6.808 Mobile and Sensor Computing

aka IoT Systems

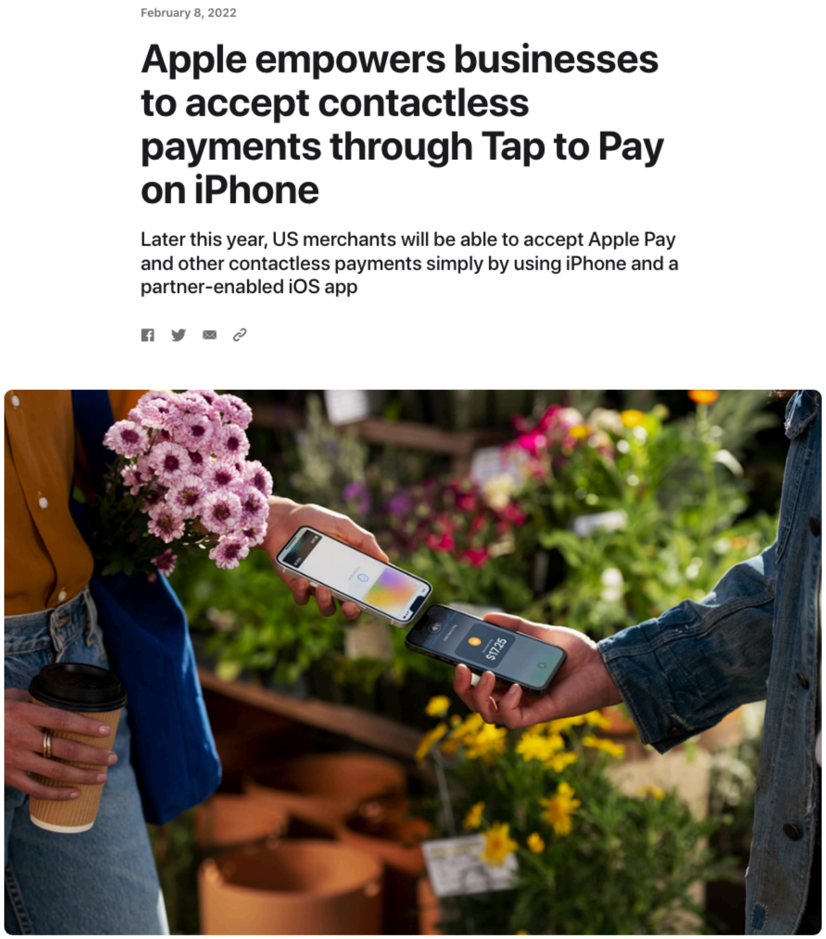
http://6808.github.io

Lecture #5:

Network Connectivity for IoT Systems

Hari Balakrishnan

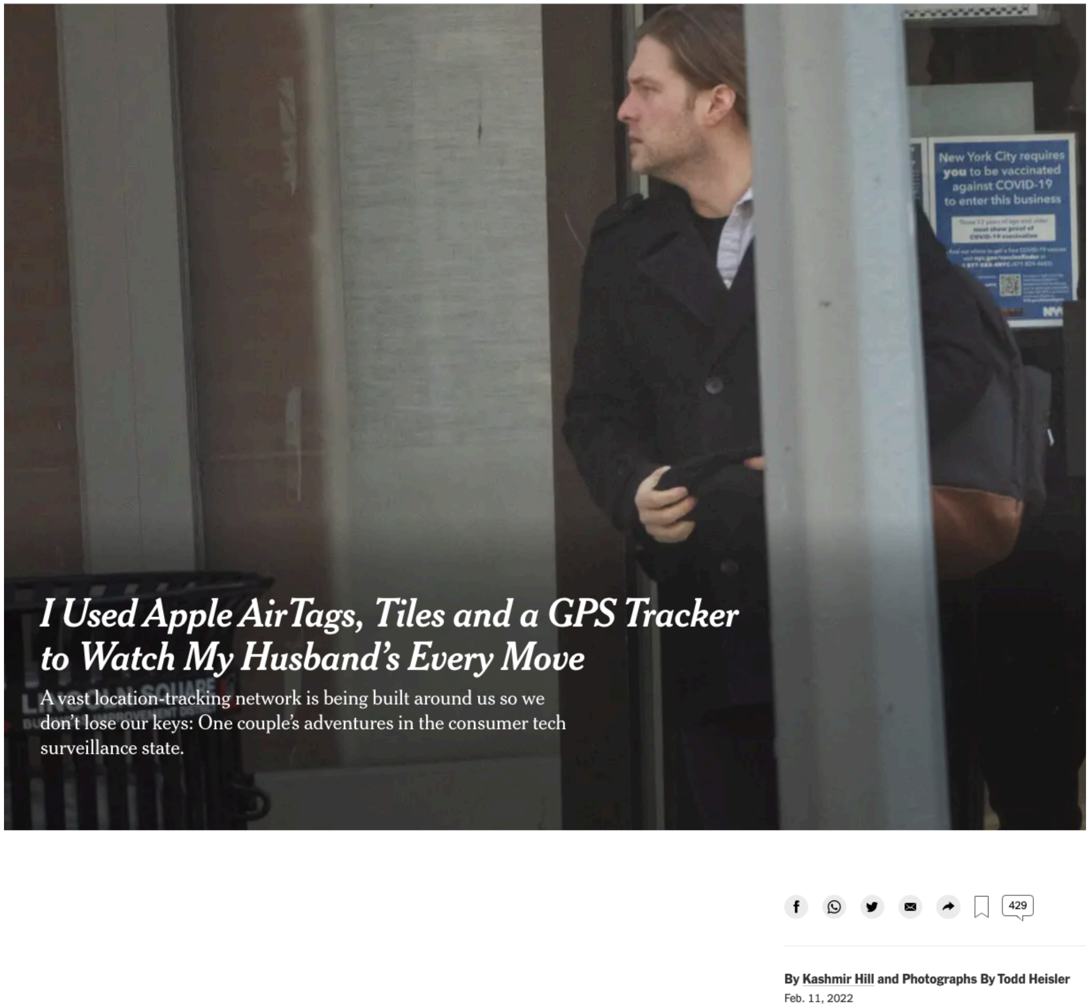
Spring 2022



February 8, 2022

Apple empowers businesses to accept contactless payments through Tap to Pay on iPhone

Later this year, US merchants will be able to accept Apple Pay and other contactless payments simply by using iPhone and a partner-enabled iOS app



I Used Apple AirTags, Tiles and a GPS Tracker to Watch My Husband's Every Move

A vast location-tracking network is being built around us so we don't lose our keys: One couple's adventures in the consumer tech surveillance state.

By Kashmir Hill and Photographs By Todd Heisler
Feb. 11, 2022

Objectives of the Upcoming Three Lectures

Learn the fundamentals, applications, and implications of
IoT network technologies

1. What are the various classes of network technologies? And how do we choose the right technology for a given application?
2. What are various routing architectures for wireless networks & IoT systems?
3. How does energy impact IoT device design?
4. How do batteryless IoT systems work?

NETWORKING: “GLUE” FOR THE IOT

IoT’s “technology push” from the convergence of

- Embedded computing
- Miniaturized sensing (MEMS)
- **Wireless network connectivity**

