the Internet of Things

Roadmap to a Connected World

MODULE | Technologies

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NETWORK CONNECTIVITY FOR IOT

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NETWORKING: "GLUE" FOR THE IOT

IoT's "technology push" from the convergence of

- Embedded computing
- Sensing & actuation
- **Wireless networks**

THE IOT CONNECTIVITY SOUP

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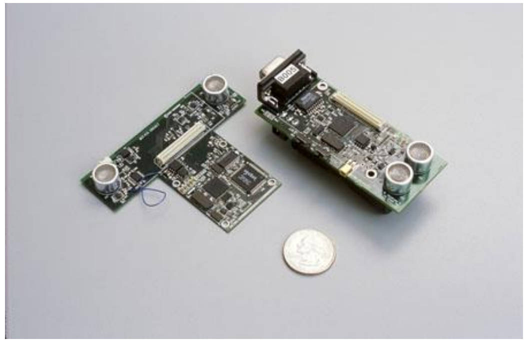
NETWORKING: “GLUE” FOR THE IOT

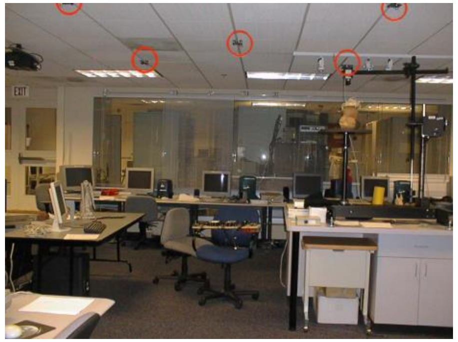
(Too) many different approaches, (too) many different standards, (too) much confusion

One size does not fit all: best network depends on application

What are the key organizing principles and ideas?

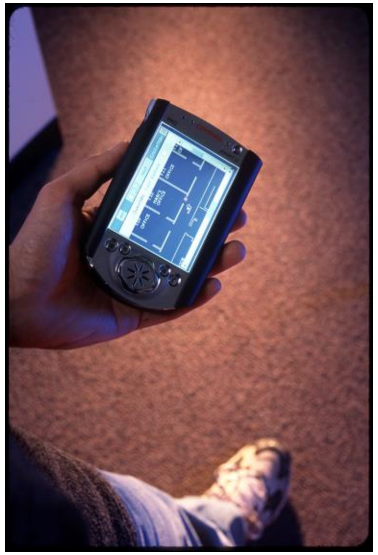
MY IOT EXPERIENCE: CRICKET



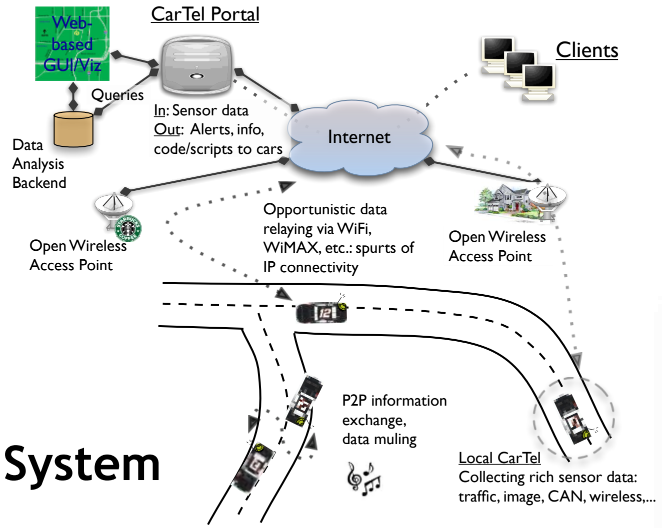


Cricket Indoor Location System

Started 1999-00, ran until 2005
Key component of MIT’s Project Oxygen
3-5 cm accuracy for indoor location
Beacons in building transmit RF and ultrasound
Listeners on mobile devices and sensors estimate distance and trilateral position
Beacons self-configure using multihop protocol

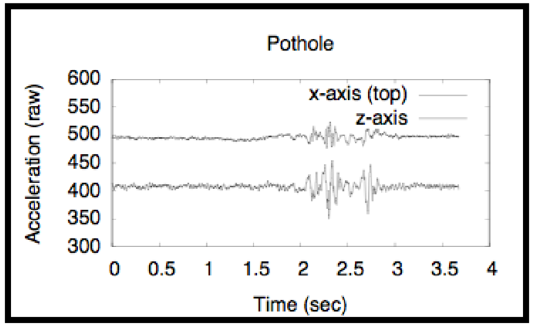


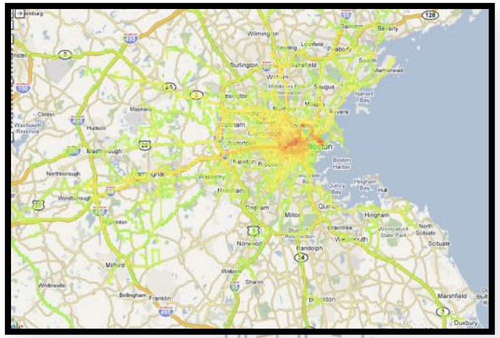
MY IOT EXPERIENCE: CARTEL



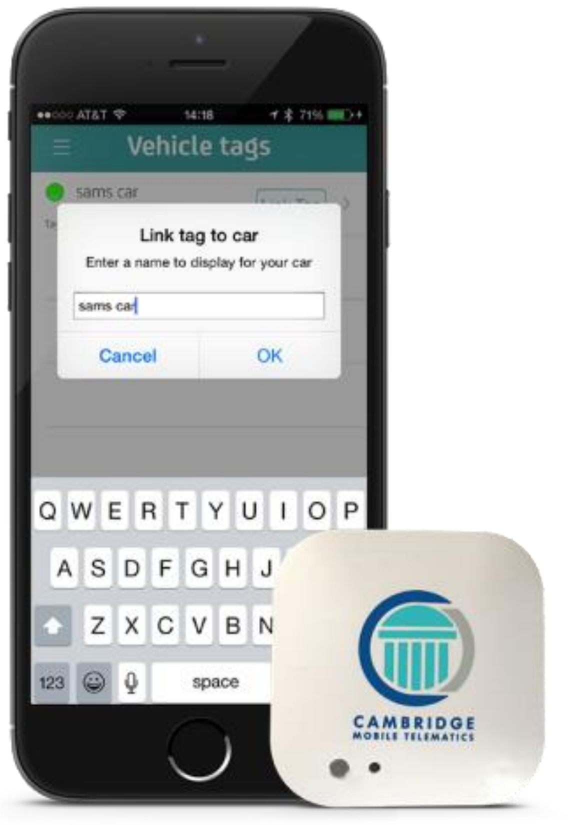
CarTel Mobile Sensing System

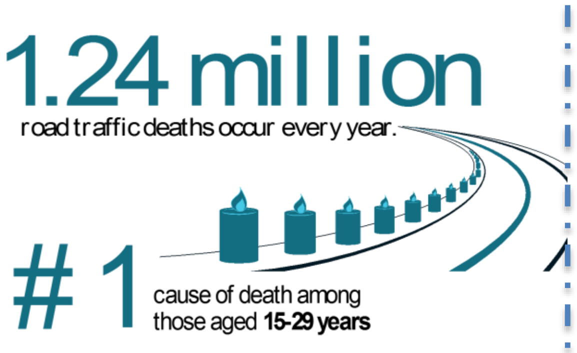
Started 2005, ran until 2011
One of the first mobile sensing systems
Transportation focus: precursor to today's "connected car" and smartphone sensing efforts
Cabernet network: QuickWifi for vehicular Wi-Fi
New map-matching algorithms
Traffic-aware routing
Pothole patrol





MY IOT EXPERIENCE: DRIVEWELL





DriveWell Safe Driving System

Started 2010-11
Commercially available (Cambridge Mobile Telematics)
Goal: Make roads safer by making drivers better
Smartphone sensing to assess driving safety
Feedback and incentives (behavioral economics)
App augmented with BLE DriveWell Tag
for real-time collision detection & roadside assistance

HOW TO MAKE SENSE OF THIS SOUP?

Bluetooth SMART
ZigBee
6LoWPAN IPv6-based Low-power Wireless Personal Area Networks
IEEE 802.15.4
WiFi diving into 900 MHz 802.11ah IEEE
LoRa

3GPP A GLOBAL INITIATIVE
WiFi a b g n ac
LTE ADVANCED
4G LTE
5G wireless

Z-WAVE
SIGFOX One network A billion dreams
INGENU
WEIGHTLESS
INSTEON
enocean

ALLSEEN ALLIANCE AllJoyn® Framework
THREAD
OPEN INTERCONNECT CONSORTIUM
industrial internet CONSORTIUM

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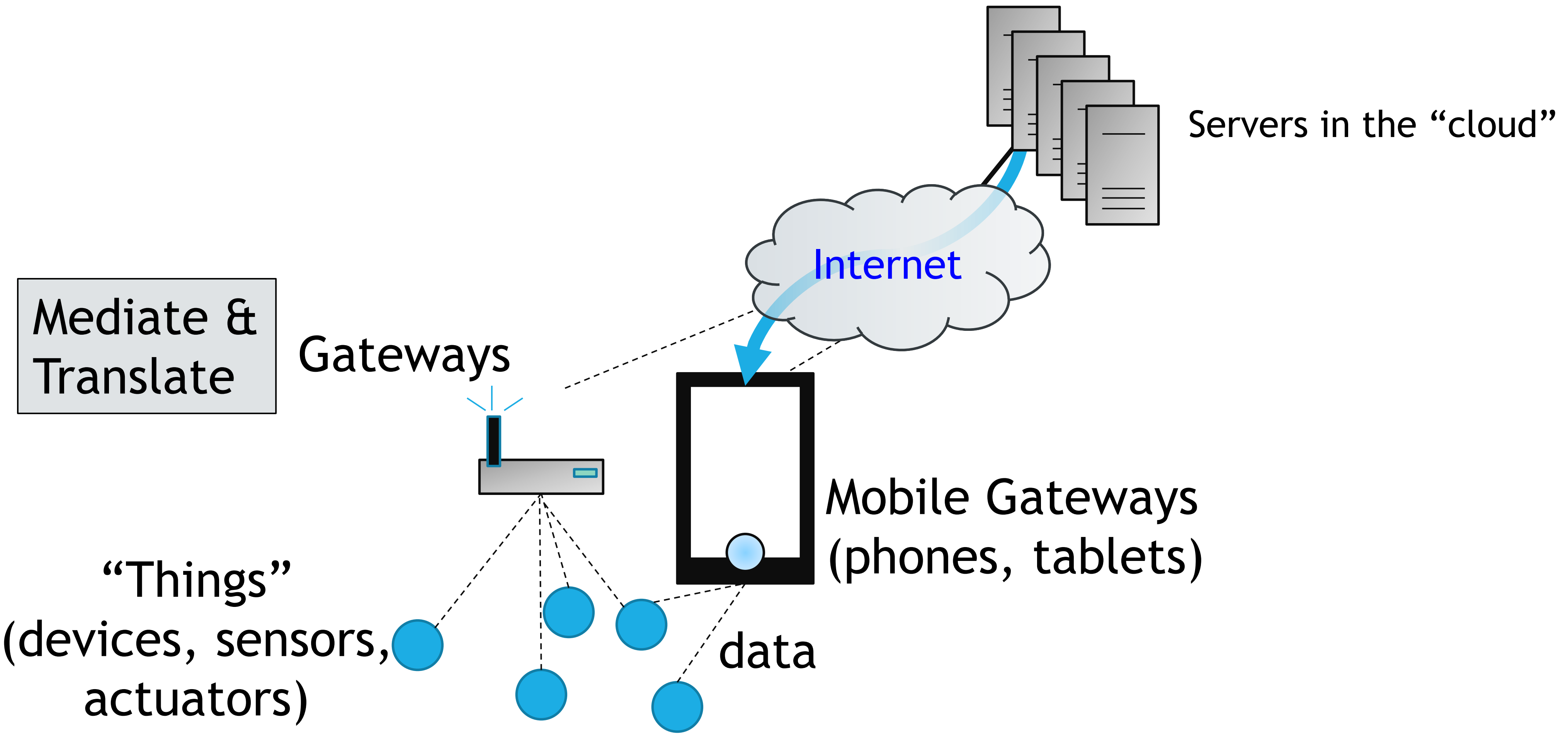
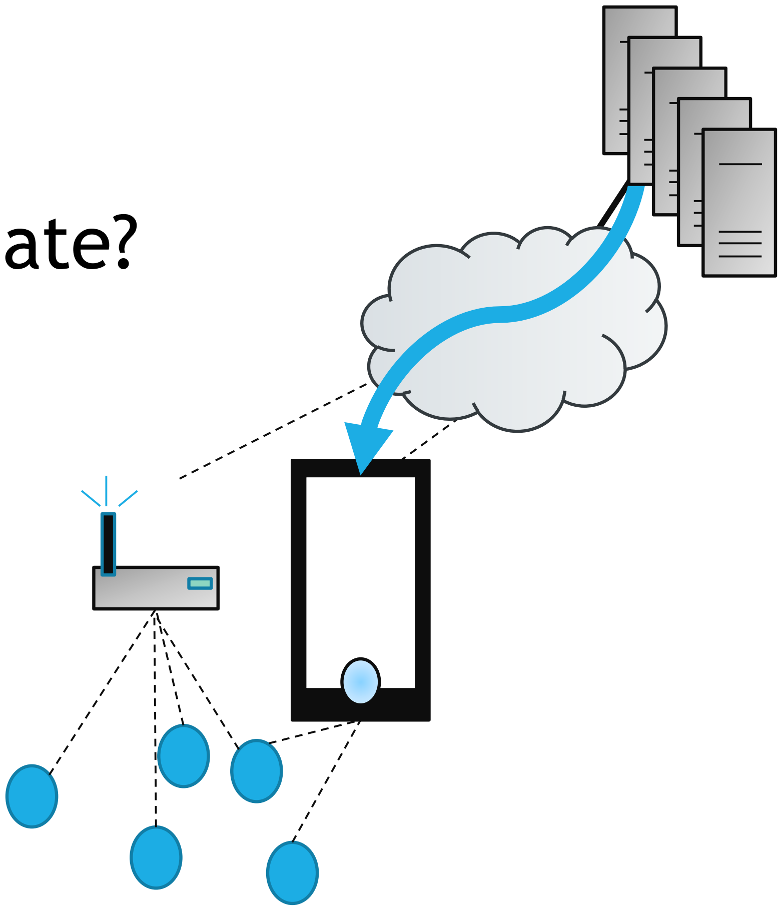
ARCHITECTURE, SIMPLIFIED



BUT, IN FACT, A RICH DESIGN SPACE

How should gateways and things communicate?

