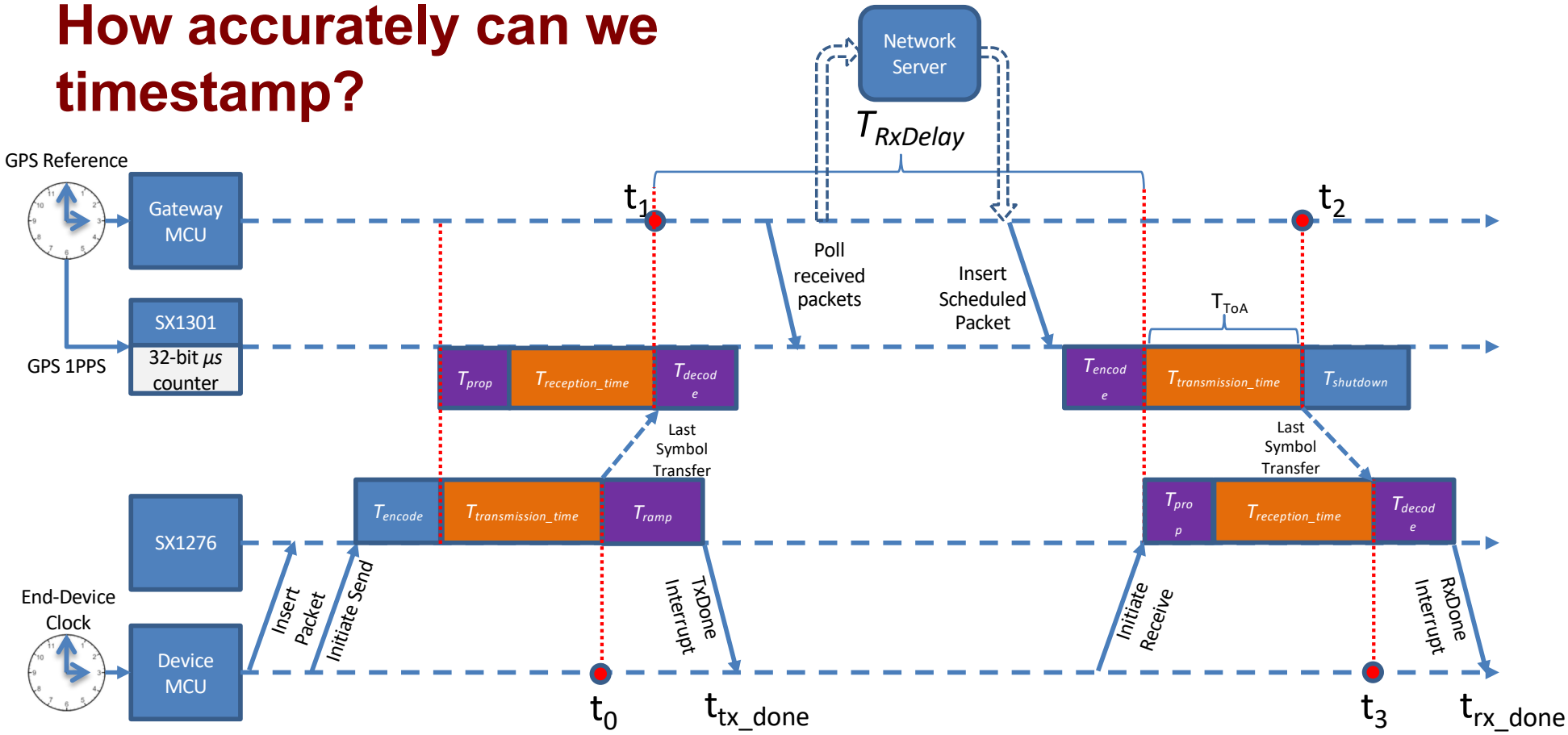
3) Frequency Offset @ RxDelay>=1

$$\theta_{Downlink} = \theta_{Uplink} + \alpha \times T_{RTT}$$
$$T_{RTT} = T_{RxDelay} + 2 \times T_{prop}$$

Drift and **propagation delays** are *very significant* with LoRaWAN!

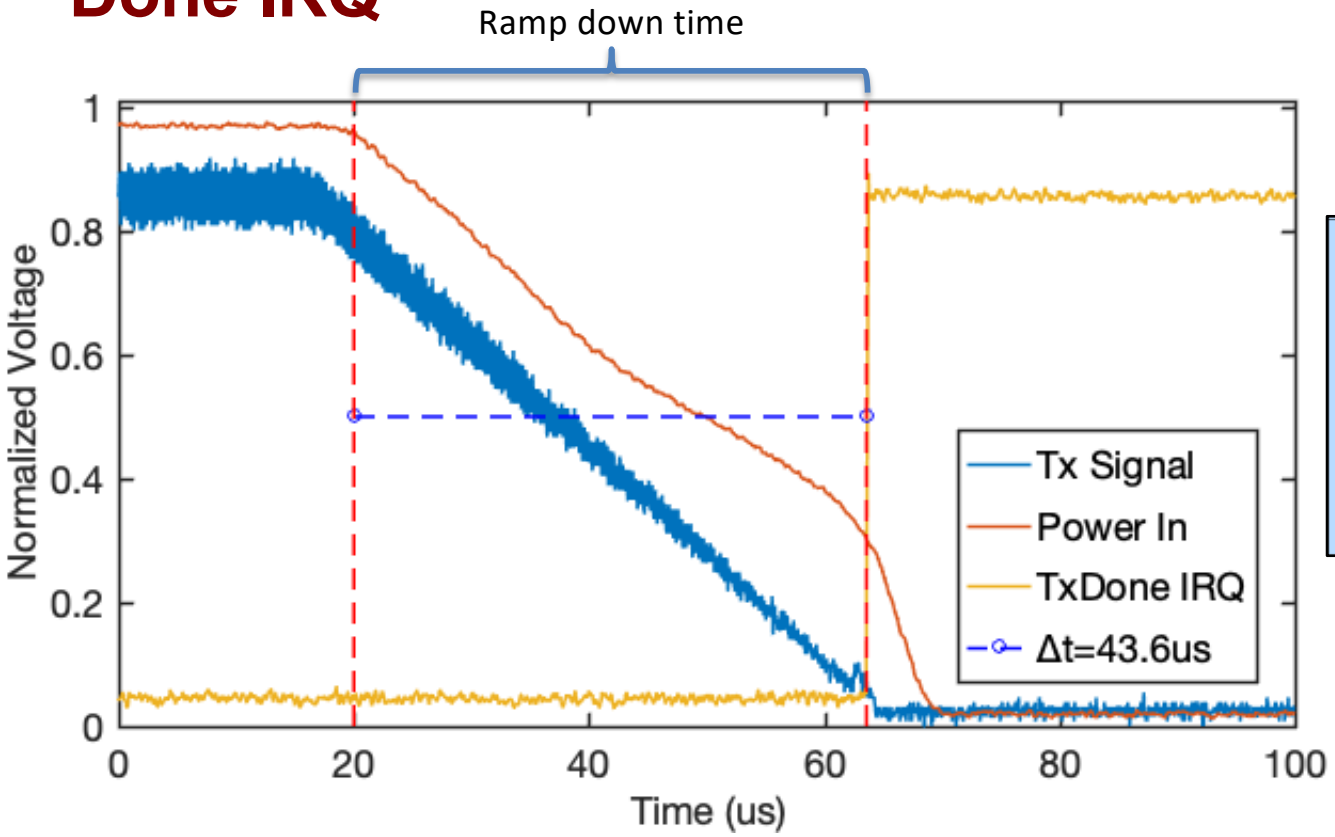
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How accurately can we timestamp?



