Bluetooth 4.0: Low Energy

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Agenda

Wireless Applications Perspective

- How do wireless devices spend energy?

What is ‘classic’ Bluetooth?

What is Bluetooth Low Energy?

- How do the components work?
- How low is the energy?

Perspective: how does ZigBee & 802.15.4 work?

What is Bluetooth Low Energy good for?

Where can we learn more?

Short range wireless application areas

	Voice	Data	Audio	Video	State
Bluetooth ACL / HS	*x*	Y	Y	*x*	*x*
Bluetooth SCO/eSCO	Y	*x*	*x*	*x*	*x*
Bluetooth low energy	*x*	*x*	*x*	*x*	Y
Wi-Fi	(VoIP)	Y	Y	Y	*x*
Wi-Fi Direct	Y	Y	Y	*x*	*x*
ZigBee	*x*	*x*	*x*	*x*	Y
ANT	*x*	*x*	*x*	*x*	Y

State = low bandwidth, low latency data

How do wireless devices spend power?

Duty Cycle: how often they are on

- The wireless world has put a lot of effort into reducing this

Protocol efficiency: what do they do when on?

- Different MACs are tuned for different types of applications

TX power: how much power they transmit

- And how efficient the transmit amplifier is

How long they have to transmit when they are on

- Data rate helps here – look at energy per bit

How much energy the signal processing consumes

- This is driven by chip silicon process if the DSP dominates
- This is driven TX power if the RF dominates

Example transmit power & efficiency comparisons

High rate: 802.11n (single antenna) vs UWB, short range

- In 90nm, an 802.11n chip might spend ~200mW in DSP, but 500mW in the TX amplifier (mostly because they are about 10% efficient on OFDM carriers) to deliver 108 Mbps instantaneous rate, maybe 40 Mbps above the MAC
- Raw energy efficiency: 108Mbps/700mW = **154Mbps/W**
- In 90nm, a WiMedia 1.2 chip might spend ~400mw in DSP, but only 20mW in the TX amplifier (because the output power is <1mW) to deliver 480 Mbps instantaneous rate, maybe 320 Mbps above the MAC
- Raw energy efficiency: 480Mbps/420mW = **1143Mbps/W**

Low rate: 802.15.4 (ISM) vs Bluetooth (ISM, LE or EDR)

- For both, TX power dominates: ~10mW RF, <5mW DSP, etc
- For IEEE 802.15.4, 250kbps/15mW = **17Mbps/W**
- For Bluetooth LE, 1Mbps/15mW = **67Mbps/W**
- For Bluetooth EDR, 3Mbps/15mW = **200Mbps/W**

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Applications dominate usage

The 802.11 MAC is a contention-based system

- If the AP is mains-powered, efficiency matters at the STA (station)
- If the medium isn't congested, the STA does not have to spend much time or power with the radio on, contending for use of the medium.
- If the medium is congested, power consumption rises fast, because the STA has to listen a long time to detect its turn to transmit or receive.

The Classic Bluetooth MAC is isochronous

- This fits the phone-to-headset application for two-way voice traffic
- It is efficient for this: both radios know when they need to be on, and off

Bluetooth Low Energy is asynchronous

- A device (server) will advertize for attention only if it needs it
- A host (client) will listen often enough to hear advertizing
- If both devices have a pre-agreed schedule, the combined usage can be tiny
  - It costs some energy to maintain a clock

What is ‘classic’ Bluetooth?

Bluetooth is a set of specifications for common short range wireless applications

- They are written, tested & maintained by the Bluetooth SIG (~16,000 members)

The specifications include:

- Core components - radios, protocols (we own everything, so we can optimize)
- Profiles (aka applications)
- **AND: we rigorously validate the specs before we Adopt them, like 3GPP**

The ‘classic’ Bluetooth radio:

- 2.4 GHz ISM band,1 M symbols/s, GFSK, 4PSK or 8PSK
- 1 MHz channel spacing, with frequency hopping
- Adaptive Frequency Hopping, for co-existence with Wi-Fi, etc
- Up to 10mW for house-scale range; up to 100 mW to go farther

Bluetooth 3.0 Generic Alternate MAC/PHY (AMP) can use additional radios: IEEE 802.11n

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What is traditional Bluetooth used for?

Top uses by volume (>2B total/year):

- Mobile phones
- Voice headsets and “Car kits”
- Stereo headsets and speakers
- PCs and tablets
- Wireless controllers for video games
- M2M applications – credit card readers, industrial automation

Although Bluetooth is commonly used for human I/O, it already has a good penetration into high reliability M2M applications.

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How much energy does traditional Bluetooth use?

Traditional Bluetooth is *connection oriented*.

- When a device is connected, a link is maintained, even if there is no data flowing.

Sniff modes allow devices to sleep, reducing power consumption to give months of battery life.

- Pairs of devices schedule when to wake up and check in

Peak transmit current is typically around 25mA.

Even though it is low power compared to things like 802.11n (e.g. Wi-Fi or Wi-Fi direct) it still consumes to much power for coin cells and energy harvesting applications

- ZigBee is better for state applications than *traditional* Bluetooth

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What is Bluetooth Low Energy?

A new radio, new protocol stack and a new profile architecture.

It's designed to run from coin cells and support an Apps Store model

- The Bluetooth SIG calls this "Smart Ready"

It is a radio standard for a new decade, enabling the **Internet of Things.** Features:

- Mostly new PHY; some parts derived from the Basic Rate (BR) radio
- New advertising mechanism, for ease of discovery & connection
- Asynchronous connection-less MAC: used for low latency, fast transactions (e.g. 3ms from start to finish)
- New Generic Attribute Profile to simplify devices and the software that uses them.
- Asynchronous Client / Server architecture

Designed to be LOWEST cost and EASY to implement

Vision: that Bluetooth LE will be to Smartphones what USB has been to desktop PCs: universal wireless connectivity

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Bluetooth low energy factsheet

Range:	~ 150 meters open field
Output Power:	~ 10mW (10dBm)
Max Current:	~ 15mA
Latency:	3 ms
Topology:	Star
Connections:	> 2 billion
Modulation:	GFSK @ 2.4 GHz
Robustness:	Adaptive Frequency Hopping, 24 bit CRC
Security:	128bit AES CCM
Sleep current	~ 1µA
Modes:	Broadcast, Connection, Event Data Models Reads, Writes

Specification or Implementation specific

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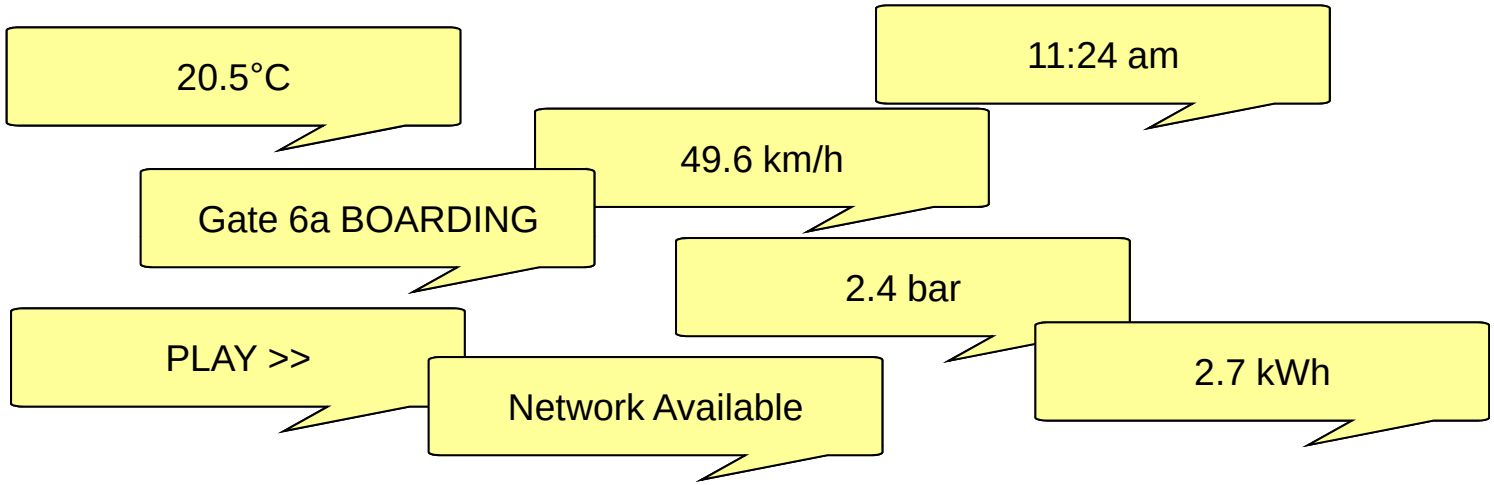
Bluetooth low energy factsheet #2

Did you notice something missing?

