Lecture 17
Embedded Systems Research

CE346 – Microprocessor System Design

Branden Ghena – Fall 2023

Some slides borrowed from:
Josiah Hester (Northwestern), Prabal Dutta (UC Berkeley)

Northwestern

Administrivia

- This is the last lecture!! 😭
  - No class after Thanksgiving
  - I’ll hold office hours in the lecture room

- Project Demos – Tuesday of Exam Week
  - Tuesday 12/5, Mudd 3514, 11:00-5:00 pm
  - Groups will do half that time (either 11-2 or 2-5)
  - I’ll request preferences and release a schedule next week

Today's Goals

- Explore sensing systems research
  - What does it mean to do "research"
  - Explore a research project in that context (Powerblade)

  - Discuss some example Sensing Research projects
    - Most shallowly
    - Signpost project deeply

Outline

- **What does research look like:**
  - **Research Overview**
  - Example: Powerblade
- Sensing Systems Research
  - Various Projects
  - Signpost

What is research anyways?

- I think of research as just “figuring stuff out”

- This is part of why research feels so vague: there are many ways to figure things out, depending on the question
  - Read papers
  - Run experiments
  - Send out surveys
  - Build something

Academic research

- We all do research all the time in our daily lives

- Academic research is mostly about the question you’re figuring out
  - Is the question important in some way?
  - Is the question something that’s not trivial to answer?
  - Does the answer provide value?

- Finding the “right” questions is **hard**

Academic research in engineering

- Often intertwines the act of “figuring out” with engineering
  - Need to build something to try out and that can answer the question
- Hard part is remembering that the question is more important than the engineering
  - Building something that only partially works is fine if it answers the question
  - We call this a research prototype
- Unfortunately, something working in a research paper is *definitely* not the same as a working product

Getting a PhD

- PhD students “do research”

- Getting a PhD requires a thesis (a good question) and a dissertation (describing and proving the answer)

- PhDs in engineering in US
  - 5-6 years average
  - Are paid for! (tuition plus $30k-40k)
  - Are not a good monetary decision in CS
    - There are other reasons for them, just not for money

Getting involved in research

- Research with faculty
  - Often take a 300-level course with a faculty and do well
  - Then talk to them about joining their lab
- NSF Research Experience for Undergrads
  - Summer programs held at universities throughout the US
  - You apply for these, like internships
- Any research counts! Even if it’s not in exactly your field
  - You’ll find more similarities than differences
  - It all looks similarly good on applications

Research outputs

- Papers (Journal, Conference, Workshops, etc.)
  - Provide a mechanism for others to find your work
  - Peer-reviewed papers are reviewed by other professors in the field to ensure that the seem valid

- Good papers do the following
  - Explain what the problem is
  - Explain why the problem is important
  - Explain how other research relates to this
  - Explain an answer to the problem
  - Prove that the answer to the problem is real
  - Explain the limitations of the answer

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Powerblade (DeBruin, Ghena, Kuo, Dutta)

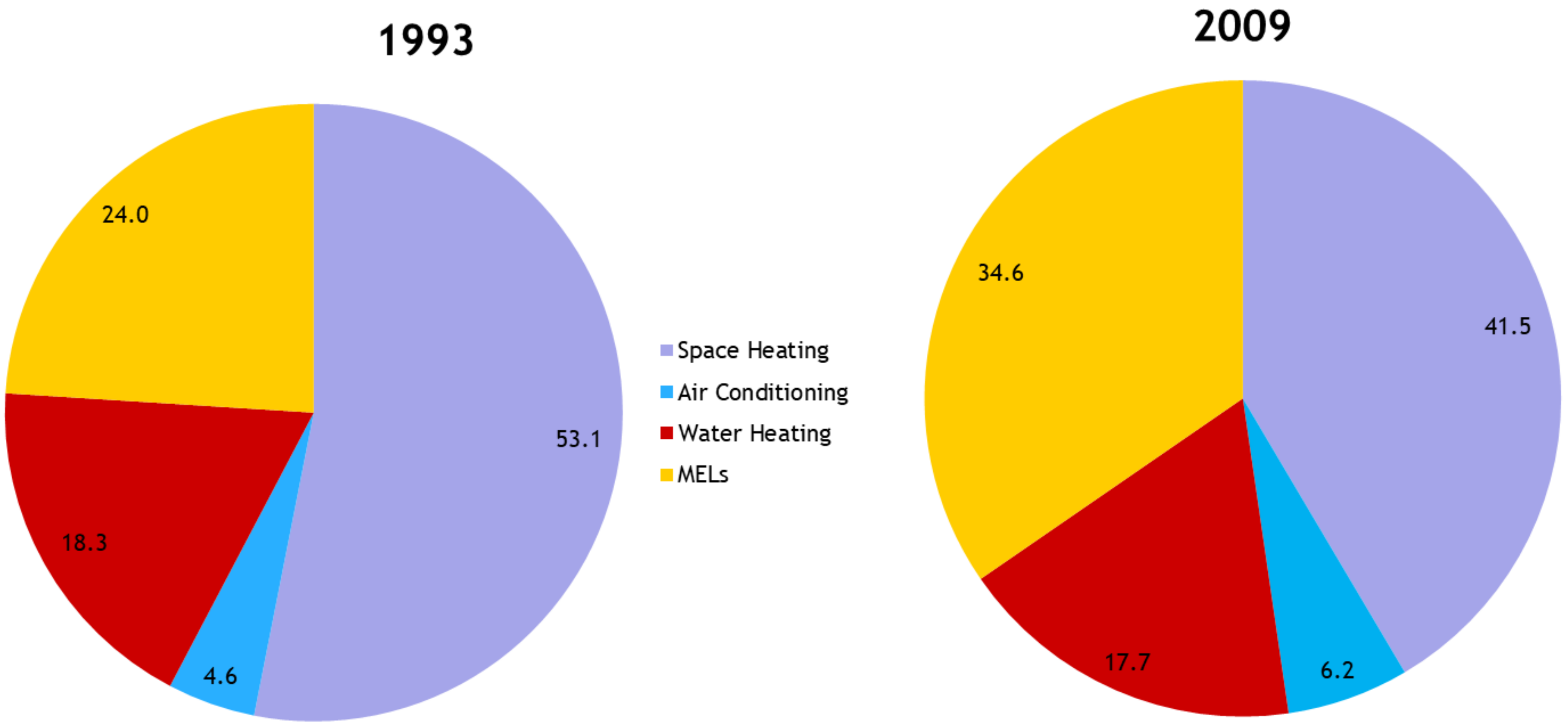
- 1” x 1” x 1/16” plug load power meter
- Measures AC voltage and current and reports real-time power draw over Bluetooth Low Energy

- Question: can a plug-load power meter be created in a 2D form factor to enable easy deployability while still being accurate?

https://brandenghena.com/projects/powerblade/debruin15powerblade.pdf

What is the problem and why is it important?

- Miscellaneous electrical loads (MELs) occupy an increasingly large percentage of overall energy use



What is the problem and why is it important?

- Existing power meters are too cumbersome for ubiquitous deployment

- Goal: **unobtrusively** measure all plug-loads in a home over a long period of time with **high fidelity** and **low cost**
    - Needs to be real-world sustainable
    - Needs to not impede daily life

How does other work relate to this?

- No other devices are as small as Powerblade
- Many use more power themselves
- Some do not have wireless communication or measure real power

Metering Device	Power Supply	Voltage	Current	Real Power?	Data Output	Static Power	Volume
Kill-A-Watt [6]	Capacitor fed	Divider	Resistor	Yes	LCD	450 mW	14.0 in^3
Watts Up [17]	Capacitor fed	Divider	Resistor	Yes	LCD or USB	590 mW	31.9 in^3
Belkin Conserve Insight [3]	Capacitor fed	Divider	Resistor	Yes	LCD	440 mW	21.8 in^3
ACme-A [26]	Capacitor fed	Divider	Resistor	Yes	802.15.4	1000 mW	13.7 in^3
ACme-B [26]	Transformer	Divider	Hall effect	Yes	802.15.4	100 mW	13.7 in^3
Monjolo [23]	Energy harvest	None	Current Transformer	No	802.15.4	4 mW	7.8 in^3
Gemini [20]	Energy harvest	Virtual	Current Transformer	Yes	802.15.4	Not Published	
PowerBlade (this work)	Resistor fed	Divider	Magnetometer	Yes	BLE	80-176 mW†	0.07 in^3

Table 1: Comparison of various power meters. PowerBlade is the smallest, lowest power, wireless true power meter. †Depends on data rate.

What is an answer to the problem?

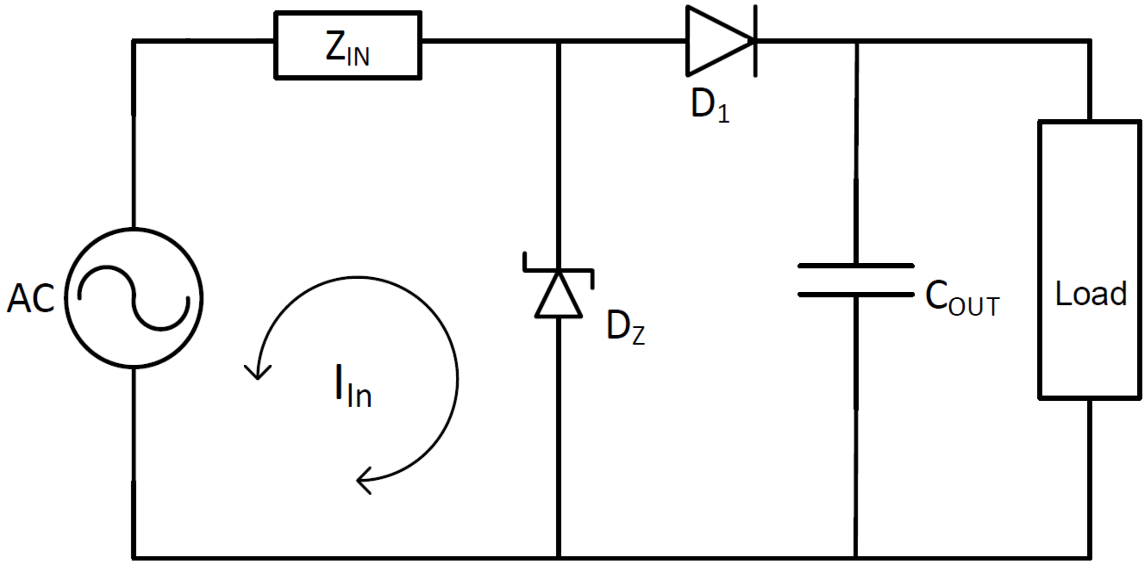
- Must re-think design of power meters from basics

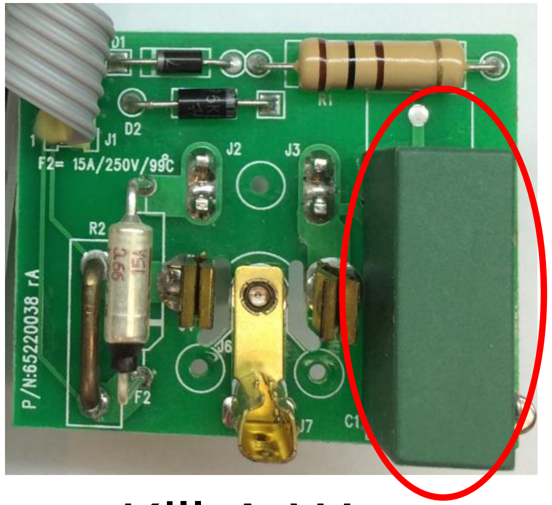
- Five core steps that a power meter must handle
    1. Convert AC mains voltage to usable DC voltage
    2. Measure voltage
    3. Measure current
    4. Calculate power and energy
    5. Communicate measurements

- Revisit each and show that it can be changed

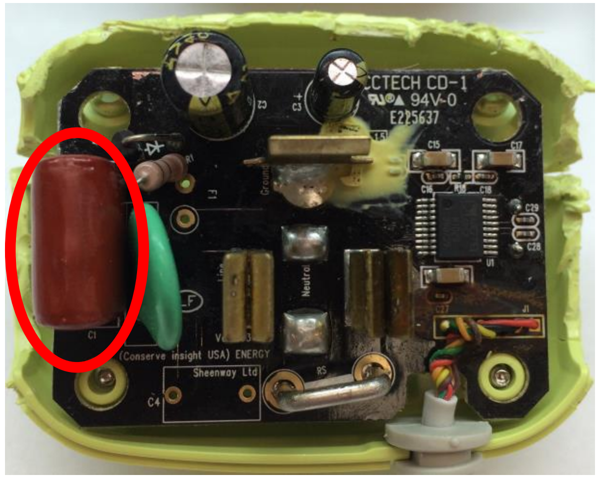
Answer - creating a usable DC voltage

- Basic circuit below applies
  - But usually Z_{in} is a large capacitor to provide enough power for the device to run
  - We can instead use a small resistor if our average current is very low (< 800 μA)





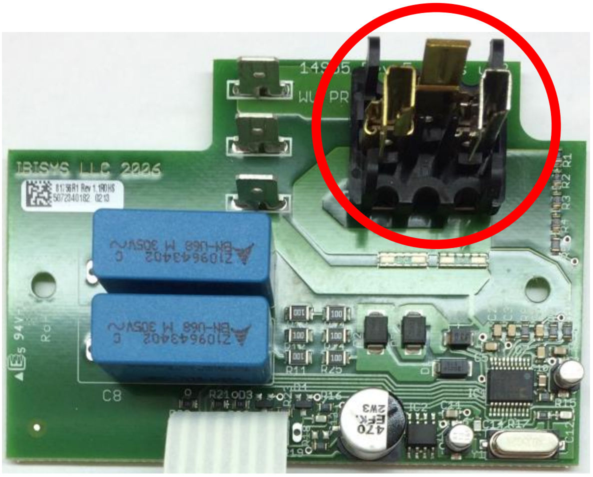
Kill-A-Watt

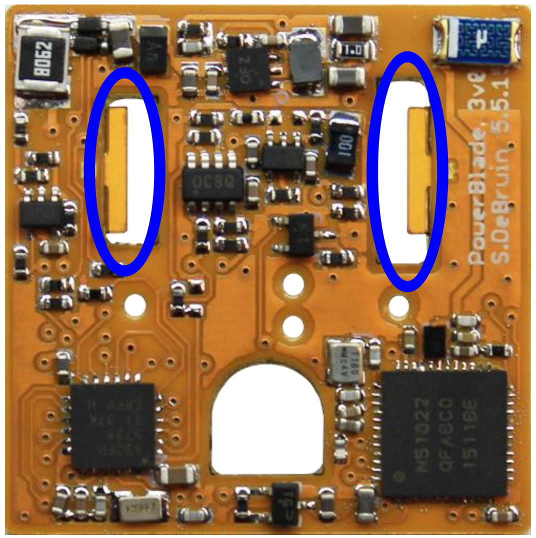


Belkin Insight

Answer - measuring voltage

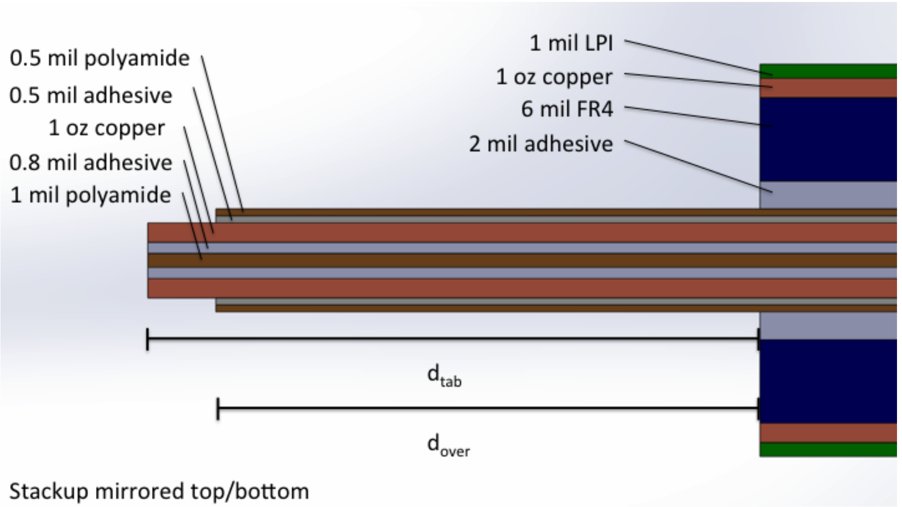
- Sockets take up a lot of physical room