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Semtech SX1276 Timing Characterization – Transmit Done IRQ

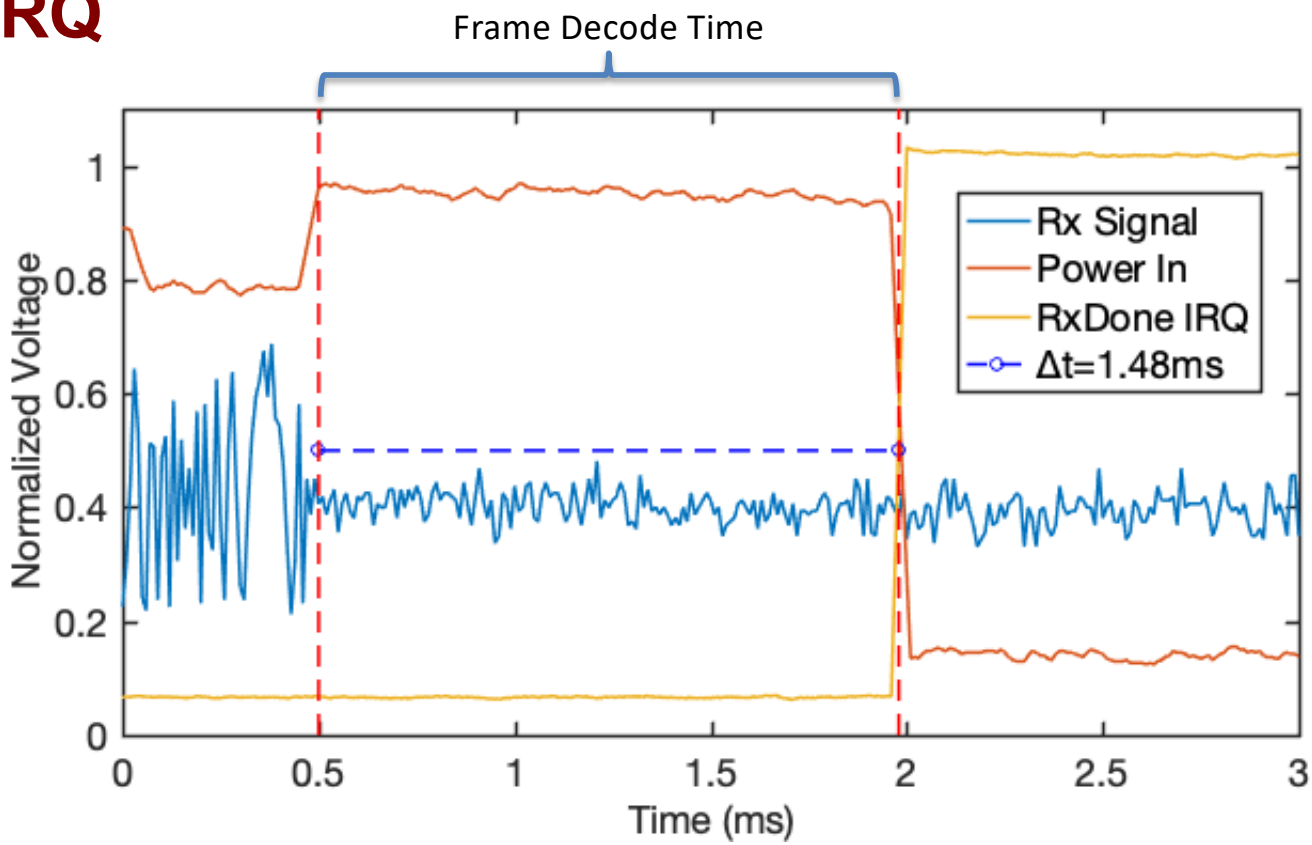


PaRamp(3:0)	rw	0x09	Rise/Fall time of ramp up/down in FSK 0000 → 3.4 ms 0001 → 2 ms 0010 → 1 ms 0011 → 500 us 0100 → 250 us 0101 → 125 us 0110 → 100 us 0111 → 62 us 1000 → 50 us 1001 → 40 us 1010 → 31 us 1011 → 25 us 1100 → 20 us 1101 → 15 us 1110 → 12 us 1111 → 10 us

[SX1276 Datasheet]

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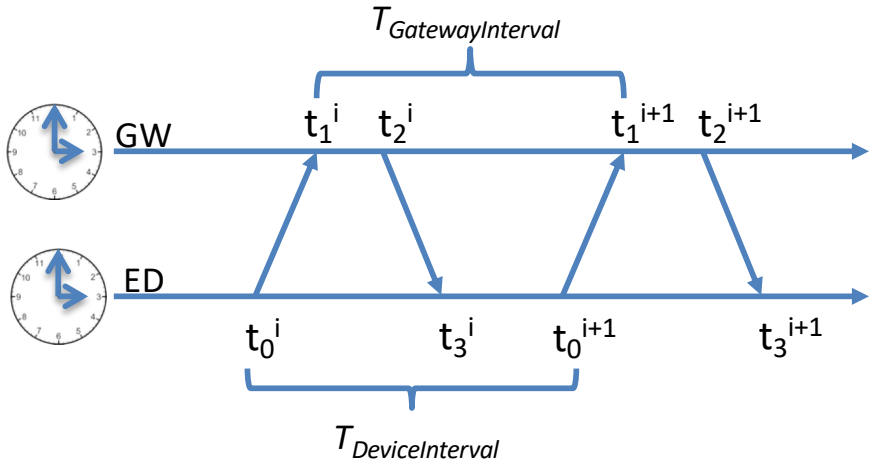
Semtech SX1276 Timing Characterization – Receive Done IRQ



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Approach

- Independently solve for drift (α) and propagation delay using two consecutive requests
- **Pros:**
  - Irrespective of range and can estimate propagation delay
  - Sync interval is device driven
- **Cons:**
  - Requires 2 requests
  - Assumes drift is constant over sync interval



$$\propto = \frac{T_{DeviceInterval}}{T_{GatewayInterval}} \qquad t_3^{i+1} - t_0^{i+1} = \propto \times RTT$$

$$RTT = T_{RxDelay} + 2 \times T_{PropDelay}$$

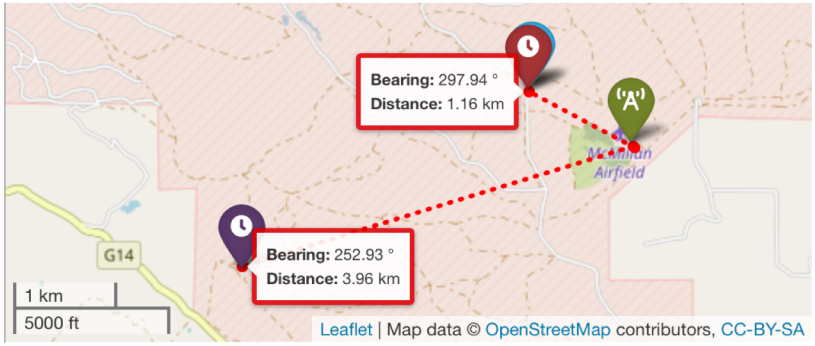
$$T_{PropDelay} = \frac{t_3^{i+1} - t_0^{i+1}}{2 \times \propto} - \frac{T_{RxDelay}}{2}$$

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Two-Step Synchronization Result

3 Devices over a 2 hour period @ 4km

Metric	Device 1	Device 2	Device 3
Distance from Gateway (*km*)	1.11	1.11	3.96
Temperature Range (*C*)	34.3 – 35.9	34.1 – 35.3	30.2 – 32.8
Synchronization Error (*μs*)	μ = 1.61 σ = 2.41	μ = 1.64 σ = 2.35	μ = 1.22 σ = 3.74
Drift Rate (*ppb*)	μ = 5 σ = 53	μ = -14 σ = 45	μ = -38 σ = 124
Propagation Delay (*μs*)	μ = 2.6 σ = 1.5 ε = -1.1	μ = 2.4 σ = 1.6 ε = -1.3	μ = 12.1 σ = 2.2 ε = -1.1
Maximum Uncertainty (*μs*) @ T_{SYNC} = 5min	37	31	73





Sensors 1 & 2



Sensor 3



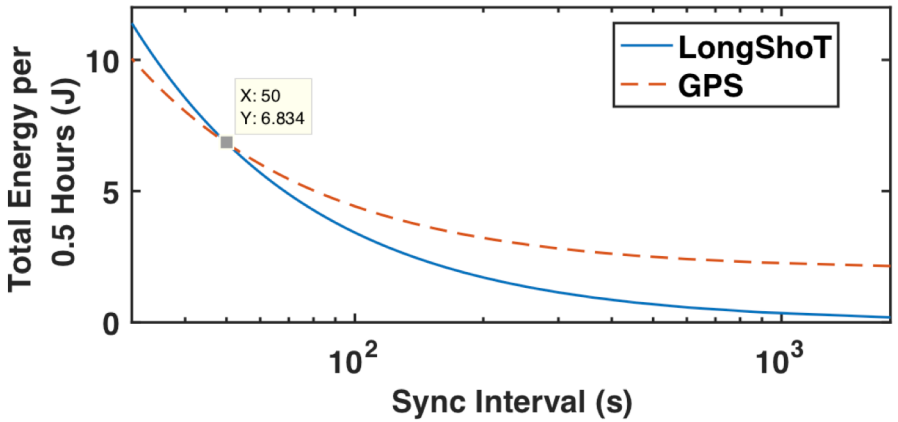
Gateway

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Energy Comparison with GPS

Semtech SX1276 @ SF10, 125kHz, +20dBm			
Tx	4 bytes	329.7 ms	396mW
Rx	8 bytes	92.67 ms	41.6mW
Energy Per Sync		**190 mJ**	