Many answers, many approaches

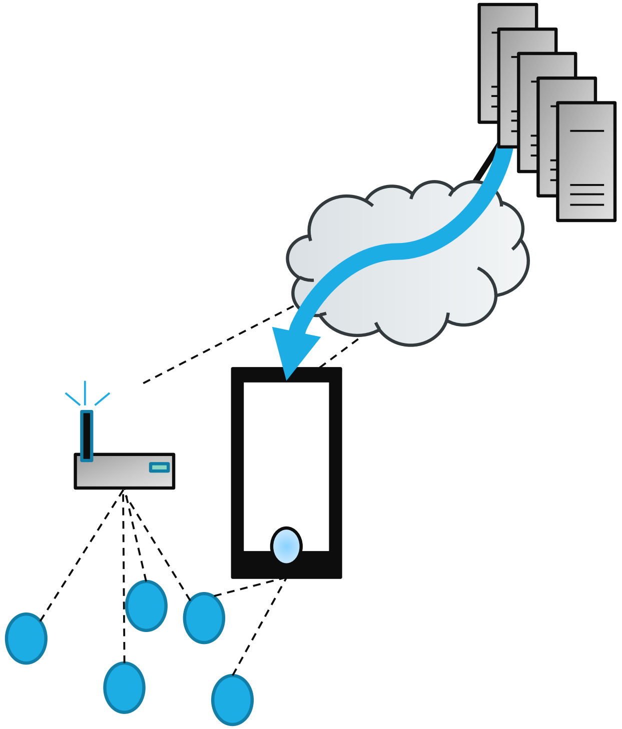


CAN'T WE JUST USE THE WIRELESS INTERNET?

Cellular and Wi-Fi

Yes, we can…

except when we can't!



WIRELESS INTERNET FOR IOT?

Cellular (LTE/4G, 3G, 2G) and Wi-Fi are

+ Widely available
+ High bandwidth (for most purposes), so can support high-rate apps

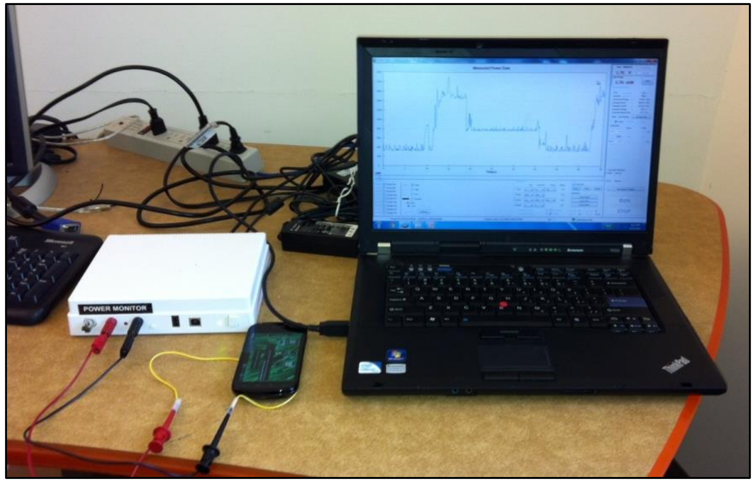
But, each has two big drawbacks

- **High power**: not suitable for battery-operated scenarios
- Cellular: often high cost (esp. per byte if usage-per-thing is low)
- Wi-Fi: OK in most buildings, but not for longer range

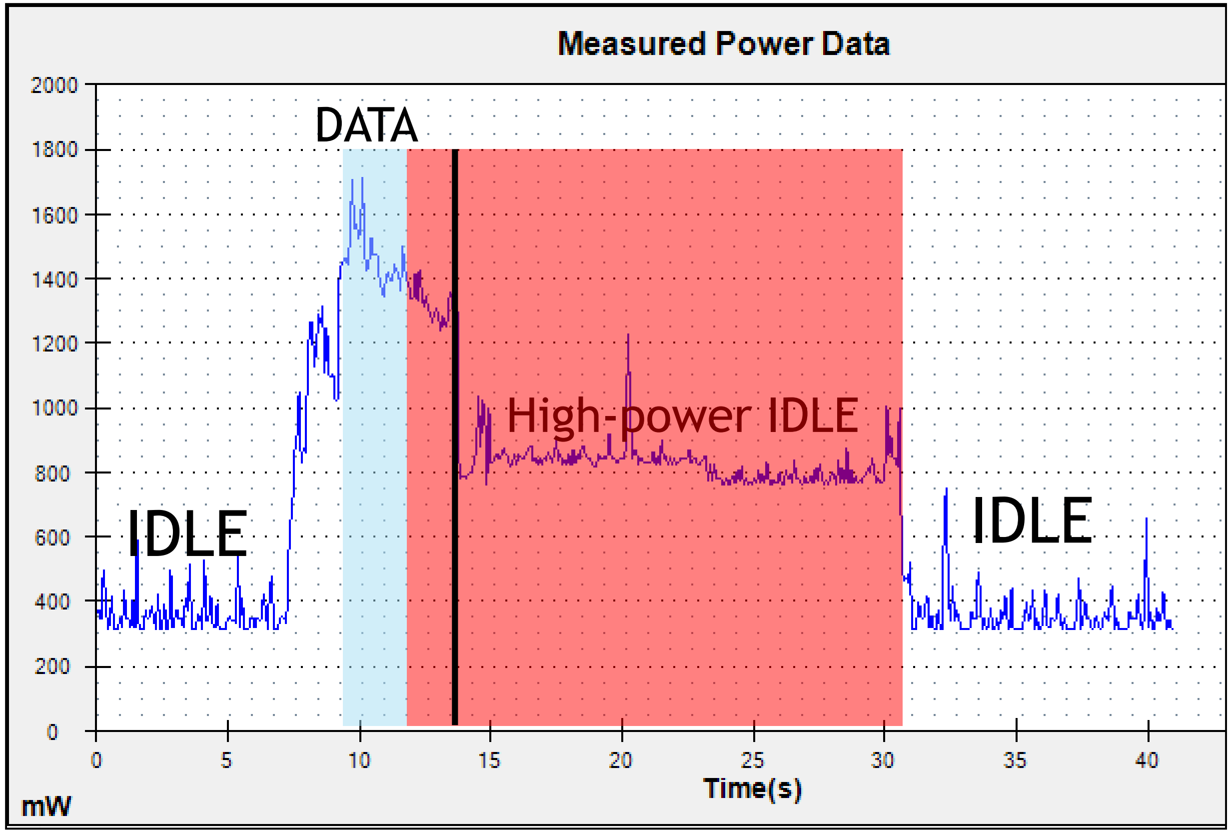
Wi-Fi: In-building powered things (speakers, washers, refrigerators, …)

Cellular: High-valued powered things (e.g., “connected car”)

CELLULAR POWER CONSUMPTION

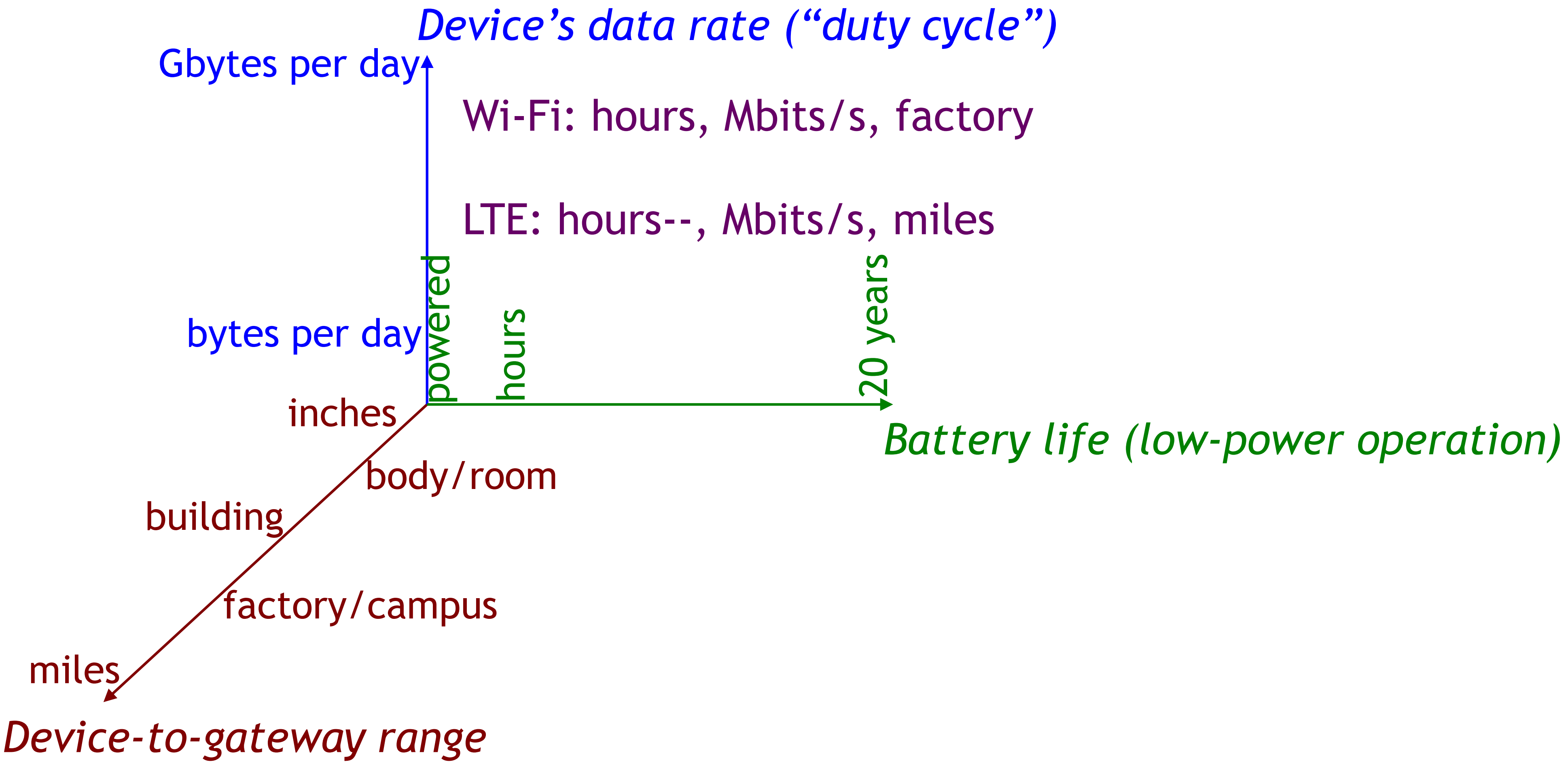


Power monitor apparatus



Deng & Balakrishnan, “Traffic-Aware Techniques to Reduce 3G/LTE Energy Consumption,” CoNext 2012.