THE IOT CONNECTIVITY 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

a b g WiFi n ac

Lte™ 4DVANCED

4G LTE

5G

Z WAVE

SIGFOX One network A billion dreams

INGENU

WEIGHTLESS™

INSTEON®

enocean

ALLSEEN ALLIANCE AllJoyn® Framework

THREAD

OPEN INTERCONNECT CONSORTIUM℠

industrial internet® CONSORTIUM

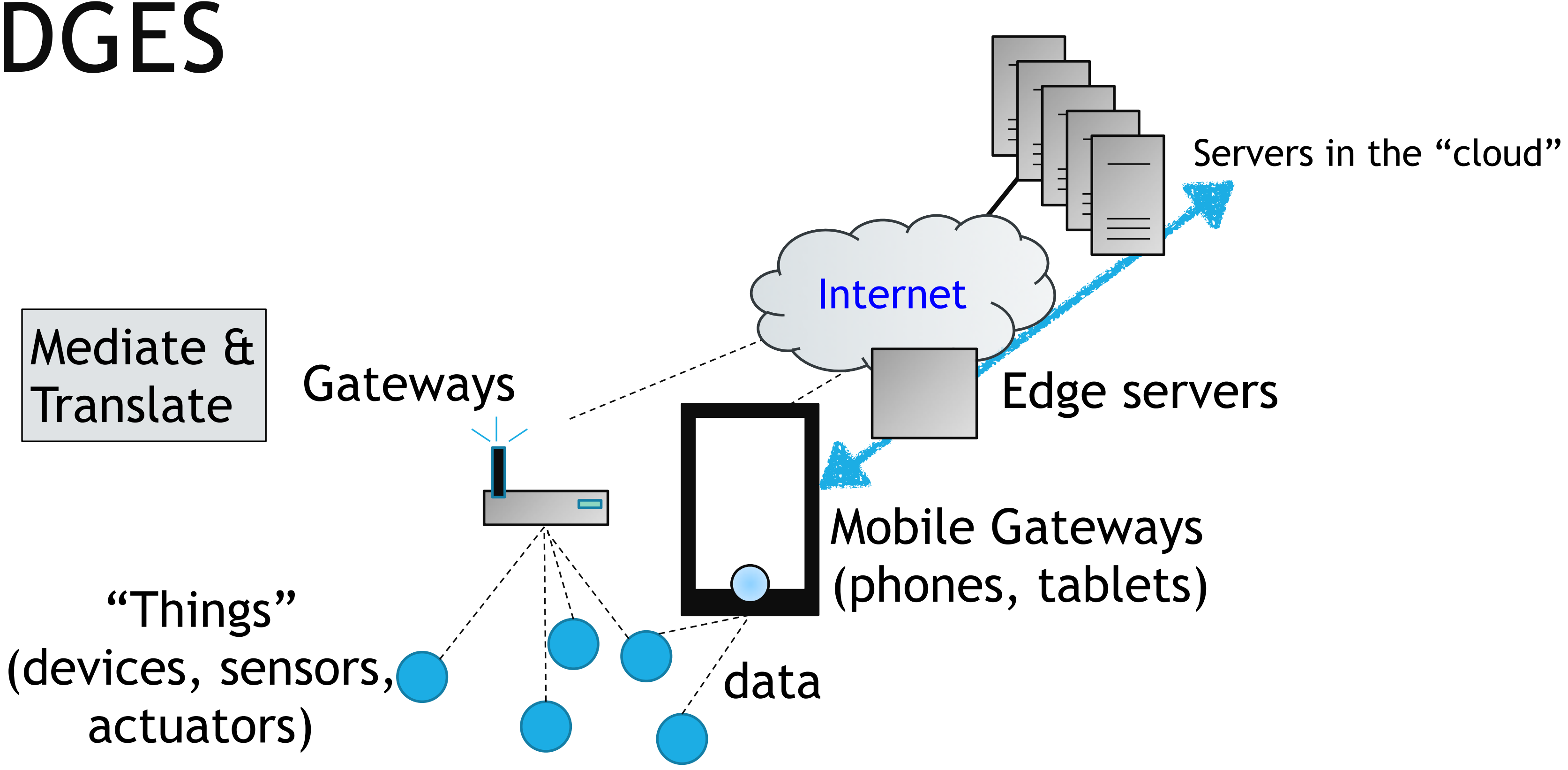
NETWORKING: “GLUE” FOR THE IOT

Many different approaches, many different proposed standards.
Much confusion

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

What are the key organizing principles and ideas?

ARCHITECTURE:DIRECT, GATEWAYS EDGES



Servers in the “cloud”

Internet

Mediate & Translate

Gateways

Edge servers

Mobile Gateways (phones, tablets)

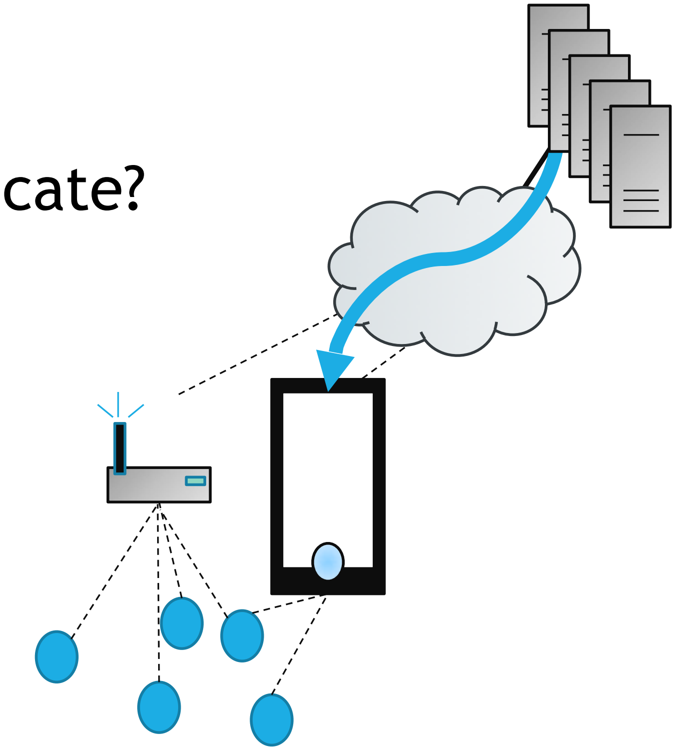
“Things” (devices, sensors, actuators)

data

BUT, IN FACT, A RICH DESIGN SPACE

How should gateways and things communicate?

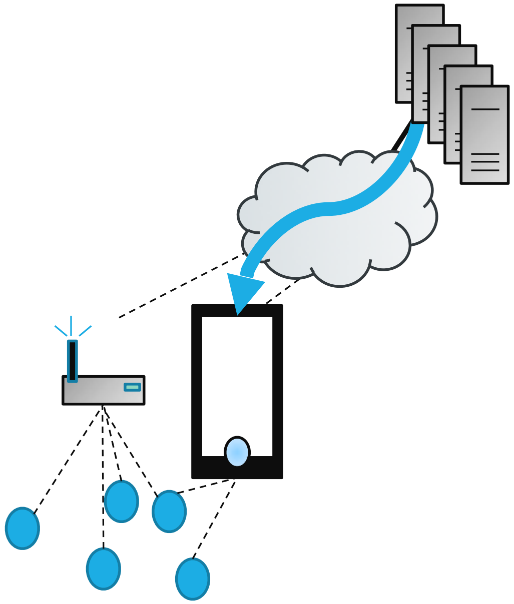
Many answers, many approaches



CAN'T WE JUST USE THE WIRELESS INTERNET?

Cellular and Wi-Fi

Yes, we can…
except when we can't!