Flexible tabs

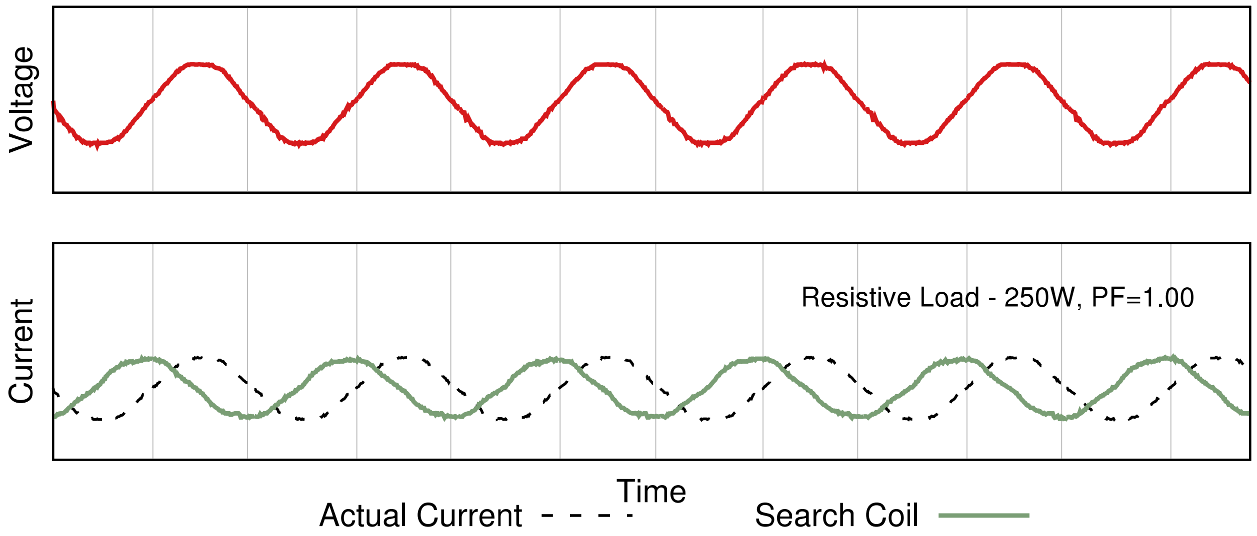
- Instead use flexible PCB tabs
- (This was finicky and non-reusable in practice)

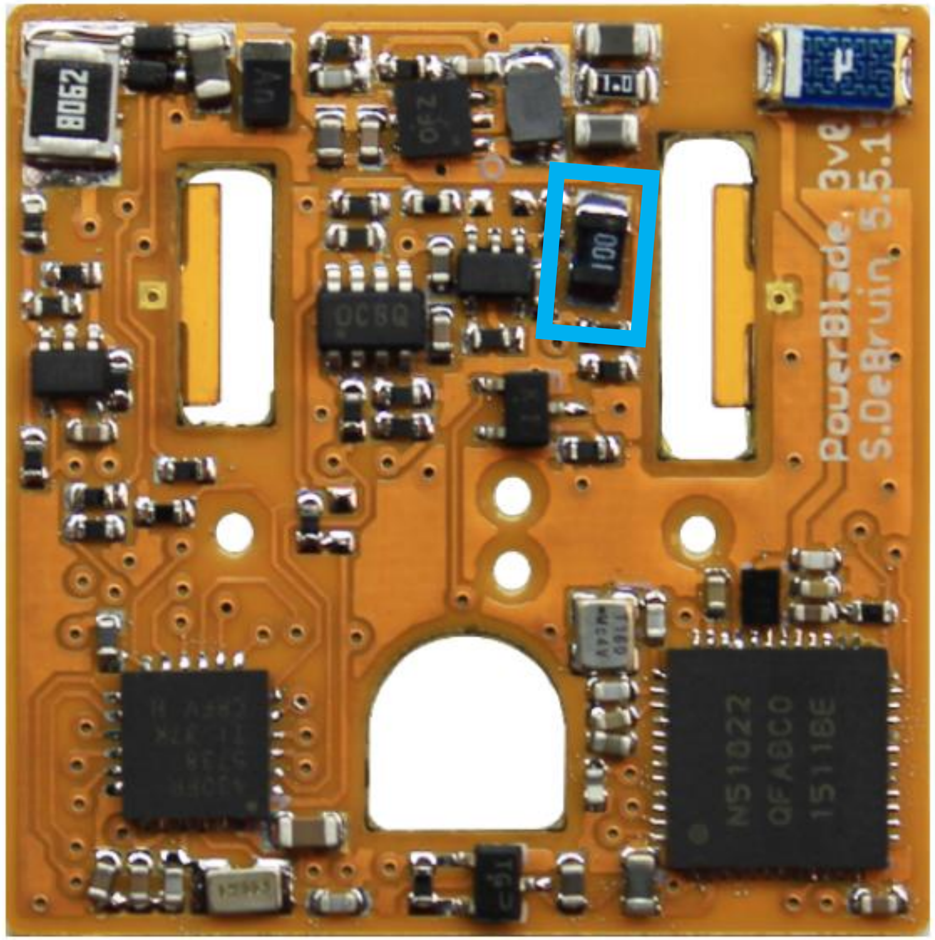


Answer - measure current

- Horizontally wound coil translates magnetic field into a voltage

- Creates a signal that is the derivative of current





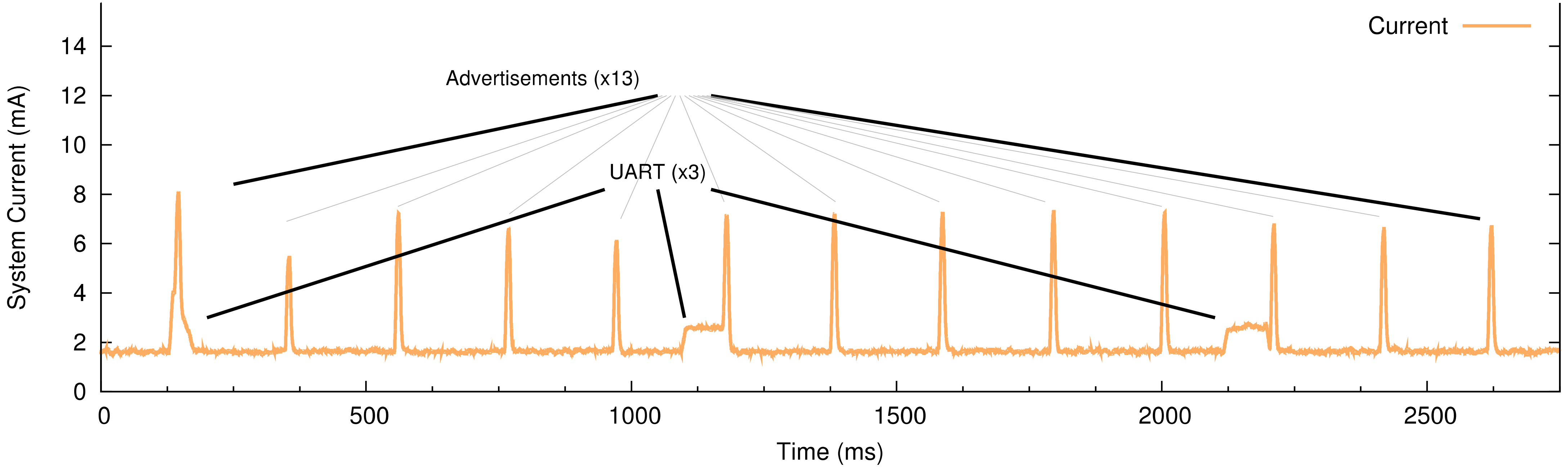
Answer - calculate power and energy

- Perform computation in a modern microcontroller
  - Keeps up with calculations that an IC usually does
  - MSP430FRxx - MSP430 with FRAM

- Can perform work at a very low average power
  - Sampling, integration, computation, and output

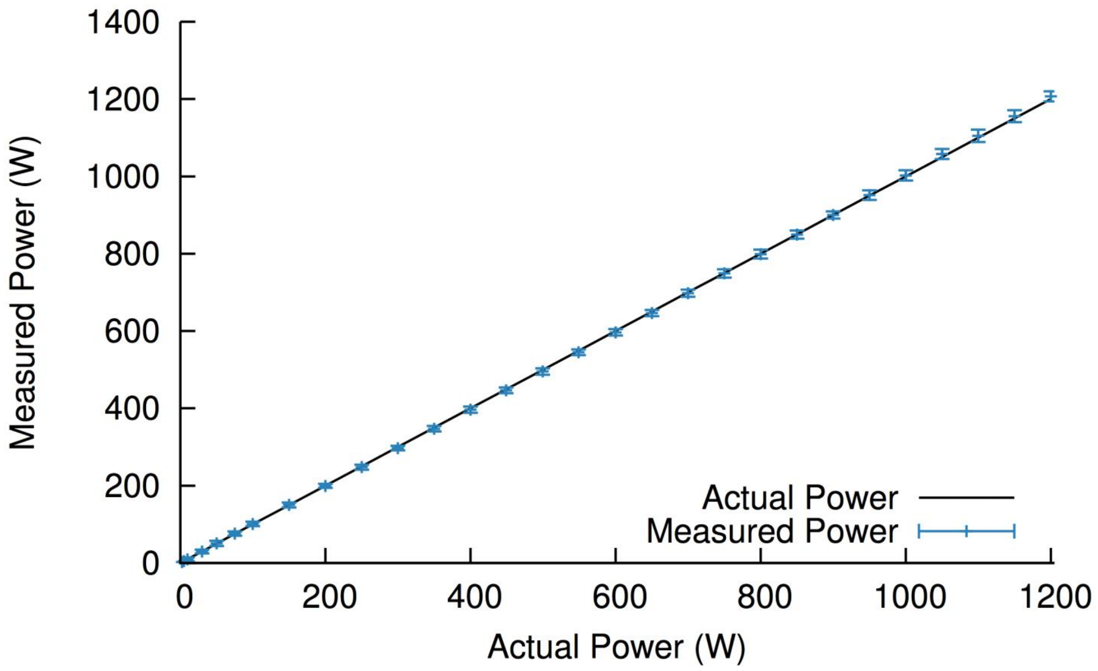
Answer - communicate measurements

- Transmitting average power over BLE presents results while keeping within energy budget
  - Update average measurements once per second
  - Send 5 packets per second for reliability



Prove that the answer to the problem is real

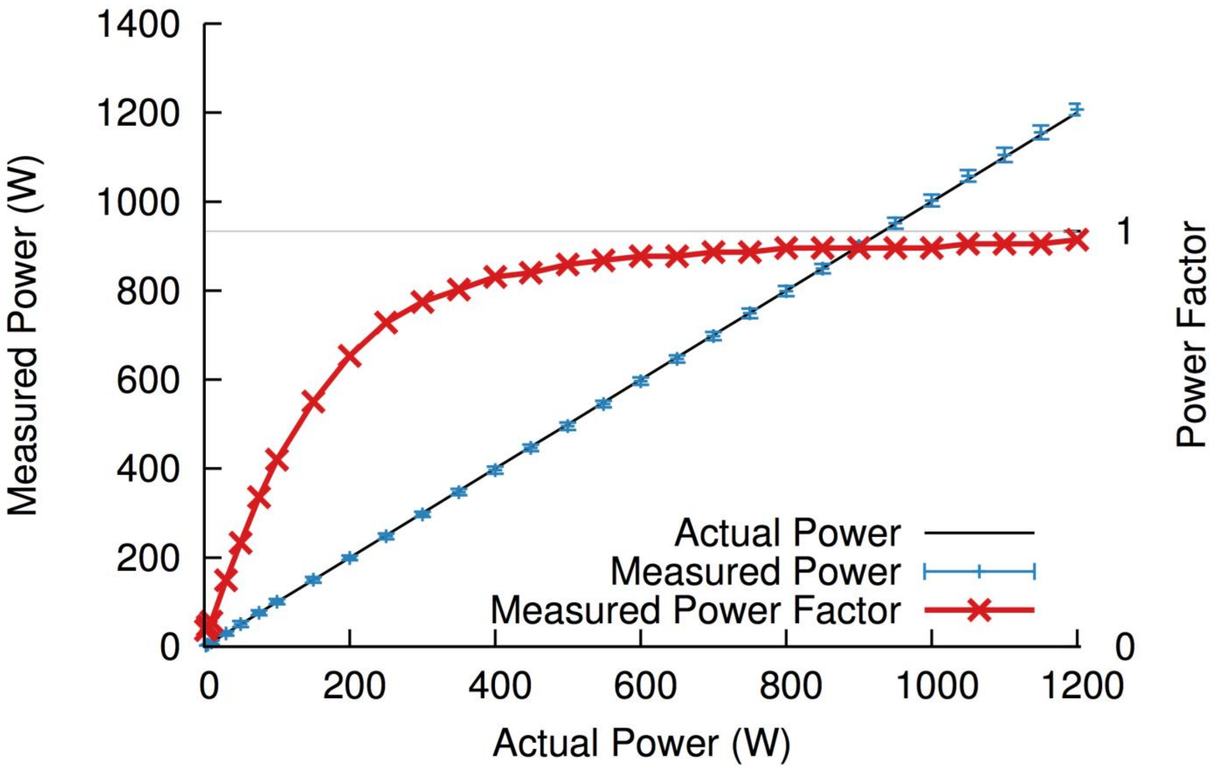
- From 2 W to 1200 W, average error is 1.13%