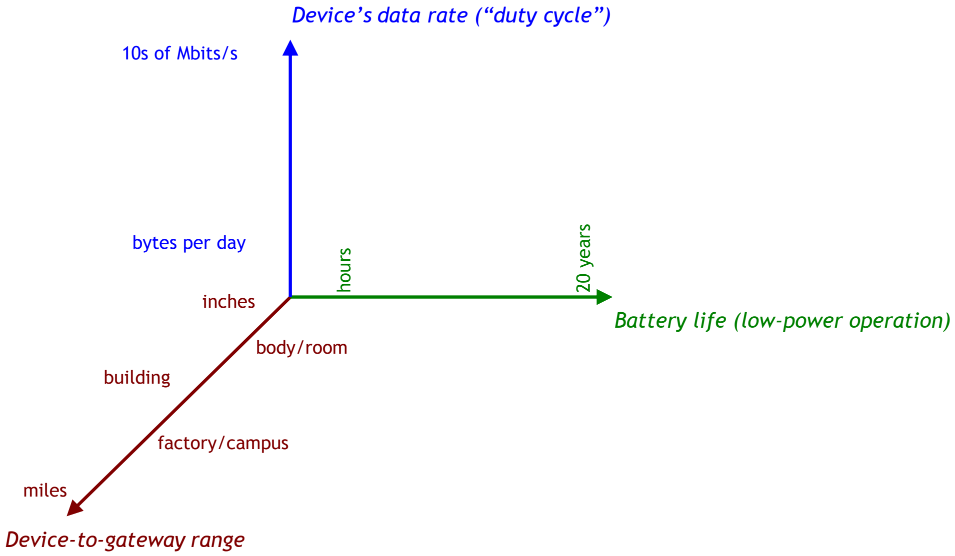
IOT NETWORK DESIGN SPACE



WHY SO MANY IOT NETWORKS?

Because engineers love inventing technologies!

But really because you can pick many interesting regions from this design space



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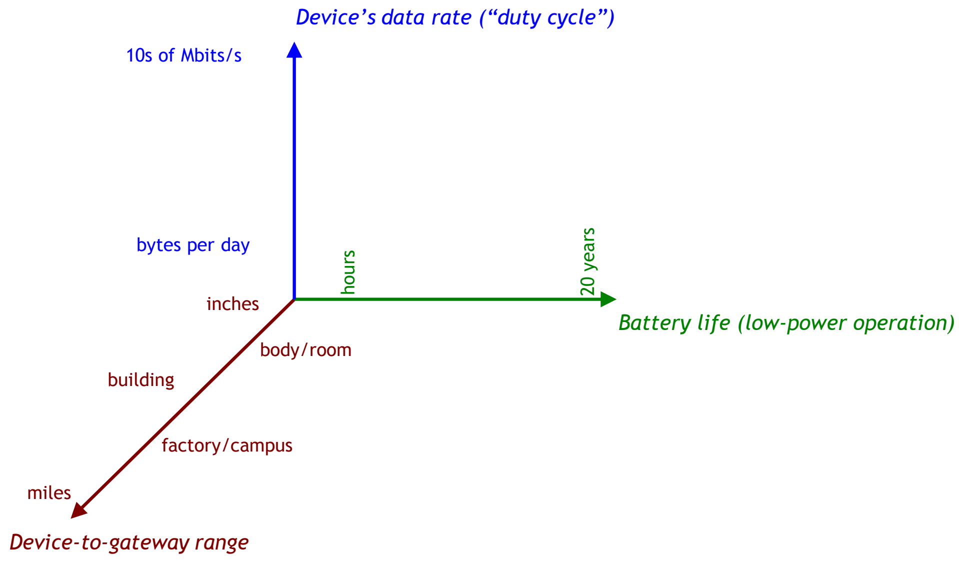
- Note, axes aren't independent
- And technology evolves fast



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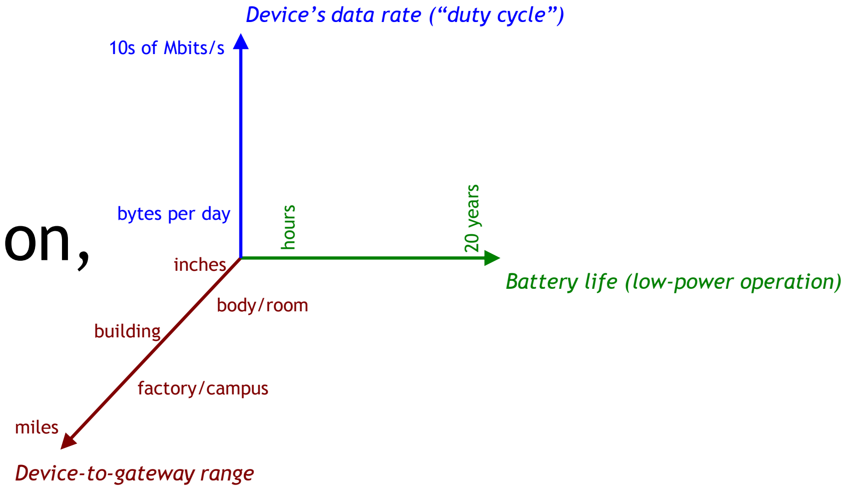
Because engineers love inventing technologies!

But really because you can pick many interesting regions from this design space

- Note, axes aren't independent
- And technology evolves fast
- And bundling into popular devices speeds-up adoption, changing the economics
  - Cf. Wi-Fi → laptops (without external cards)
  - Bluetooth classic → cell phones → wireless headsets
  - Bluetooth Low Energy (BLE) → iPhone then Android smartphones → "body/room" with months-to-years at low duty cycles



BODY/ROOM-AREA EXAMPLE: BLE

Bluetooth® SMART

Device's data rate ("duty cycle")

peak: ~100s of kbits/s

Months-to-years if ~100s kbytes per day

Battery life (low-power operation)

Started as "Wibree" by Nokia (2006)
Dominant technology today
Because of smartphones
Smartphones as gateways
- Wearables, fitness trackers
- Vehicles (bikes, cars)

body/room
10 meters typical
50 meters under good conditions with high TX
Longer range might not always be good

Device-to-gateway range

HOW DOES BLE WORK?

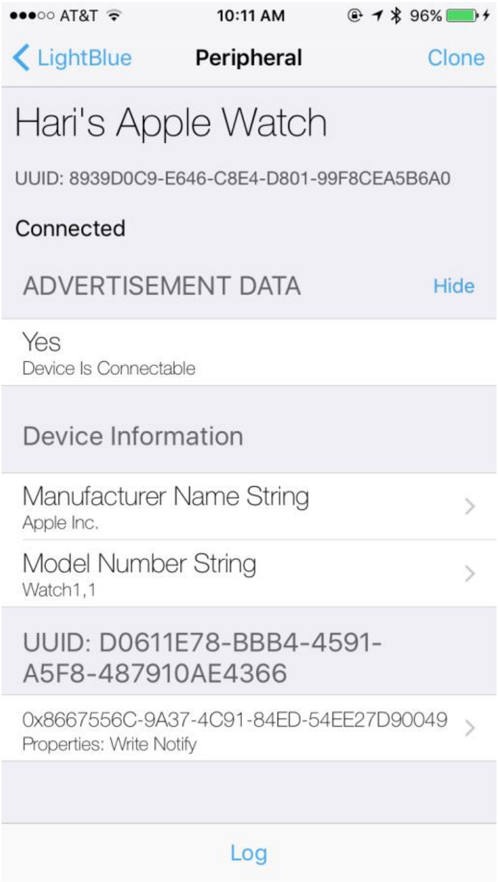
Two parts:

1. Advertisements (aka “beaconing”) for device discovery
2. Connection phase to exchange data

Peripheral: device with data
Central: gateway

orld

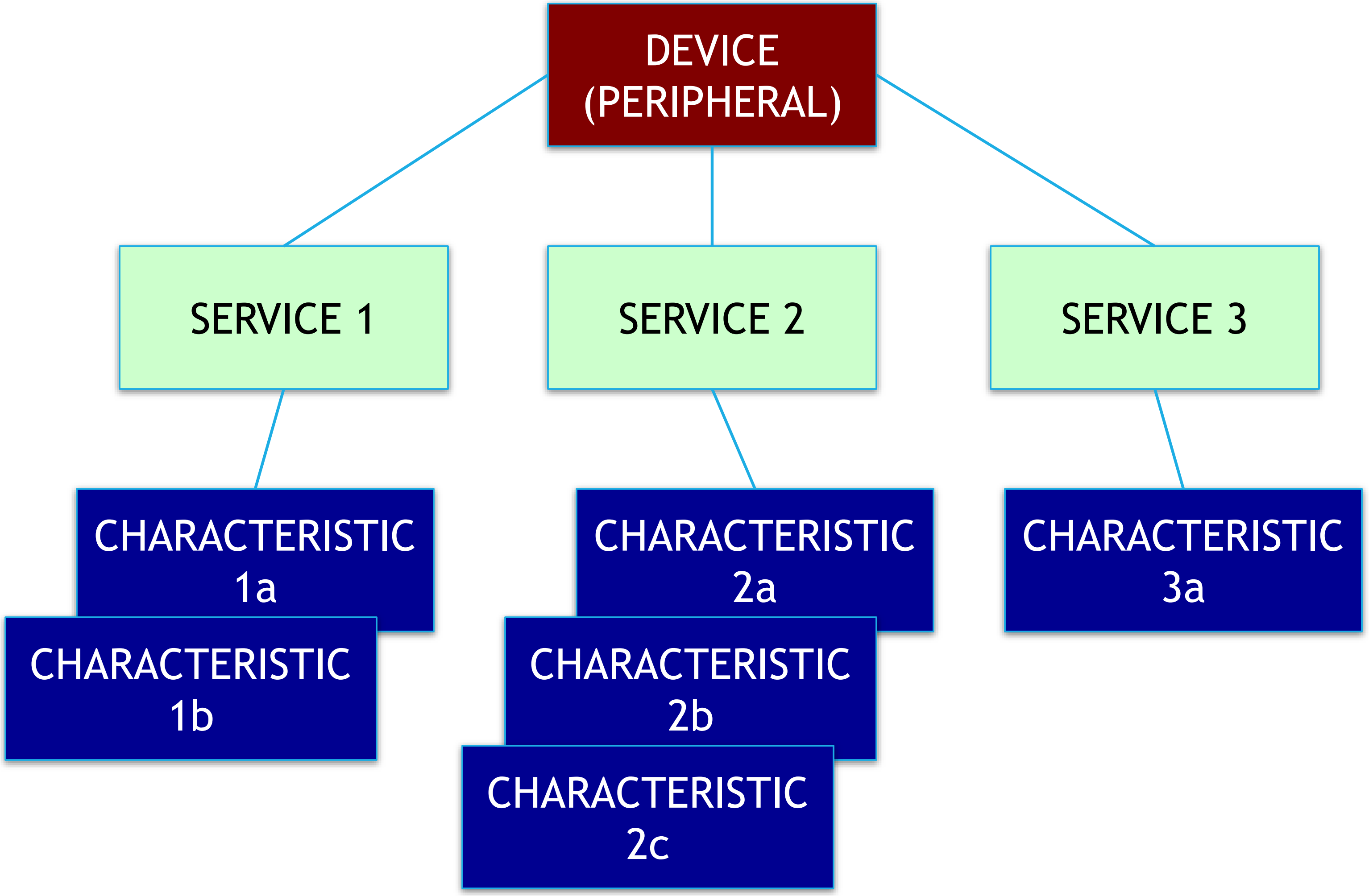
BLE ADVERTISEMENTS ARE PERIODIC



Typical period: 100 ms ("iBeacon")
Less frequent is fine
Triggered advertisements are often a good idea

Trade-off between energy consumed
and discovery latency

ON CONNECTION



READABLE
READ/WRITE
NOTIFICATIONS

Usually support OTA (over-the-air upgrades)

ON CONNECTION: MAC PROTOCOL

Central orchestrates data communication
Key idea: time-schedule to reduce energy consumption

On connect: exchange parameters
- Frequency hopping sequence
- Connection interval, i.e., periodicity of data exchange (T milliseconds)

Every T milliseconds, Central and Peripheral exchange up to 4 packets, alternating turns

Then Peripheral can go back to sleep until next interval

BATTERY LIFETIME CALCULATION

Consider an IoT system with coin-cell battery-powered nodes
Battery: 250 mAh (milliamp-hours) capacity; 3 Volts
Recall that power = voltage * current and energy = power * time
So this battery has 0.75 amp-hour-volts = 0.75*3600 Joules = 2.7 kJ of energy

Example of BLE current draw:
Standby: 1 microAmp (typically in the 1-10 microAmp range)
Receive (RX): 3.3 mA
Transmit (TX): 4 mA

Suppose device transmits every second: how long does the battery last?

BATTERY CALCULATION (CONT.)