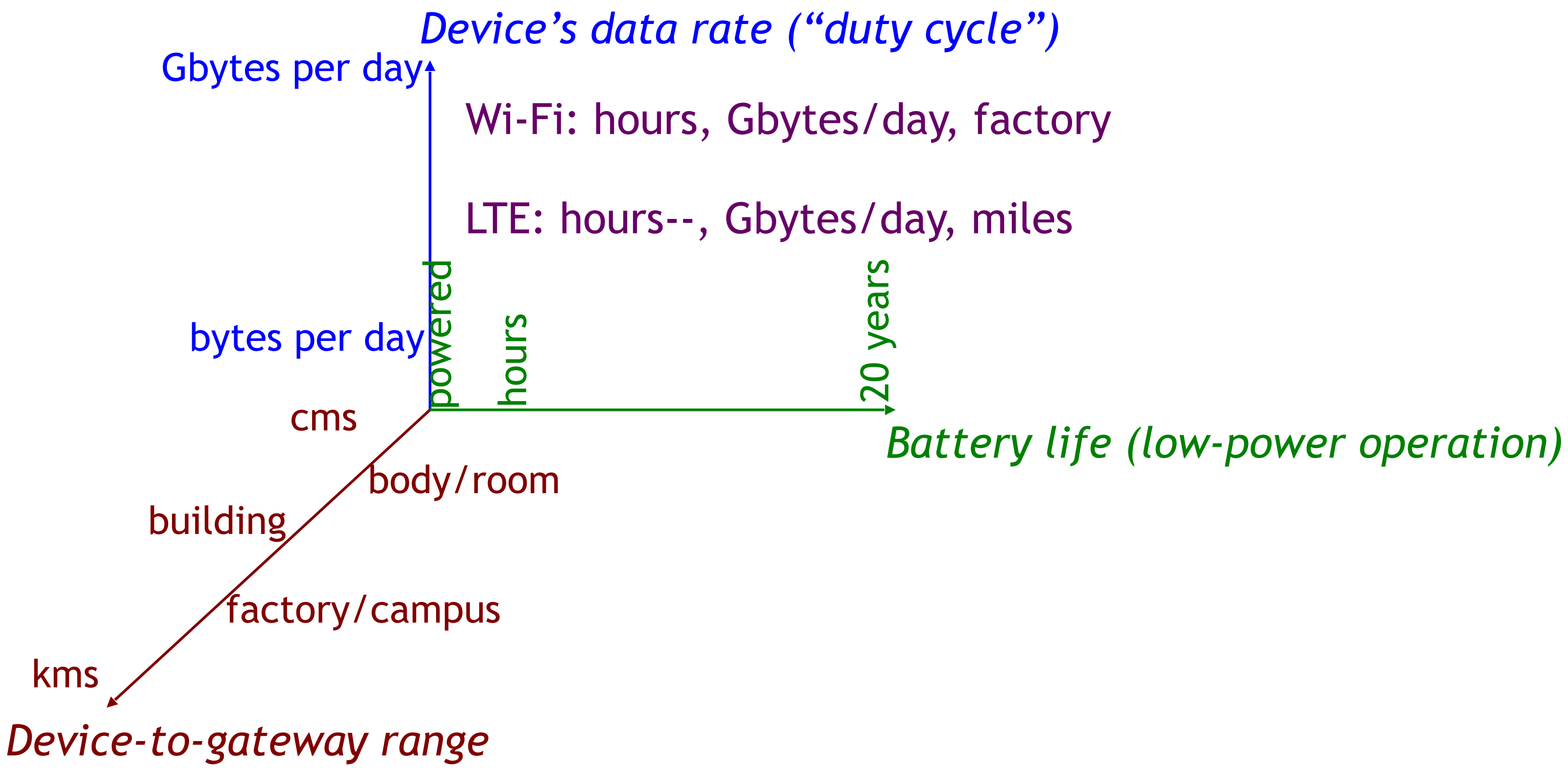
WIRELESS INTERNET FOR IOT?

Cellular (5G, LTE/4G, 3G, 2G) and Wi-Fi are
+ Widely available (cellular in the wide-area and Wi-Fi for static uses)
+ High bandwidth (for most purposes), so can support high-rate apps

But, each has two big drawbacks
- **High power**: not ideal 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")

IOT NETWORK DESIGN SPACE



Device's data rate ("duty cycle")

Gbytes per day

bytes per day

Wi-Fi: hours, Gbytes/day, factory

LTE: hours--, Gbytes/day, miles

powered

hours

20 years

Battery life (low-power operation)

cms

body/room

building

factory/campus

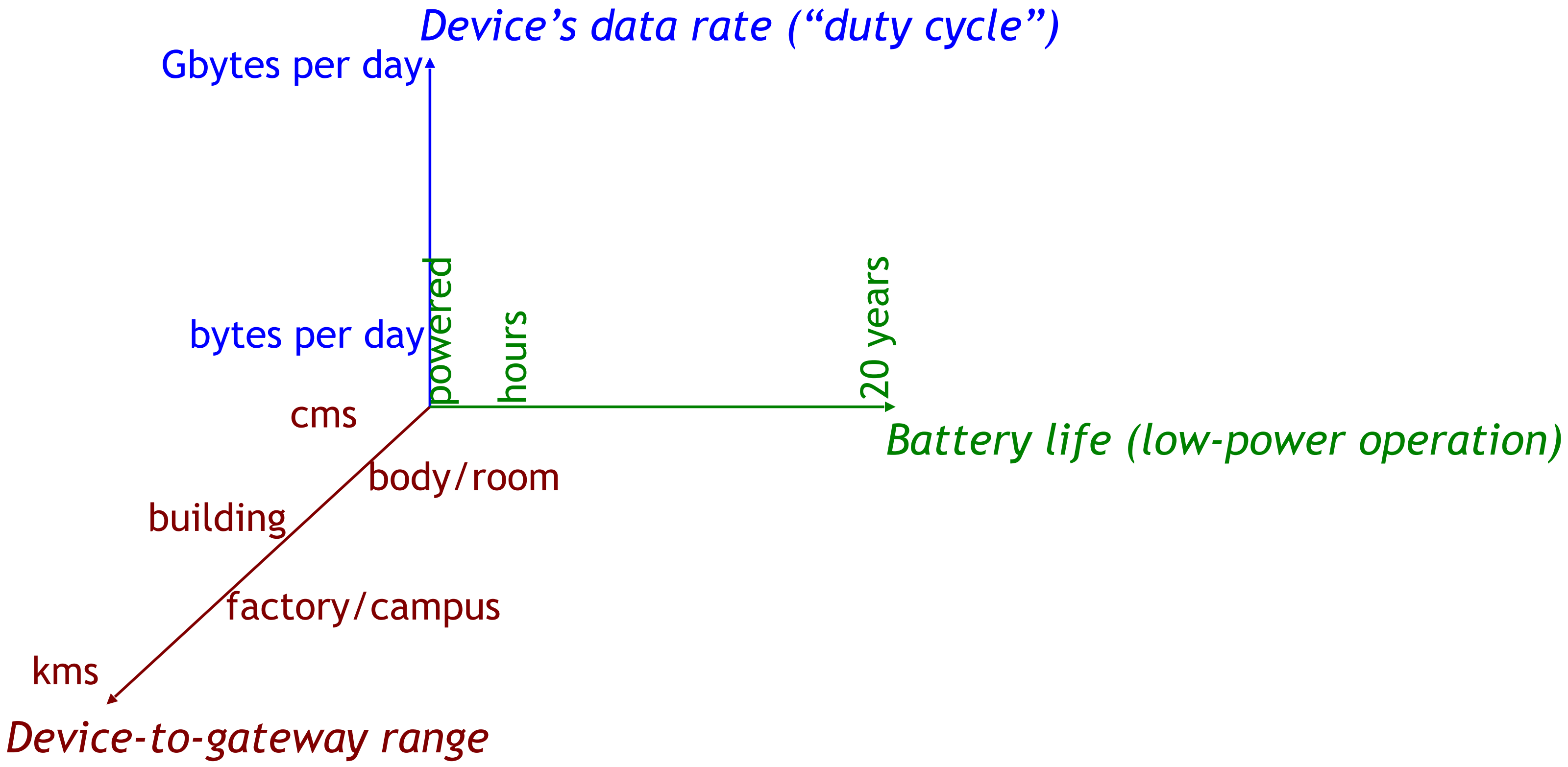
kms

Device-to-gateway range

WHY SO MANY IOT NETWORKS?

Because engineers love inventing technologies!

Because you can pick from this design space

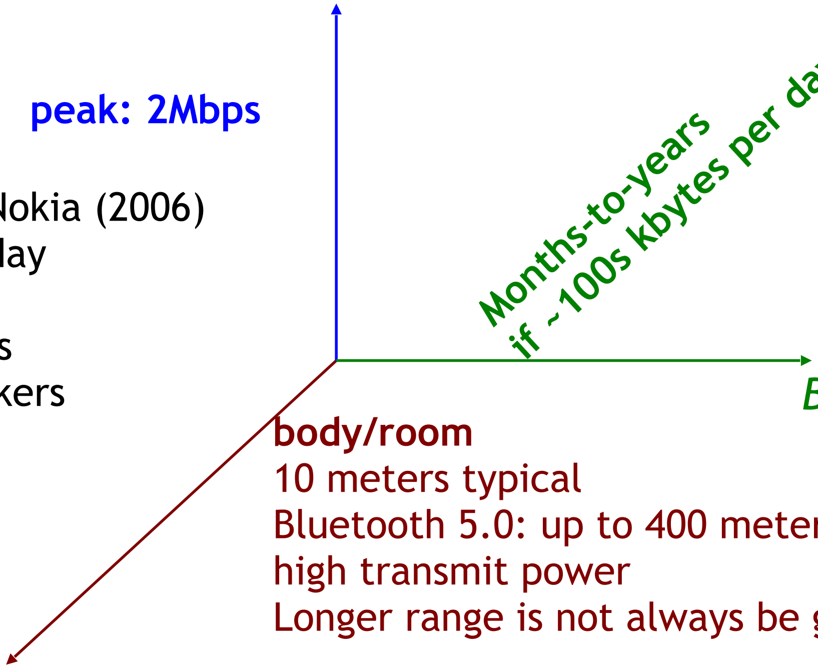


WHY SO MANY IOT NETWORKS?