Data Throughput

- For Bluetooth low energy, data throughput is not a meaningful parameter. It does not support streaming.
- It has a data rate of 1 Mbps, but is not optimised for file transfer.
- It is designed for sending small chunks of data (exposing state).

Designed for exposing state



- It’s good at small, discrete data transfers.
- Data can triggered by local events.
- Data can be read at any time by a client.
- Interface model is very simple (GATT)

It’s about the Internet of Things

Things have data

&

Web Services want this data

Bluetooth low energy provides the technology to connect these two.

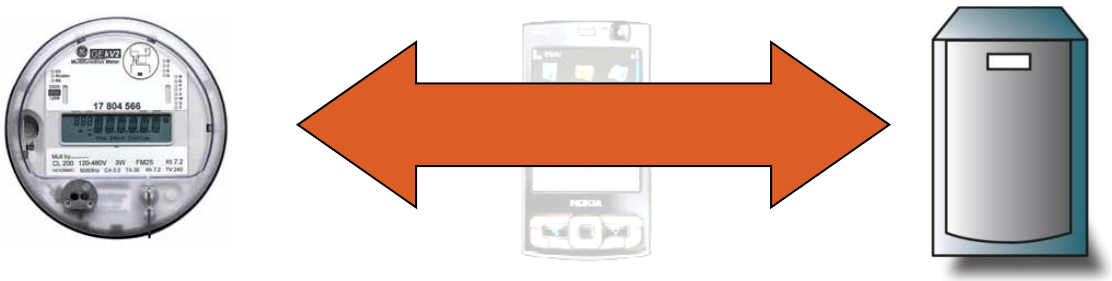
Bluetooth Low Energy needs generic gateways

Devices that support *Bluetooth* low energy Gateway functionality need to provide a transparent pipe from a device to an IP address.

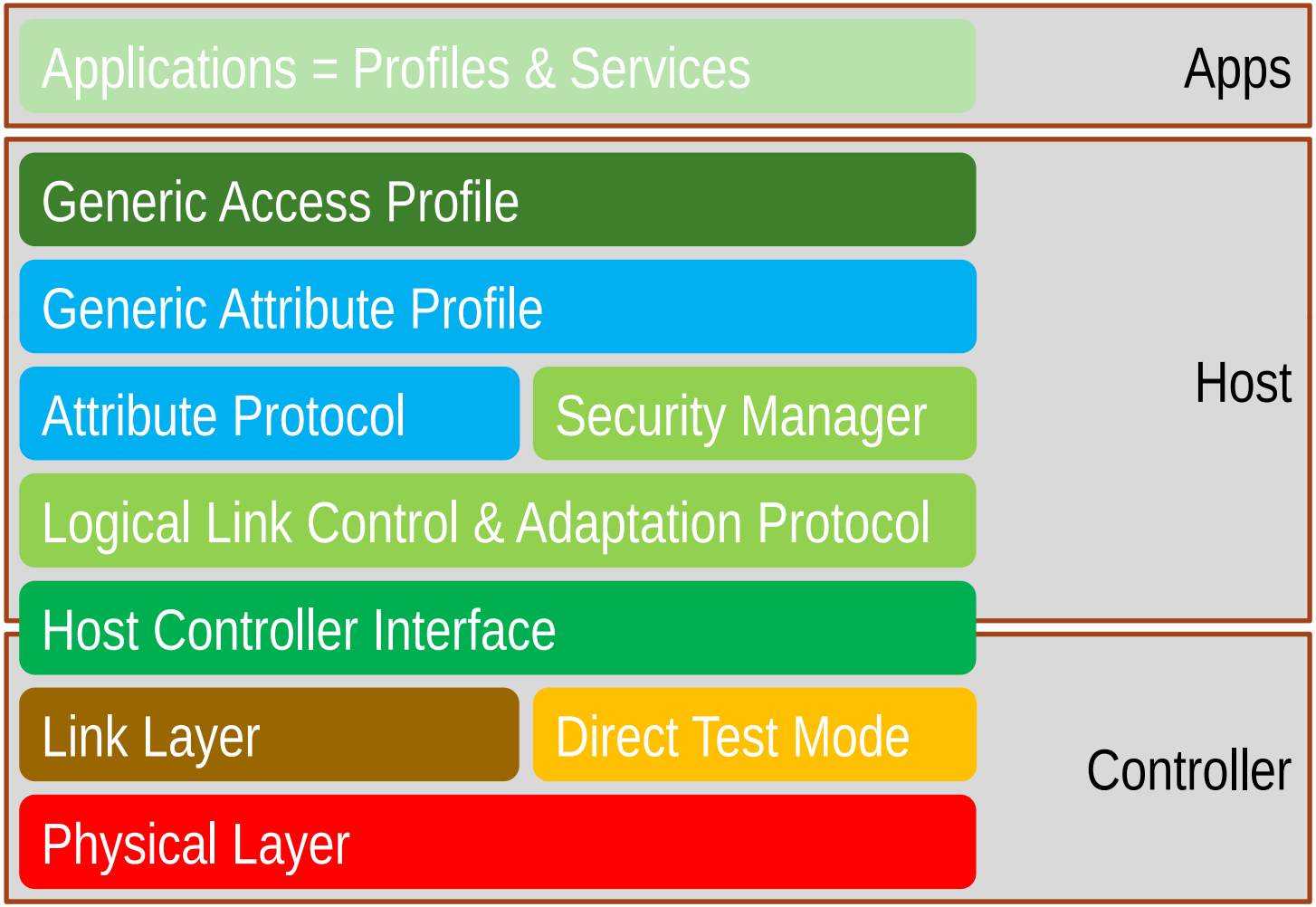
Middleware at the IP address can access the device directly as if it were a collector talking to it locally.

The Gateway device plays no part other than in acting as a pipe.

Today, there is no accepted standard for generic gateways, for Bluetooth or for Zigbee – and we all need one.



What are the pieces?



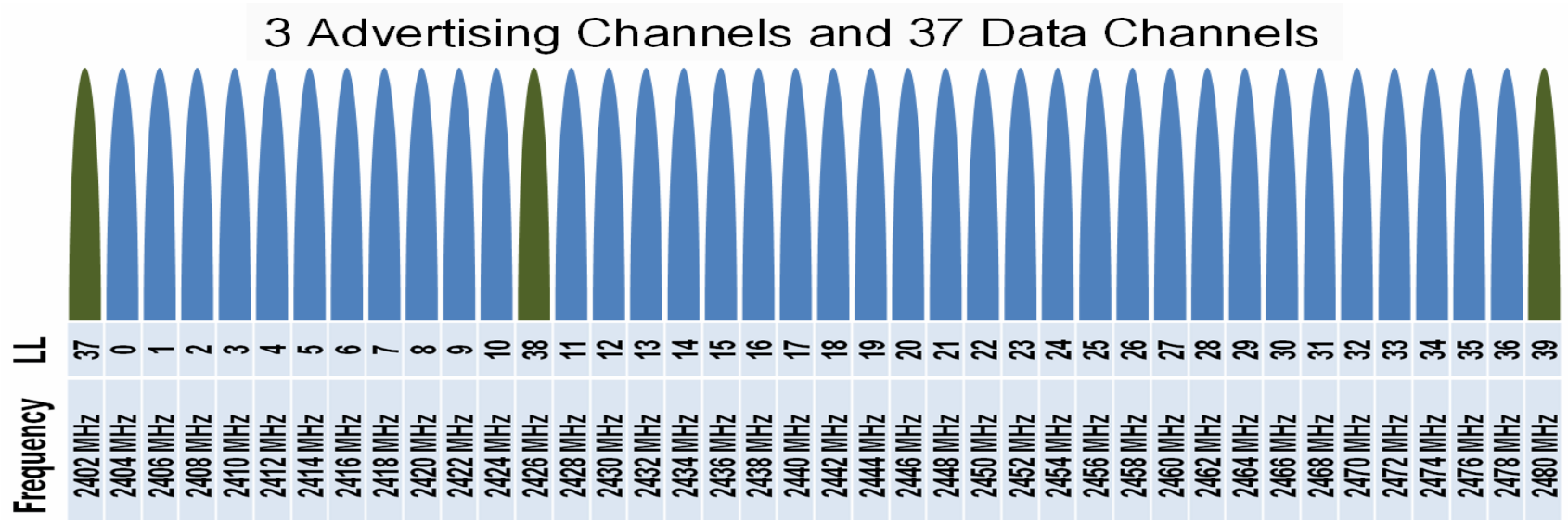
How does it work: new radio

2.4 GHz ISM band

1 Mbps GFSK

- Larger modulation index than classic Bluetooth (better range)