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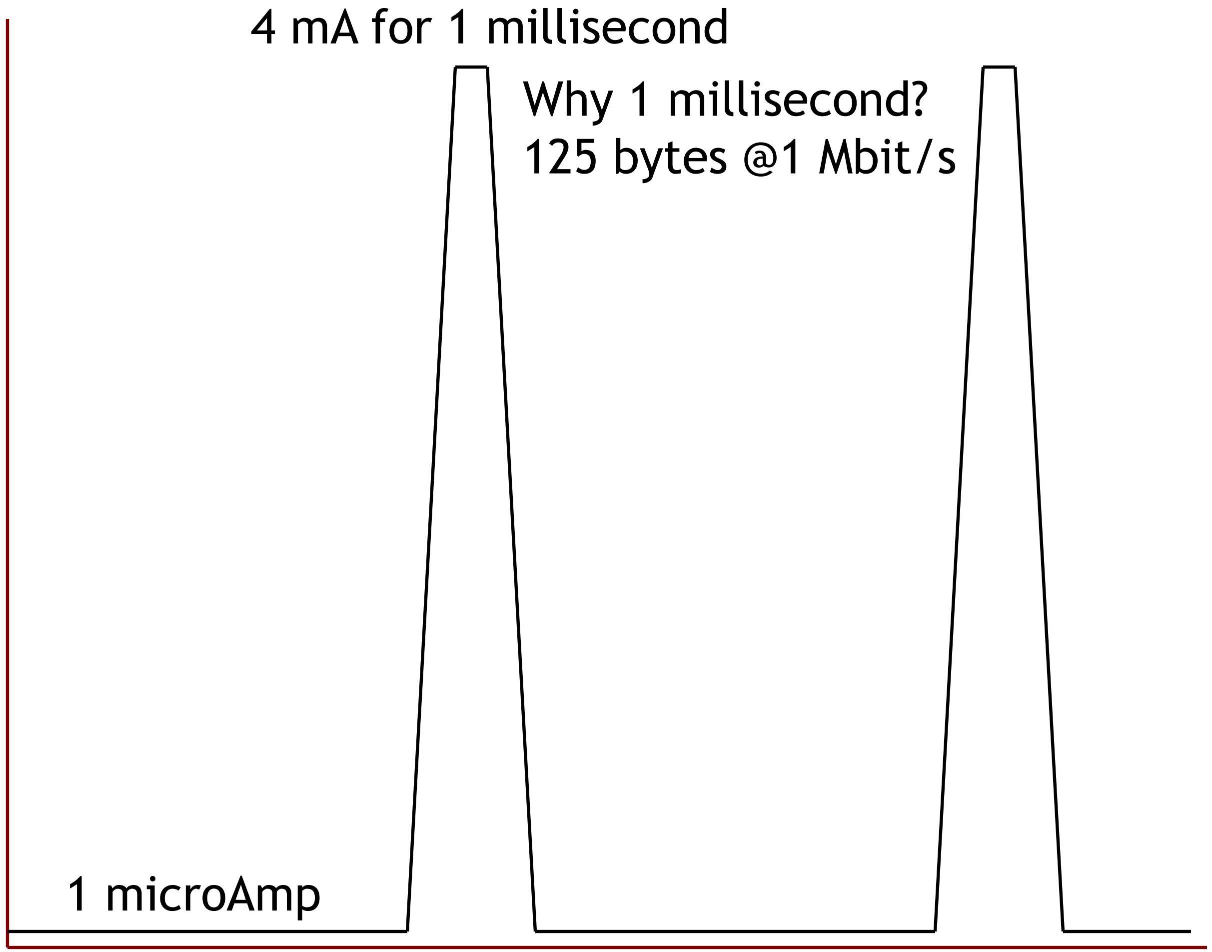
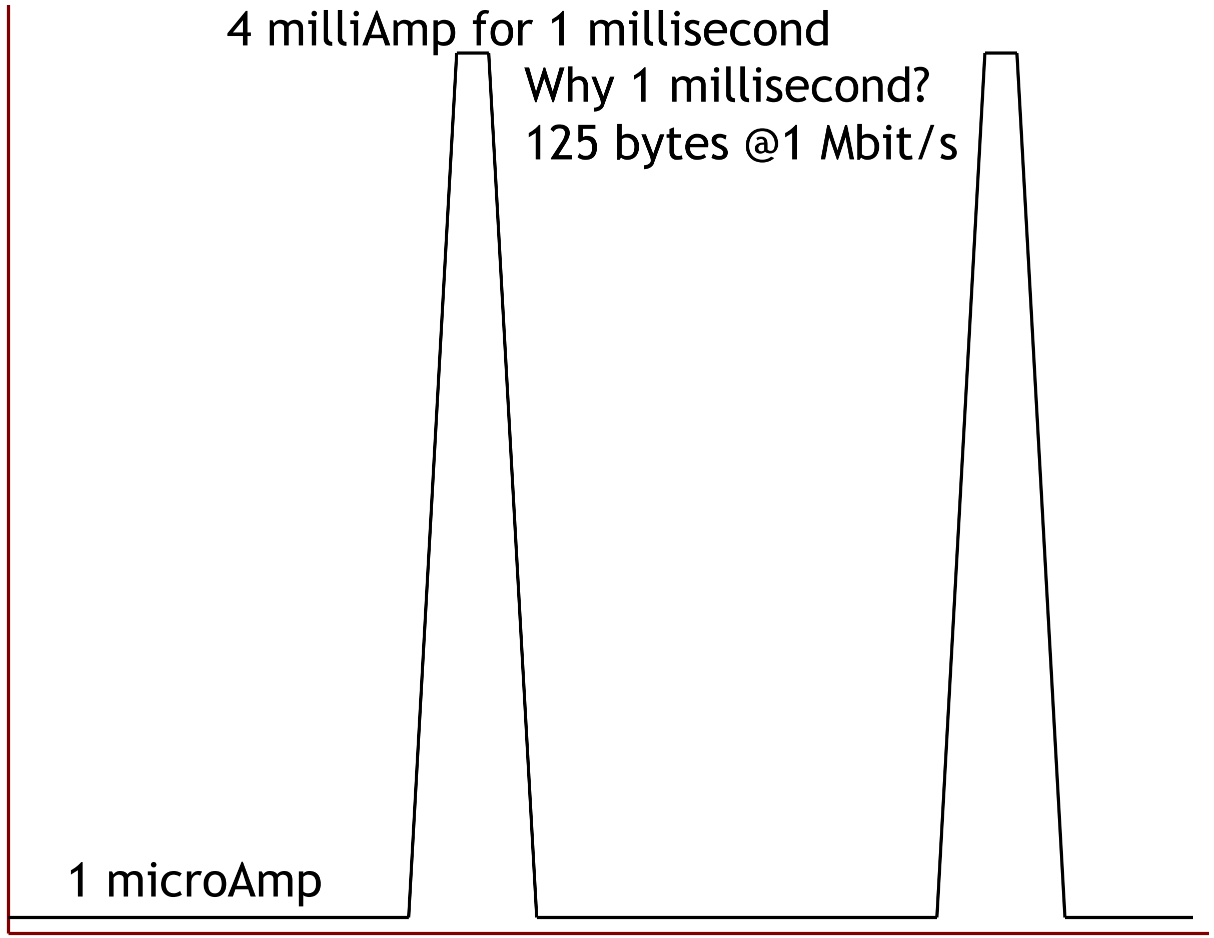


BATTERY CALCULATION (CONT.)



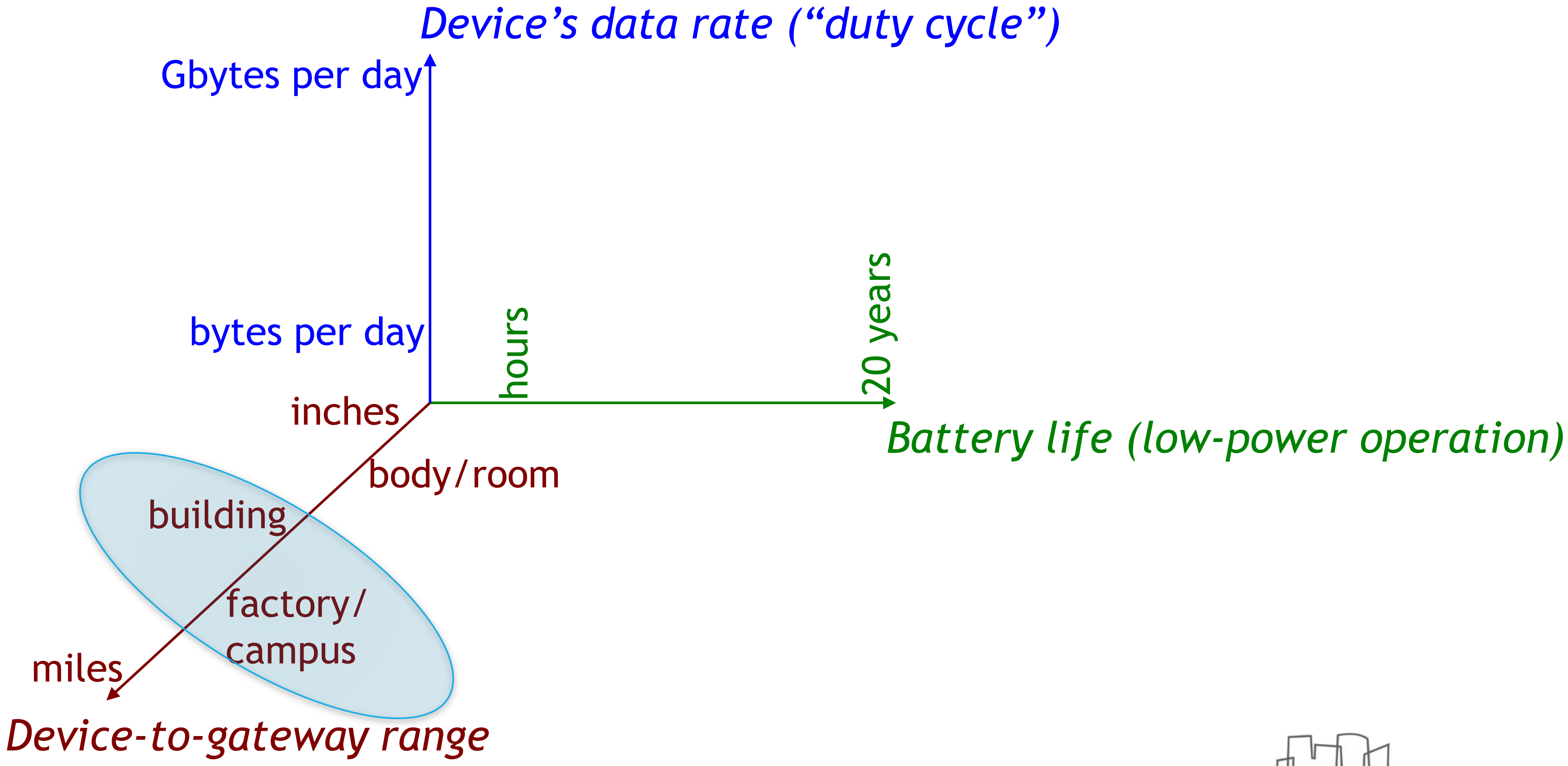
Ramp-up and down: 1 milliAmp for 5 milliseconds

Over a 1 second interval, average current is:
4 microAmps (xmit) +
5 microAmps (ramping) +
1 microAmp (standby)
= 10 microAmps

Therefore, battery lifetime
= 250 mAh / 10 microAmps
= 250 mAh / 0.01 mA
= 25,000 hours
= 2 years and 10 months

This works because it's sleeping most of the time!

EXTENDING COMMUNICATION RANGE



EXTENDING RANGE: MESH NETWORKS

1980s: DARPA packet radio networks

1990s: mobile ad hoc networks (MANET)

The DARPA Packet Radio Network Protocols

JOHN JUBIN AND JANET D. TORNOW, ASSOCIATE, IEEE

Invited Paper

In this paper we describe the current state of the DARPA packet radio network. Fully automated algorithms and protocols to organize, control, maintain, and move traffic through the packet radio network have been designed, implemented, and tested. By means of protocols, networks of about 50 packet radios with some degree of nodal mobility can be organized and maintained under a fully distributed mode of control. We have described the algorithms and illustrated how the PRNET provides highly reliable network transport and datagram service, by dynamically determining optimal routes, effectively controlling congestion, and fairly allocating the channel in the face of changing link conditions, mobility, and varying traffic loads.

I. Introduction

In 1973, the Defense Advanced Research Projects Agency (DARPA) initiated research on the feasibility of using packet-switched, store-and-forward radio communications to provide reliable computer communications [1]. This development was motivated by the need to provide computer network access to mobile hosts and terminals, and to provide computer communications in a mobile environment. Packet radio networking offers a highly efficient way of using a multiple-access channel, particularly with bursty traffic [2]. The DARPA Packet Radio Network (PRNET) has evolved through the years to be a robust, reliable, operational experimental network [3]. The development process has been of an incremental, evolutionary nature [4]; as algorithms were designed and implemented, new versions of the PRNET with increased capabilities were demonstrated. The PRNET has been in daily operation for experimental purposes for nearly ten years. In this paper we describe the current state of the DARPA PRNET.

We begin by providing a synopsis of the PRNET system concepts, attributes, and physical components in Section II. In Section III, we illustrate the mechanisms by which a packet radio automatically keeps track of a potentially continuously changing network topology. In Section IV, we describe the algorithms used to route a packet through the packet radio communications subnet. In Section V, we examine the protocols for transmitting packets. In Section VI, we describe some of the hardware capabilities of the packet radio that strongly influence the design and characteristics of the PRNET protocols. We conclude by looking briefly at some applications of packet radio networks and by summarizing the state of the current technology.