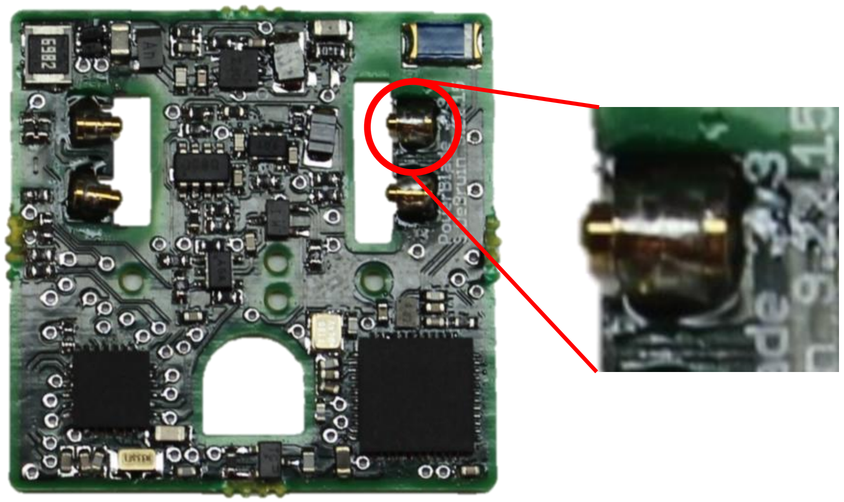
Device	Power Factor	Power	PowerBlade Error	
150 W Bulb	1.00	162.17 W	-0.99 W	0.61%
Fridge	1.00	108.22 W	-5.30 W	4.90%
Drill (Max)	0.99	253.21 W	2.96 W	1.26%
Toaster	0.99	827.87 W	-22.11 W	2.67%
Vacuum	0.98	1246.96 W	15.24 W	1.22%
Microwave	0.92	1729.73 W	16.01 W	0.93%
Hot Air Gun	0.83	305.54 W	-1.93 W	0.63%
TV (Normal)	0.62	196.23 W	-9.03 W	4.60%
TV (Static Image)	0.61	129.51 W	-4.00 W	3.09%
50 W CFL	0.61	48.57 W	-9.51 W	19.58%
Xbox One	0.57	50.44 W	-0.83 W	1.65%
MacBook	0.51	52.68 W	-4.49 W	8.52%
Blender	0.49	106.63 W	36.97 W	34.67%
Router	0.46	9.11 W	-0.62 W	6.81%
Drill (Low)	0.30	51.10 W	20.40 W	39.92%

Explain the limitations

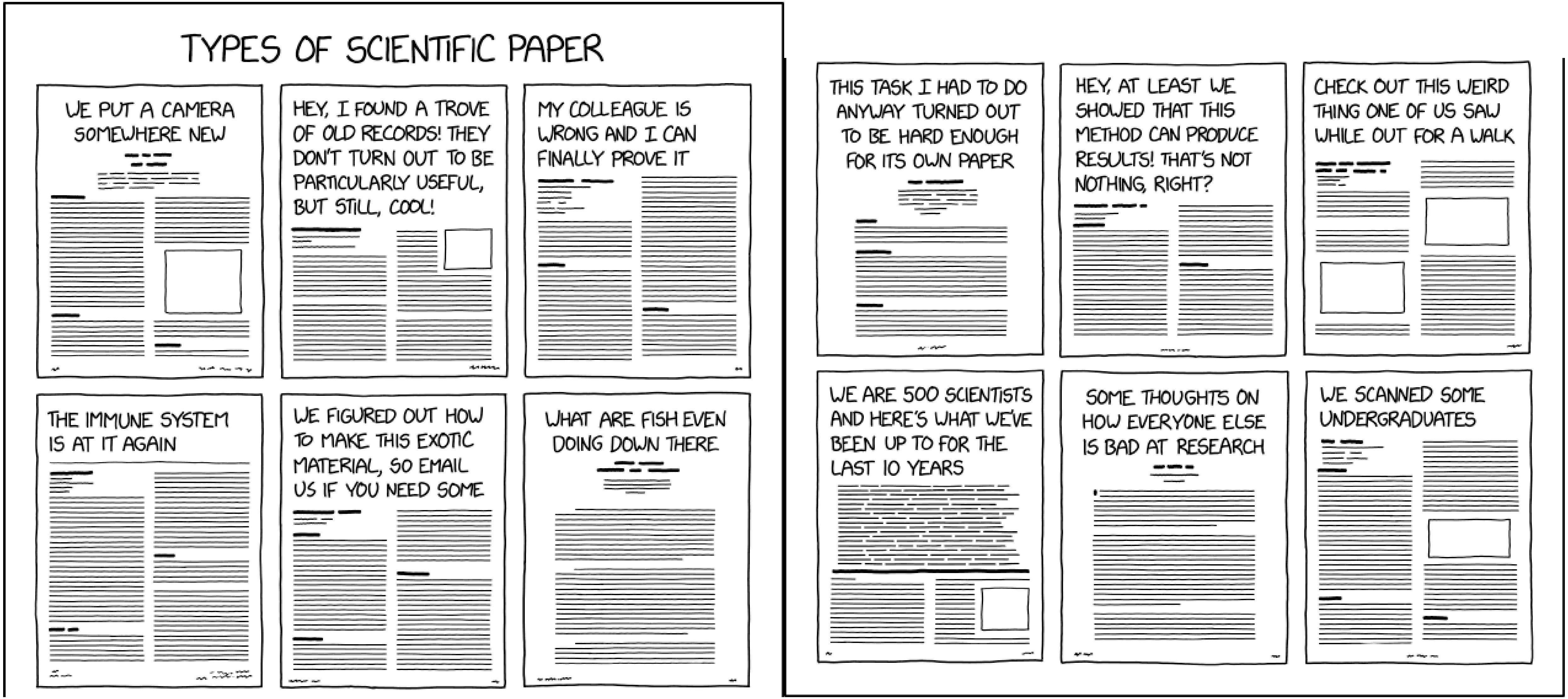
- Power factor measurements are very power at low wattages
  - Although the wattage itself remains accurate



- Also change to pogo pins for better, repeatable contact



Break + xkcd



https://xkcd.com/2456/

Outline

- What does research look like:
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  - Example: Powerblade
- **Sensing Systems Research**
  - **Various Projects**
  - Signpost

Conferences for sensing systems research

- SenSys
  - Conference on Embedded Networked Sensor Systems
- IPSN
  - Conference on Information Processing in Sensor Networks
- EWSN
  - Conference on Embedded Wireless Systems and Networks
- MobiCom
  - Conference on Mobile Computing and Networking
- UbiComp
  - Conference on Pervasive and Ubiquitous Computing

- Various other systems or HCI venues
  - Occasionally Electrical or Civil Engineering venues too

Sensing systems research

- Combination of engineering and exploration

- Generally divides into two different focuses
  - Often projects will mix some of each domain

- Platforms
  - How to improve the capabilities of sensing systems
  - Examples: lower power, better wireless, new sensors

- Applications
  - How to use sensing systems to meet some desired goal
  - Examples: track human interactions, measure household energy use

Sensing systems research

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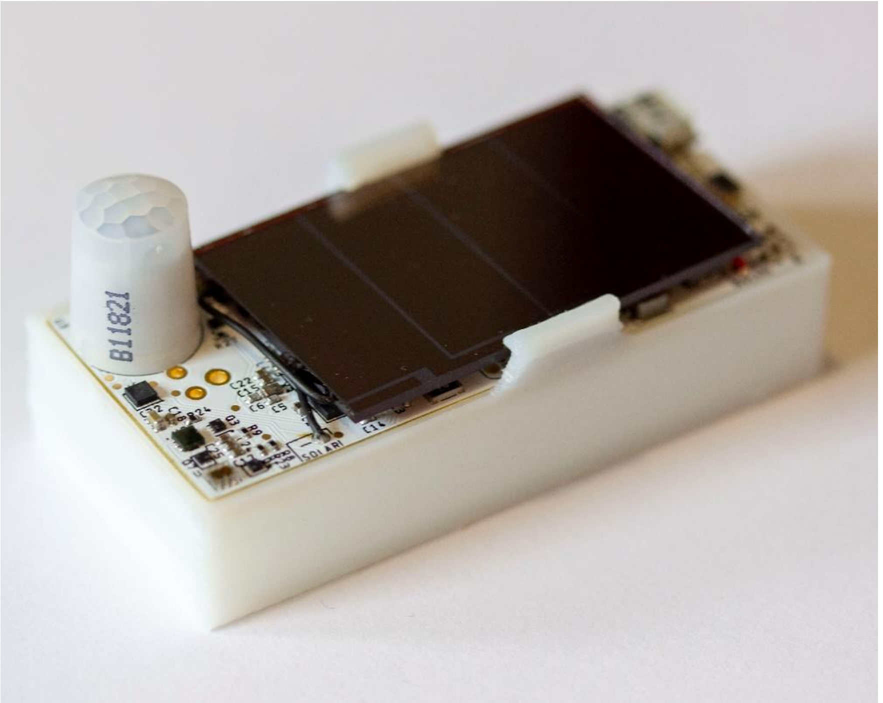
Permamote (Jackson, Adkins, Dutta)

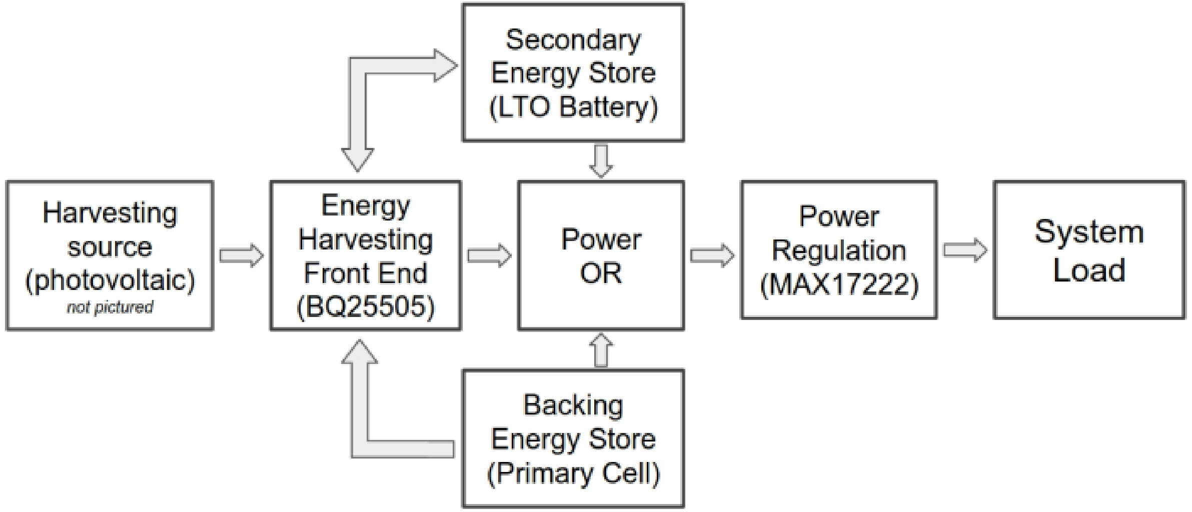


- Goal: create a 10-year wireless sensor

- Solutions
  - Modern sensors and microcontroller

  - Energy harvesting combined with rechargeable battery

  - Non-rechargeable battery as backup power



https://lab11.eecs.berkeley.edu/content/pubs/jackson19capacity.pdf

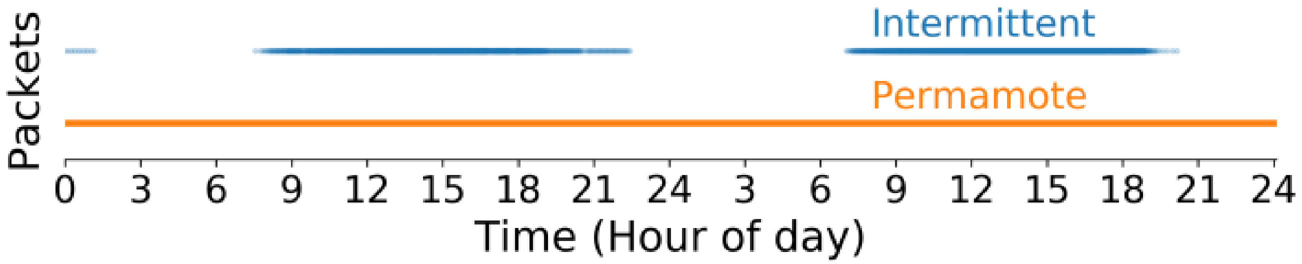
Permamote low energy design

- Uses components with extremely low idle power to limit energy needs

- Combination of harvesting plus battery enables continuous operation

Component	Function	Active Power	Idle Power
Nordic NRF52840	Processor	56 µA/MHz	940 nA [a]
	Radio	5.2 mA @ 0 dbm	— [a]
Ambiq AB1815-T3	Real time clock	55 nA	N/A [b]
ST Micro LIS2DW12	Accelerometer	1 uA @ 12.5 Hz	50 nA
Maxim MAX44009	Light sensor	650 nA	N/A [b]
Intersil ISL29125	Color sensor	56 µA	500 nA
Silicon Labs SI7021	Humidty sensor	1.5 µA @ 1 Hz	60 nA
TE Connectivity MS5637	Pressure sensor	0.6 - 5 µA @ 1 Hz	10 nA
Panasonic EKMB11011	PIR Occupancy	100 µA	1 uA

[a] Sleep current for both processor and radio. [b] No shutdown or idle mode.