40 Channels on 2 MHz spacing:



How does it work: new Link Layer

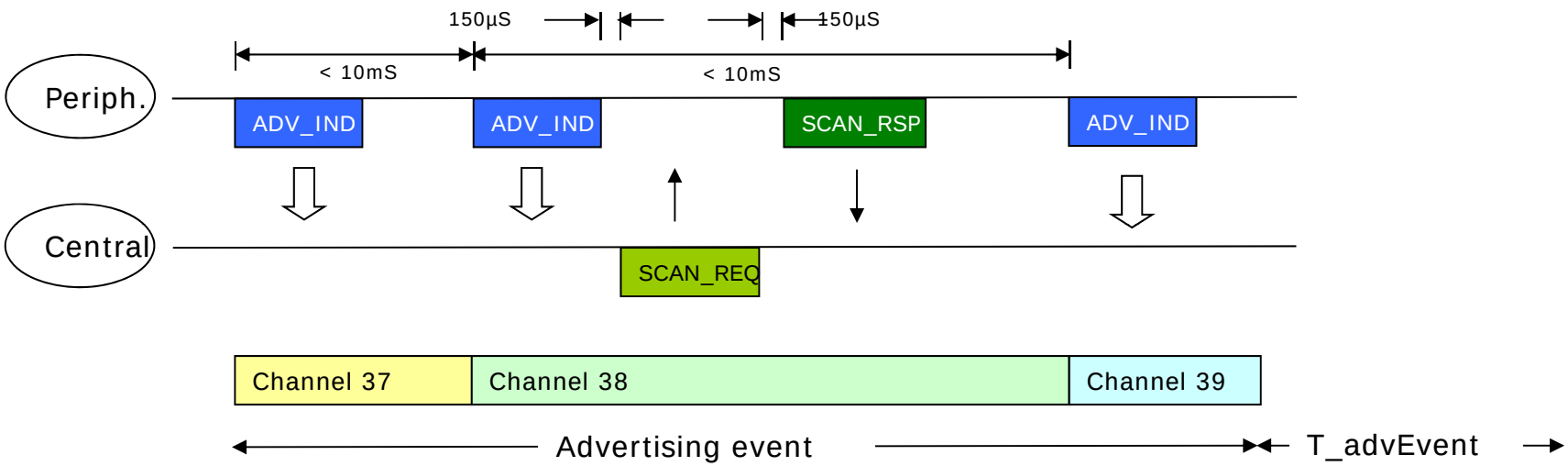
Low Complexity

1 packet format
2 Protocol Data Unit types – Advertising or Data Channel
7 Advertising Protocol Data Unit Types
7 Link Layer Control Procedures

Useful Features

Adaptive Frequency Hopping
Low Power Acknowledgement
Very Fast Connections

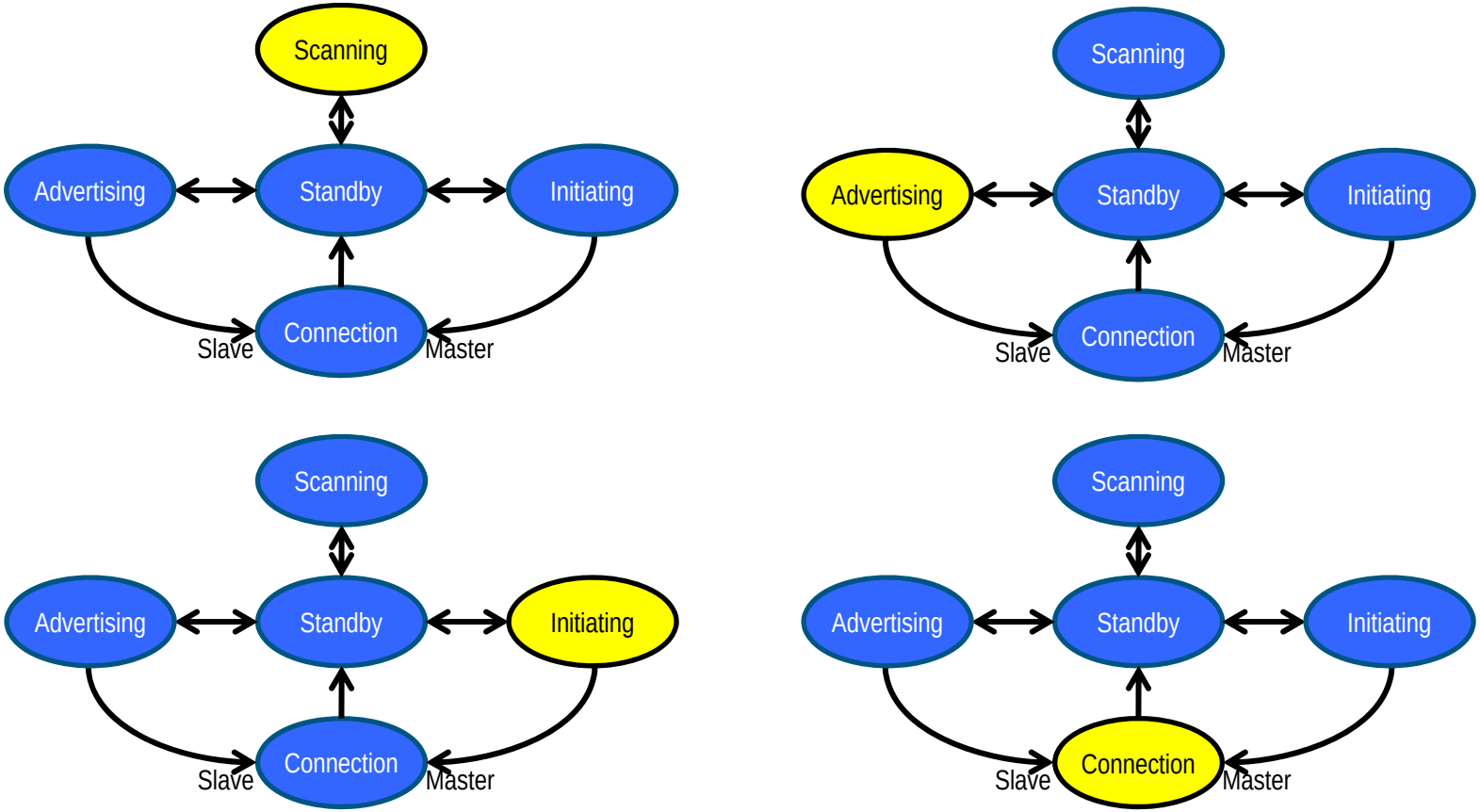
How does it work: advertising



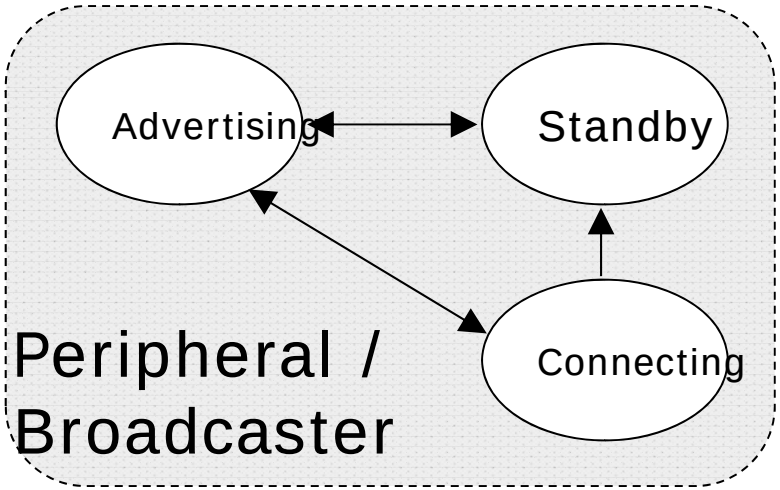
Devices can advertise for a variety of reasons:

- To broadcast promiscuously
- To transmit signed data to a previously bonded device
- To advertise their presence to a device wanting to connect
- To reconnect asynchronously due to a local event