Manuscript received February 1, 1986; revised July 30, 1986. The work of J. Jubin was supported by the Defense Advanced Research Projects Agency of the Department of Defense under Contract MDA903-85-C-0205. The work of J. D. Tornow was supported by the Defense Advanced Research Projects Agency of the Department of Defense under Contract MDA903-85-C-0254.

J. Jubin is with Collins Defense Communications, Rockwell International, Richardson, TX 75081, USA.

J. D. Tornow is with SRI International, Menlo Park, CA 94025, USA.

II. Description of the Packet Radio System

A. Broadcast Radio

The PRNET provides, via a common radio channel, the exchange of data between computers that are geographically separated. As a communications medium, broadcast radio (as opposed to wires and antenna-directed radio) provides important advantages to the user of the network. One of the benefits is mobility; a packet radio (PR) can operate while in motion. Second, the network can be installed or deployed quickly; there are no wires to set up. A third advantage is the ease of reconfiguration and redeployment. The PRNET protocols take advantage of broadcasting and common-channel properties to allow the PRNET to be expanded or contracted automatically and dynamically. A group of packet radios leaving the original area simply departs. Having done so, it can function as an autonomous group and may later rejoin the original network or join another group.

The broadcasting and common channel properties of radio have disadvantages too. These properties, for all practical purposes, prohibit the building of a radio that is able to transmit and receive at the same time. Therefore, the PRNET protocols must attempt to schedule each transmission when the intended PR is not itself transmitting. Also, transmissions often reach unintended PRs and interfere with intended receptions. Therefore, the protocols must attempt to schedule each transmission when the intended PR is not receiving another PR's transmission.

B. Automated Network Management

The PRNET features fully automated network management. It is self-configuring upon network initialization, reconfigures upon gain or loss of packet radios, and has dy-

0018-9219/87/0100-0021$01.00 © 1987 IEEE

A Performance Comparison of Multi-Hop Wireless Ad Hoc Network Routing Protocols

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Computer Science Department
Carnegie Mellon University
Pittsburgh, PA 15213

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Abstract

An ad hoc network is a collection of wireless mobile nodes dynamically forming a temporary network without the use of any existing network infrastructure or centralized administration. Due to the limited transmission range of wireless network interfaces, multiple network "hops" may be needed for one node to exchange data with another across the network. In recent years, a variety of new routing protocols targeted specifically at this environment have been developed, but little performance information on each protocol and no realistic performance comparison between them is available. This paper presents the results of a detailed packet-level simulation comparing four multi-hop wireless ad hoc network routing protocols that cover a range of design choices: DSDV, TORA, DSR, and AODV. We have extended the *ns*-2 network simulator to accurately model the MAC and physical-layer behavior of the IEEE 802.11 wireless LAN standard, including a realistic wireless transmission channel model, and present the results of simulations of networks of 50 mobile nodes.

1 Introduction

In areas in which there is little or no communication infrastructure or the existing infrastructure is expensive or inconvenient to use, wireless mobile users may still be able to communicate through the formation of an *ad hoc network*. In such a network, each mobile node operates not only as a host but also as a router, forwarding packets for other mobile nodes in the network that may not be within direct wireless transmission range of each other. Each node participates in an ad hoc routing protocol that allows it to discover "multi-hop" paths through the network to any other node. The idea of ad hoc networking is sometimes also called *infrastructureless networking* [13], since the mobile nodes in the network dynamically establish routing among themselves to form their own network "on the fly." Some examples of the possible uses of ad hoc networking include students using laptop computers to participate in an interactive lecture, business associates sharing information during a meeting, soldiers relaying information for situational awareness on the battlefield [12, 21], and emergency disaster relief personnel coordinating efforts after a hurricane or earthquake.

This work was supported in part by the National Science Foundation (NSF) under CAREER Award NCR-9502725, by the Air Force Materiel Command (AFMC) under DARPA contract number F19628-96-C-0061, and by the AT&T Foundation under a Special Purpose Grant in Science and Engineering. David Maltz was also supported under an IBM Cooperative Fellowship, and Yih-Chun Hu was also supported by an NSF Graduate Fellowship. The views and conclusions contained here are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either express or implied, of NSF, AFMC, DARPA, the AT&T Foundation, IBM, Carnegie Mellon University, or the U.S. Government.

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Many different protocols have been proposed to solve the multi-hop routing problem in ad hoc networks, each based on different assumptions and intuitions. However, little is known about the actual performance of these protocols, and no attempt has previously been made to directly compare them in a realistic manner.

This paper is the first to provide a realistic, quantitative analysis comparing the performance of a variety of multi-hop wireless ad hoc network routing protocols. We present results of detailed simulations showing the relative performance of four recently proposed ad hoc routing protocols: DSDV [18], TORA [14, 15], DSR [9, 10, 2], and AODV [17]. To enable these simulations, we extended the *ns*-2 network simulator [6] to include:

- *Node mobility.*
- A *realistic physical layer* including a radio propagation model supporting propagation delay, capture effects, and carrier sense [20].
- *Radio network interfaces* with properties such as transmission power, antenna gain, and receiver sensitivity.
- The *IEEE 802.11 Medium Access Control (MAC) protocol* using the Distributed Coordination Function (DCF) [8].

Our results in this paper are based on simulations of an ad hoc network of 50 wireless mobile nodes moving about and communicating with each other. We analyze the performance of each protocol and explain the design choices that account for their performance.

2 Simulation Environment

ns is a discrete event simulator developed by the University of California at Berkeley and the VINT project [6]. While it provides substantial support for simulating TCP and other protocols over conventional networks, it provides no support for accurately simulating the physical aspects of multi-hop wireless networks or the MAC protocols needed in such environments. Berkeley has recently released *ns* code that provides some support for modeling wireless LANs, but this code cannot be used for studying multi-hop ad hoc networks as it does not support the notion of node position; there is no spatial diversity (all nodes are in the same collision domain), and it can only model directly connected nodes.

In this section, we describe some of the modifications we made to *ns* to allow accurate simulation of mobile wireless networks.

2.1 Physical and Data Link Layer Model

To accurately model the attenuation of radio waves between antennas close to the ground, radio engineers typically use a model that attenuates the power of a signal as $1/r^2$ at short distances (r is the distance between the antennas), and as $1/r^4$ at longer distances. The crossover point is called the *reference distance*, and is typically around 100 meters for outdoor low-gain antennas 1.5m above the ground plane operating in the 1–2GHz band [20]. Following this practice, our signal propagation model combines both a free space propagation model and a two-ray ground reflection model. When a transmitter is within the reference distance of the receiver, we use

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EXTENDING RANGE: MESH NETWORKS

Late 90s, 2000s: Sensor networks

Next Century Challenges: Scalable Coordination in Sensor Networks

Deborah Estrin
Ramesh Govindan
John Heidemann
Satish Kumar

USC/Information Sciences Institute
4676 Admiralty Way
Marina del Rey, CA 90292, USA
{estrin,govindan,johnh,kkumar}@isi.edu

An Application-Specific Protocol Architecture for Wireless Microsensor Networks

Wendi B. Heinzelman, *Member, IEEE*, Anantha P. Chandrakasan, *Senior Member, IEEE*, and Hari Balakrishnan, *Member, IEEE*

2000s: Mesh networks for Internet

Architecture and Evaluation of an Unplanned 802.11b Mesh Network

John Bicket, Daniel Aguayo, Sanjit Biswas, Robert Morris
M.I.T. Computer Science and Artificial Intelligence Laboratory
jbicket, aguayo, biswas, rtm @csail.mit.edu

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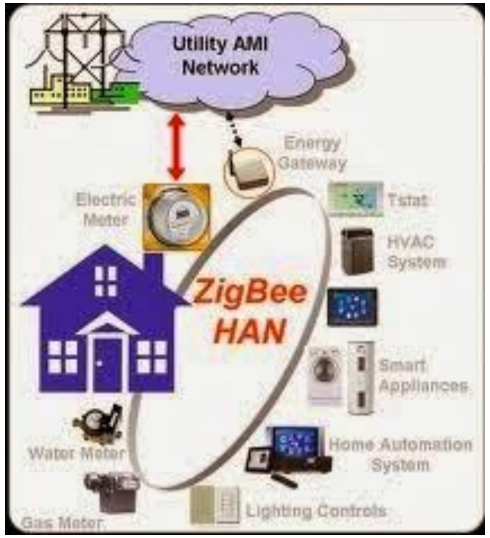
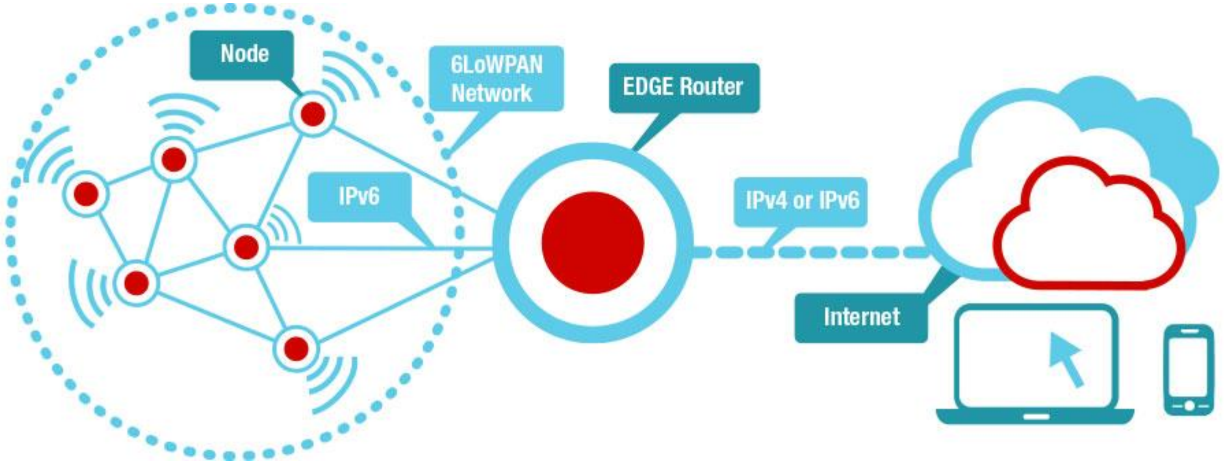
EXTENDING RANGE: MESH NETWORKS

2010s: Mesh networks for IoT

Zigbee



6LoWPAN: IPv6 over low-power wireless personal area networks

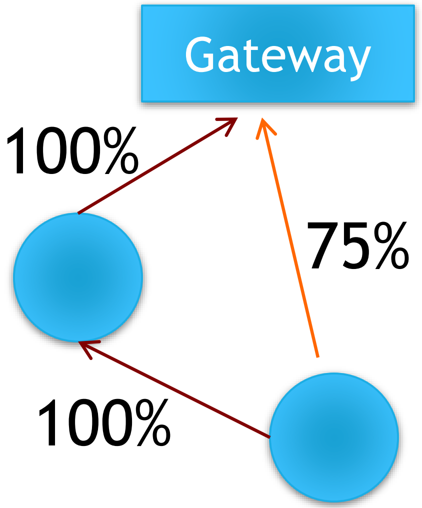


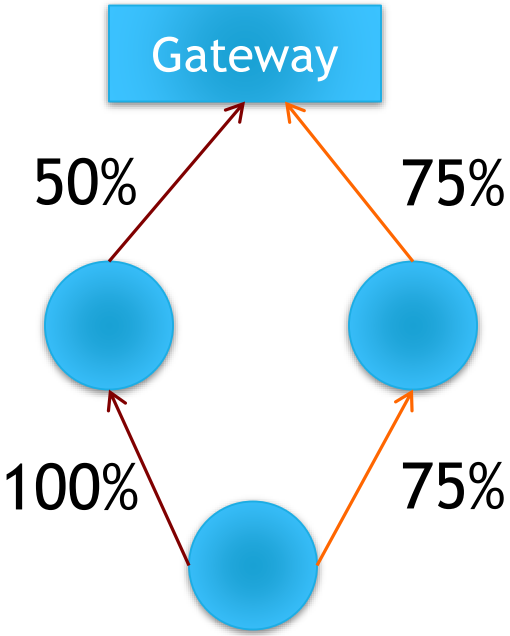
http://processors.wiki.ti.com/index.php/Contiki-6LOWPAN (Creative commons)

Both (typically) run over the 802.15.4 MAC standard
Routing protocol with different metrics, such as “expected transmission time”
Use case: devices communicating with gateway across multiple hops
Node duty cycles higher, some nodes do much more work

WIRELESS MESH ROUTING

Each link delivers a packet with some probability
What path should be used for a packet?