OriginGPS 1411 Receiver @ 1.8V			
Start Mode	**T_{TTFF}**	**Power**	**Energy**
Cold (bootup)	35s	77mW	2695 mJ
Warm (>=30m)	32s	67mW	2144 mJ
Hot (<30m)	2s	67mW	134 mJ

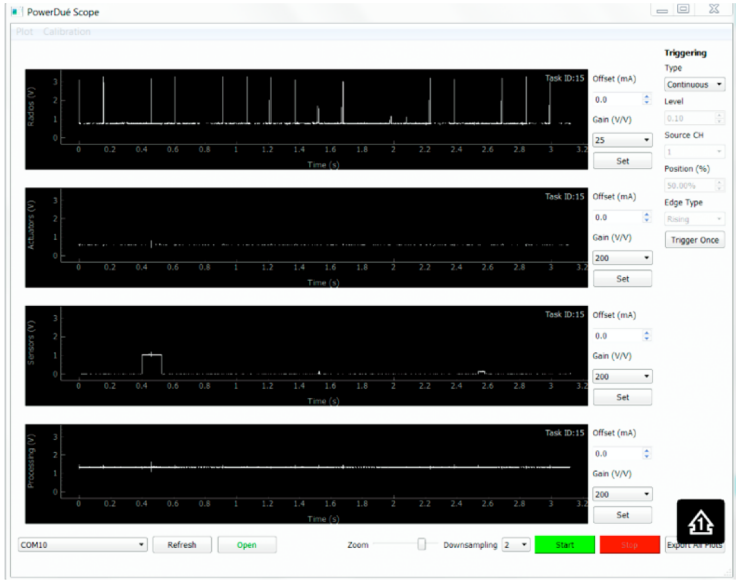


Approach	Total Energy per Day			
	T_{SYNC} = 10s	**T_{SYNC} = 50s**	**T_{SYNC} = 100s**	**T_{SYNC} = 1000s**
LongShoT	1,641.6 J	328.32 J	**164.16 J**	**16.42 J**
GPS Receiver	**1,157.8 J**	**328.03 J**	212.16 J	105 J

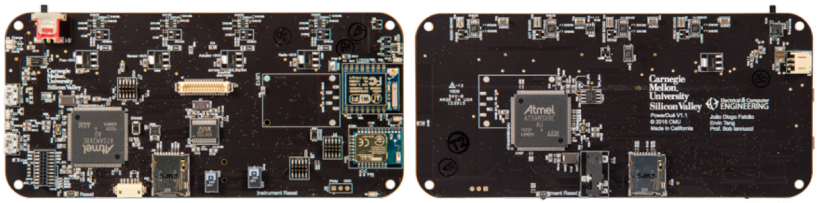
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PowerDué: Power / Energy Aware Programming

- Proxy for a class of sensor devices
  - Selection of radios (BLE, WiFi, LoRa)
  - CORTEX M3 processor, MicroSD, 9DOF IMU, I2S CODEC, camera
  - Four separate power domains
  - Dedicated instrumentation processor
- Eclipse or Arduino IDE
- Bare-metal or FreeRTOS
- Custom PowerScope

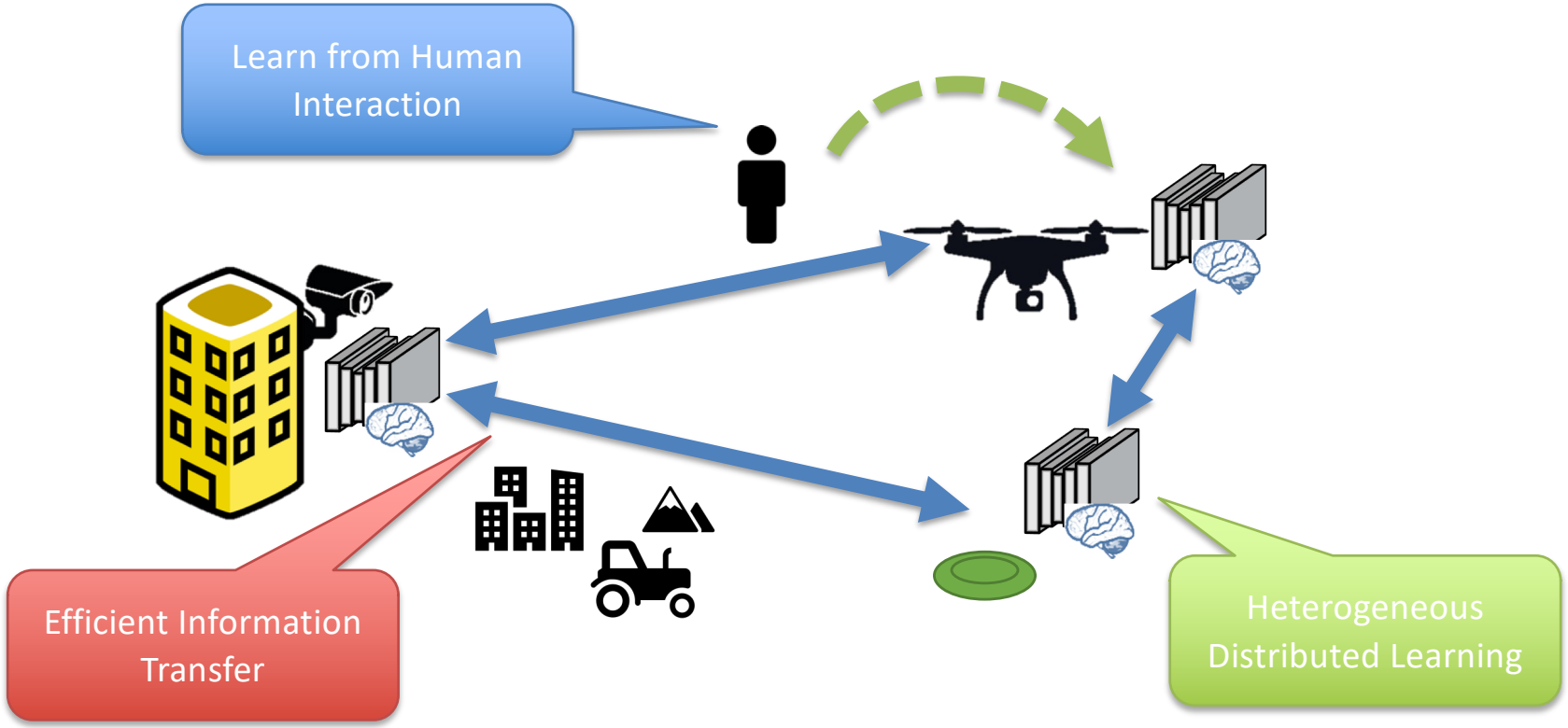


CMU's PowerDué
Power/Energy Self-Aware
Development System



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Synchronized Multisensory Learning



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ClickBAIT:
Click-Based Accelerated Incremental Training

Ervin Teng, Bob Iannucci

In the context of an autonomous real-time learner,
how do we maximize the benefit of
every human-provided training event?