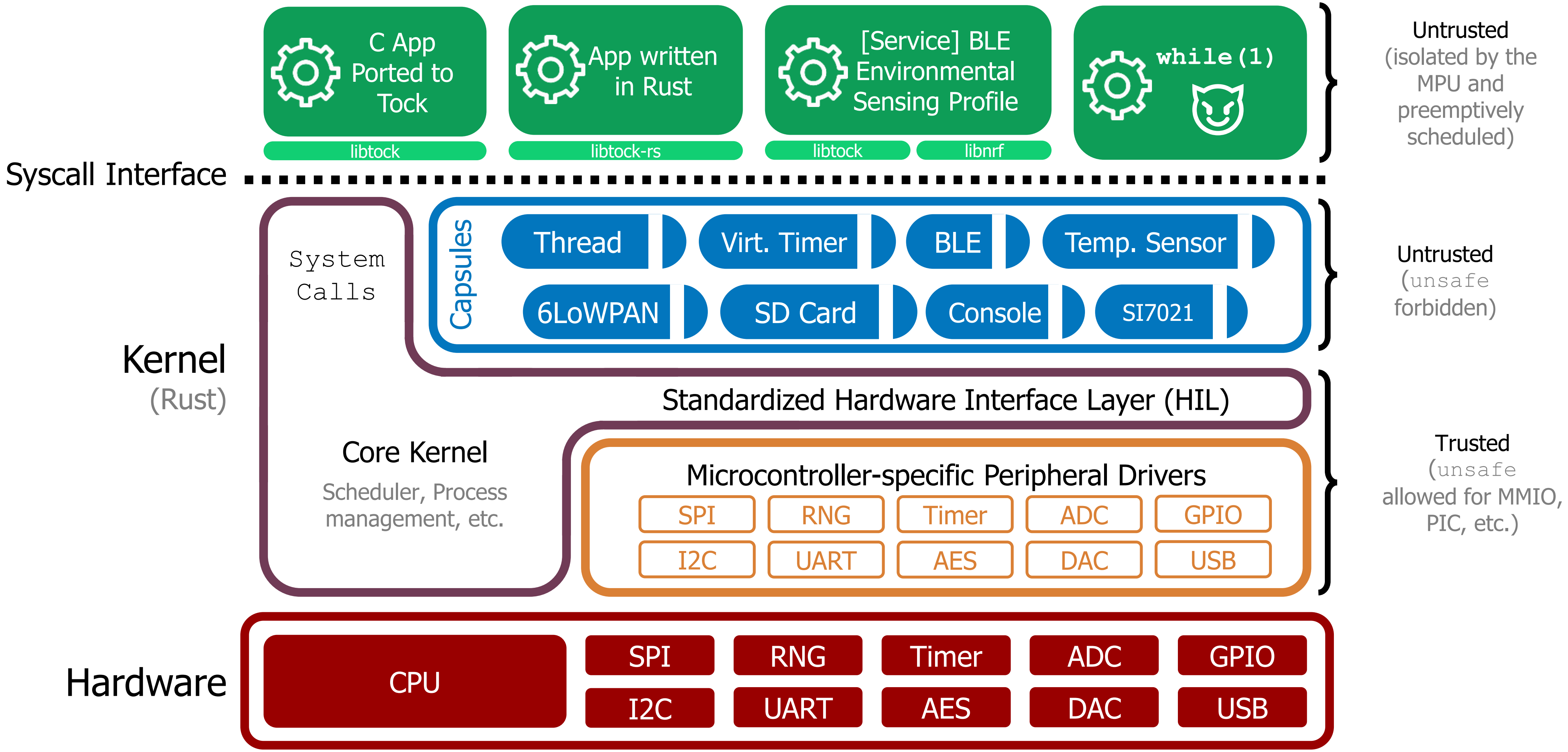
Tock (Levy, Campbell, Ghena, Giffin, Pannuto, Dutta, Levis)

- Goal: safe and reliable embedded OS
  - Demonstrate this is possible on small embedded platforms

- Solutions
  - Dedicated OS kernel with separate applications
  - Protect applications with hardware features
    - Memory Protection Unit
  - Protect kernel with language features
    - Rust programming language

https://lab11.eecs.berkeley.edu/content/pubs/levy17multiprogramming.pdf

Tock software organization



Sensing systems research

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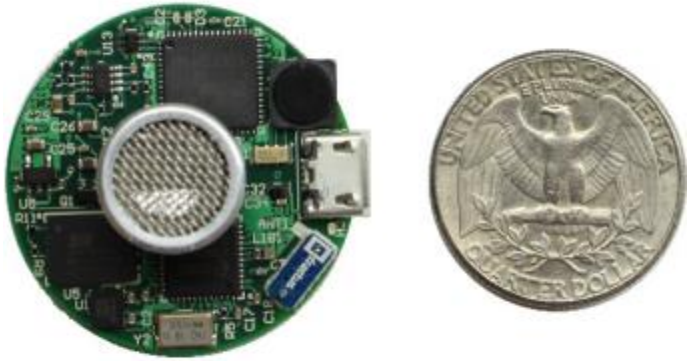
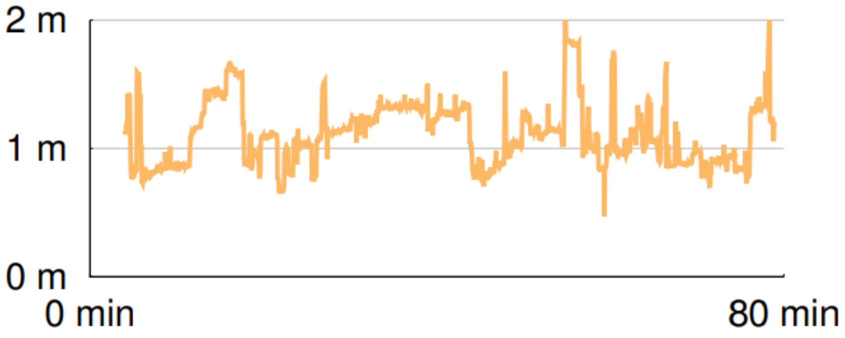
Opo (Huang, Kuo, Pannuto, Dutta)

- Goal: sense distance of human interactions
  - Real-time, high accuracy, deployable

- Solutions
  - Ultrasonic allows for low-power detection of nearby devices
  - Also provides directionality

  - Measure difference in arrival time of RF and Ultrasonic to determine distance

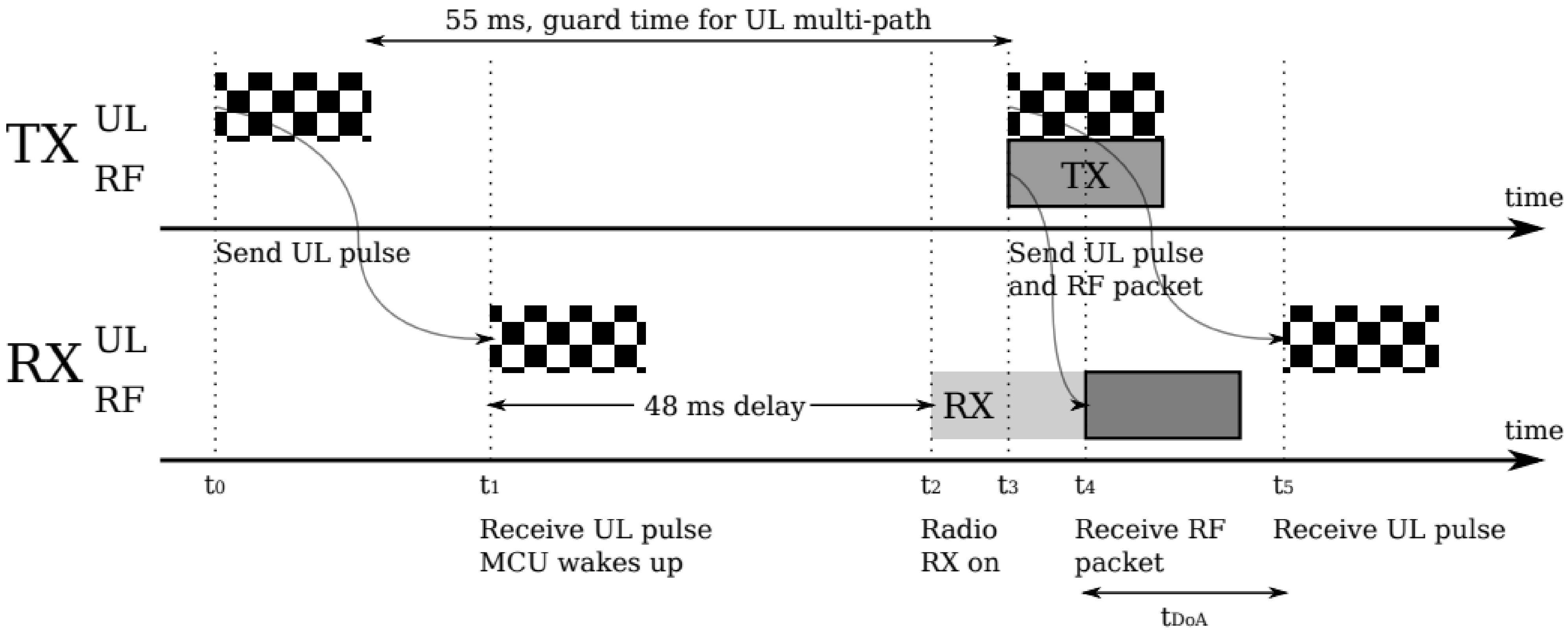




https://lab11.eecs.berkeley.edu/content/pubs/huang14opo.pdf

Opo low-energy ranging

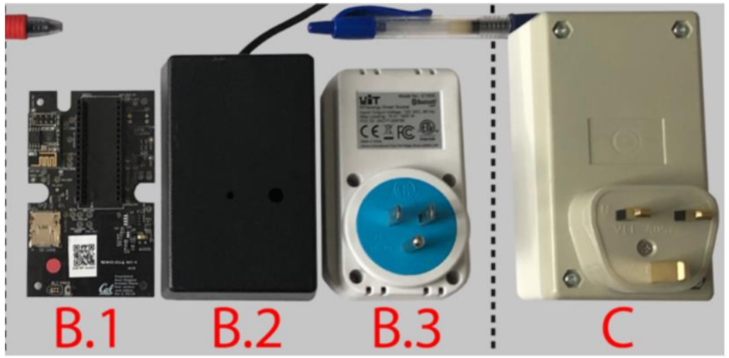
- RX of ultrasonic pulse wakes the device
- Listens for RF and ultrasonic to measure time difference



Powerwatch (Klugman, Adkins, et al.)

- Goal: measure electric grid reliability in developing regions
- "Access alone is insufficient. Reliability matters too."

- Solutions:
  - Wall-powered sensor with battery-backup to detect outages and report over cellular
  - Infrastructure to collect measurements and cross-correlate
  - Create a team to manage the deployment

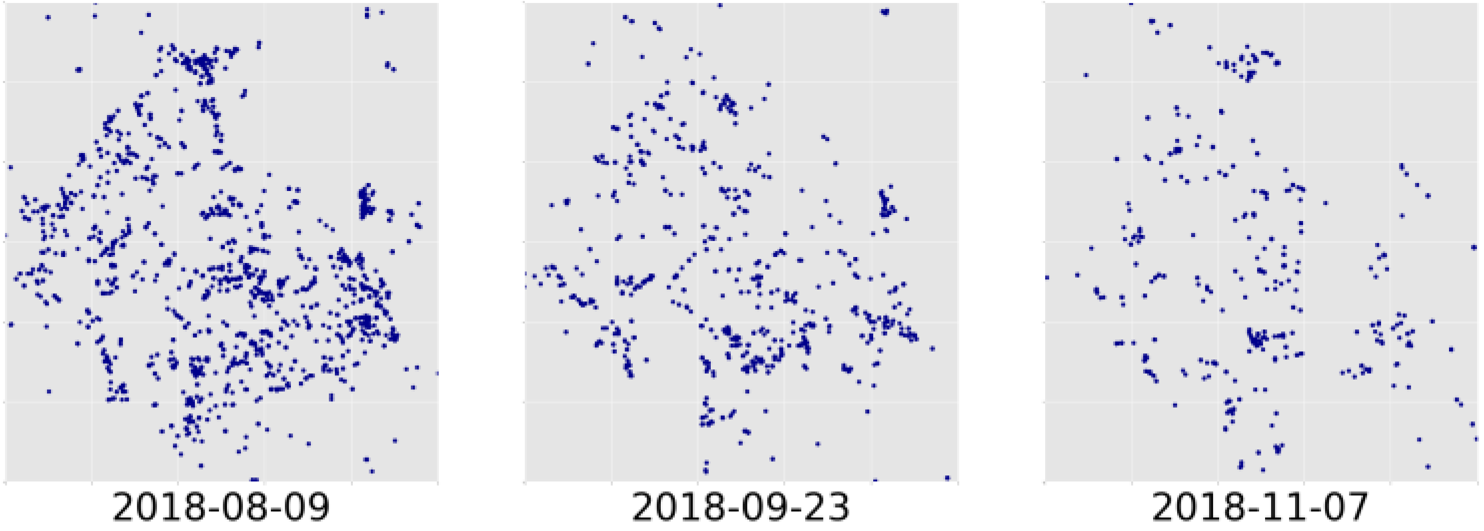


https://lab11.eecs.berkeley.edu/content/pubs/klugman19scale.pdf

Powerwatch deployments require continuous upkeep

- Handing someone a sensor does not guarantee long deployment

- Initially 1000 devices fell to 600, then 300 over three months



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The Signpost Project

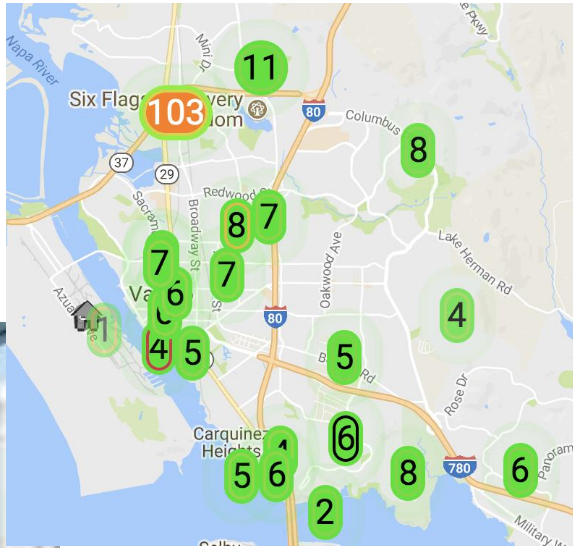
- An example of "Platforms" research

- Goal: platform that enables low-effort city-scale sensing deployments

What things might we want to sense at the scale of a city?