- 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

BLUETOOTH LOW ENERGY (BLE): "ROOM"-AREA

Bluetooth® SMART



Device's data rate ("duty cycle")

peak: 2Mbps

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

Battery life (low-power operation)

body/room
10 meters typical
Bluetooth 5.0: up to 400 meters under good conditions with high transmit power
Longer range is not always be good

Device-to-gateway range

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

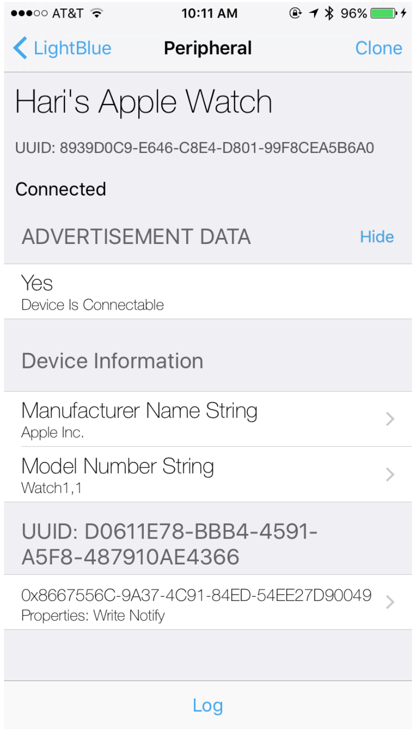
HOW DOES BLE WORK?

Two parts:

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

Peripheral: device with data
Central: gateway

BLE ADVERTISEMENTS ARE PERIODIC



Hari's Apple Watch

UUID: 8939D0C9-E646-C8E4-D801-99F8CEA5B6A0

Connected

ADVERTISEMENT DATA

Yes
Device Is Connectable

Device Information

Manufacturer Name String
Apple Inc.

Model Number String
Watch1,1

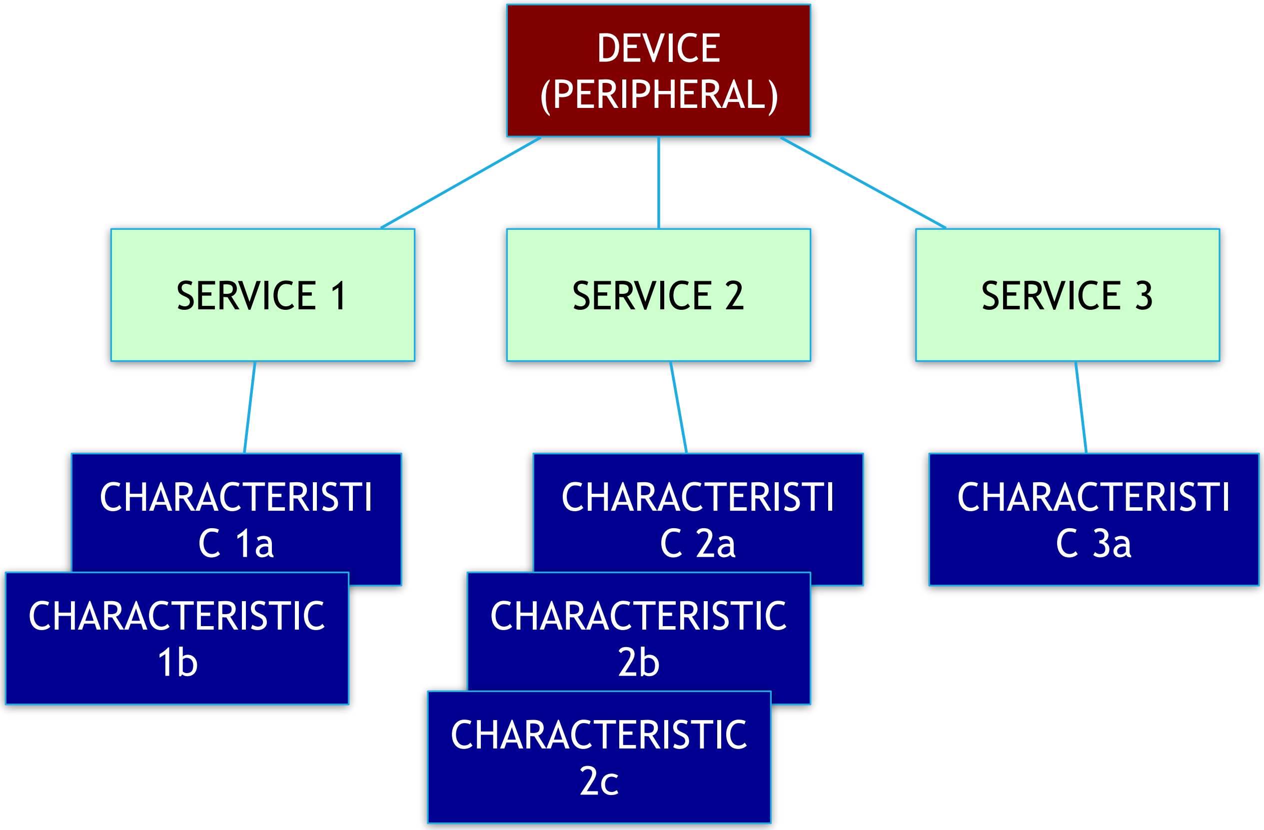
UUID: D0611E78-BBB4-4591-A5F8-487910AE4366

0x8667556C-9A37-4C91-84ED-54EE27D90049
Properties: Write Notify

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



DEVICE (PERIPHERAL)

SERVICE 1

SERVICE 2

SERVICE 3

CHARACTERISTIC 1a

CHARACTERISTIC 1b

CHARACTERISTIC 2a

CHARACTERISTIC 2b

CHARACTERISTIC 2c

CHARACTERISTIC 3a

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: 1000 mAh (milliamp-hours) capacity; 3 Volts
Recall that power = voltage * current and energy = power * time
So this battery has 3 amp-hour-volts = 3*3600 Joules = 10.8 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.)