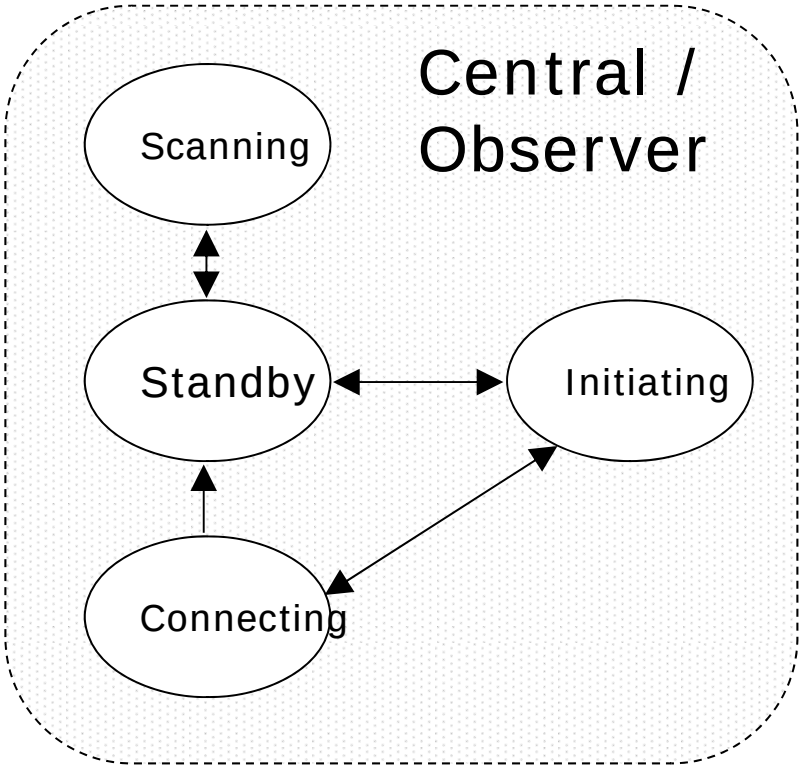
How does it work: 4 active states



How it works: peripheral states & central states

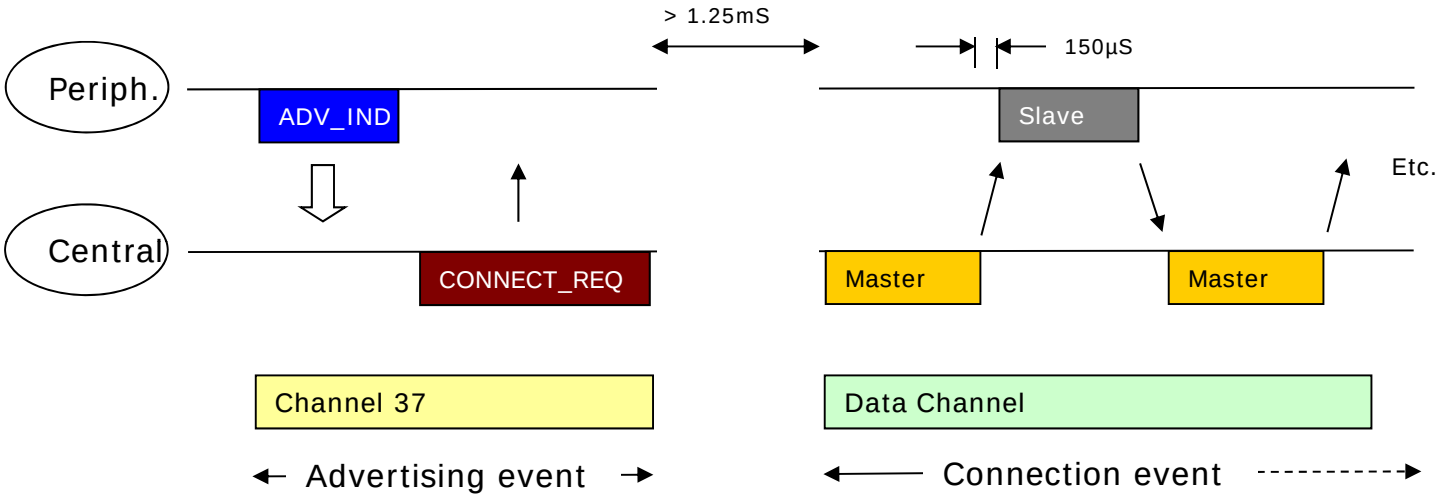


A Broadcaster cannot enter the Connecting state.



An Observer cannot enter the Initiating State.

How does it work: data transactions

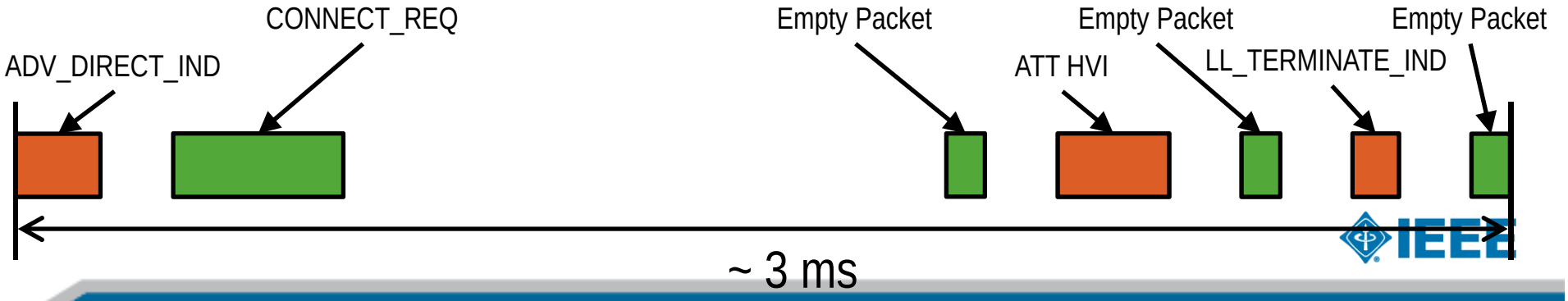


Once a connection is made:

- Master informs slave of hopping sequence and when to wake
- All subsequent transactions are performed in the 37 data channels
- Transactions can be encrypted
- Both devices can go into deep sleep between transactions.

Let's add it up, for a minimal transaction

Time (us)	Master Tx	Radio Active (us)	Slave Tx
0		176	ADV_DIRECT_IND
326	CONNECT_REQ	352	
1928	Empty Packet	80	
2158		144	Attribute Protocol Handle Value Indication
2452	Empty Packet (Acknowledgement)	80	
2682		96	LL_TERMINATE_IND
2928	Empty Packet (Acknowledgement)	80	



How low can the energy get?

Try calculating energy per transaction

- Assume an upper bound of 3 ms per minimal transaction
- Est TX power is 15mW (mostly TX power amp for 40 nm chips).
- For 1.5v battery, this is 10ma. 0.015 W x .003 sec = 45 micro Joule

How long could a sensor last on a battery?

- An example battery: Lenmar WC357, 1.55v, 180mAh, $2.
- 180mAh/10ma = 18 hours = 64,800 seconds = 21.6M transactions
- Suppose this sensor sends a report every minute = 1440/day
- For just the BT LE transactions, this is 15,000 days, or >40 yr
- This far exceeds the life of the battery and/or the product

In fact, the communication cost will be only part.

- This sensor could run on scavenged power, e.g. ambient light.

Your mileage may vary

The previous slide calculated 45 uJ for the minimum transaction

- This number is an upper bound because it budgets 15mW for the entire 3 ms time, although the radio time is much smaller
- OTOH, more complex transactions may need more radio traffic

The low duty cycle on both sides depends on having a clock that gives each device an approximate time to wake up and transact business

- This can be as simple as a 32kHz oscillator, like those in watches
- The client/scanner/listener needs to wake up earlier and listen longer to accommodate clock frequency skew
- This is a common feature in CSR and some competing chips

The sensor itself draws power. That energy might exceed the power spent on the wireless link.

- In practice, the radio power might be a minority of the power budget

How does it work: Attribute Protocol

Clients and Servers

- Servers expose Attributes
- Clients use them

16 bit address space of handles – address within a device

Each attribute has a Universal Unique ID (UUID) – what it is?

- 16-bit if standardized by the Bluetooth SIG
- 128-bit if invented by the manufacturer
- **Note: that manufacturers can add value without waiting for the SIG**

The protocol supports a handful of actions:

- Clients: Discover or Find, Read, Write, Confirm an Indication
- Servers: respond to Client actions, Notification and Indication