Air quality monitoring

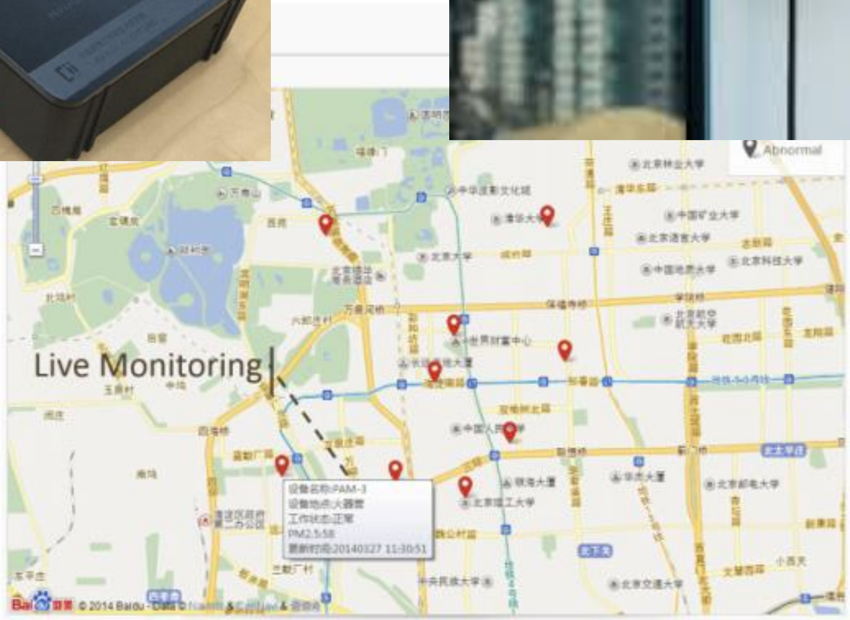
[2]

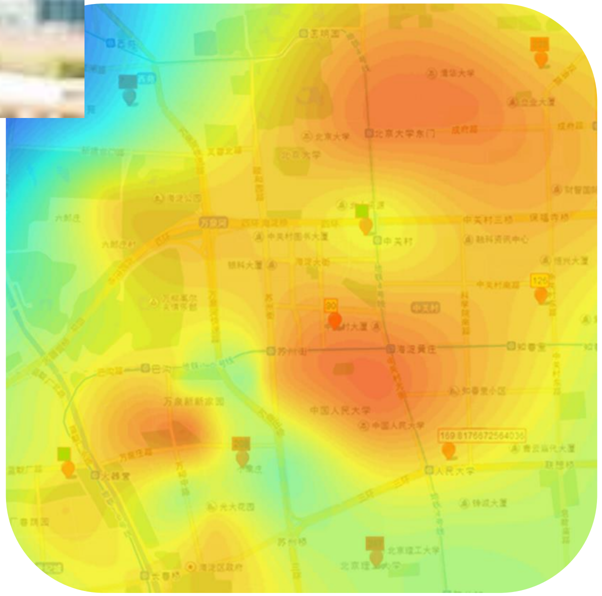


[2]

[1]

[1]

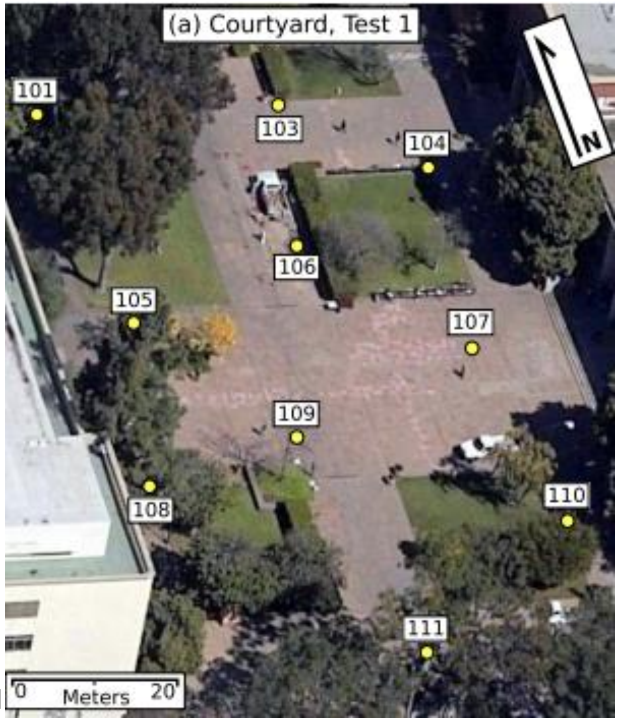




[1] Cheng et al. AirCloud: a cloud-based air-quality monitoring system for everyone. 2014.

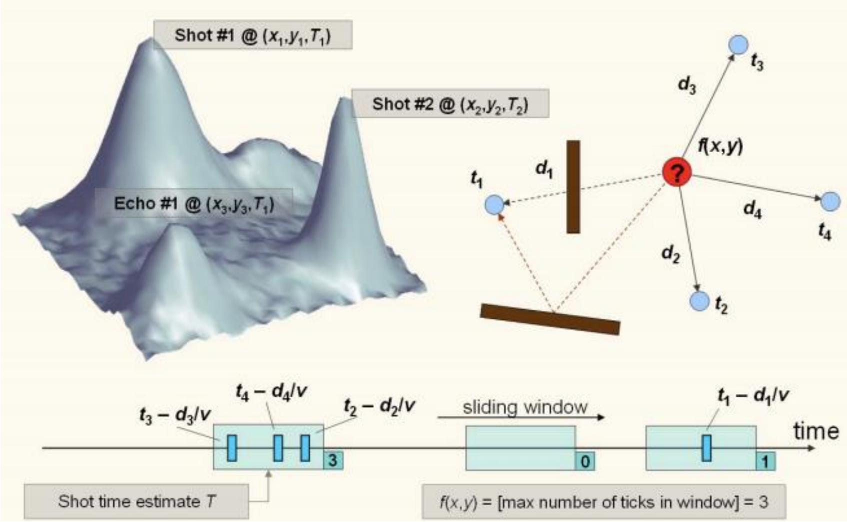
[2] Purple Air. 2018.

Audio detection, classification, and localization

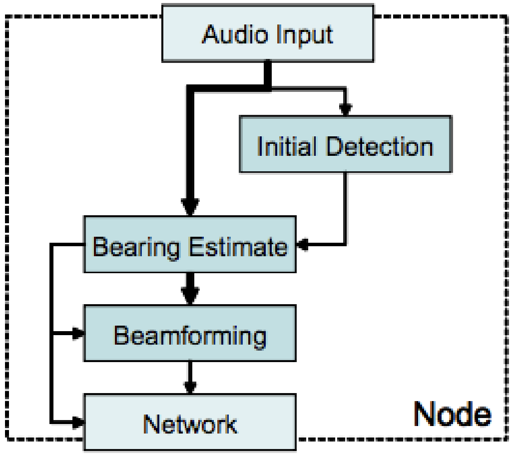


[1]


[3]



[2]



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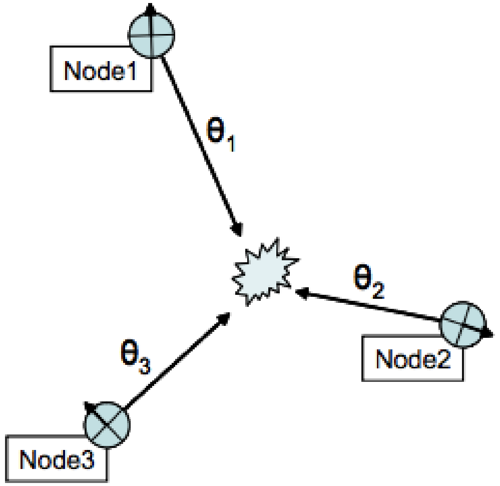
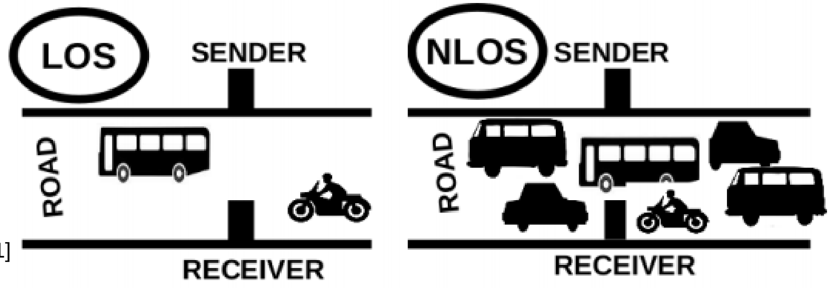


[1] Girod et al. The Design and Implementation of a Self-Calibrating Distributed Acoustic Sensing Platform. 2006.
[2] Lédeczi et al. Multiple Simultaneous Acoustic Source Localization in Urban Terrain. 2005.
[3] Sounds of New York City. 2016.

Traffic queue sensing and congestion control

[1]



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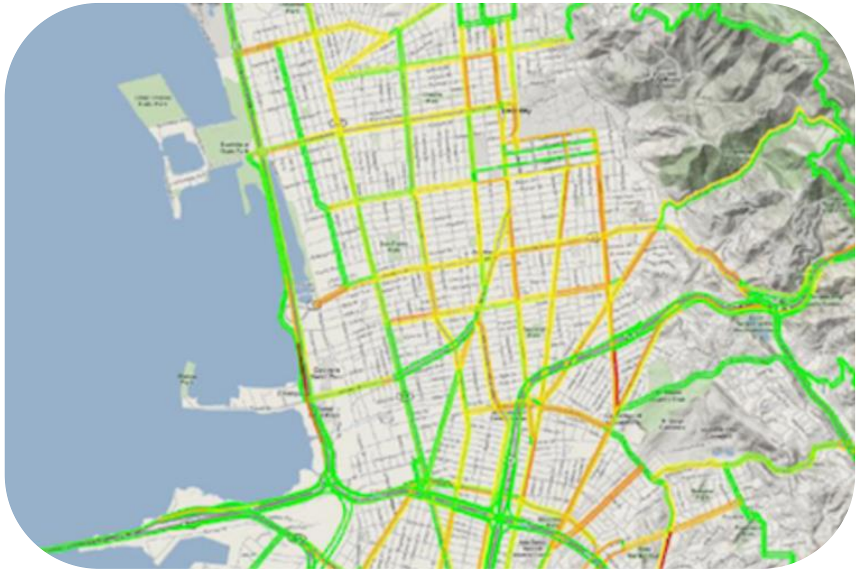

[1]

[1] Sen et al. Kyun Queue: A Sensor Network System To Monitor Road Traffic Queues, 2012

NIST

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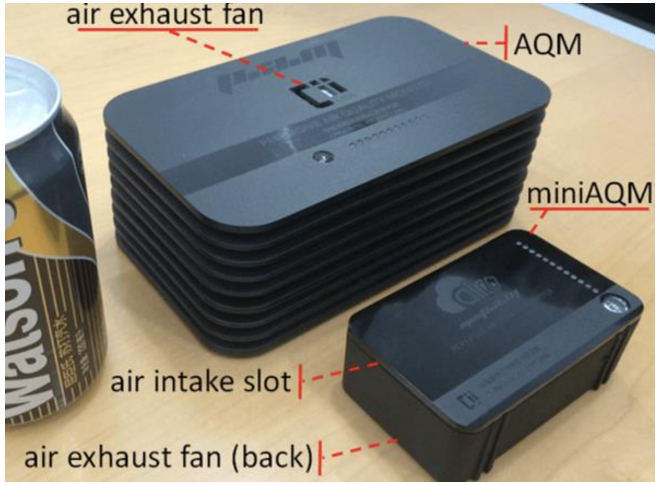
U.S. Department of Transportation

Smart Nation
SINGAPORE
Many Smart Ideas • One Smart Nation

The City of
SAN DIEGO

1. City-Scale Sensing Introduction
2. **Signpost**
   - **Motivation**
   - Shared Resources
   - Deployability
   - Implementation
   - Evaluation

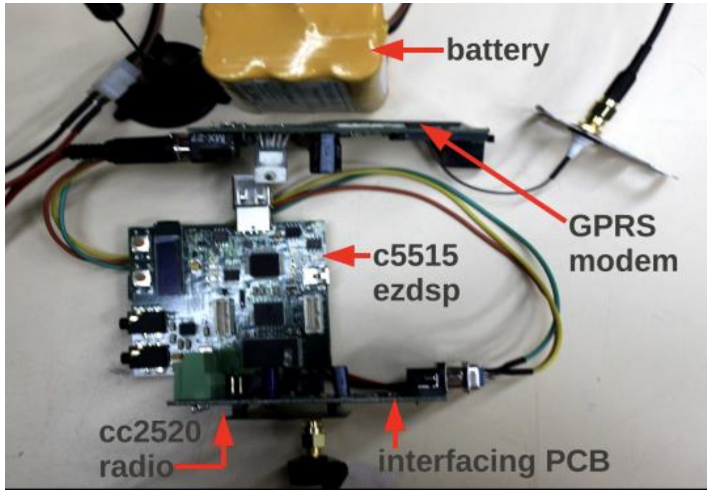
Air Quality Monitoring

[1] 

Urban Noise Classification

[2] 

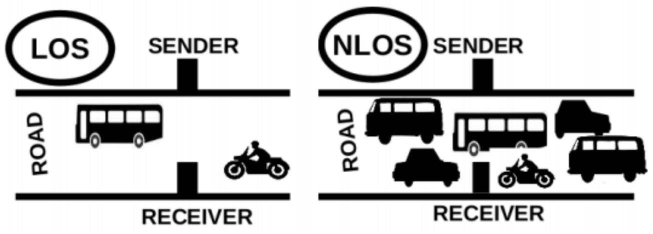
Traffic Queue Sensing

[3] 

Lots of interesting applications and interested parties.
But let's look at the process of actually creating and deploying an application.

[1] Cheng et al. AirCloud: a cloud-based air-quality monitoring system for everyone. 2014. [2] Sounds of New Your City. 2016. [3] Sen et al. Kyun Queue: A Sensor Network System To Monitor Road Traffic Queues, 2012

Many steps to building traffic queue sensing



Sensing Hypothesis/Hardware

[1] Sen et al. Kyun Queue: A Sensor Network System To Monitor Road Traffic Queues, 2012

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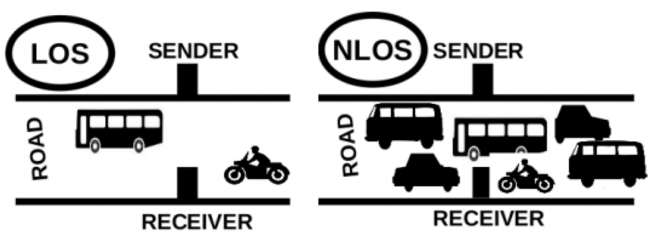
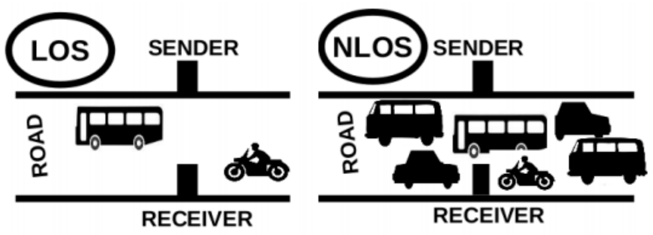


Sensing Hypothesis/Hardware

Networking Networking Driver

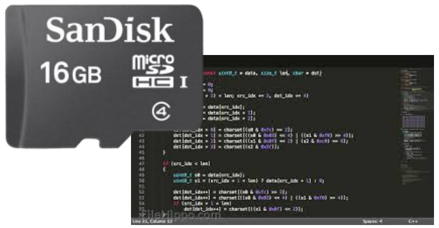
[1] Sen et al. Kyun Queue: A Sensor Network System To Monitor Road Traffic Queues, 2012

Many steps to building traffic queue sensing



Sensing Hypothesis/Hardware

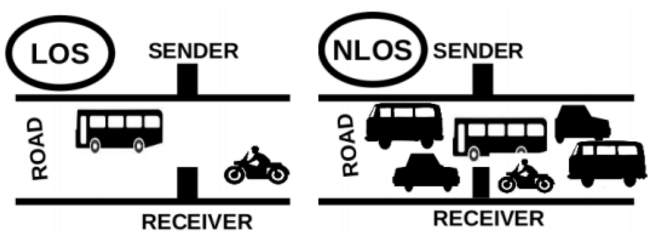
Networking Networking Driver



Storage Storage Driver

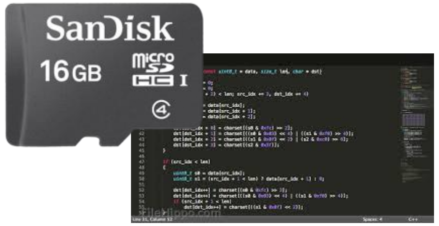
[1] Sen et al. Kyun Queue: A Sensor Network System To Monitor Road Traffic Queues, 2012