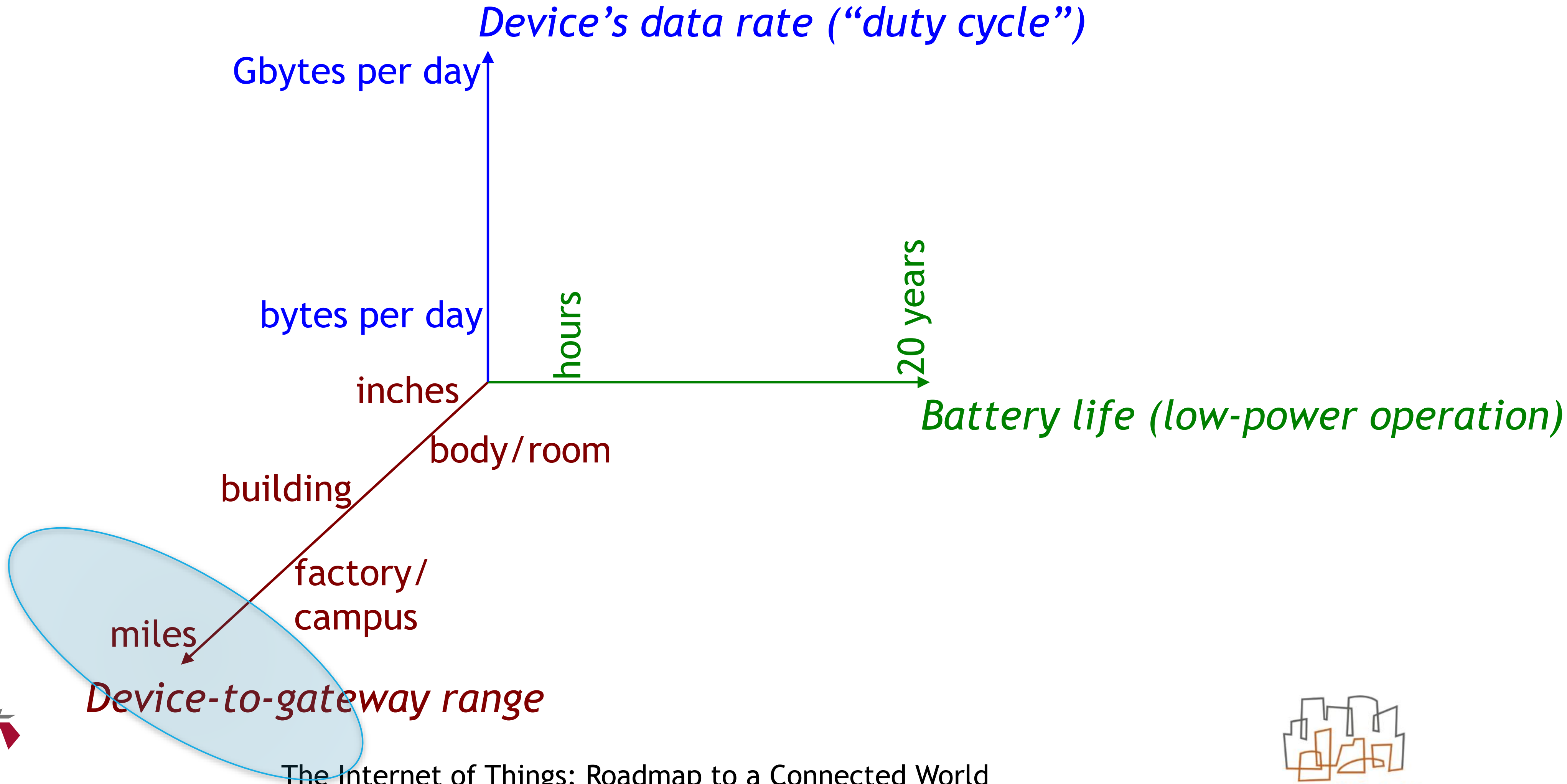


ETX: Expected Transmission Count (expected tx time if link rate fixed)

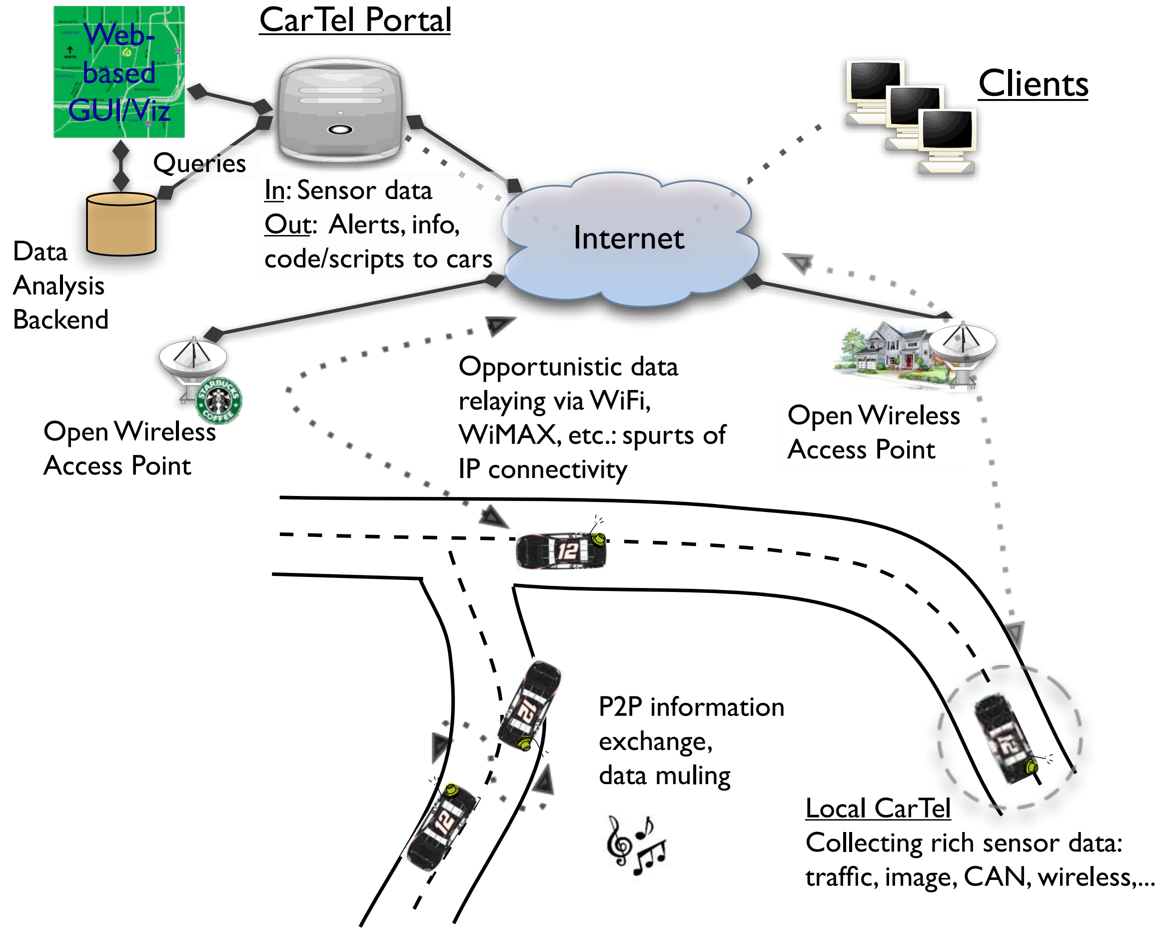
On single link =
1 / Probability of packet delivery

Add for each link on path and pick smallest

EVEN LONGER RANGE (CITY-SCALE)



WHEN THE INTERNET IS MILES AWAY



Use mobile devices as **data mules**

Trade-off: delay

Delay-tolerant network (DTN)

WHAT IF WE WANT LONG RANGE AND LOW DELAY?

"Long-range IoT networks"
Examples: Sigfox, LoRaWAN, cellular IoT proposals (narrowband LTE, etc.)

Low-power designs (months to years of battery life)

Low or ultra-low throughput (a few bytes per day to achieve long-enough battery life at a rate of a few kbps)
Networks like LoRaWAN also include localization capabilities

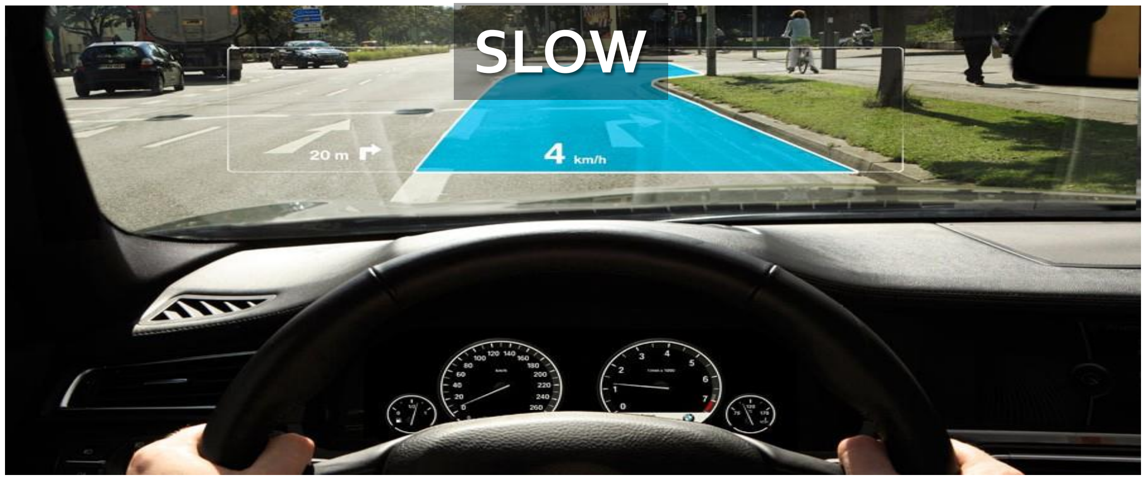
WHAT IF WE WANT LONG RANGE AND LOW DELAY

Second choice: Cellular (of course!)
Examples: LTE/4G, 3G, etc.

High-power consumption, so only when power isn't an issue

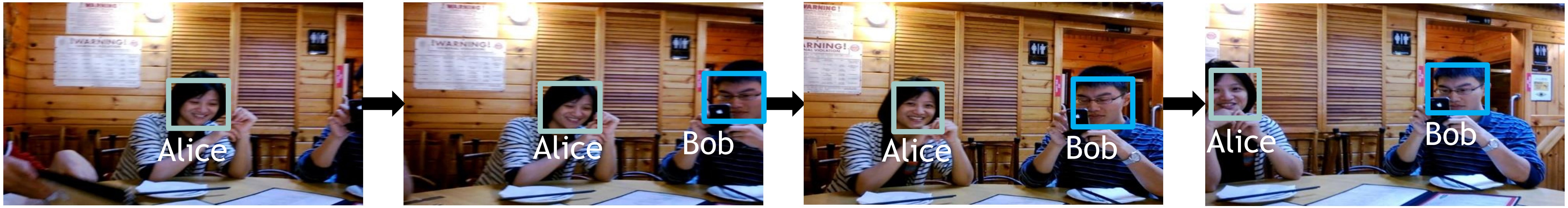
Delay still a concern for **data-intensive, latency-sensitive applications**

CONTINUOUS RECOGNITION APPS



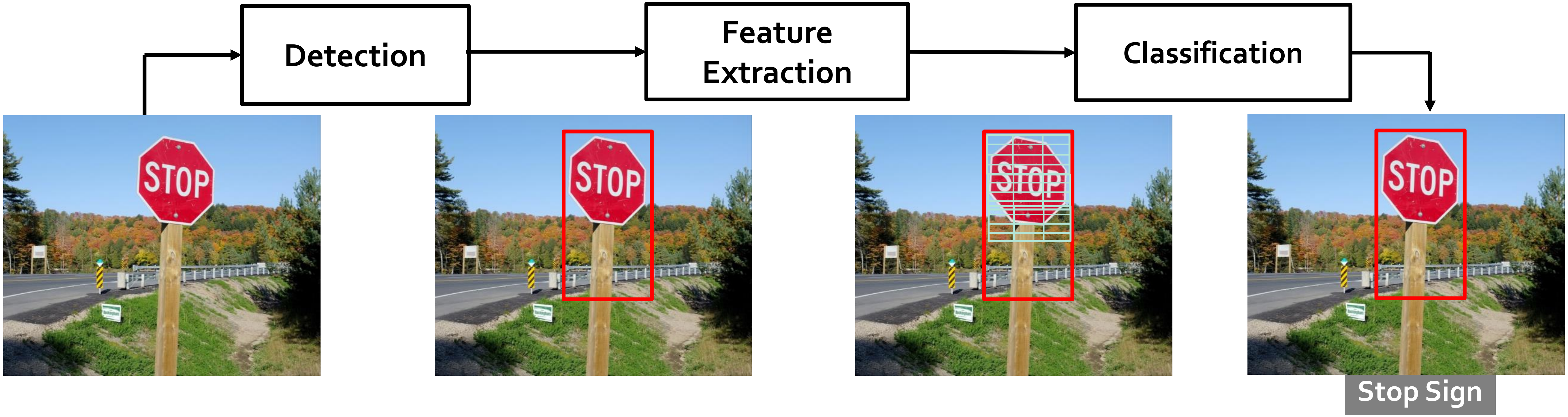
GLIMPSE: CONTINUOUS REAL-TIME RECOGNITION

- Continuous, real-time object recognition on mobile devices in a video stream
- Continuously ***identify*** and ***locate*** objects in each frame