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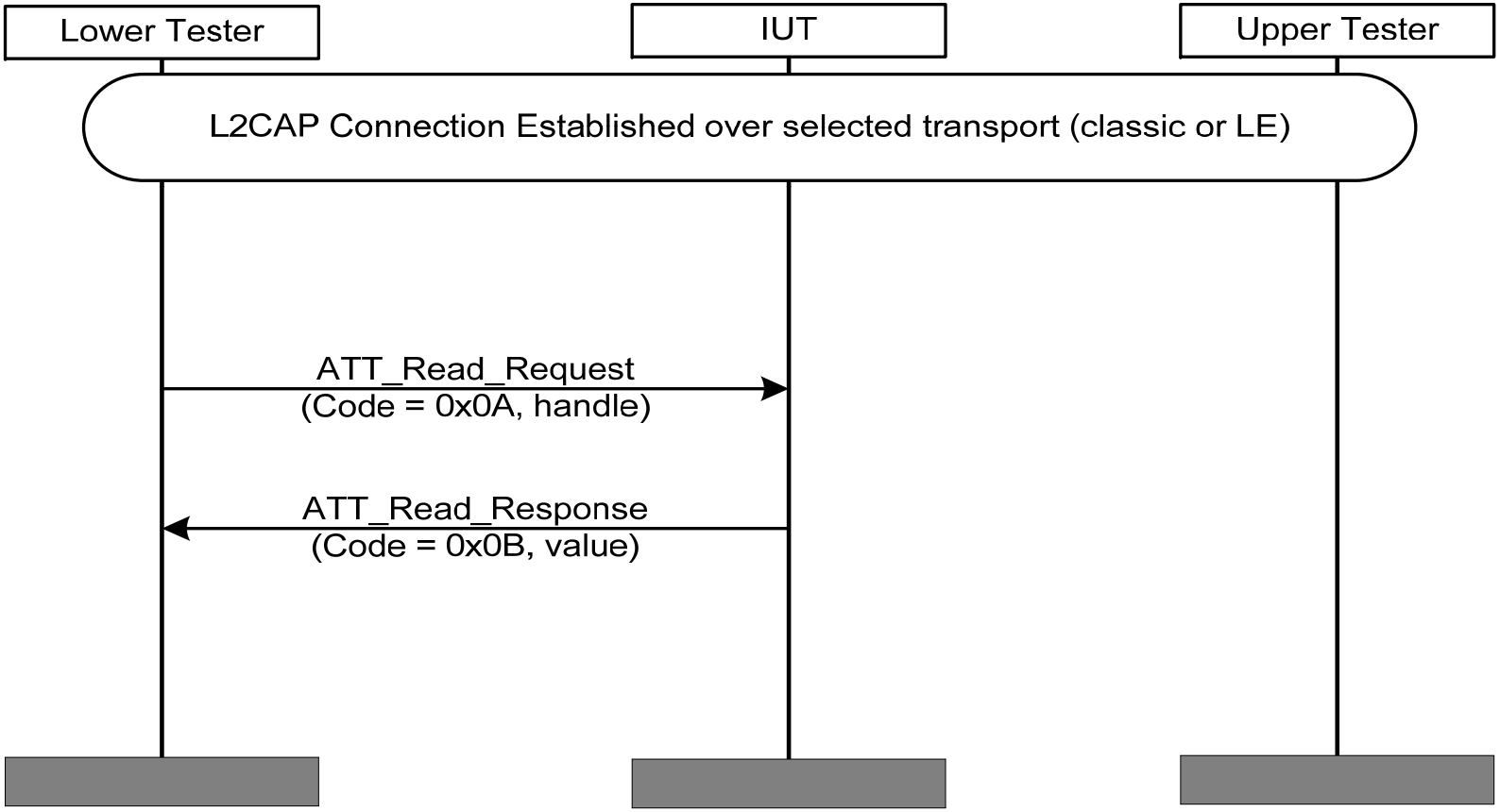
Simple ATT transaction: read something



How does it work: Generic Attribute Profile

Simple Servers

Those servers provide attributes:

- Characteristics, and descriptors for those characteristics
- Services: which can include characteristics and/or other services

Expose the state of the server.

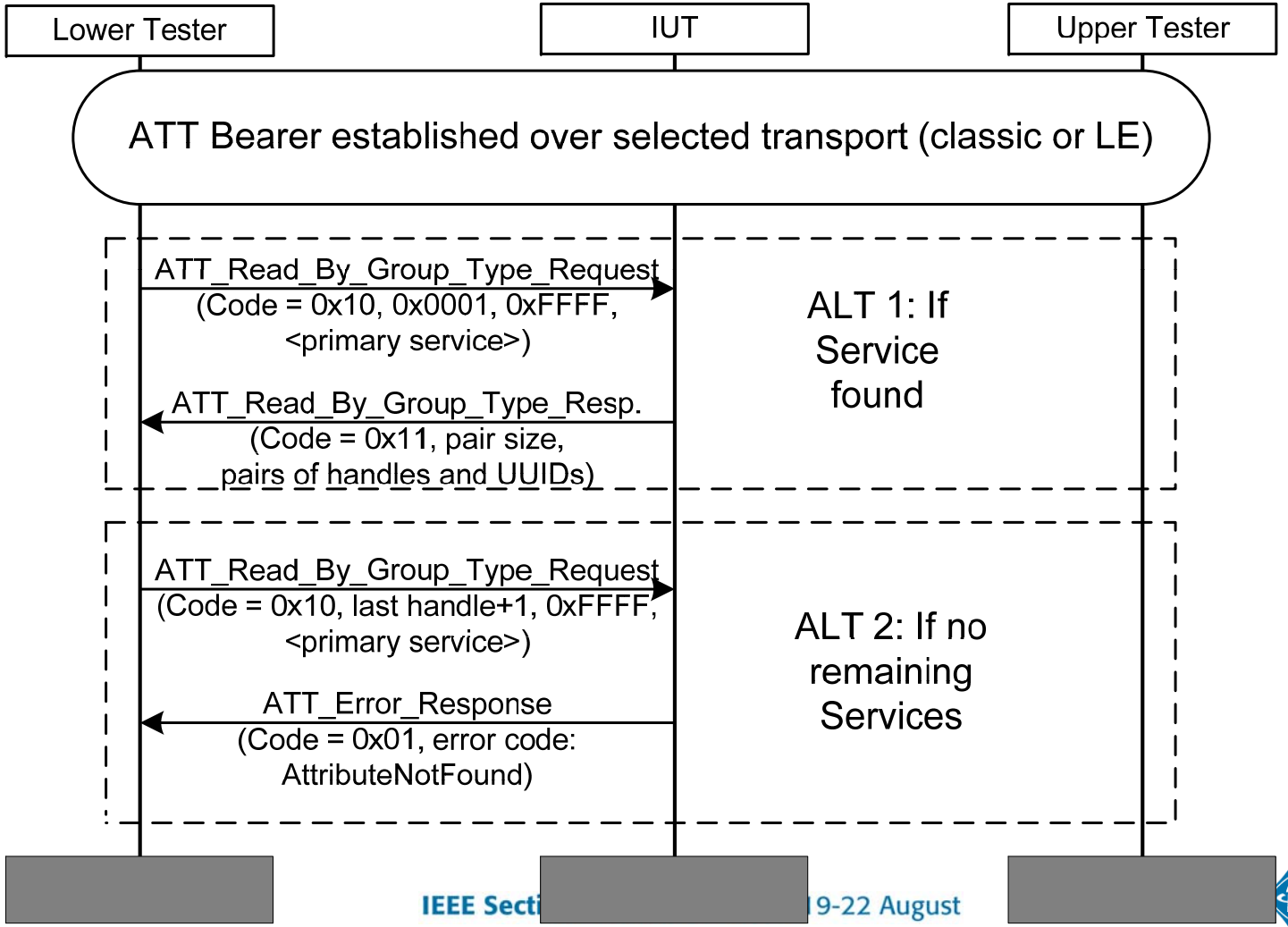
Allows choice of security level: 128 bit AES CCM optional

Use the Attribute Protocol for transport

Defines Data Formats:

- Low Energy encapsulates all of the protocols and formats into the core. This makes profile development much faster and easier.
- The format is easy to encode in XML.

Busy GATT procedure: interrogate a server



Extension: gateways

Any system that can connect to Low Energy devices AND to a wide area network can serve as a gateway:

- Your home PC should see devices around your home
- Your smart phone should see all the devices around you

The simplicity of GATT servers should make it easy to represent those devices over the web.

Problem: no consensus yet on how these work

Candidate solution: Constrained Application Protocol

- Reference: draft-ietf-core-coap-09
- Only 4 operations: Confirmable (CON), Non-confirmable (NON), Acknowledge (ACK) and Reset (RST)
- This reads like a constrained subset of HTTP (Hyper Text Transfer Protocol, used everywhere on the Web)

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What is Bluetooth Low Energy Good for?

Connecting the things we carry with us:

- Watches: remote display from other devices
- Tags: locate objects or keep track of them (e.g. warning if you walk away)
- Health & fitness sensors (e.g. pedometer in your shoes)
- Body sensors (e.g. blood pressure, pulse rate, blood glucose, etc)

Accessing the things around us:

- Fobs: use proximity as a security/access control means
- Home and office automation

Low duty cycle M2M communication:

- Sensors and controls in homes, offices and factories

Communication within a system

- Car to car wheels/tires

Connecting anything that has intrinsic data to the Internet

Opportunities

New classes of gadgets

- Around a person
- Around a house
- In your car

New applications on PCs and smart phones

- Use those devices

New web services

- Anything can connect to the Web

New Social Applications

- Your beer glass can talk to your Facebook page

The billion unit markets for wireless:

	TAM*
Phone accessories (internet / apps centric devices)	> 10 billion
Smart Energy (meters & displays).	~ 1 billion
Home Automation (white goods and HVAC)	> 5 billion
Health, Wellness, Sports & Fitness	> 10 billion
Assisted Living	> 5 billion
Animal Tagging (food assurance)	~ 3 billion
Intelligent Transport Systems	> 1 billion
M2M (Internet connected devices)	> 10 billion

* TAM – Total Addressable Market

What are the USE CASES planned for BT 4.0?