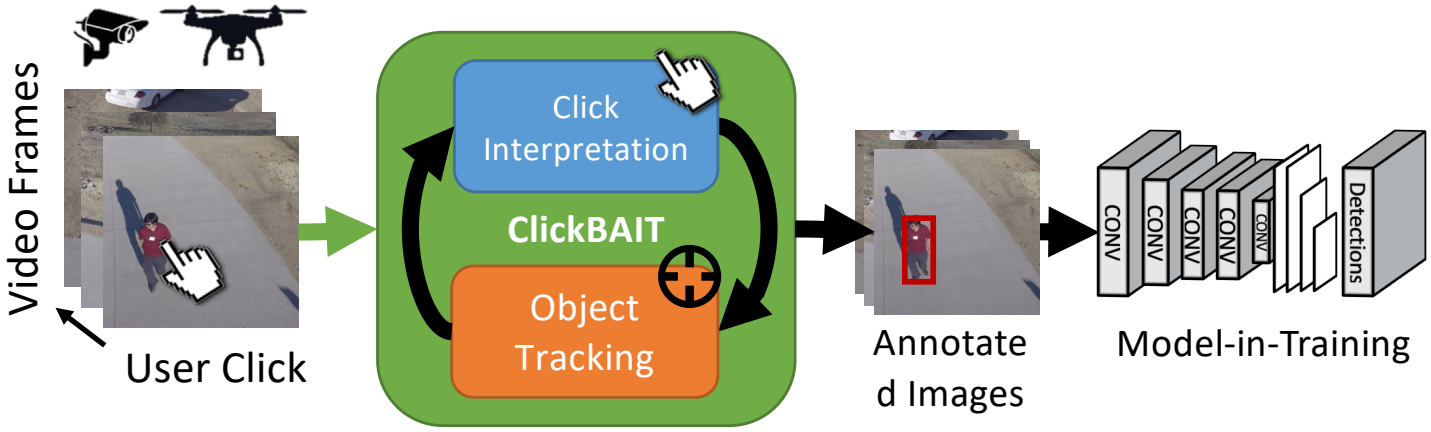
Ref: [5]

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The ClickBAIT Framework

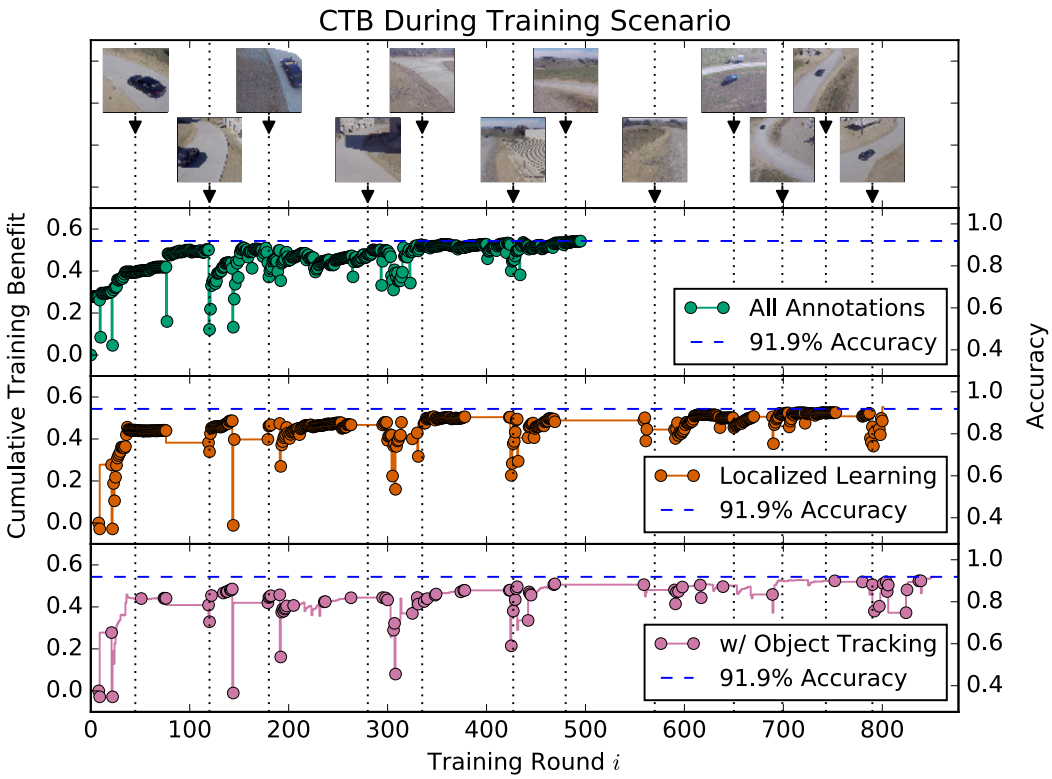


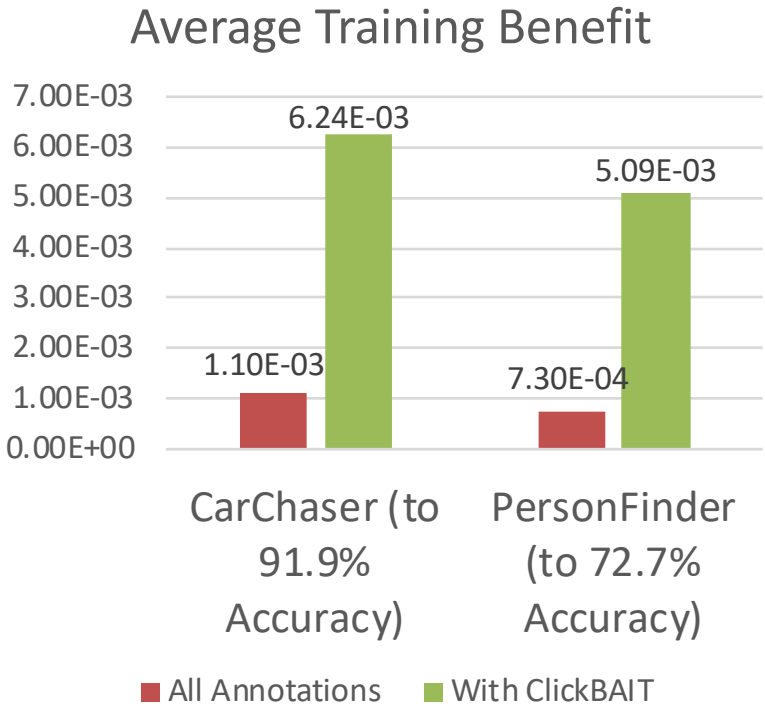
- Goal: Make human interactions more useful *(study)*
- Constraint: Interaction is a single click or button press



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Results: Classification





5-7 x improvement

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SWATT:
Synchronized Wide-Area Target Tracking

Ervin Teng, Cef Ramirez, Bob Iannucci

In multi-system deployments,
can we share information from one system to another
for automated learning?

Ref: [6]

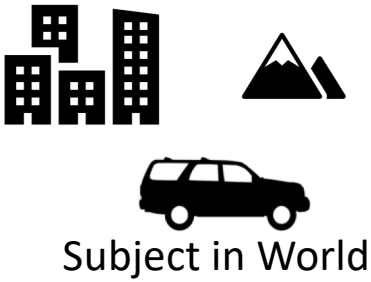
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Wide-Area Monitoring