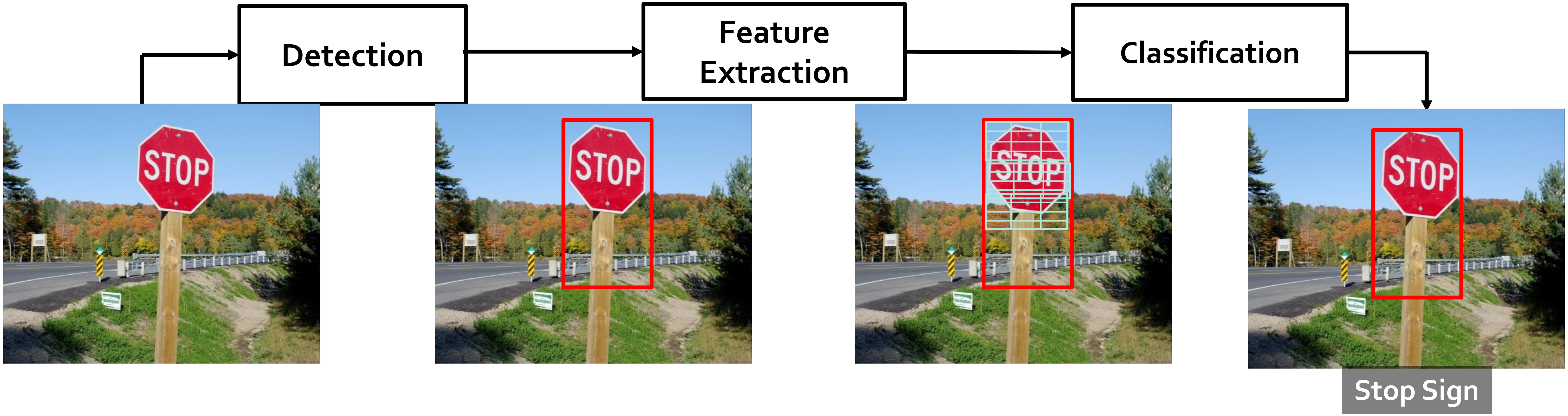
T. Chen, L. Ravindranath, S. Deng, P. Bahl, H. Balakrishnan, SenSys 2015

RECOGNITION PIPELINE



T. Chen, L. Ravindranath, S. Deng, P. Bahl, H. Balakrishnan, SenSys 2015

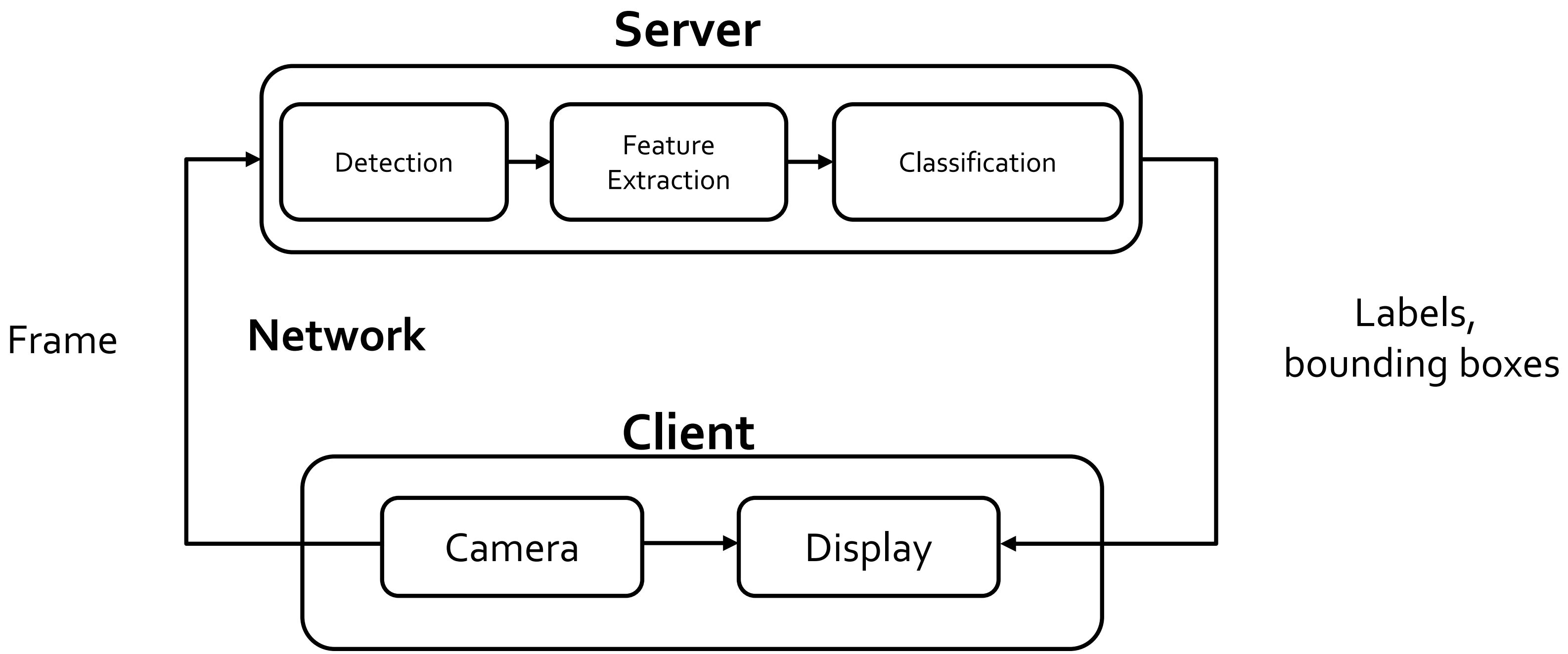
RECOGNITION PIPELINE



Computationally expensive and memory-intensive

- Server is hundreds of times faster than embedded/mobile computer
- Scaling to large number of images requires servers

SOLUTION: SERVER OFFLOAD

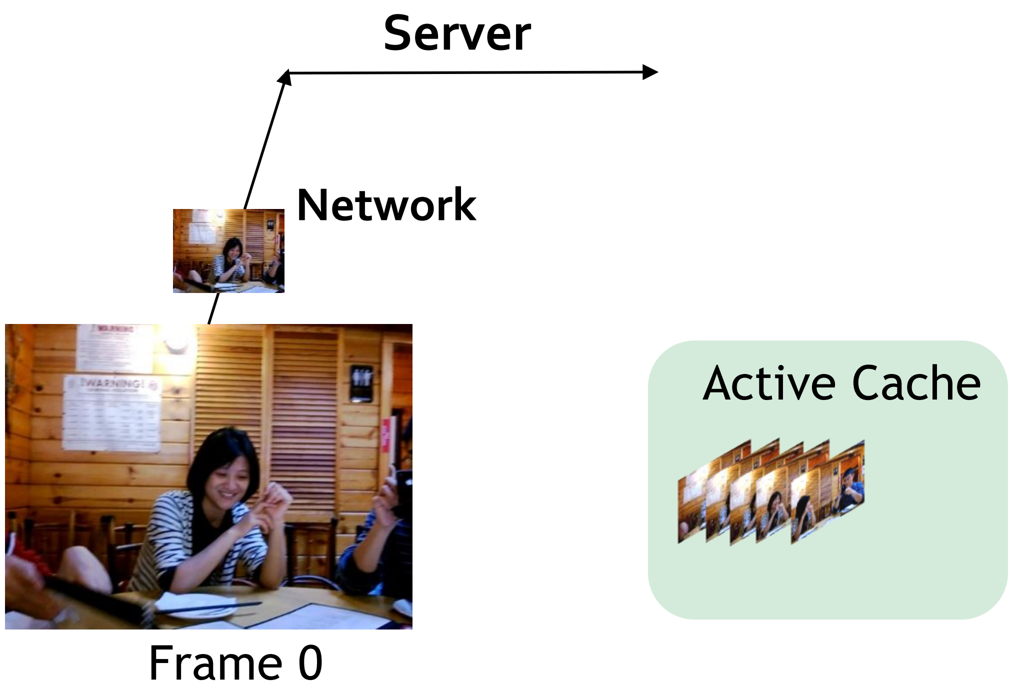


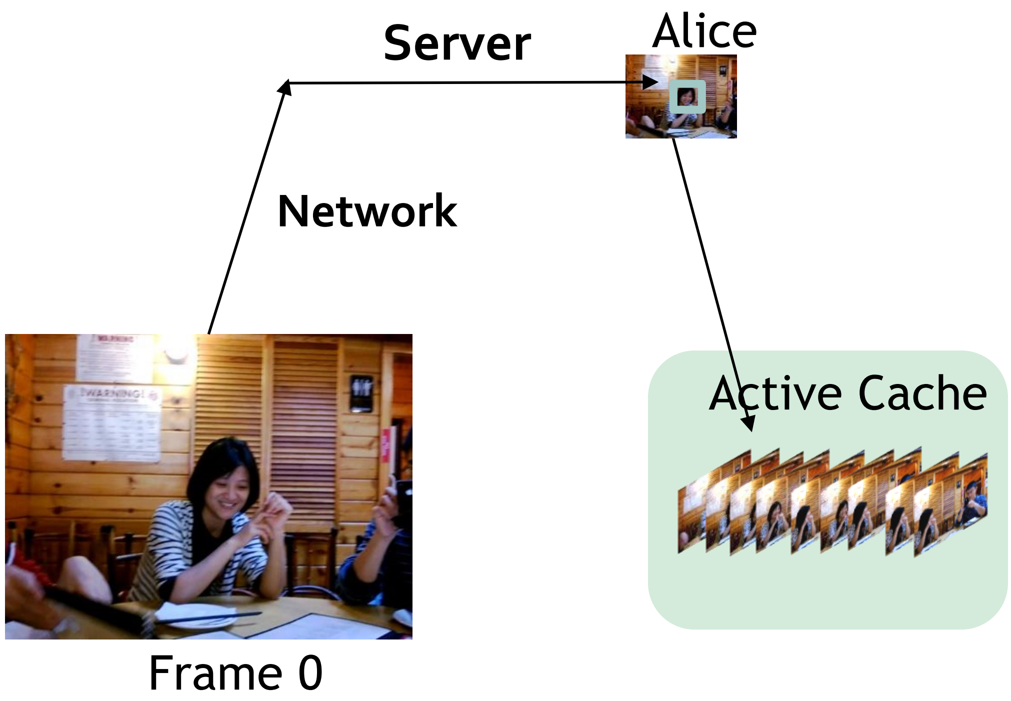
Two big challenges

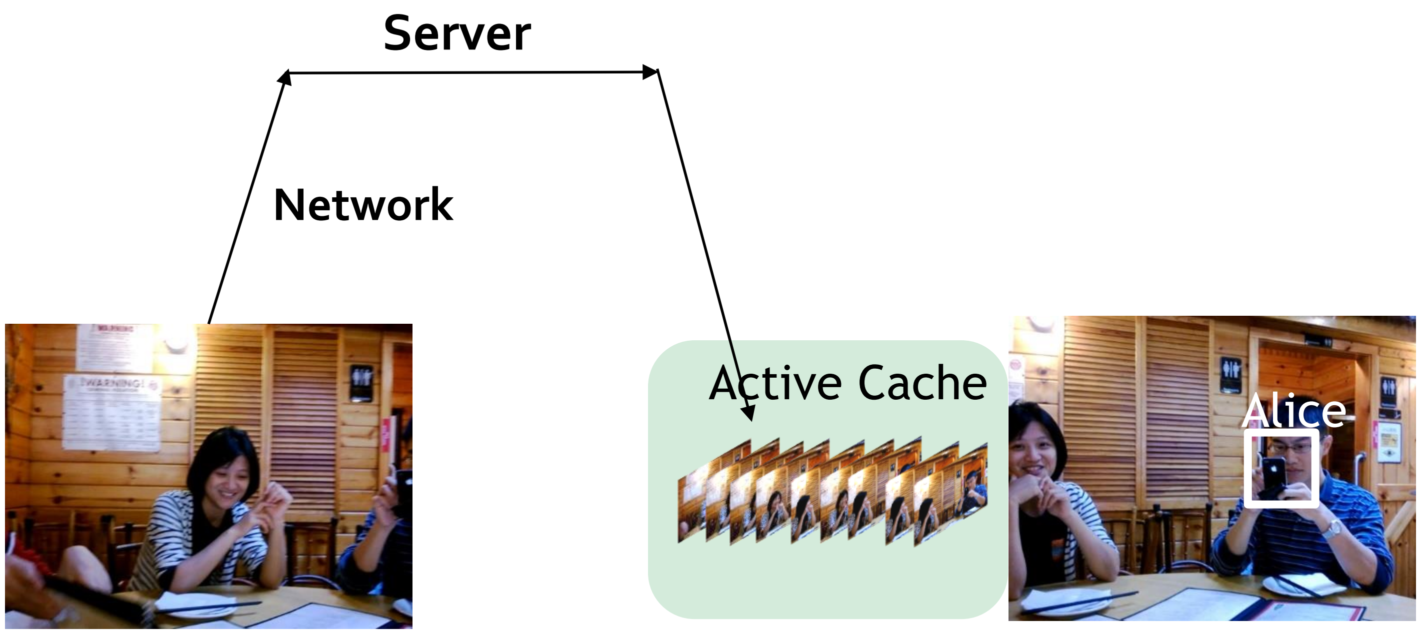
1. **End-to-end latency** lowers object recognition accuracy
2. **Bandwidth** and **battery-**efficiency