- Proximity
- Time
- Emergency
- Network availability
- Personal User Interface
- Simple remote control
- Browse over Bluetooth
- Temperature Sensor
- Humidity Sensor
- HVAC
- Generic I/O (automation)
- Battery status
- Heart rate monitor
- Physical activity monitor
- Blood glucose monitor
- Cycling sensors
- Pulse Oximeter
- Health Thermometer

Most of these were standardized in the last 18 months

Example use: proximity

It can enable proximity detection

- I'm in the car
- I'm in the office
- I'm in the meeting room
- I'm in the movie theater

It can enable presence detection

- Turn the lights on when I walk around the house
- Automatically locks the door when I leave home
- Turns the alarm off if I'm already awake

Keep track of things

- My kid is running around in public
- Where are my keys, my cell phone, my wallet …

Proximity demonstration

Proximity cartoon

Everyday objects can become sensors

My pulse is…

My blood glucose is…

My temperature is…

…and monitor things unobtrusively

How to build on Bluetooth Low Energy

Applications:

- Host applications that use nearby Low Energy devices
- Web applications that use remote Low Energy devices

Devices:

- Use new Profiles from the SIG (see above lists)
- Define proprietary profiles:
  - Define the attributes of the device
    1. Services
    2. Characteristics
    3. Descriptors
    4. Behavior
  - Define proprietary 16-byte UUIDs for these attributes

Predictions

ZigBee will gain some traction where connectivity to PCs or mobile phones isn't necessary

- This requires something to provide user control
- This requires something to provide the network gateway

Bluetooth Low Energy is becoming a free add-on to mobile phones, PCs and some other devices that use classic Bluetooth now – they will switch to dual mode devices

- The prediction is 370 million mobile phones will be sold with BT LE this year

The Bluetooth ecosystem will define two tools:

- APIs for use in PC host OS and in Smartphone OS (mostly done)
- Internet gateways (under study)

The Bluetooth ecosystem will define even more Profiles

- Entrepreneurs will define proprietary profiles

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Calls to Action

Learn about Bluetooth Low Energy

Ask questions, today or later (see contact info)

See resources on a later slide

Think about how to use it to satisfy market needs

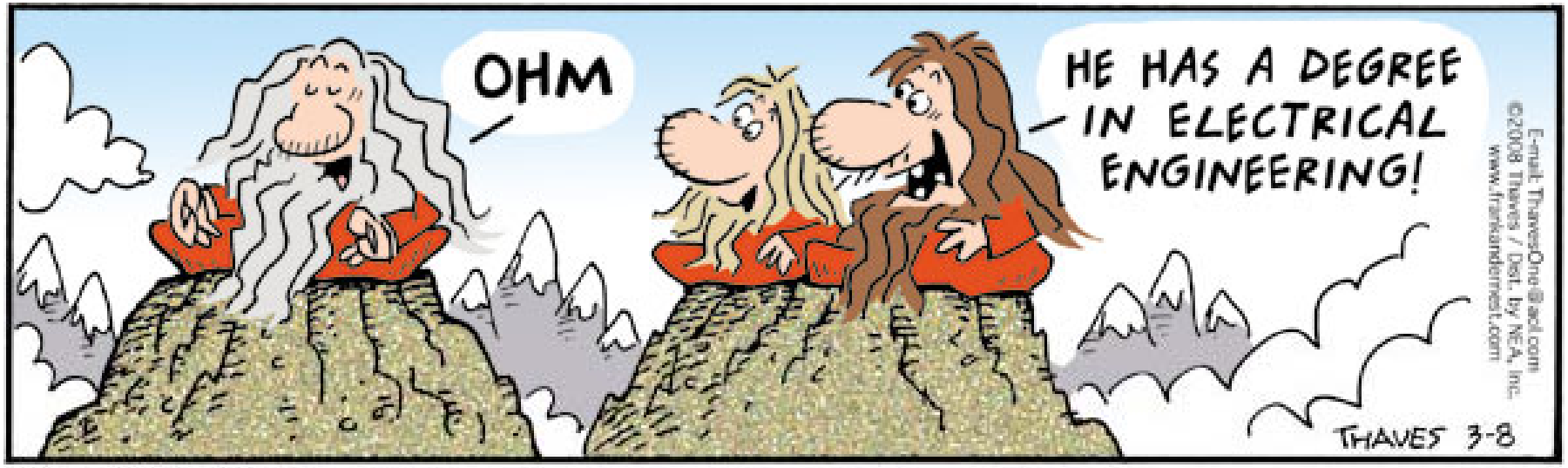
The list of use cases above is just a start

Find partners to deliver value

There were dozens of companies who did IOP testing to validate the specification

CSR is one of at least a half dozen chip makers

Questions?



Resources:

SIG site: http://www.bluetooth.com/lowenergy

The Bluetooth 4.0 specification:
http://www.bluetooth.com/Specification%20Documents/Core_V40.zip

Bluetooth Low Energy Training from 2010 All Hands Meeting:
https://www.bluetooth.org/DocMan/handlers/DownloadDoc.ashx?doc_id=228441

Articles on Bluetooth Low Energy: www.nickhunn.com

Book: Essentials of Short Range Wireless, Hunn

Book: forthcoming book on Bluetooth Low Energy by Robin Heydon.

ZigBee Technology: www.zigbee.org. See Jan 2008 release.

Article: "ZigBee Technology: Wireless Control that Simply works"
http://intranet.da-iict.org/~ranjan/sn/papers/Zigbee.pdf

Book: ZigBee Wireless Networking, by Gislasan

Book: ZigBee Wireless Networks and Transceivers, by Farahani

IEEE 802.15: http://ieee802.org/15/; https://mentor.ieee.org/802.15

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Backup #1: Zigbee

Competitive perspective: how does ZigBee work?

You all have choices. The most significant of several in this space are ANT, Z-wave and the ZigBee Alliance.

ZigBee is the older and better established of the three.

- ZigBee is based on the IEEE 802.15.4 MAC and PHY

Technical Description:

- PHY: 802.15.4
- MAC: 802.15.4
- Middle layers: NWK
- Upper layers: applications

Administrative comparisons:

- Market presence
- Testing
- IP sharing

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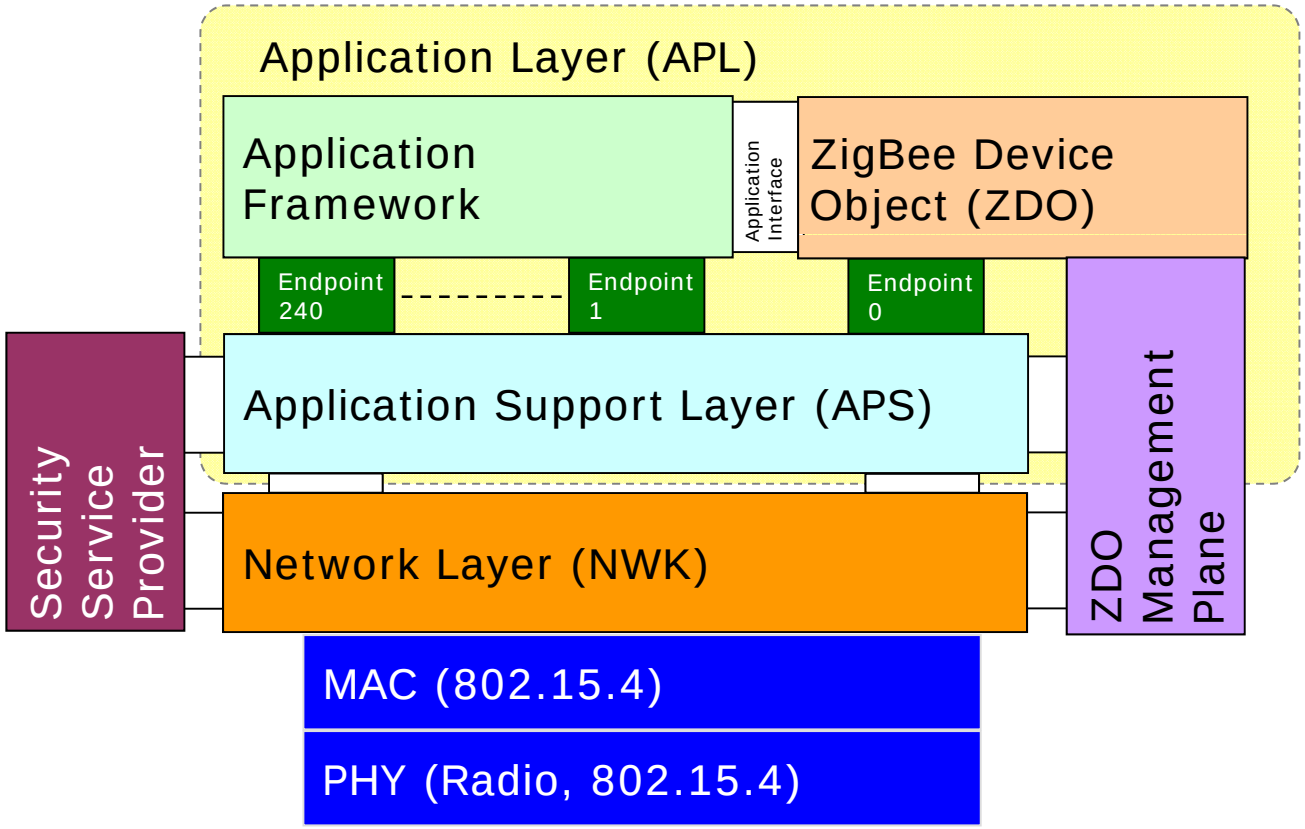
The ZigBee stack