- Human-Intensive



Fixed Camera



Subject in World



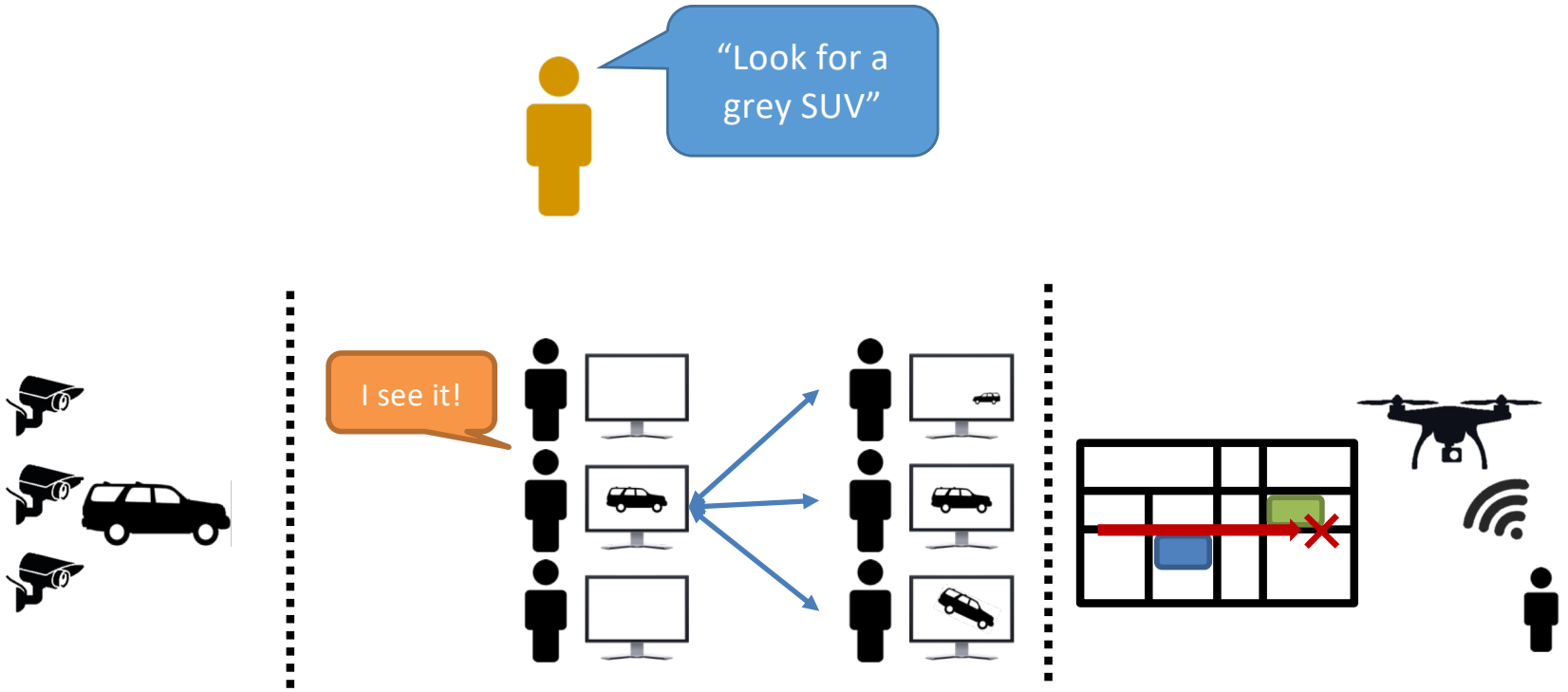
Robotic Platform



Ground Sensor

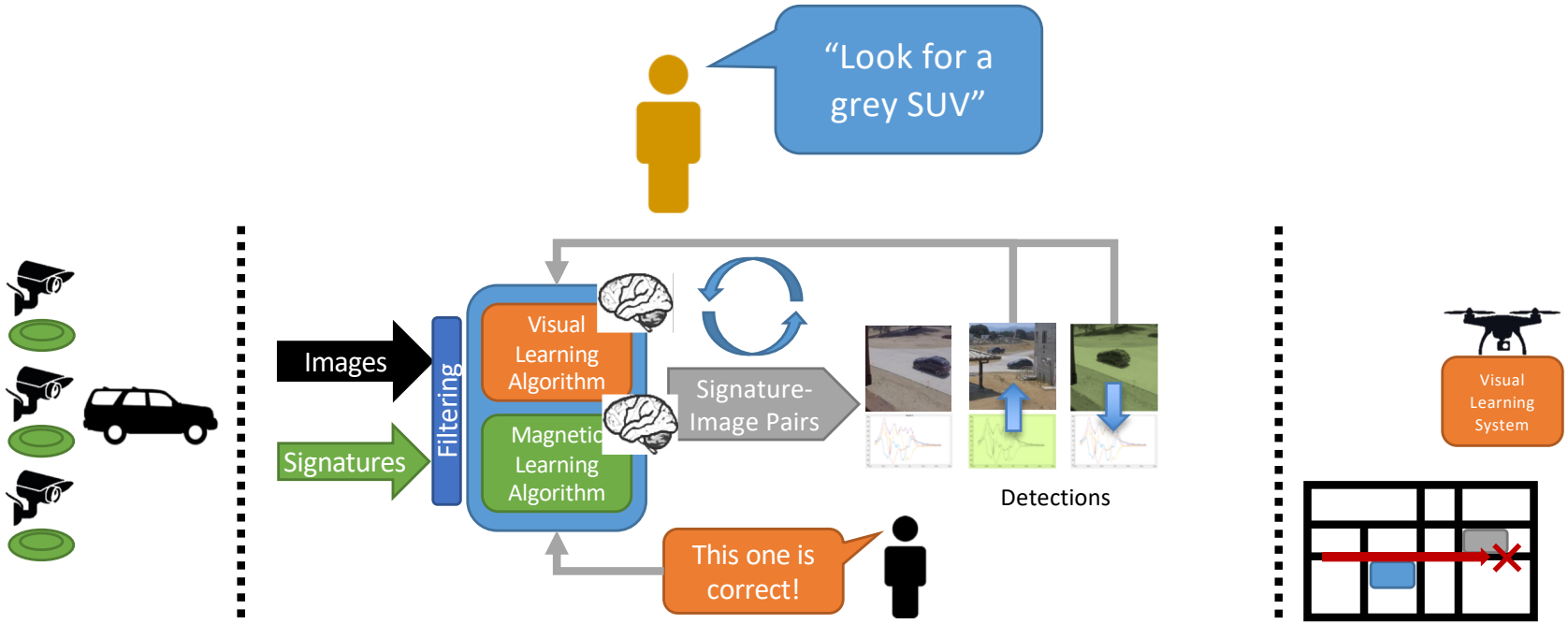
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Example: Tracking a Car

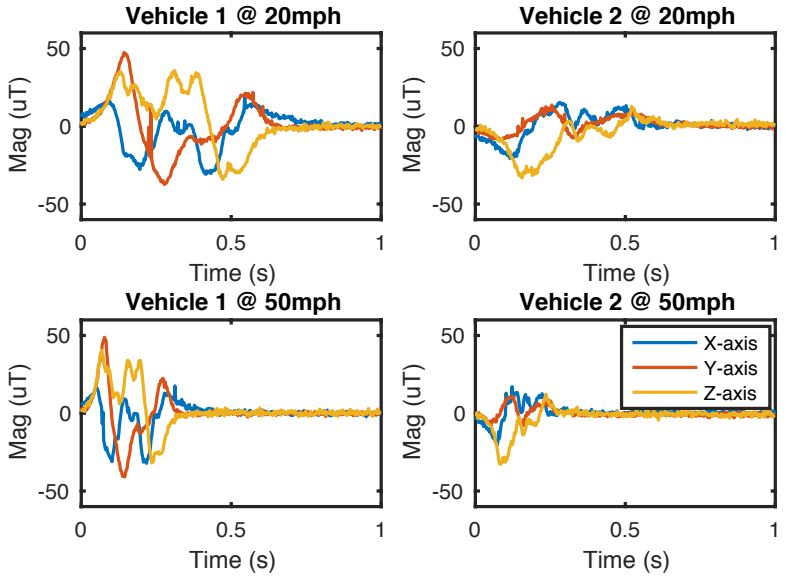


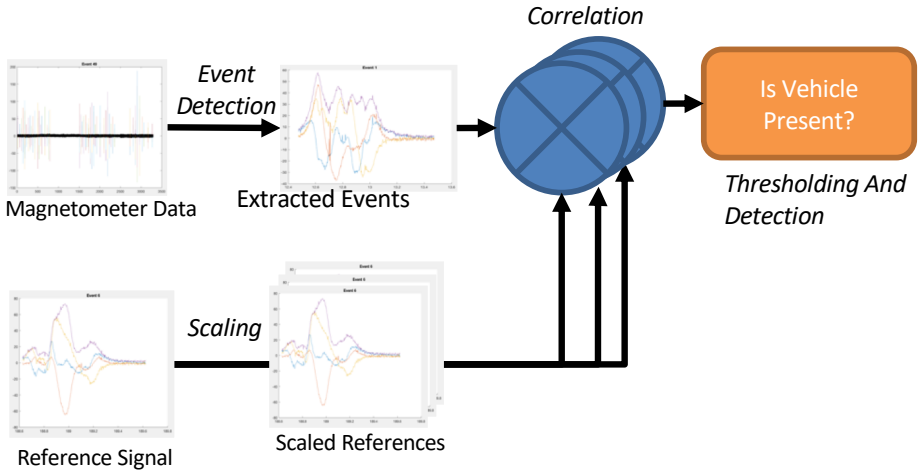
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SWATT: Real-time Learning



Identifying Vehicles Magnetically





Vehicles have *unique traces that condense with velocity*

Create a classifier for each vehicle type

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SWATT: Conclusions

- Coupling two or more learning sensor systems enables collaborative self-learning
  - Magnetic signatures – detect vehicles (>90% precision in our experiments)
  - Simple events (from the magnetic sensors) can help train a visual object detector
  - Learning improves as the system scales, but performs surprisingly well even with small systems (<10 cameras)