Consider an IoT system with coin-cell battery-powered nodes
Battery: 1000 mAh capacity and 3 Volts
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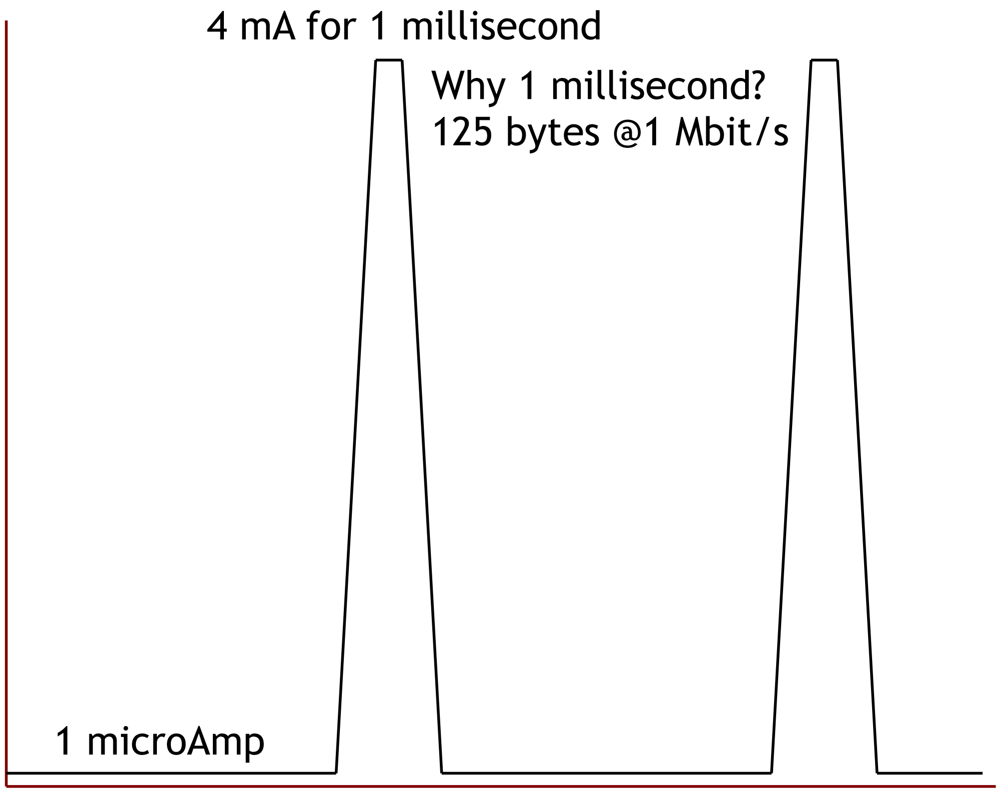
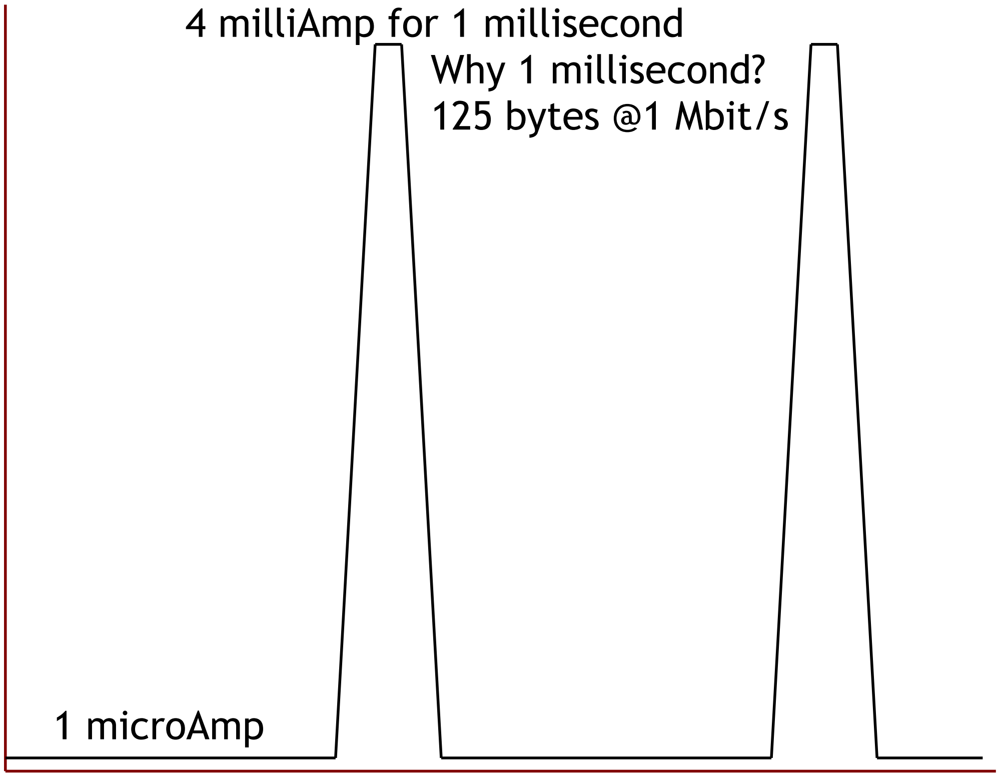
Example of BLE current draw:
Standby: 1 microAmp (typically in the 1-10 microAmp range)
Receive (RX): 3.3 mA
Transmit (TX): 4 mA
Ramping up and down (combined): 1 mA for 5 ms

Suppose device transmits every second: how long does the battery last?
Depends on how long the xmit lasts: let's assume 125 bytes at 1 Mbit/s (i.e. 1 ms)



BATTERY CALCULATION (CONT.)



Why 1 millisecond?
125 bytes @1 Mbit/s

Battery capacity: 1000 mAh (milliAmp-hours)
Ramp-up and down: 1 milliAmp for 5 milliseconds

Energy consumed in 1 second is:
(4*0.001 (xmit) +
1*0.005 (ramping) +
1 microAmp (standby)) x 3V
= 10 microAmps x 3V

Therefore, battery lifetime
= 1000 mAh / 10 microAmps
= 1000 mAh / 0.01 mA
= 100,000 hours
= 11+ years!

Saves energy because it’s sleeping most of the time!

But of course an IoT device also does sensing,
some computation, perhaps some storage, etc.

“THE IOT GATEWAY PROBLEM”

Application-level gateways prevalent for IoT today
Usually need a smartphone app to interact with IoT data/devices
Problem: “Siloed” architecture

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Should smartphones become generic BLE gateways (with OS support)
Any phone talking with any peripheral device via BLE

- Should phones become IPv6 routers for peripheral devices?
- Should phone proxy a device’s Bluetooth profile to cloud servers?

“THE IOT GATEWAY PROBLEM”

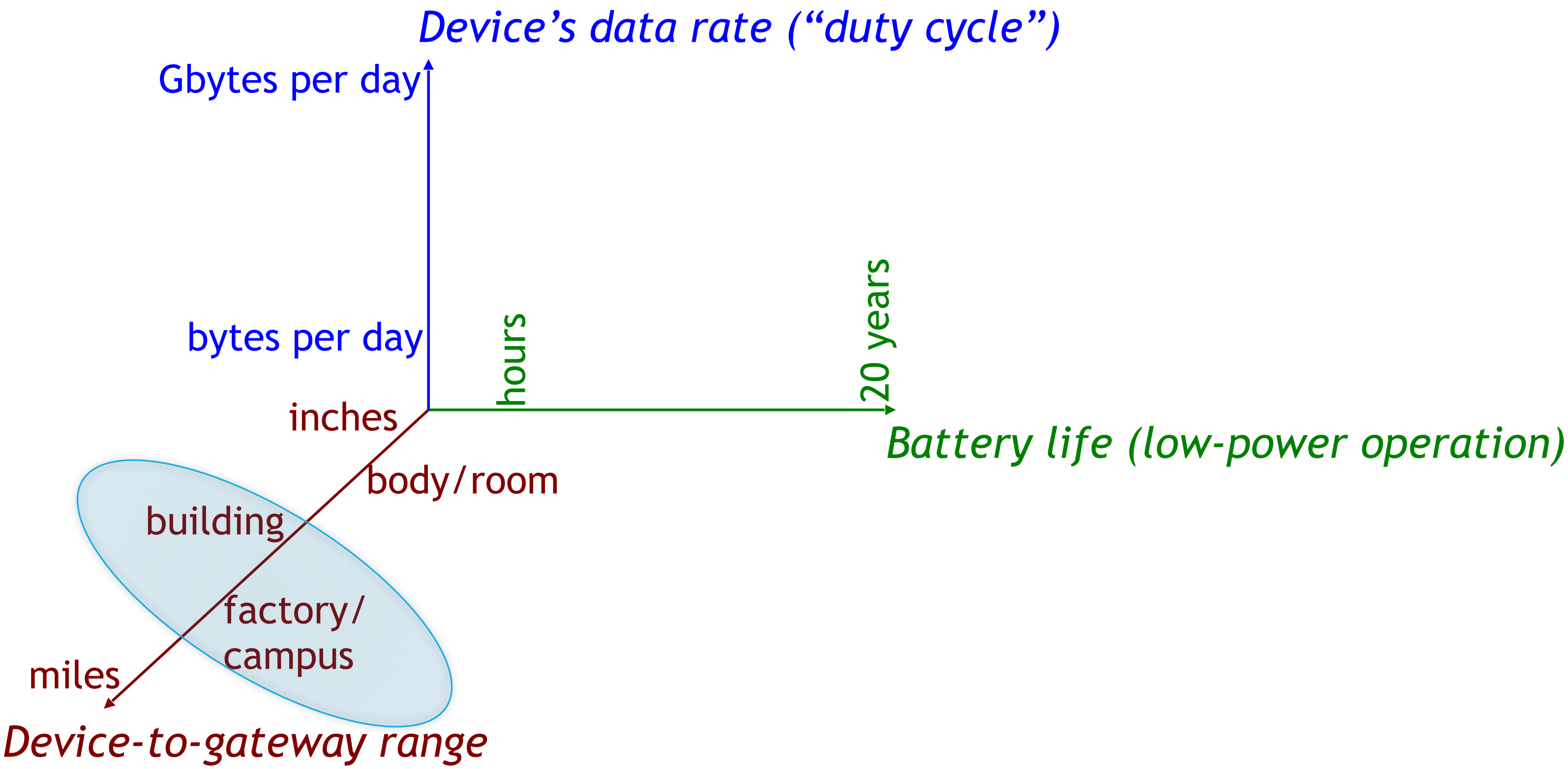
Should smartphones become generic BLE gateways (with OS support)
Any phone talking with any peripheral device via BLE

- Should phones become IPv6 routers for peripheral devices?
- Should phone proxy a device’s Bluetooth profile to cloud servers?