802.15.4 PHY

IEEE 802.15.4 defines several PHY options:

- 2450 MHz QPSK PHY
- 868/915 MHz: BPSK PHY; ASK PHY; O-QPSK PHY
- Note: 802.15.4a adds several more, including DS-UWB

ZigBee uses the ISM band (2450 MHz) PHY

- Worldwide spectrum (same as Bluetooth, Bluetooth LE, 802.11g, etc)
- Up to 250 kbps

802.15.4 ISM modulation

- 4 bits/symbol; 32 chip PN sequence/symbol; 2M chips/s => 250kbps
- Chips are QPSK on a selected carrier (next slide)

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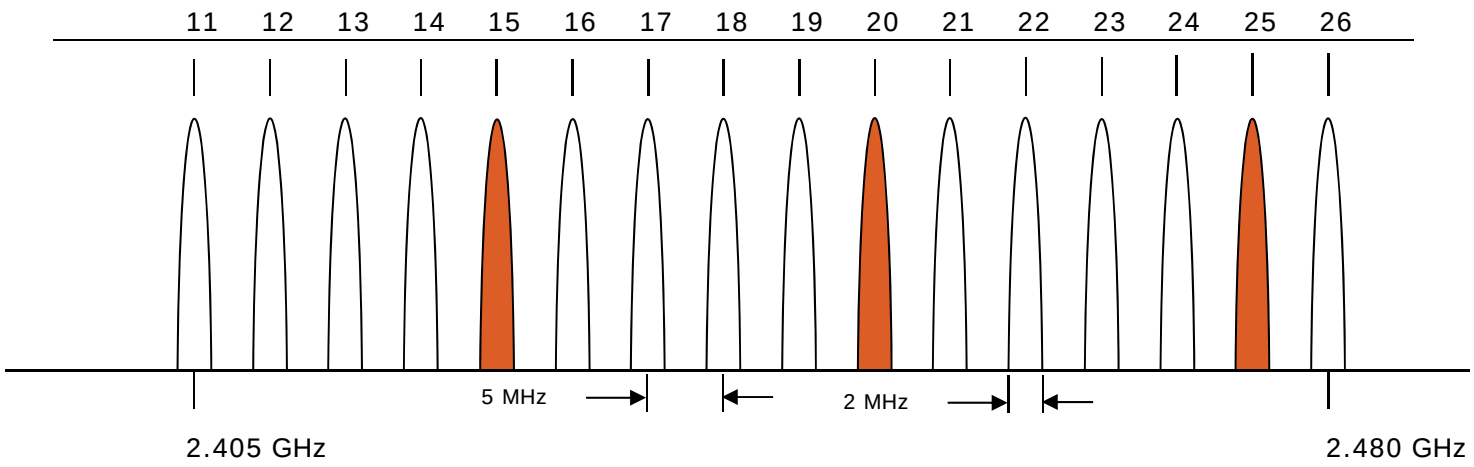
Frequency usage for 802.15.4 / ZigBee



Note: RF4CE only uses channels 15, 20 & 25

802.15.4 MAC

Versatile:

- Supports multiple connection models:
  - peer-to-peer
  - Piconet
  - mesh
- Supports asynchronous and isochronous uses:
  - contention-free in a managed superframe
  - contention within a superframe

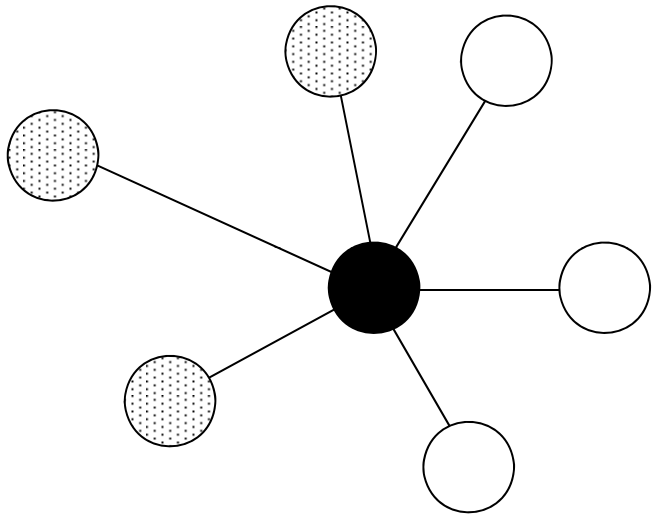
Frame types:

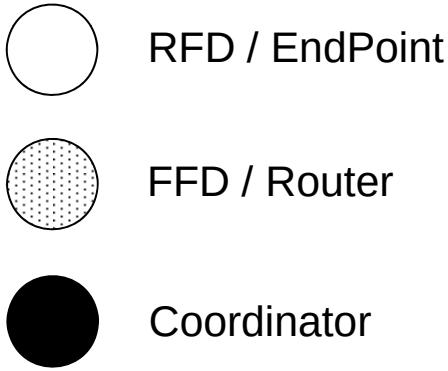
- Beacons, used by coordinators if Superframes used
- Data frames and acknowledgement frame
- MAC command frame

ZigBee NWK layer functions

1. Starting a network
2. Join and leave a network
3. Configuring a new device: configure the stack for operation as required.
4. Addressing: The ZigBee coordinator assigns addresses to devices joining the network.
5. Synchronization within a network: synchronize with another device either through tracking beacons or by polling.
6. Security: apply security to outgoing frames and removing security to terminating frames
7. Routing: route frames to their intended destinations, particularly through a mesh of bi-lateral connections.