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Autonomous Curiosity

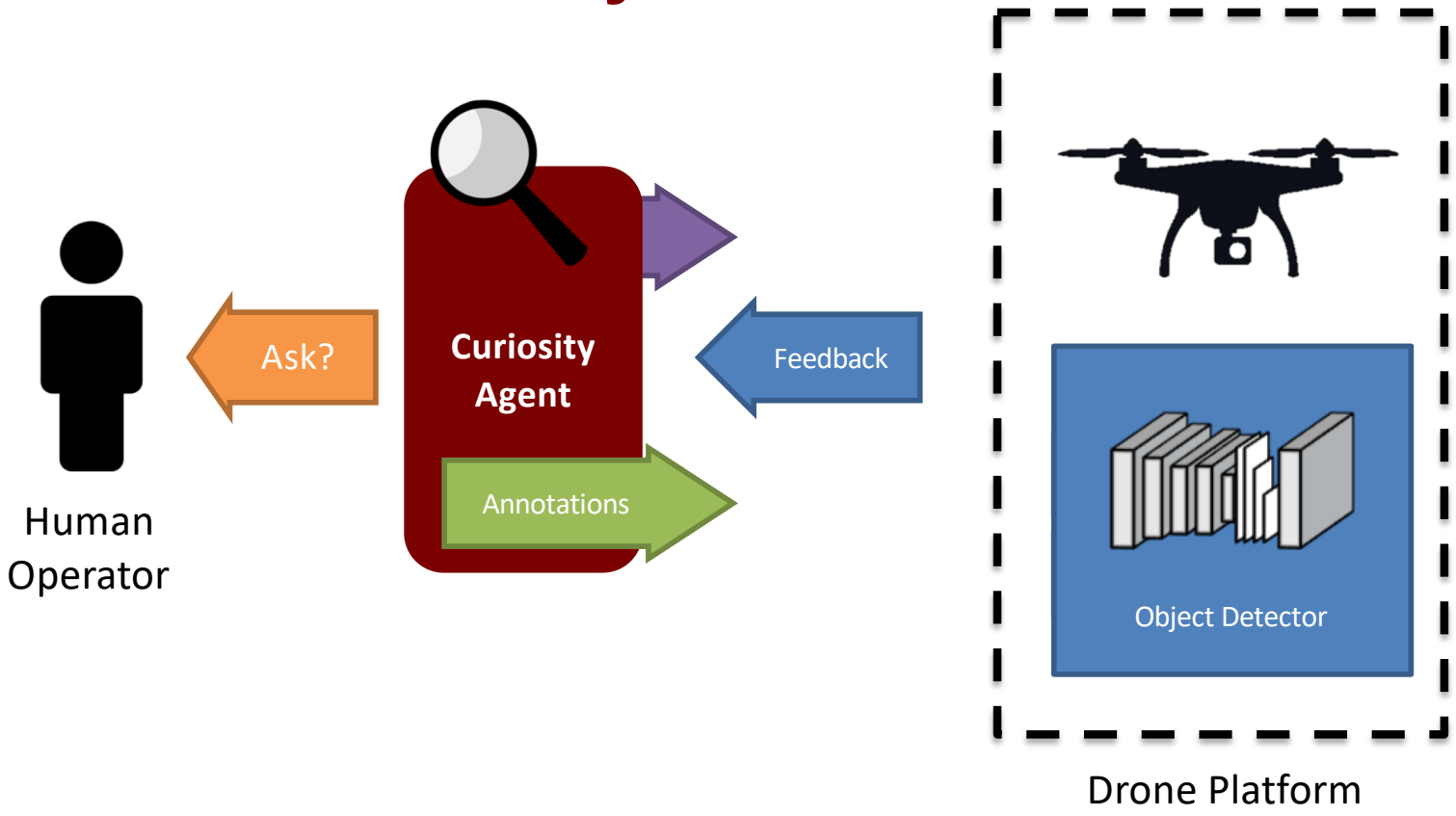
Ervin Teng, Bob Iannucci

Can we automate drone motion such that
incremental training benefit per user interaction
is maximized for a real-time training system (e.g. ClickBAIT)

Ref: [7]

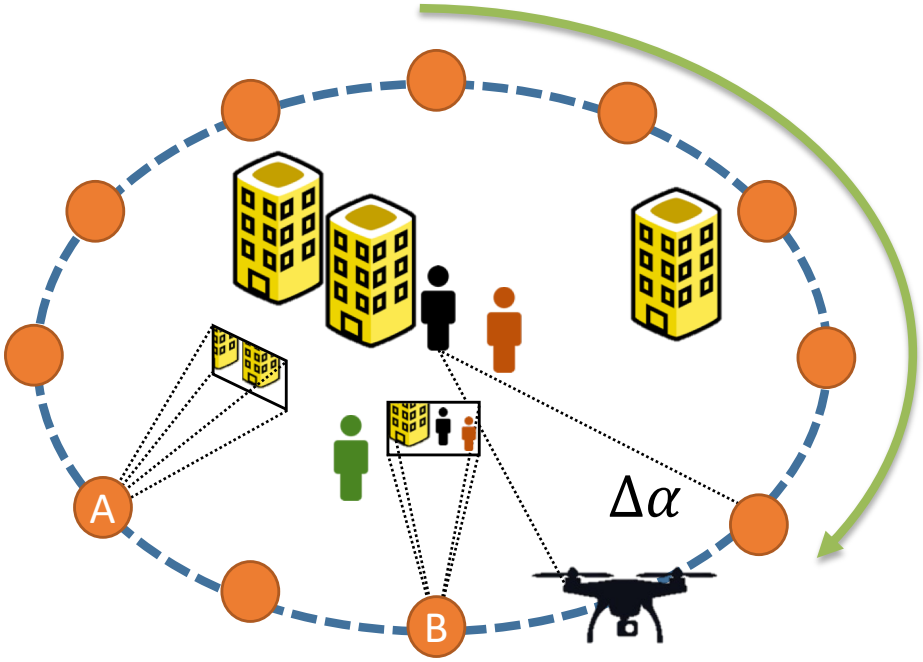
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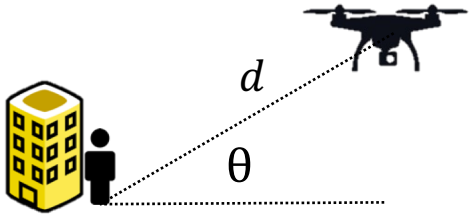
Autonomous Curiosity



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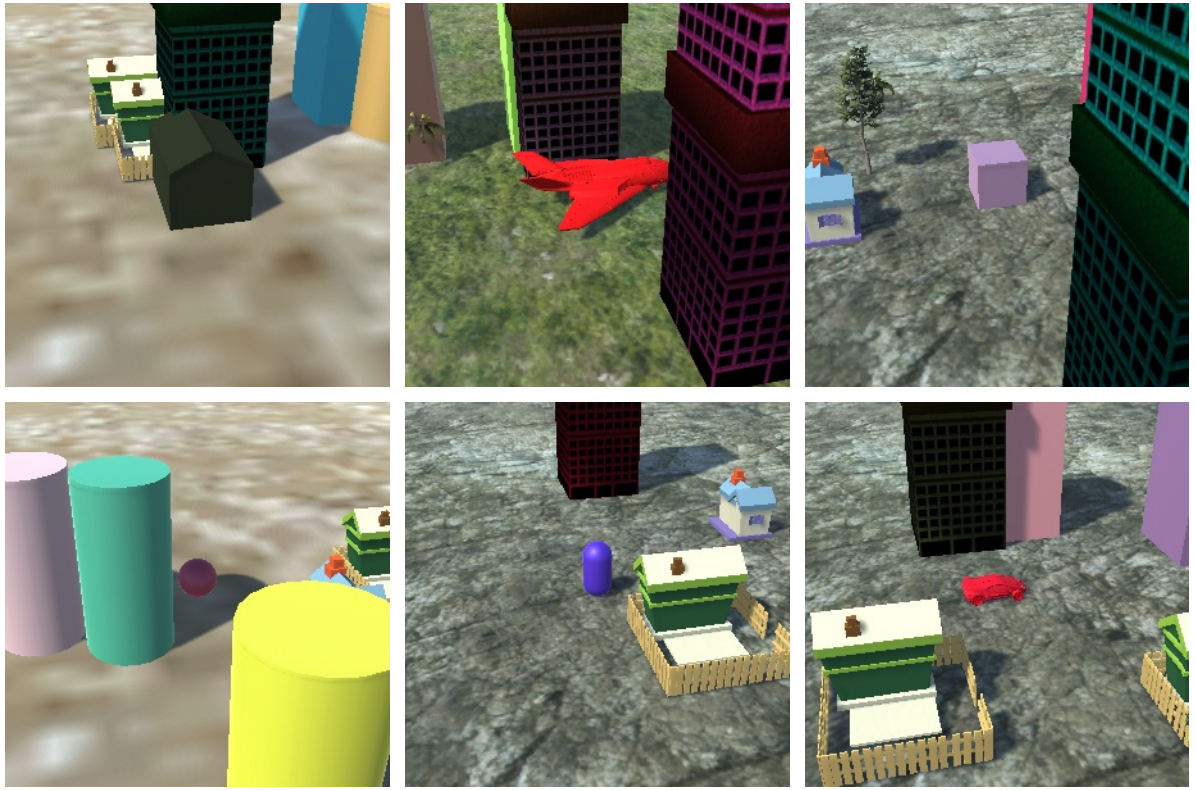
Scenario Setup