IDEA: DEVICE-SIDE ACTIVE CACHE

Cache and run tracking through the cached frames




Server
Alice
Network
Active Cache
Frame 0



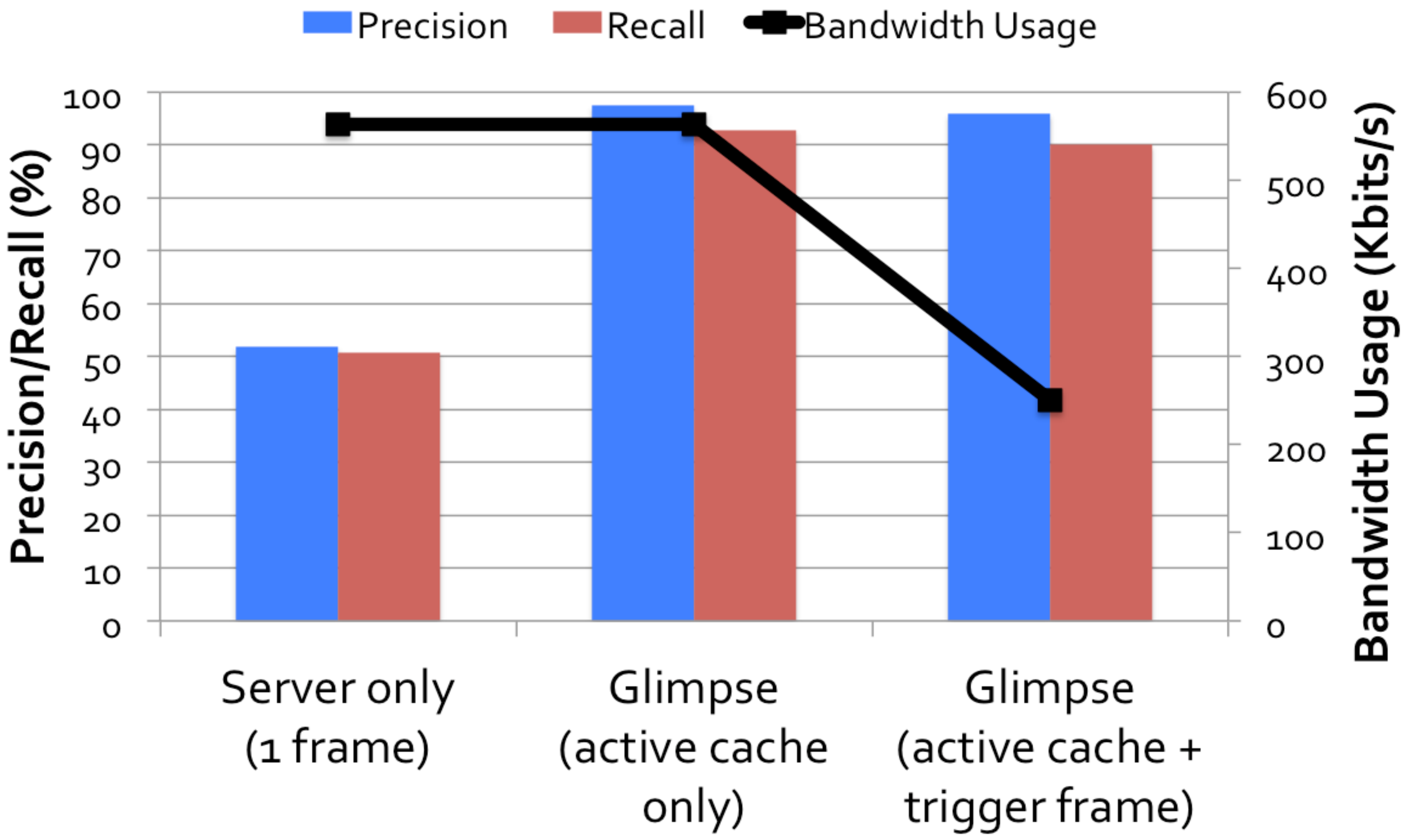
Frame 0

Frame 30

Run tracking from Frame 0 to Frame 30

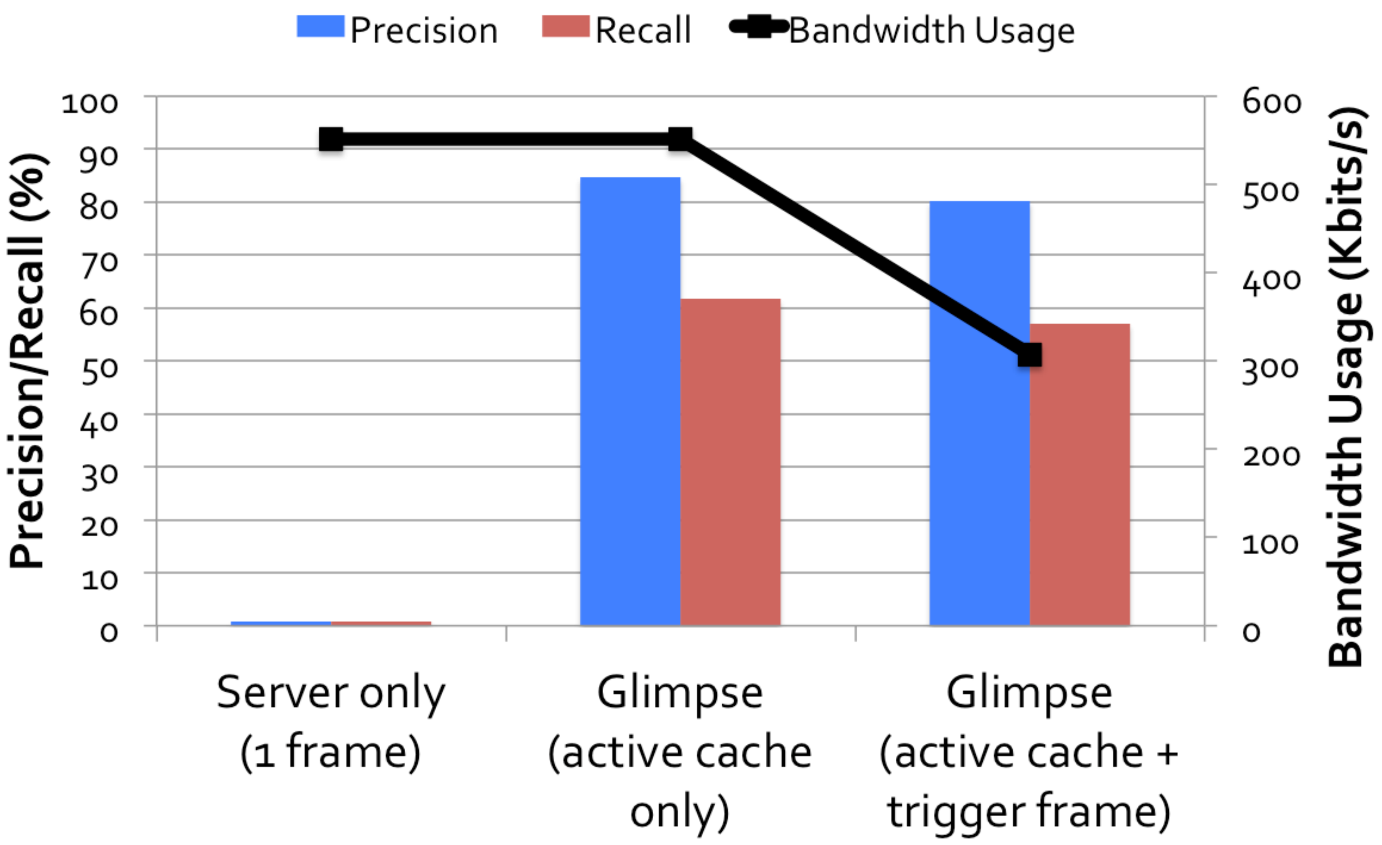
PERFORMANCE ON FACES

Average end-to-end frame delay to server and back: 430 ms



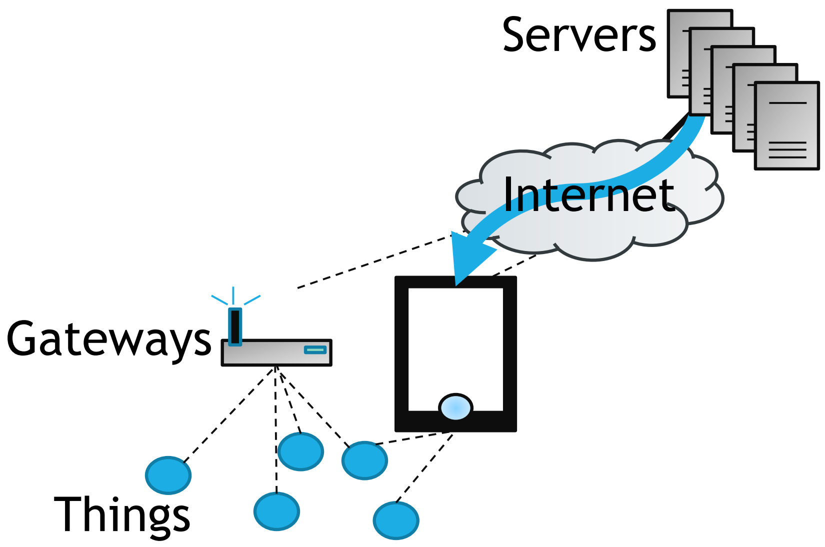
PERFORMANCE ON ROAD SIGNS

Average end-to-end frame delay to server and back: 520 ms



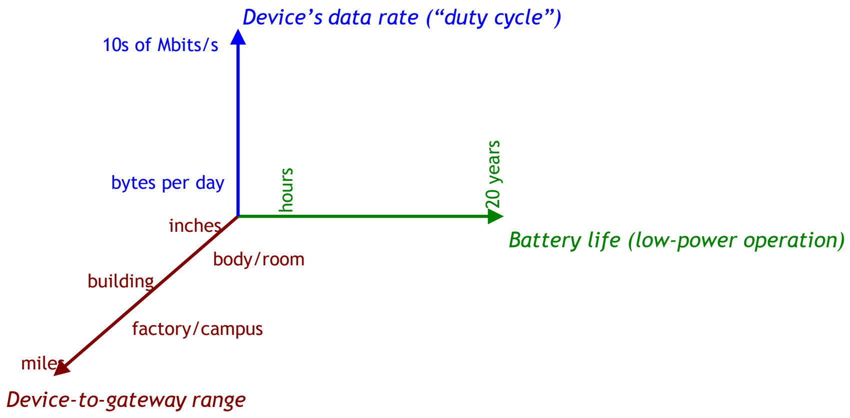
WHAT HAVE WE LEARNED?

Rich design space for things-gateway communication



Think along three dimensions:

1. data rate/duty cycle
2. battery
3. range



Three case studies

1. Low-power design (Bluetooth LE): advertisement, time-scheduled MAC
2. Range extension techniques: muling & meshing (Zigbee, 6LoWPAN)
3. Data-intensive IoT: continuous recognition

OPEN QUESTIONS AND FUTURE WORK

We are not even at the end of the beginning of IoT!
(Who wants to turn on a light bulb by going to an app?!)

What if you want city-scale, high-rate, low-power sensing?
(e.g., high-fidelity vibration, weather, image sensors)

Current systems gated by standby power (microWatts)
Recent advances have shown nanoWatt standby power
How will this change IoT networks?

Current IoT apps are "siloed" from each other
How to integrate them?

DE-SILOING

Today: build IoT devices/sensors, build an app, build a cloud service
Vertically-integrated: hard to integrate and slows innovation
Gateway functions are repeatedly invented

The issue: real value is in the data, not in the devices!

Possible (non-exclusive) approaches

1. Coordinate access to data via server-side APIs in the cloud
2. Provide access to data in smartphone apps via "kits" (HomeKit, Healthkit, Google Fit, …)
3. Develop a generic gateway (multiple technologies)

PREDICTIONS

1. Shake-up in standards: multiple winners, but they will divide up the “three-dimensional space”
2. Ultra-low power IoT systems and networks
3. Compute-intensive (data-intensive) IoT systems and networks
4. De-siloed architectures
5. Smarthone-centric v. hidden (ubiquitous) computing

THANK YOU!

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