Many steps to building traffic queue sensing



Sensing Hypothesis/Hardware

Networking   Networking Driver



Storage   Storage Driver

Sustainable Power

[1] Sen et al. Kyun Queue: A Sensor Network System To Monitor Road Traffic Queues, 2012

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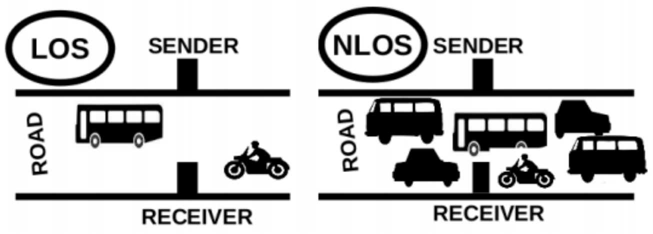
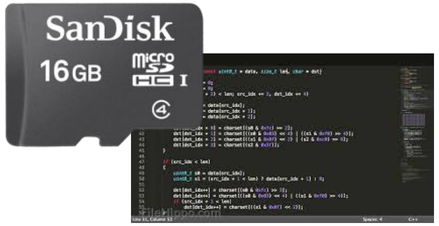


Sensing Hypothesis/Hardware

Networking Networking Driver



Storage Storage Driver

Sustainable Power

Weatherproof Casing

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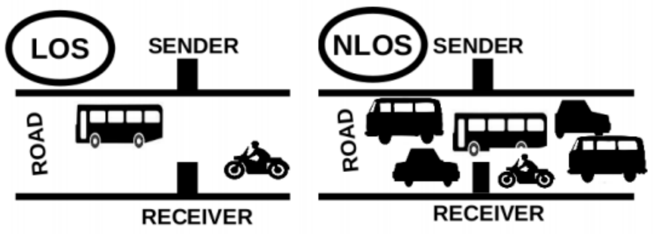
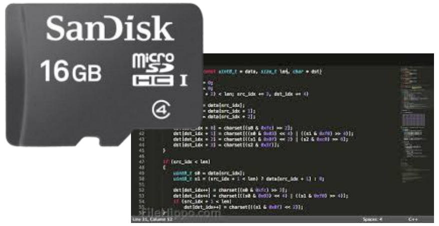


Sensing Hypothesis/Hardware

Networking Networking Driver



Storage Storage Driver

Sustainable Power

Weatherproof Casing

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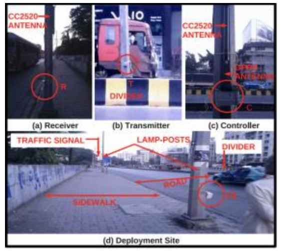


Deploy

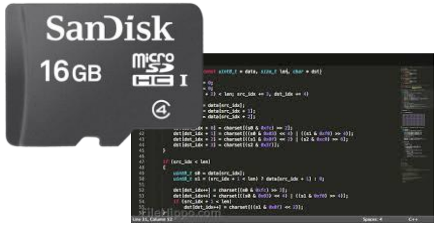
[1] Sen et al. Kyun Queue: A Sensor Network System To Monitor Road Traffic Queues, 2012

Key functions are repeated

[1]

Sensing Hypothesis/Hardware

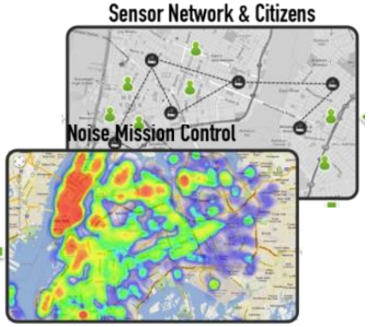
Networking Networking Driver



Storage Storage Driver

Sustainable Power

Weatherproof Casing



[1]

Deploy

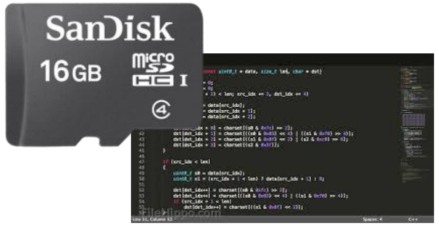
[1] Sounds of New York City. 2016

Key functions are repeated

[1] 

Sensing Hypothesis/Hardware

Networking Networking Driver



Storage Storage Driver

Sustainable Power

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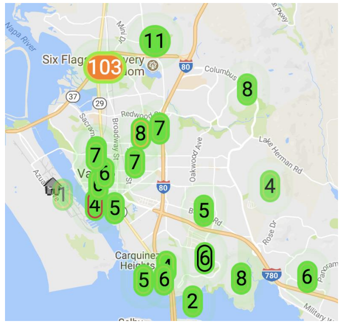
[1] 

Deploy

[1] Purple Air. 2018

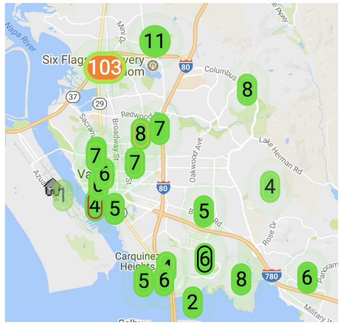
Signpost Enables City-Scale Sensing

[1]

Sensing Hypothesis/Hardware

Integrate with Signpost

[1]



Deploy

Joshua Adkins, **Branden Ghena**, Neal Jackson, Pat Pannuto, Samuel Rohrer, Bradford Campbell, and Prabal Dutta
”The Signpost Platform for City-Scale Sensing." *IPSN’18* - https://brandenghena.com/projects/signpost/adkins18signpost.pdf

[1] Purple Air. 2018.

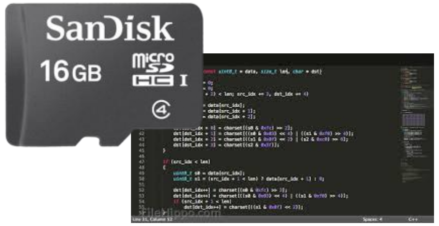
1. City-Scale Sensing Introduction
2. **Signpost**
   - Motivation
   - **Shared Resources**
   - Deployability
   - Implementation
   - Evaluation

Key functions are repeated

[1] 

Sensing Hypothesis/Hardware

Networking Networking Driver



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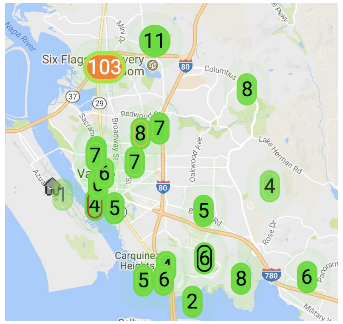
[1] 

Deploy

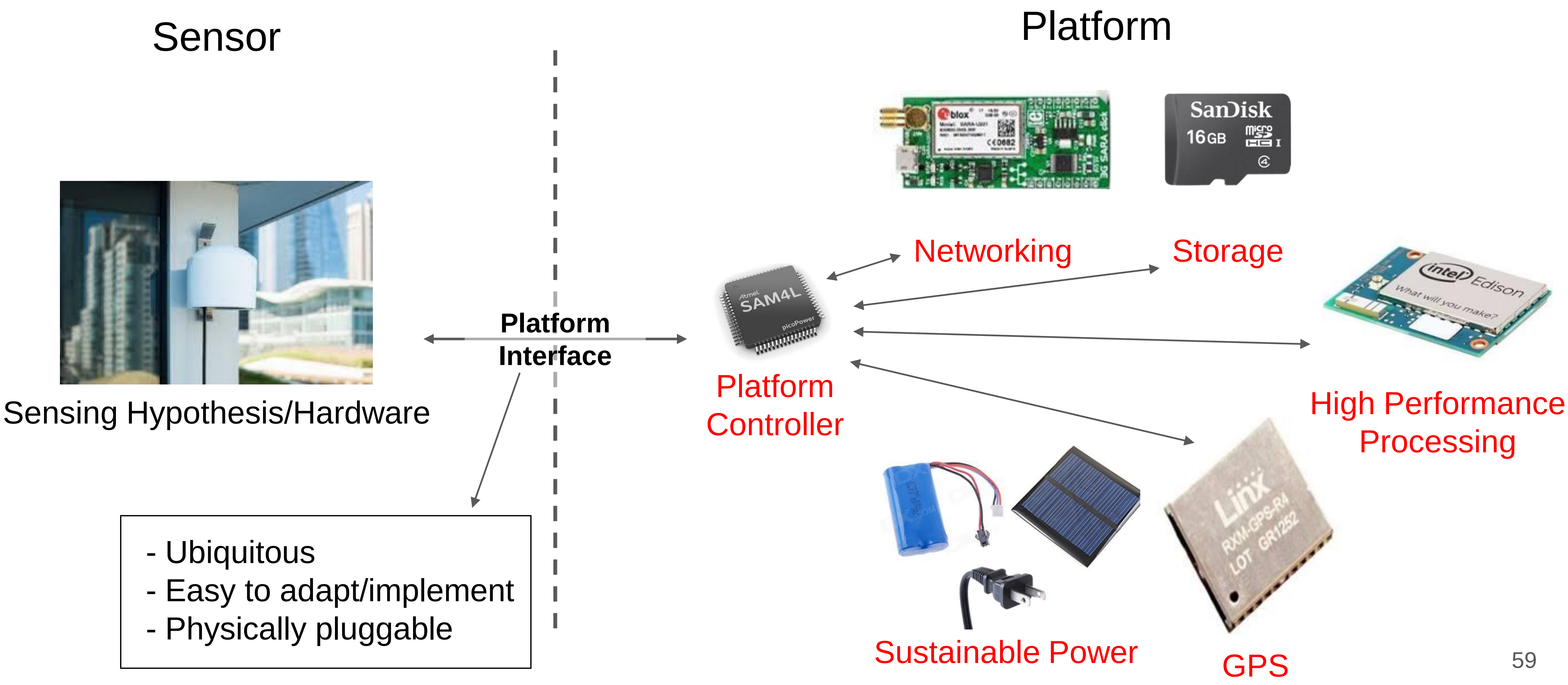
[1] Purple Air. 2018

Higher power/linux class processing

Can be provided with a GPS

Deployment	Services Needed						
	Power	Networking	Processing	Storage	Time	Synch	Location
Caraoke [3]							
Bouillet et al. [4]							
Aircloud [5]							
Girod et al. [6]							
Ledeczi et al. [7]							
SenseFlow [8]							
Argos [9]							
SONYC [1]							
Kyun Queue [10]							
Micronet [11]							

Software abstraction through a single interface



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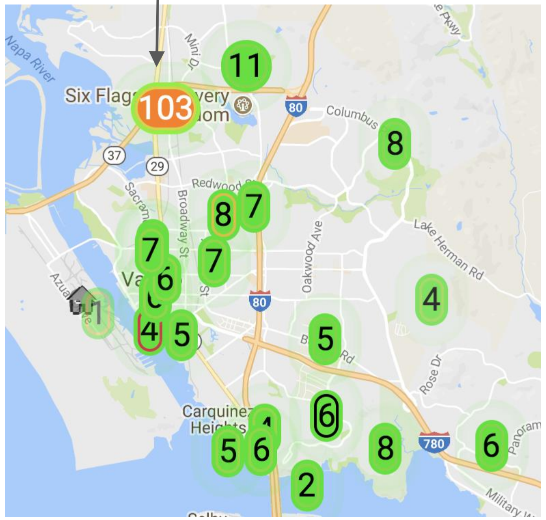
Some applications require granularity

Data can change greatly in low distances

Outlier



Deployment overhead drives cost

- Expensive to work with the city
- Time consuming
- Not conducive to experimentation!

Do not rely on wired infrastructure

- No wired power
  - Solar provides more power density than batteries
- No wired networking
- Should not modify existing infrastructure

Multi-tenancy is beneficial to testbeds

One deployment can enable many stakeholders simultaneously

- Need to ensure that they do not conflict

Air Quality Monitoring

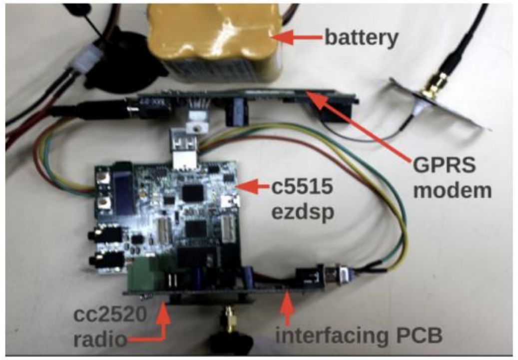
Urban Noise Classification

Traffic Queue Sensing

[1]

[2]

[3]



1. City-Scale Sensing Introduction
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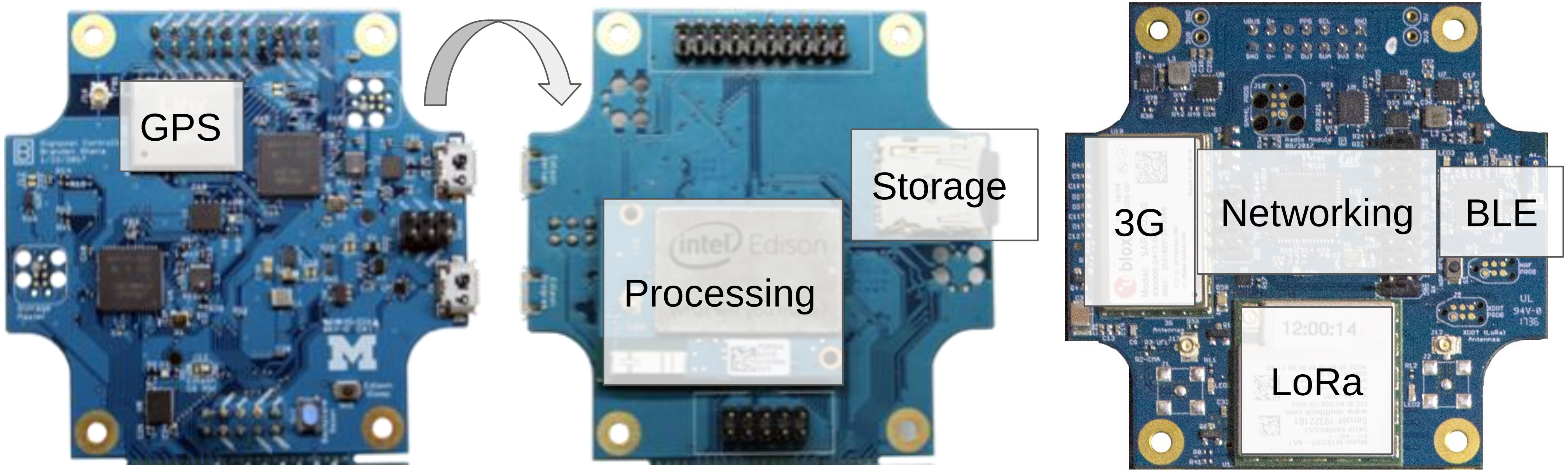
   - Evaluation