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Simulation for Training

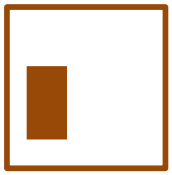


Deep Reinforcement Learning

State



Image

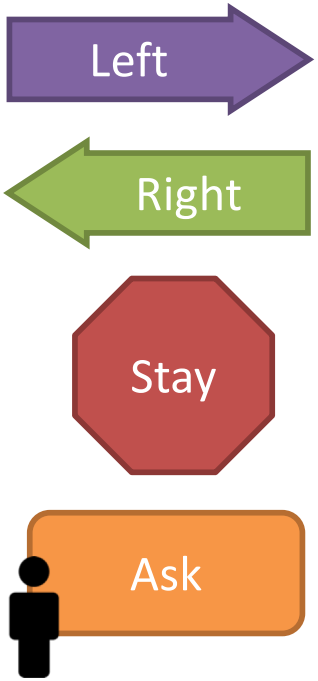


What I'm Learning

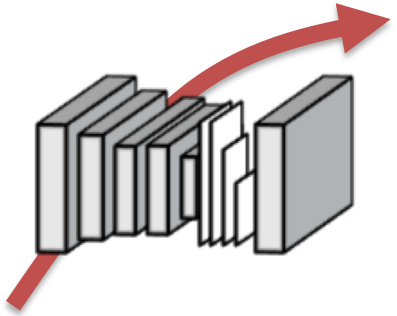


What I've Learned

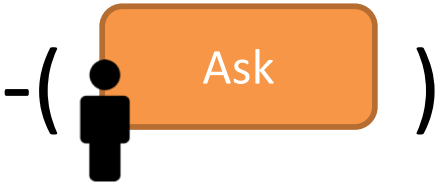
Actions



Reward

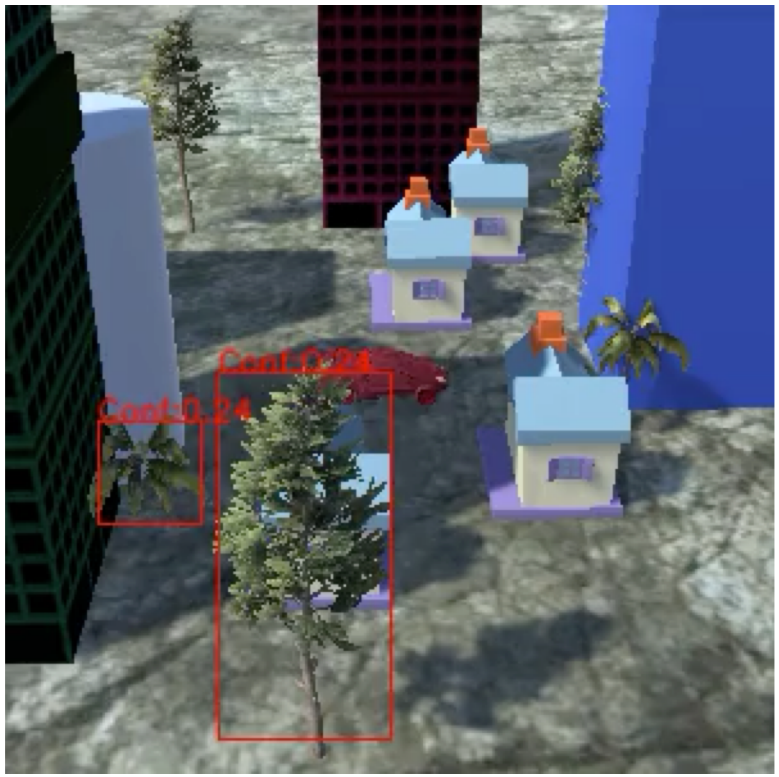


Improvement of the Detector



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Results - Learned Behavior



In Simulation

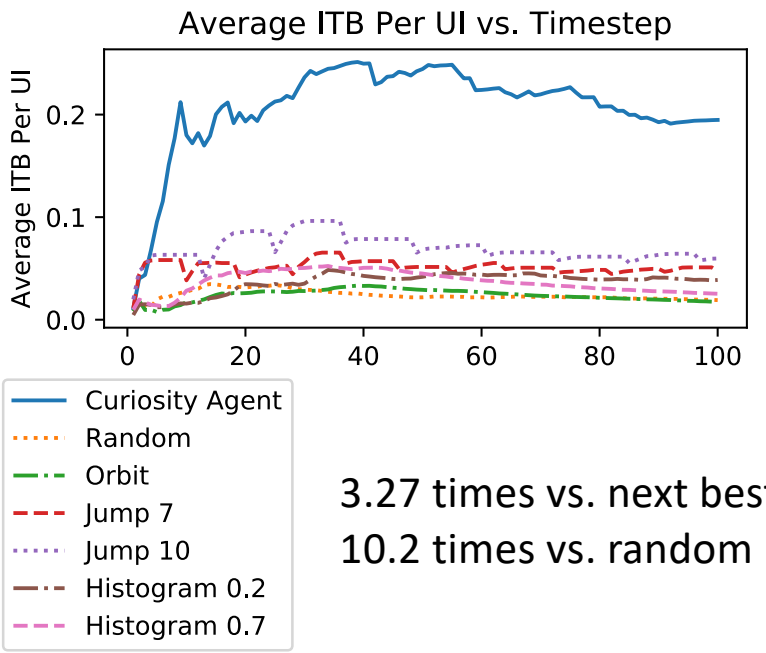


In the Field

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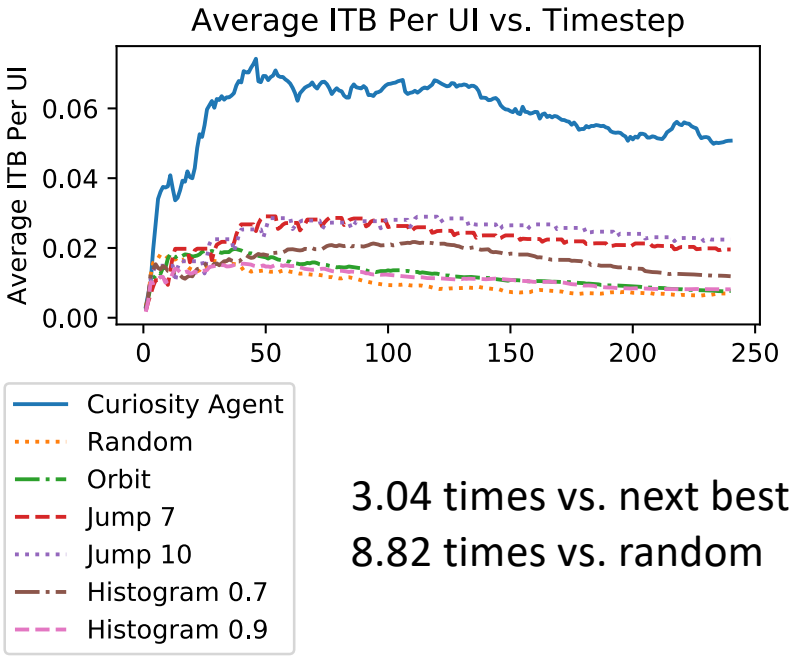
Results - Incremental Training Benefit