Is this a good idea? Will it work?

Value is in the data, not connectivity
Incentives are a problem
    For device makers?
    For app developers?
    For smartphone users?

EXTENDING COMMUNICATION RANGE



EXTENDING RANGE: MESH NETWORKS

1980s: DARPA packet radio networks

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.

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-

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

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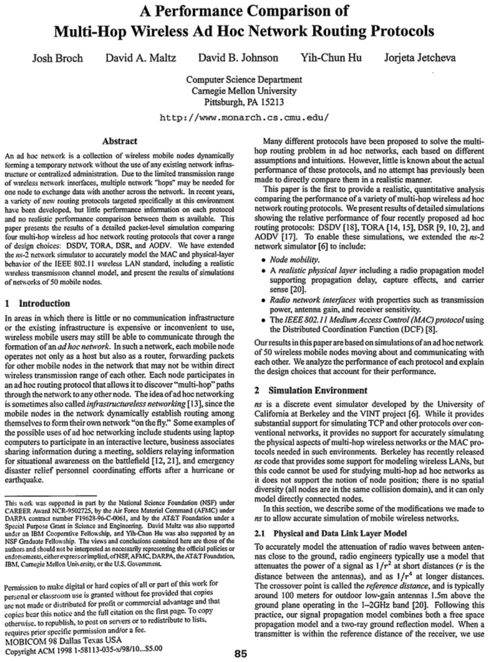
1990s: mobile ad hoc networks (MANET)



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

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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.

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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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.

MOBICOM 98 Dallas Texas USA

EXTENDING RANGE: MESH NETWORKS

Late 90s, 2000s: Sensor networks

Next Century Challenges: Scalable Coordination in Sensor Networks

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Abstract

Networked sensors—those that coordinate amongst themselves to achieve a larger sensing task—will revolutionize information gathering and processing both in urban environments and in inhospitable terrain. The sheer numbers of these sensors and the expected dynamics in these environments present unique challenges in the design of unattended autonomous sensor networks. These challenges lead us to hypothesize that sensor network coordination applications may need to be structured differently from traditional network applications. In particular, we believe that *localized algorithms* (in which simple local node behavior achieves a desired global objective) may be necessary for sensor network coordination. In this paper, we describe localized algorithms, and then discuss *directed diffusion*, a simple communication model for describing localized algorithms.

1 Introduction

Integrated low-power sensing devices will permit remote object monitoring and tracking in many different contexts: in the field (vehicles, equipment, personnel), the office building (projectors, furniture, books, people), the hospital ward (syringes, bandages, IVs) and the factory floor (motors, small robotic devices). Networking these sensors—empowering them with the ability to *coordinate* amongst themselves on a larger sensing task—will revolutionize information gathering and processing in many situations. Large scale, dynamically changing, and robust sensor colonies can be deployed in inhospitable physical environments such as remote geographic regions or toxic urban locations. They will also enable low maintenance sensing in more benign, but less accessible, environments: large industrial plants, aircraft interiors etc.

To motivate the challenges in designing these sensor networks, consider the following scenario. Several thousand sensors are rapidly deployed (*e.g.*, thrown from an aircraft) in remote terrain. The sensors coordinate to establish a communication network, divide the task of mapping and monitoring the terrain amongst themselves in an energy-efficient manner, adapt their overall sensing accuracy to the remaining total resources, and re-organize upon sensor failure. When additional sensors are added or old sensors fail, the sensors re-organize themselves to take advantage of the added system resources.

Several aspects of this scenario present systems design challenges different from those posed by existing computer networks (Section 2). The *sheer numbers* of these devices, and their unattended deployment, will preclude reliance on broadcast communication or the configuration currently needed to deploy and operate networked devices. Devices may be battery constrained or subject to hostile environments, so individual *device failure* will be a regular or common event. In addition, the configuration devices will *frequently change* in terms of position, reachability, power availability, and even task details. Finally, because these devices interact with the physical environment, they, and the network as a whole, will experience a significant range of *task dynamics*.

The WINS project [1] has considered device-level communication primitives needed to satisfy these requirements. However, these requirements potentially affect many other aspects of network design: routing and addressing mechanisms, naming and binding services, application architectures, security mechanisms, and so forth. This paper focuses on the principles underlying the design of services and applications in sensor networks. In particular, since the sensing is inherently distributed, we argue that sensor network applications will themselves be distributed.

Many of the lessons learned from Internet and mobile network design will be applicable to designing sensor network applications. However, this paper hypothesizes that sensor networks have different enough requirements to at least warrant re-considering the overall structure of applications and services. Specifically, we believe there are significant robustness and scalability advantages to designing applications using *localized* algorithms—where sensors only interact with other sensors in a restricted vicinity, but nevertheless collectively achieve a desired global objective (Section 3). We also describe *directed diffusion*, a promising model for describing localized algorithms (Section 4).

Our research project is starting to investigate the design of localized algorithms using the directed diffusion model. These ideas were developed in the context of a DARPA ISAT study, chaired by one of the authors (Estrin). The

Mobicom '99 Seattle Washington USA

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*

***Abstract*—Networking together hundreds or thousands of cheap microsensor nodes allows users to accurately monitor a remote environment by intelligently combining the data from the individual nodes. These networks require robust wireless communication protocols that are energy efficient and provide low latency. In this paper, we develop and analyze low-energy adaptive clustering hierarchy (LEACH), a protocol architecture for microsensor networks that combines the ideas of energy-efficient cluster-based routing and media access together with application-specific data aggregation to achieve good performance in terms of system lifetime, latency, and application-perceived quality. LEACH includes a new, distributed cluster formation technique that enables self-organization of large numbers of nodes, algorithms for adapting clusters and rotating cluster head positions to evenly distribute the energy load among all the nodes, and techniques to enable distributed signal processing to save communication resources. Our results show that LEACH can improve system lifetime by an order of magnitude compared with general-purpose multihop approaches.**

***Index Terms*—Data aggregation, protocol architecture, wireless microsensor networks.**

I. INTRODUCTION

ADVANCES iN sensor technology, low-power electronics, and low-power radio frequency (RF) design have enabled the development of small, relatively inexpensive and low-power sensors, called *microsensors*, that can be connected via a wireless network. These wireless microsensor networks represent a new paradigm for extracting data from the environment and enable the reliable monitoring of a variety of environments for applications that include surveillance, machine failure diagnosis, and chemical/biological detection. An important challenge in the design of these networks is that two key resources—communication bandwidth and energy—are significantly more limited than in a tethered network environment. These constraints require innovative design techniques to use the available bandwidth and energy efficiently.

In order to design good protocols for wireless microsensor networks, it is important to understand the parameters that are relevant to the sensor applications. While there are many ways in which the properties of a sensor network protocol can be evaluated, we use the following metrics.

A. Ease of Deployment

Sensor networks may contain hundreds or thousands of nodes, and they may need to be deployed in remote or dangerous environments, allowing users to extract information in ways that would not have been possible otherwise. This requires that nodes be able to communicate with each other even in the absence of an established network infrastructure and predefined node locations.

B. System Lifetime

These networks should function for as long as possible. It may be inconvenient or impossible to recharge node batteries. Therefore, all aspects of the node, from the hardware to the protocols, must be designed to be extremely energy efficient.

C. Latency

Data from sensor networks are typically time sensitive, so it is important to receive the data in a timely manner.

D. Quality

The notion of "quality" in a microsensor network is very different than in traditional wireless data networks. For sensor networks, the end user does not require all the data in the network because 1) the data from neighboring nodes are highly correlated, making the data redundant and 2) the end user cares about a higher-level description of events occurring in the environment being monitored. The quality of the network is, therefore, based on the quality of the aggregate data set, so protocols should be designed to optimize for the unique, application- specific quality of a sensor network.

This paper builds on the work described in [11] by giving a detailed description and analysis of low-energy adaptive clustering hierarchy (LEACH), an application-specific protocol architecture for wireless microsensor networks. LEACH employs the following techniques to achieve the design goals stated: 1) randomized, adaptive, self-configuring cluster formation; 2) localized control for data transfers; 3) low-energy media access control (MAC); and 4) application-specific data processing, such as data aggregation or compression. Simulation results show that LEACH is able to achieve the desired properties of sensor networks.