The Signpost Platform

Core modules provide shared resources

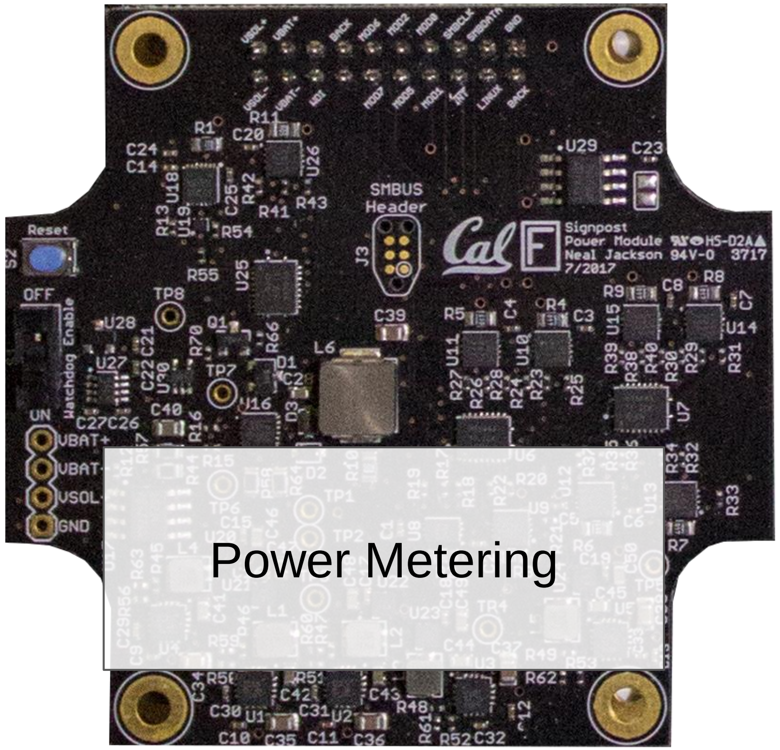
Control Module

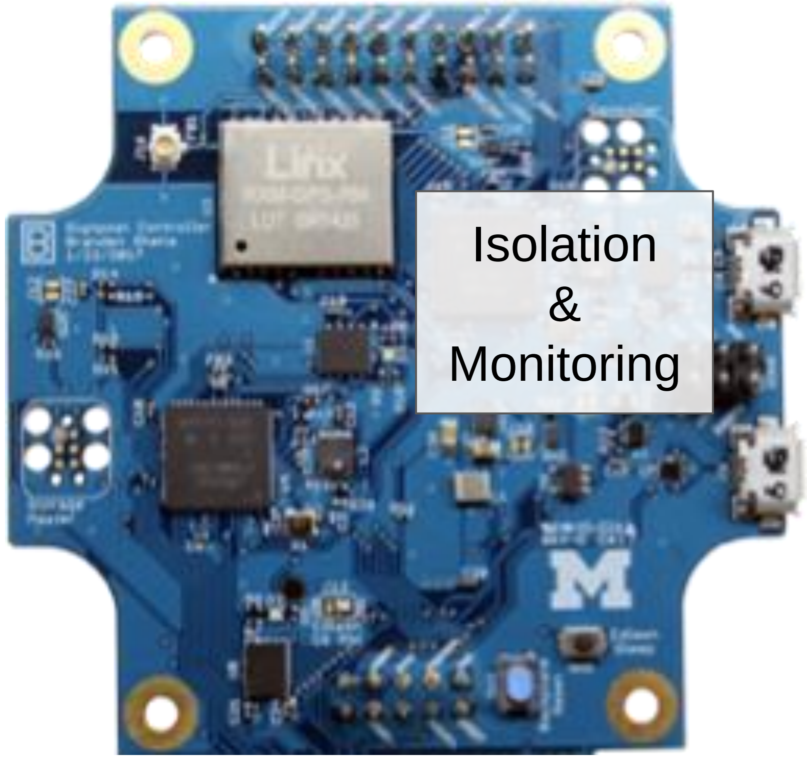
Radio Module



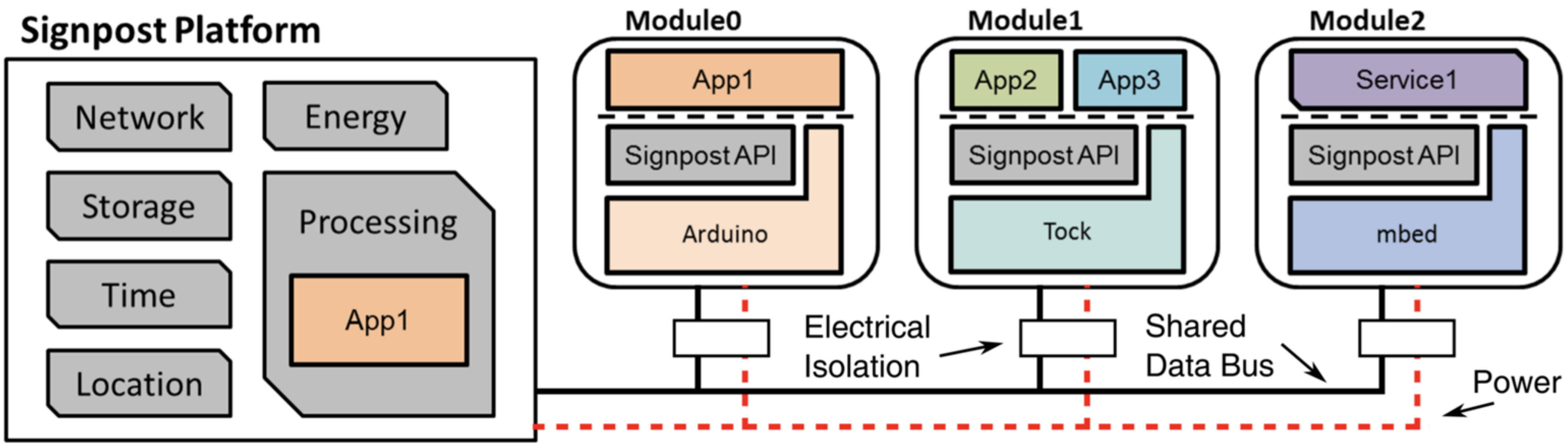
Making the platform modular supports upgradeability

Measurement and isolation support multi-tenancy

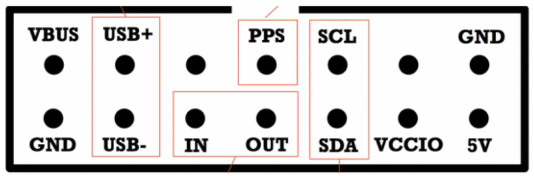




Standard interface for accessing shared resources



Any software framework can be used for modules

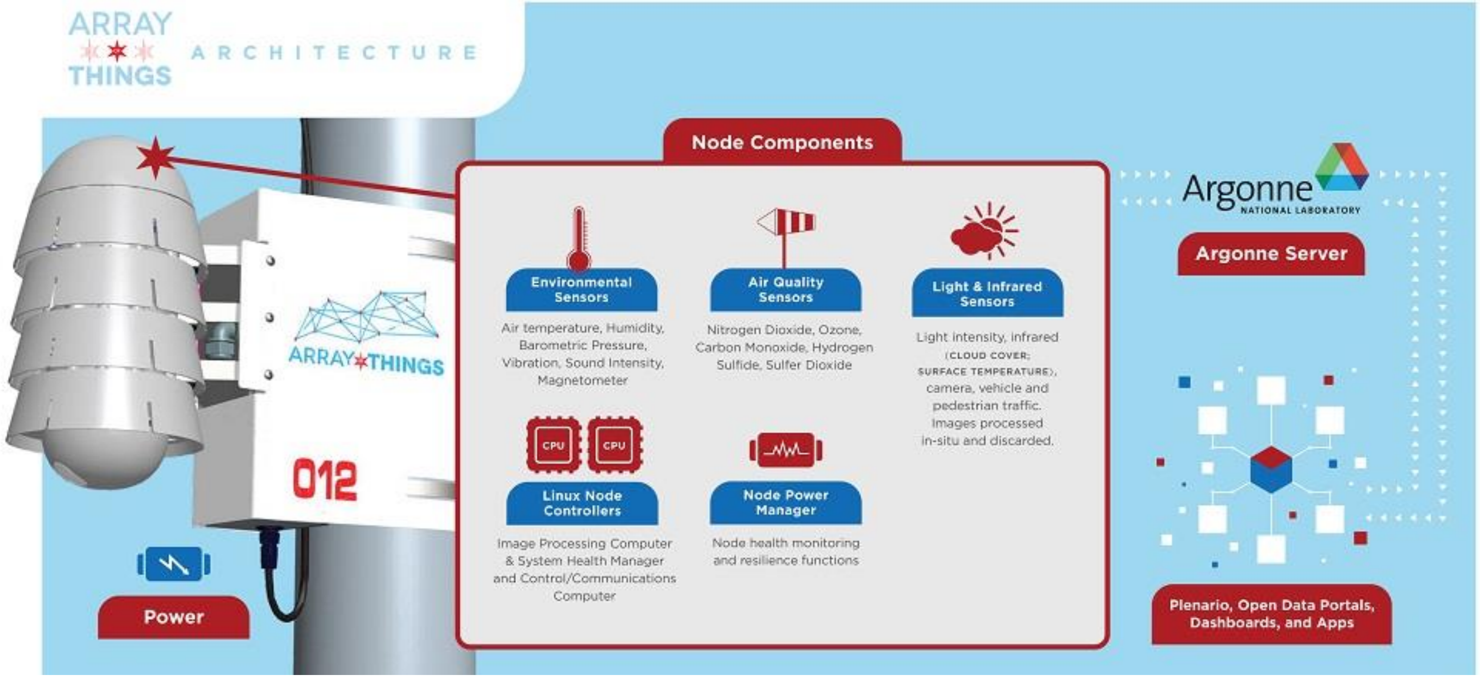


Only I2C and GPIO required

Optional
PPS 100ns global synch
USB

Array of Things is one platform approach

- Include sensors as platform resources
- Applications are software that act on sensor data
- High-power hardware and expensive to deploy



Signpost explores the other end of the spectrum

What can we do with less?

- Low-power, low-capability, extremely deployable
- Limited provided resources, but lots of extensibility

Focus on modularity

- Too difficult to start from scratch for every upgrade/change
  - Components are more expensive
  - Deployments is more difficult
- The platform should be viewed as shared infrastructure!
  - Amortize cost with multiple sensors and applications

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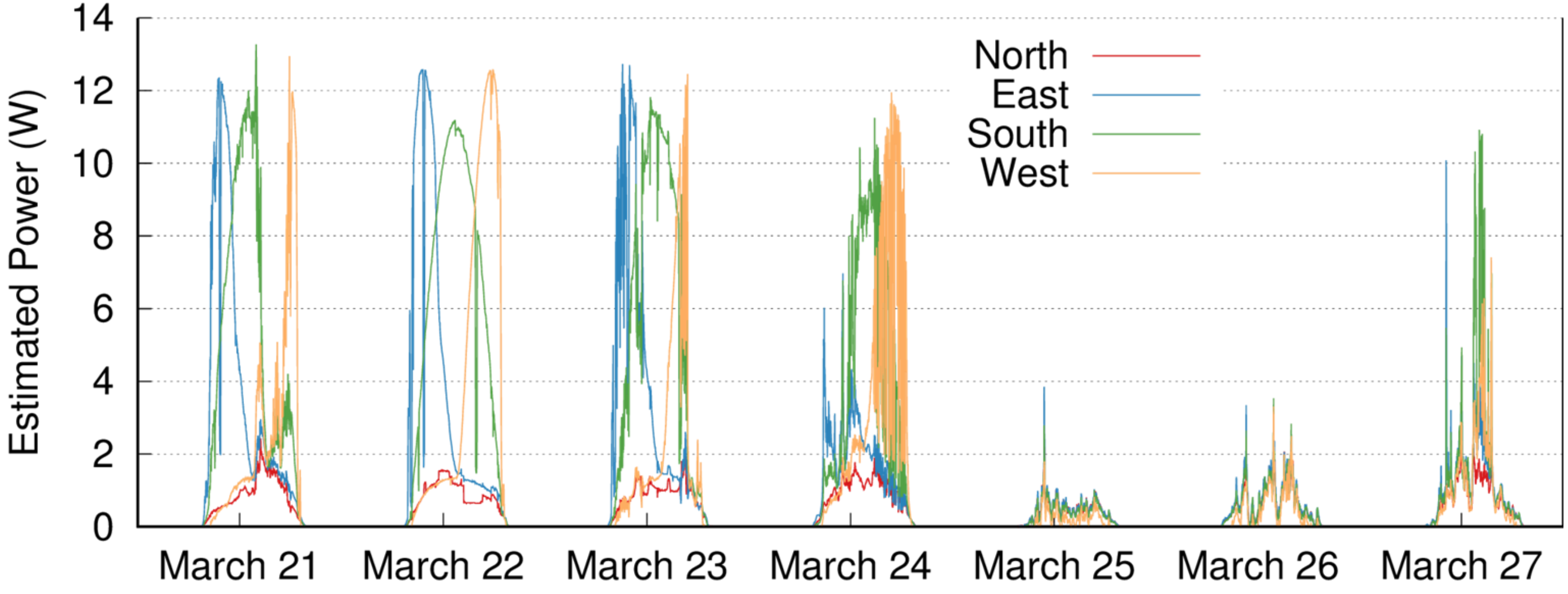
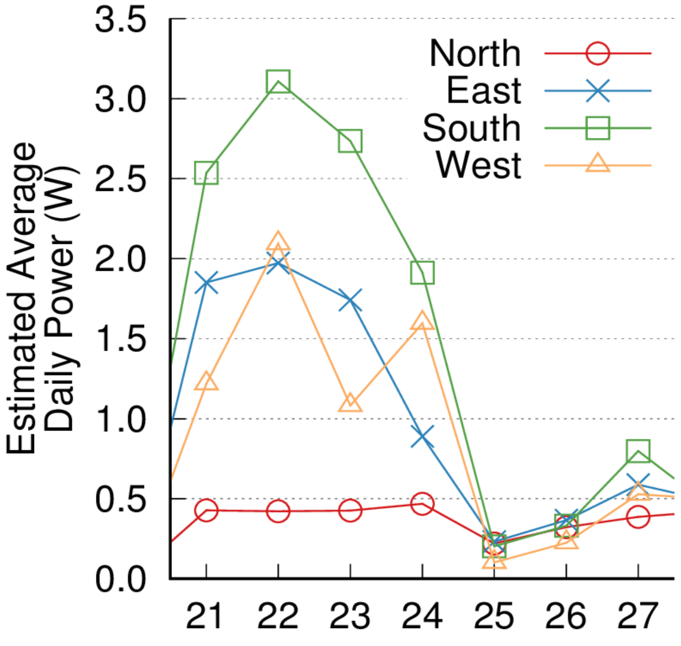
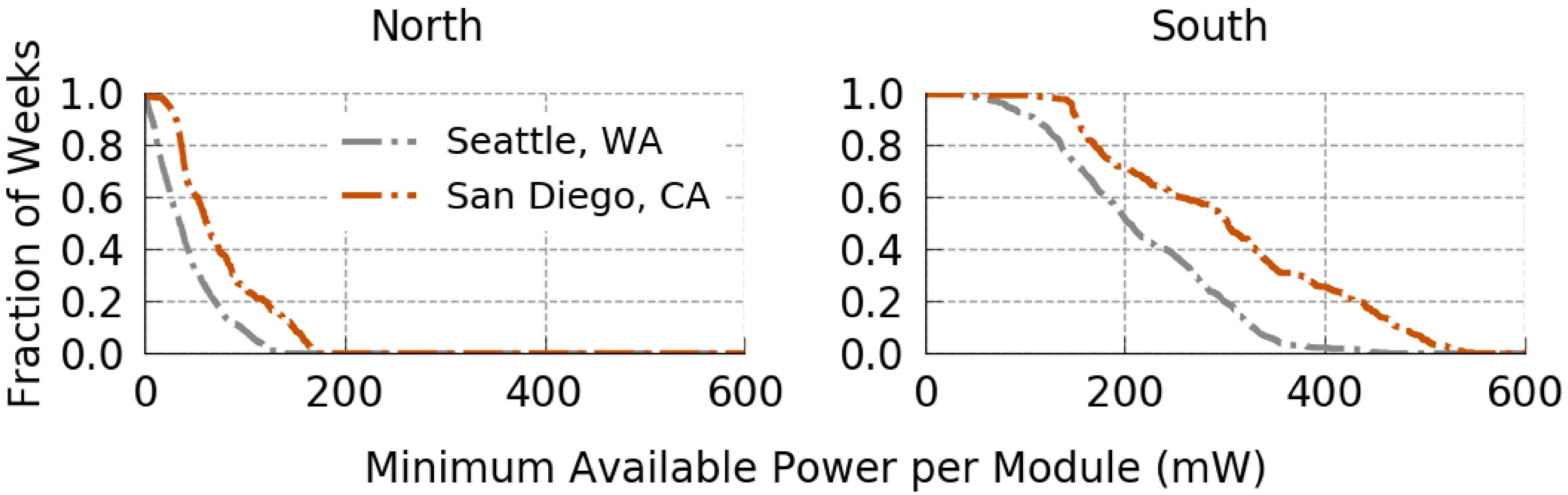
How much power does a Signpost harvest?