In Simulation



3.27 times vs. next best
10.2 times vs. random

In the Field



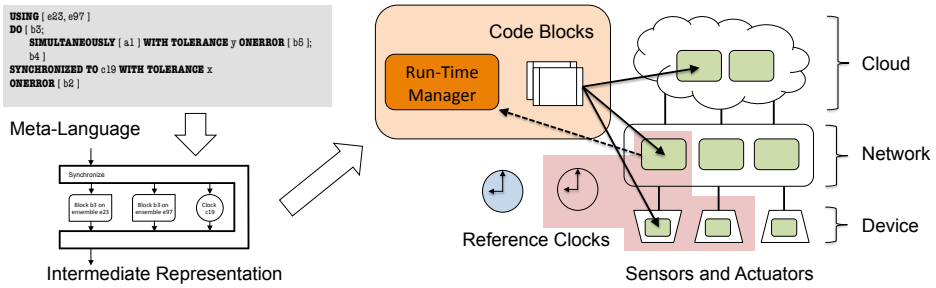
3.04 times vs. next best
8.82 times vs. random

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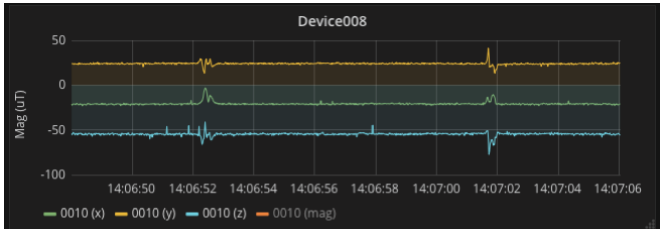
TickTalk: Programming the CPS Platform

- Present: “apps” made smartphones a force of nature
- Future: “apps” that pervade the **network and devices**
  - Manage device power
  - Manage time
  - Separately address program correctness and program distribution
  - Integrated federation services (*e.g.,* search engines for sensed data)

CMU’s proposed TickTalk programming environment

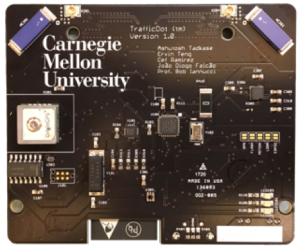


Application: Crowdsourced Traffic Calming

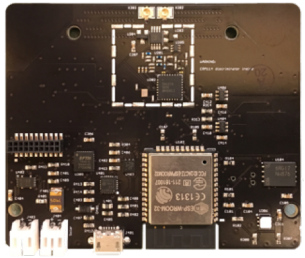


Machine learning: identifying speed by magnetic signature

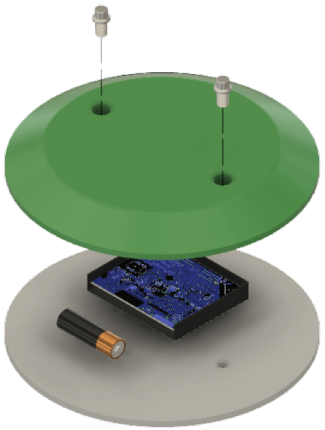
Hierarchical power management:
designed for city-infrastructure lifetime



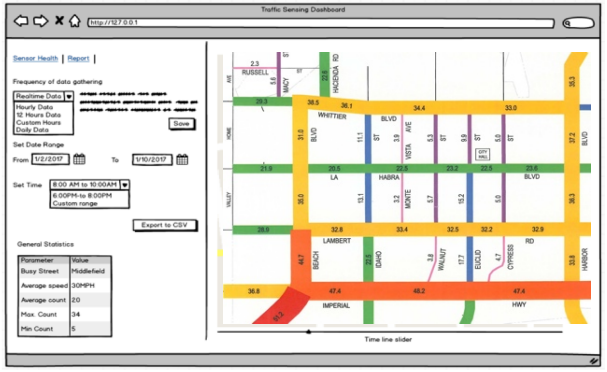
PCB top

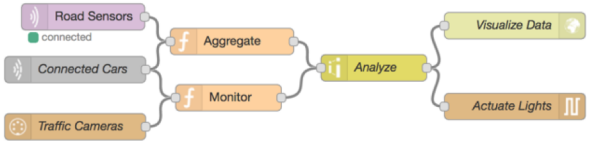


PCB bottom



Road-worthy enclosure





Database, coding and visualization tools to address the programming challenge

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Application: Environmental Sensing

- Challenge: demonstrate the benefits of
  - Inexpensive devices
  - Long-range low-power networking
  - Custom software framework
  - Rapid prototyping
- … for the purpose of non-contact stream height sensing



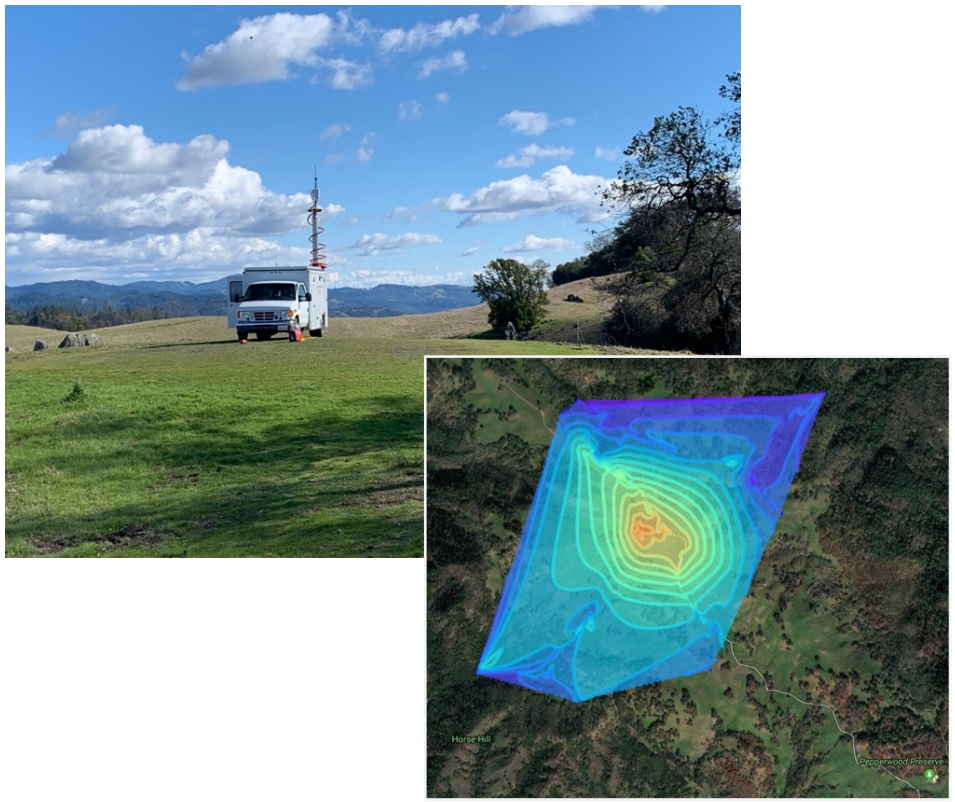
Pepperwood Preserve,
Santa Rosa

USGS
science for a changing world

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RF Modeling and Measurement

- Using a LoRa gateway as the reference point, we collect LoRa RSSI data from a LoRa-enabled handheld device
- Data are interpolated to give a first-order picture of propagation
- We match this against RF prediction based on a path loss model and real topography
- Results are used to recommend gateway location(s)



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Unique Research Tool: The CROSSMobile RF Lab



- Stand-alone LTE network
- First (known) amateur radio LTE network
- Base of ops for ML-on-drone research
- Base of ops for LP-WAN research





- Four sources of power (diesel gen, gasoline gen, three marine batteries, shore power) – solar?
- Five connections back to the internet (AT&T/Verizon, satellite, WiFi, point-to-point wireless, ethernet)
- Software-defined radios
- Flexible RF and network configuration
- 42’ pneumatic mast
- 4-5 outings per year

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… and a Mobile Ham Shack

- Sometimes it is just really handy to have an 11,000 lb base for a big antenna



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Tip o' The Hat to the SRI "Bread Van"

Compare to photo: Computer History Museum
https://www.computerhistory.org/atchm/born-in-a-van-happy-40th-birthday-to-the-internet/



Don Nielson



Vint Cerf

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Summary

- The IoT brings new opportunities and new challenges that call for a systems approach
  - Inherently cyber-physical
  - Energy limits are the root of many challenges
  - Distributed, federated
  - Time will be a first-order concept in programming
- Device-centric networking
- Well-matched to the “study / develop / deploy /evaluate / repeat” approach
- Some domain-specific tooling really helps

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Thank you!

http://ccsg.ece.cmu.edu

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References

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7. Teng, Ervin and Bob Iannucci. *Autonomous Curiosity for Real-Time Training Onboard Robotic Agents*. 2019 IEEE Winter Conference on Applications of Computer Vision (WACV) (2019): 1486-1495

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