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2000s: Mesh networks for Internet

Architecture and Evaluation of an Unplanned 802.11b Mesh Network

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ABSTRACT

This paper evaluates the ability of a wireless mesh architecture to provide high performance Internet access while demanding little deployment planning or operational management. The architecture considered in this paper has unplanned node placement (rather than planned topology), omni-directional antennas (rather than directional links), and multi-hop routing (rather than single-hop base stations). These design decisions contribute to ease of deployment, an important requirement for community wireless networks. However, this architecture carries the risk that lack of planning might render the network's performance unusably low. For example, it might be necessary to place nodes carefully to ensure connectivity; the omni-directional antennas might provide uselessly short radio ranges; or the inefficiency of multi-hop forwarding might leave some users effectively disconnected.

The paper evaluates this unplanned mesh architecture with a case study of the Roofnet 802.11b mesh network. Roofnet consists of 37 nodes spread over four square kilometers of an urban area. The network provides users with usable performance despite lack of planning: the average inter-node throughput is 627 kbits/second, even though the average route has three hops.

The paper evaluates multiple aspects of the architecture: the effect of node density on connectivity and throughput; the characteristics of the links that the routing protocol elects to use; the usefulness of the highly connected mesh afforded by omni-directional antennas for robustness and throughput; and the potential performance of a single-hop network using the same nodes as Roofnet.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless communication*; C.2.2 [**Computer-Communication Networks**]: Network Protocols—*Routing protocols*

MobiCom'05, August 28–September 2, 2005, Cologne, Germany.

General Terms

Design, Experimentation, Measurement, Performance

Keywords

Mesh networks, Multi-hop wireless networks, Ad hoc networks, Wireless routing, Route metrics

1. INTRODUCTION

Community wireless networks typically share a few wired Internet connections among many users spread over an urban area. Two approaches to constructing community networks are common. The first approach is to carefully construct a multi-hop network with nodes in chosen locations and directional antennas aimed to engineer high-quality radio links [31, 8, 29]; these networks require well-coordinated groups with technical expertise, but result in high throughput and good connectivity. The second approach consists of individuals operating "hot-spot" access points to which clients directly connect [5, 4]. These access points often operate independently and are loosely connected, if at all. Access-point networks do not require much coordination to deploy and operate, but usually do not provide as much coverage per wired connection as multi-hop networks.

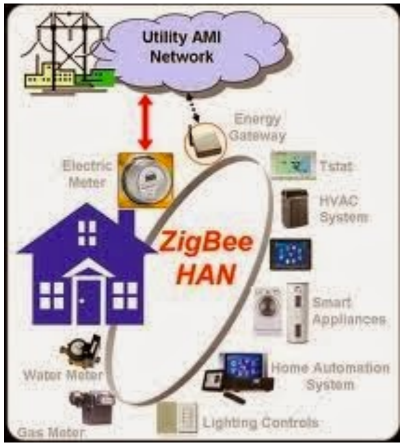
A more ambitious vision for community networks would combine the best characteristics of both network types, operating without extensive planning or central management but still providing wide coverage and acceptable performance. This paper provides an evaluation of such an architecture, consisting of the following design decisions:

1. Unconstrained node placement, rather than a topology planned for coverage or performance. The network should work well even if the topology is determined solely by where participants happen to live.
2. Omni-directional antennas, rather than directional antennas used to form particular high-quality links. Users should be able to install an antenna without knowing in advance what nodes the antenna might talk to. Nodes should be able to route data through whatever neighbors they happen to find.
3. Multi-hop routing, rather than single-hop base stations or access points. Multi-hop routing can improve coverage and performance despite lack of planning and lack of specifically engineered links.

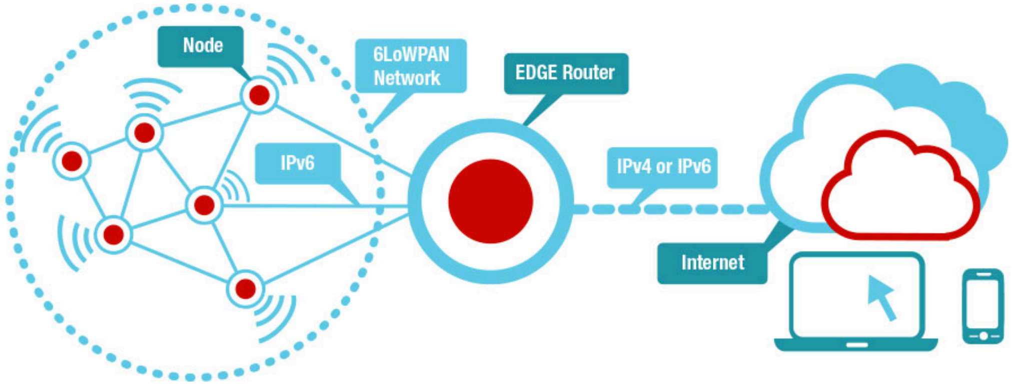
EXTENDING RANGE: MESH NETWORKS

2010s: Mesh networks for IoT

Zigbee



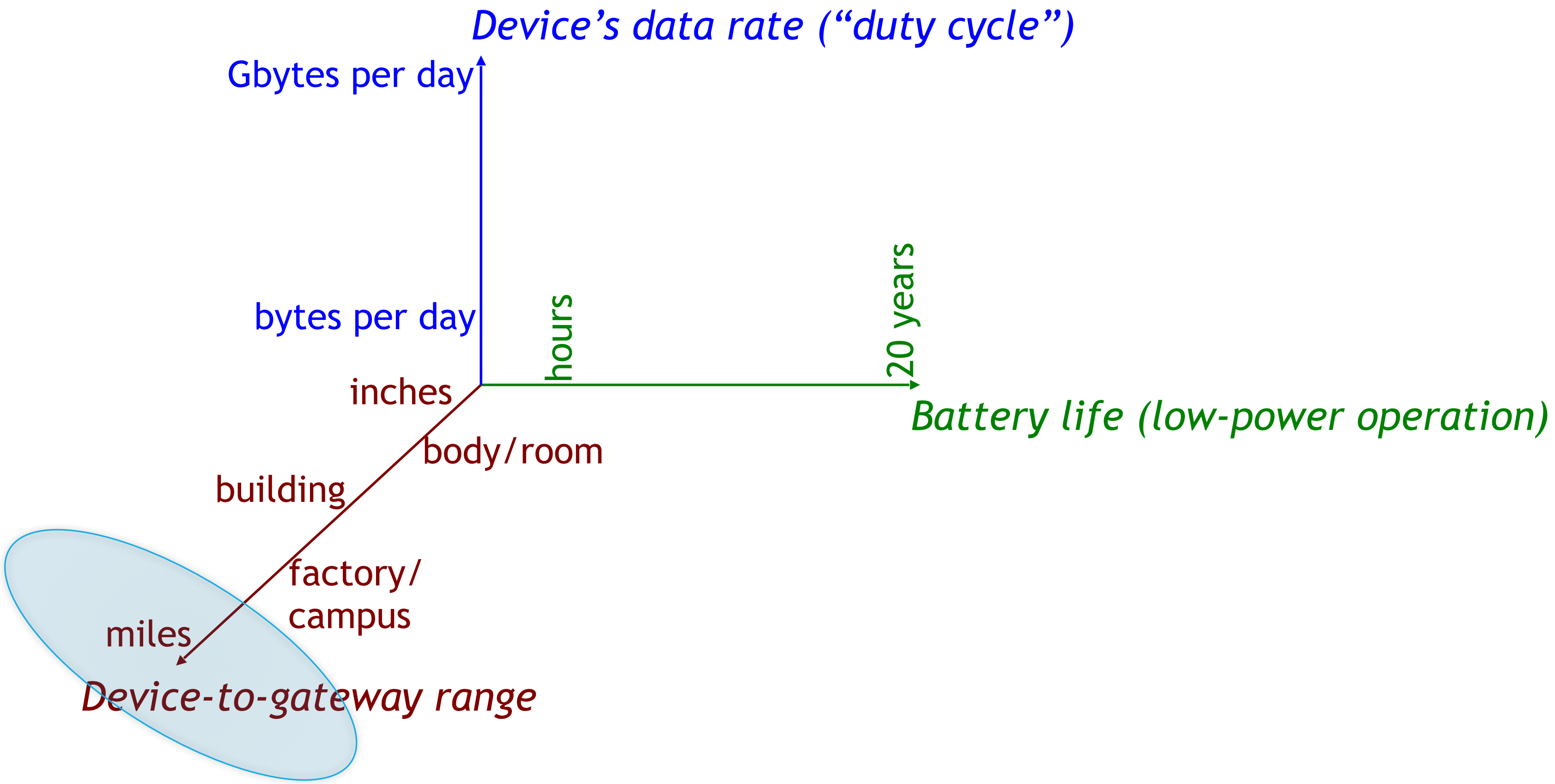
6LoWPAN: IPv6 over low-power wireless personal area networks