Higher daily variations than directional variations

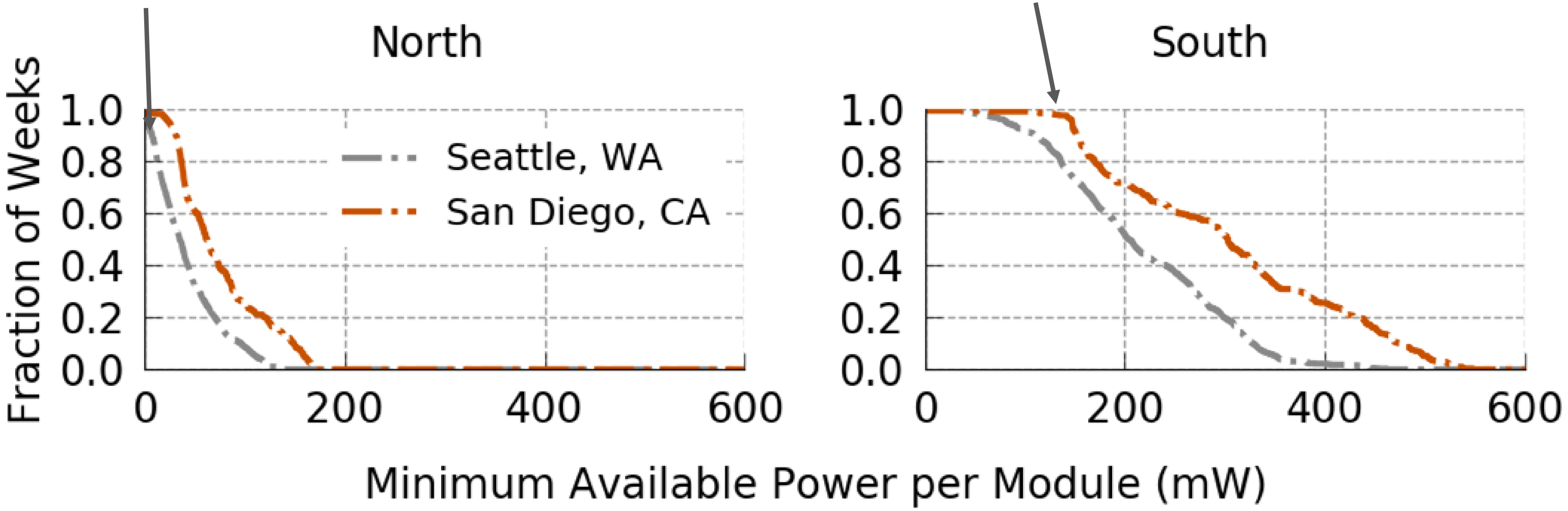
How much power can each module draw?



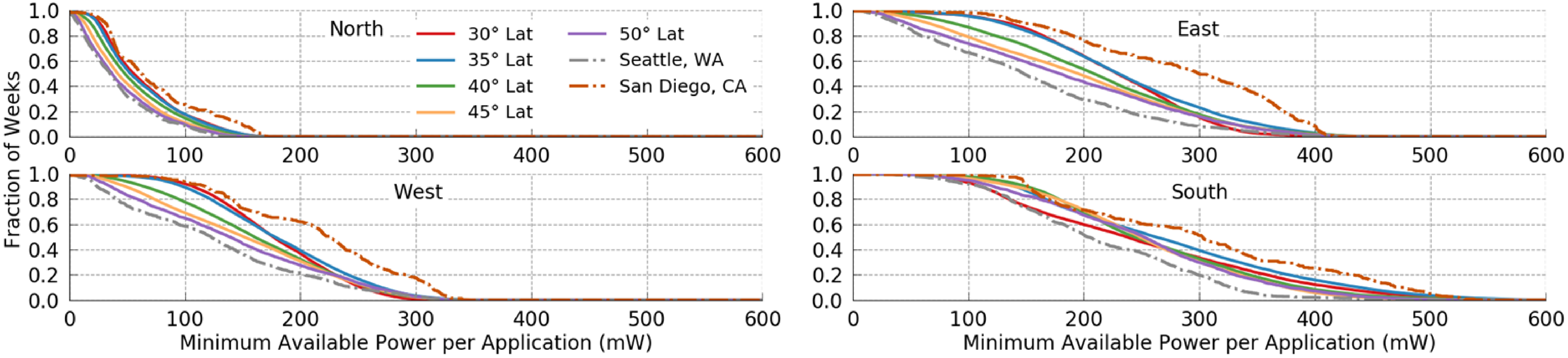
How much power can each module draw?

Seattle 95th Percentile = 3 mW

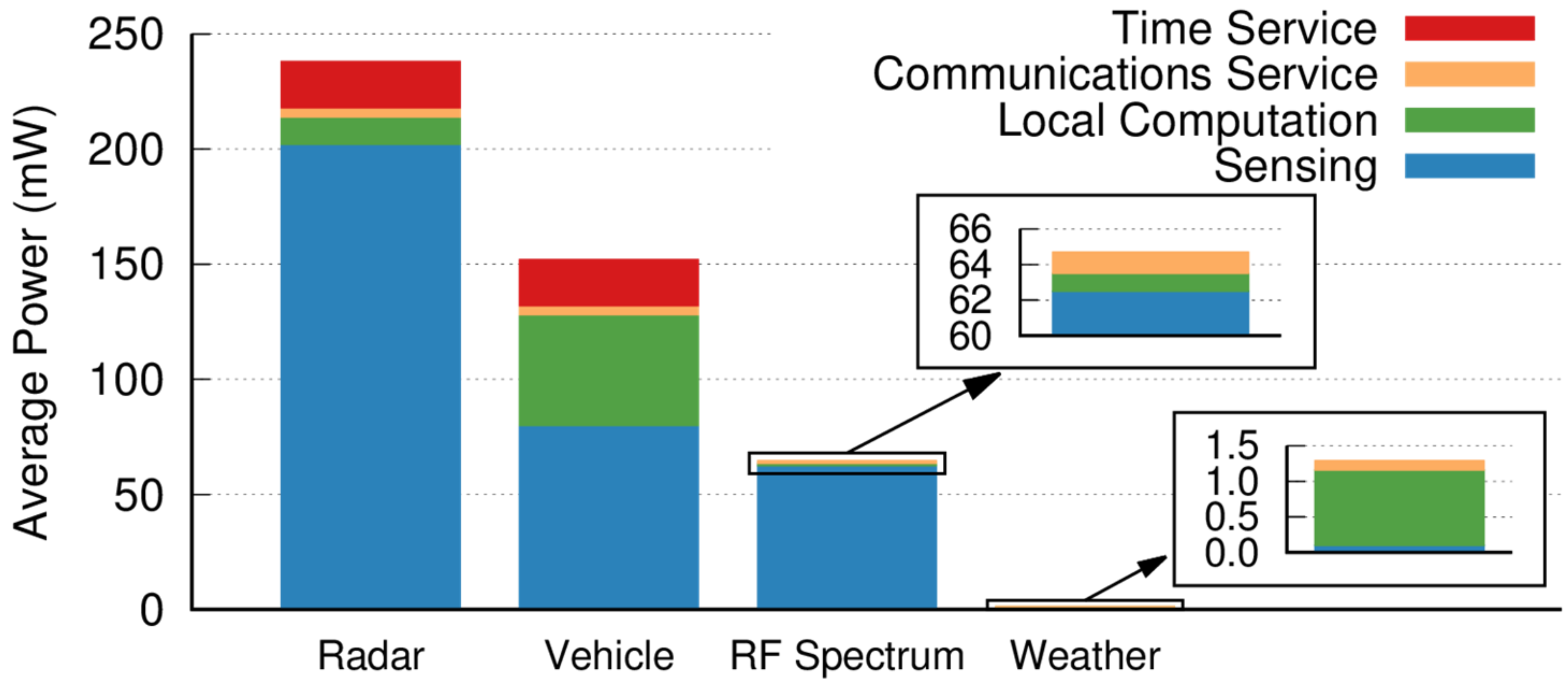
San Diego 95th Percentile = 162 mW



How much power can each module draw?

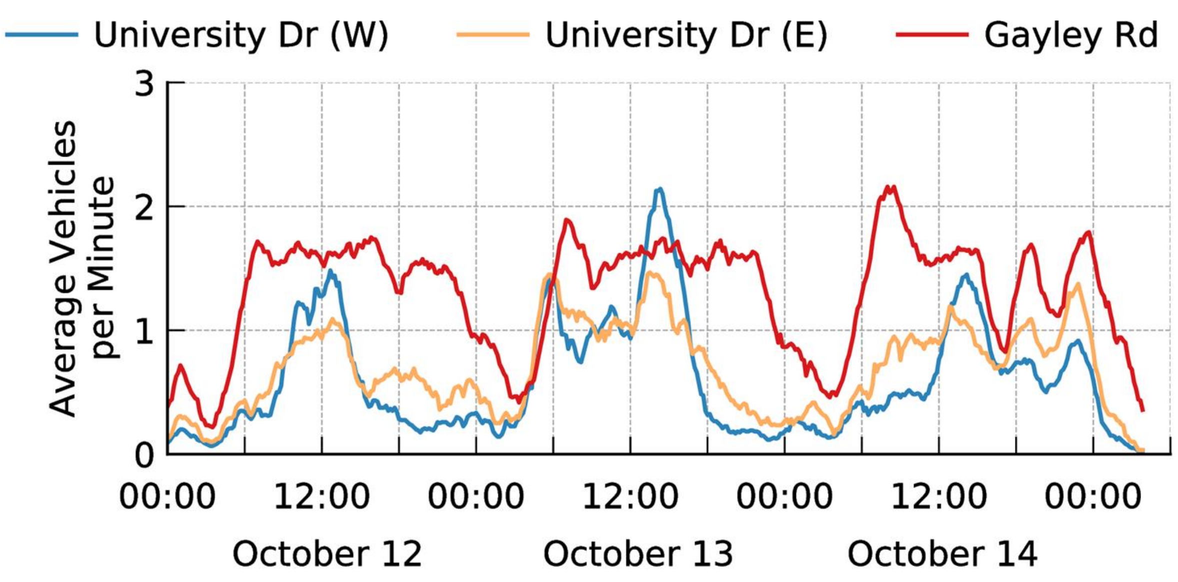


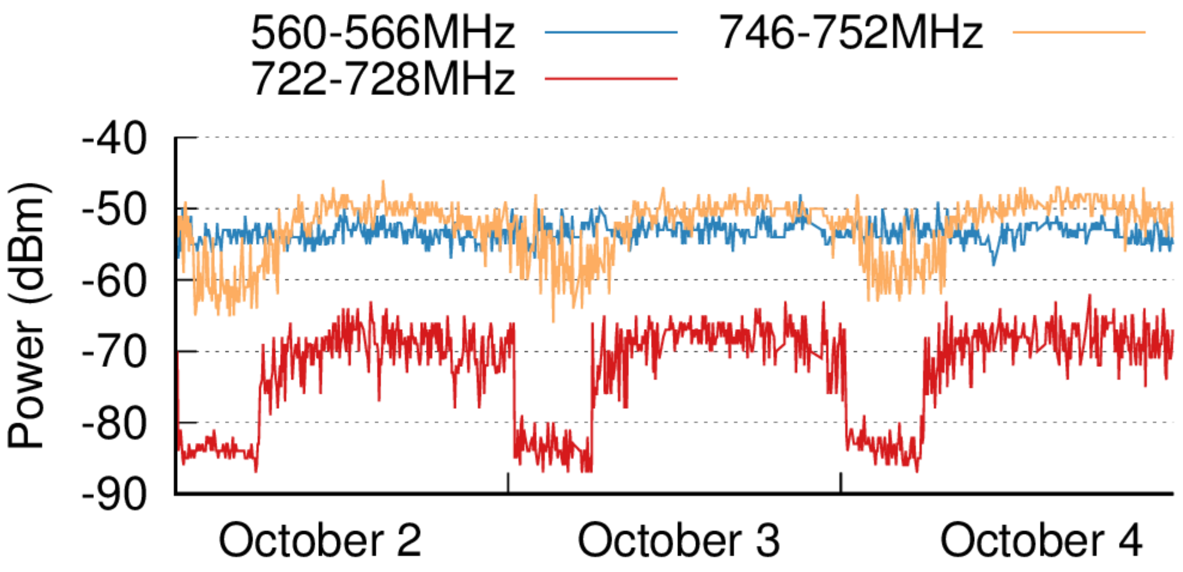
Resources are charged to modules which use them



Applications running on Signpost

- Environmental monitoring (posting to Weather Underground)
- Vehicle counting (and bell tower)
- TV whitespace sensing





Outline

- What does research look like:
  - Research Overview
  - Example: Powerblade
- Sensing Systems Research
  - Various Projects
  - Signpost