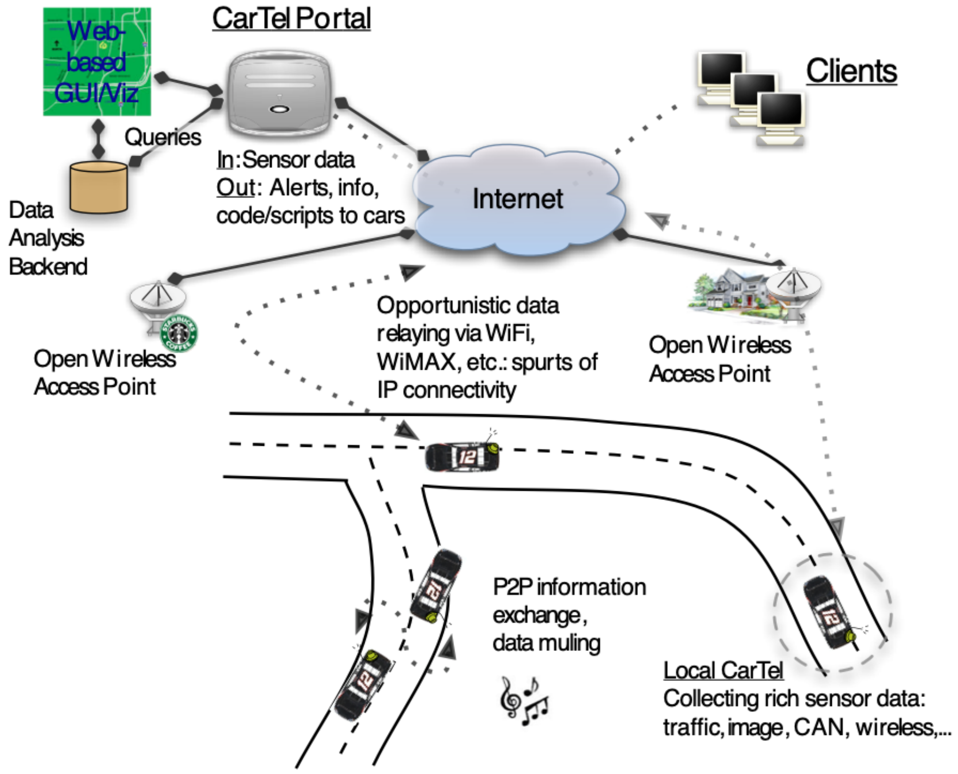
http://processors.wiki.ti.com/index.php/Contiki-6LOWPAN (Creative commons)

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

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.), 5G

Some of these are 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

These haven't seen wide deployment yet

WHAT IF WE WANT LONG RANGE AND LOW DELAY

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

High-power consumption, so only when energy isn’t an issue
Relatively high cost (>$10 per device today plus monthly usage cost)

Variable delay of cellular networks is still a concern for **data-intensive, latency-sensitive applications**
(Cf. topic later in the term on continuous object recognition)

WHAT IS 5G?

“Unifying solution” offered by cellular providers

A unifying connectivity fabric

Always-available, secure cloud access

Enhanced mobile broadband

Mission-critical services

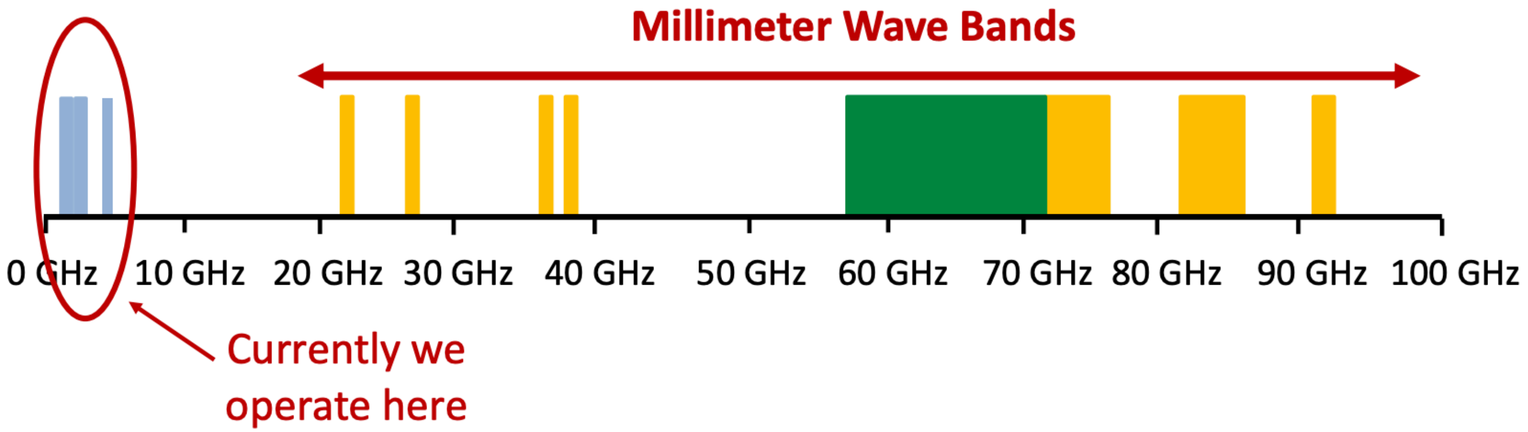
Massive Internet of Things

Qualcomm

WHAT IS NEW IN 5G?

Millimeter Wave Technology

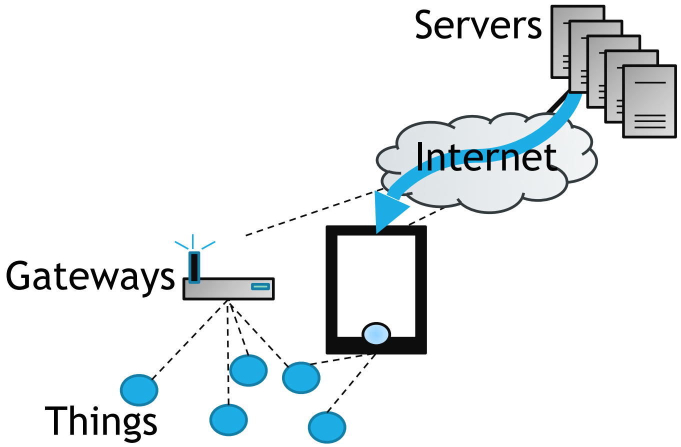
Huge bandwidth available at millimeter wave frequencies



Millimeter Wave can support data rates of multi-Gbps

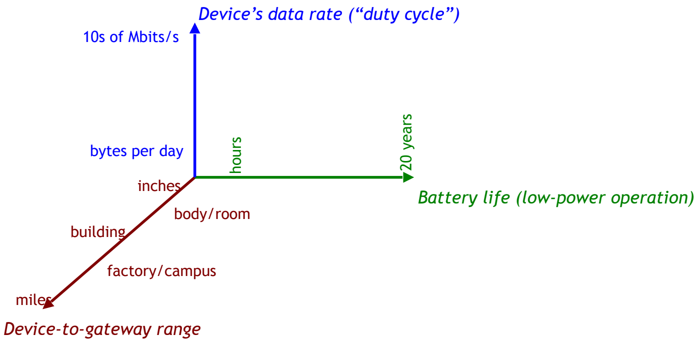
WHAT HAVE WE LEARNED?

Rich design space for things-gateway communication



Think along three dimensions:

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



Examples:

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

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, open gateways for specific apps?

5. Smartphone-centric v. hidden (“ubiquitous”) computing

> The most profound technologies are those that **disappear**
>
> - Mark Weiser

Objectives of the the Three Lectures Series

Learn the fundamentals, applications, and implications of
IoT connectivity technologies

1. What is the overall IoT system architecture? ✓
2. What are the various classes of connectivity technologies? And how do we choose the "right" technology for a given application? ✓
3. What are various routing architectures for wireless networks & IoT systems? **next lecture**
4. How does energy impact IoT device design? And how do batteryless IoT systems work? ✓