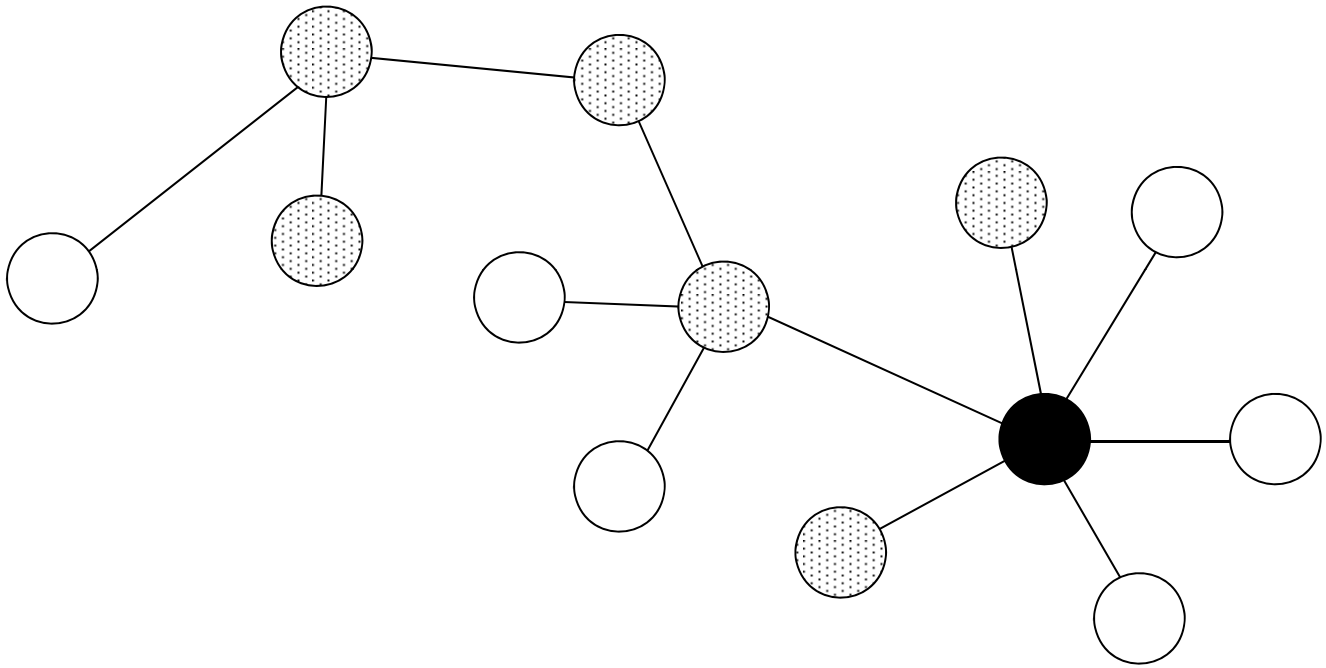
Basic topology of 802.15.4



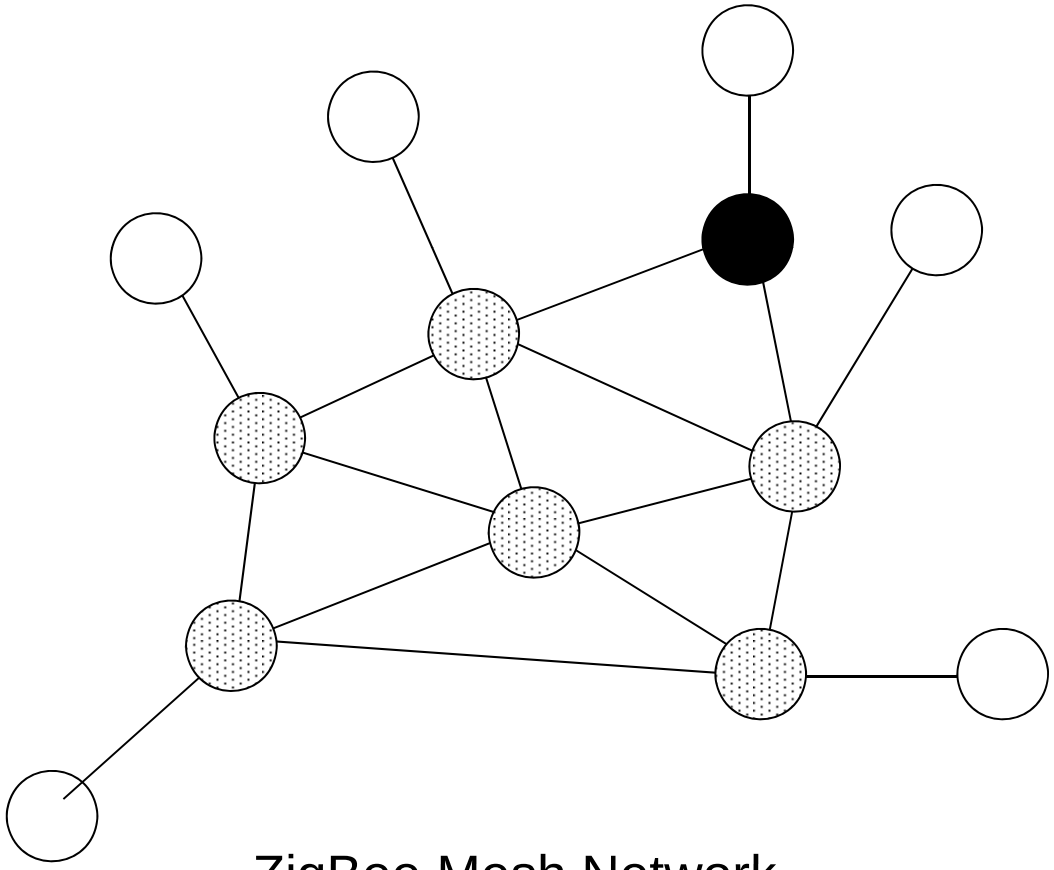


Star Network

ZigBee: Cluster tree network



ZigBee PRO: mesh



ZigBee Mesh Network

ZigBee Applications Layer (APL)

Each device NWK layer has two Service Access Points:

- NLME-SAP (control plane) to access the Device Object
- NLDE-SAP (data plane) to access the Applications

Each APS (Applications Support Sublayer) can handle up to 240 distinct Application Objects (APSDE-SAP)

Application Objects are defined by the ZigBee Alliance

- 16-bit Device Description code space

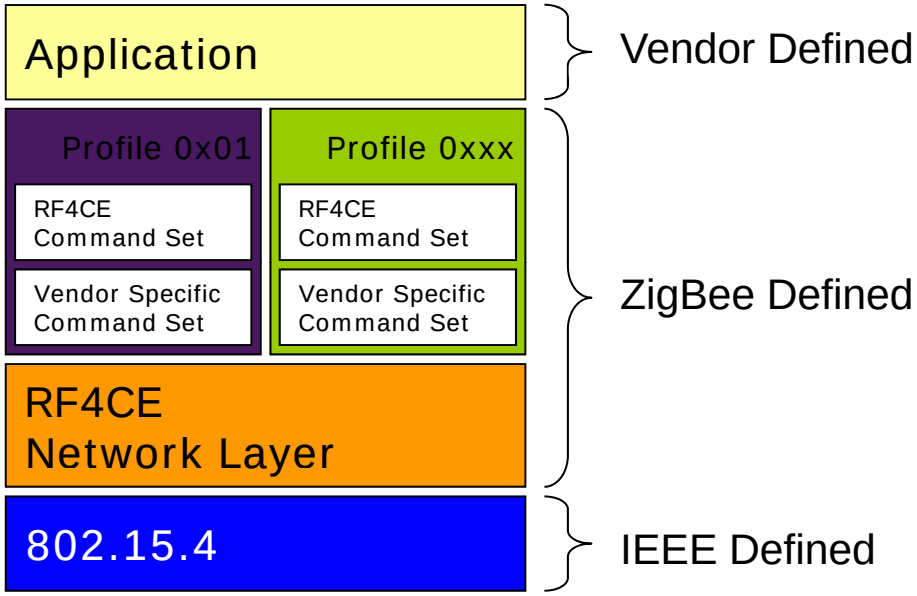
Each Applications Object defines several descriptors:

- Node, power, simple [,complex] [,user]

Each simple descriptor supports one or more (16-bit) clusters of commands and attributes:

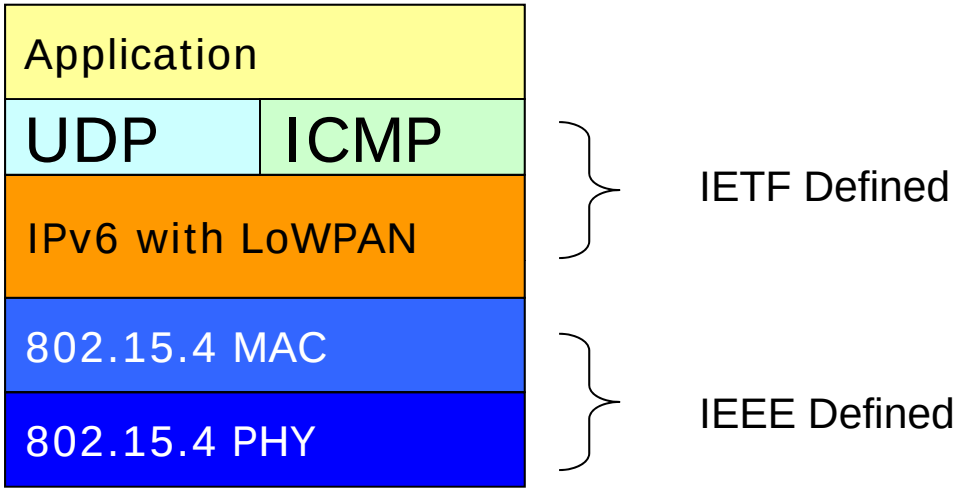
- Attribute identifiers, commands

Example ZigBee application: RF4CE



- Targeted at Remote Control
- Uses three channels only – 15, 20 & 25.
- Some market penetration with Set Top Boxes

A different use of 802.15.4: 6LoWPAN



- An initiative to “squeeze” IPv6 addressing into reasonably sized wireless packets.
- Being adopted for ZigBee’s Smart Energy Profile 2.0

ZigBee & Bluetooth Low Energy

Business comparison:

- ZigBee is older, and evolved. The most recent is 2008.
- ZigBee has press and SDO mindshare, but *still* not a lot of shipments yet.
- Market barrier: connectivity – ZigBee is not in PCs or mobile phones.

Technical comparison:

- ZigBee is low power; Bluetooth LE is even lower. Detailed analysis depends on specific applications and design detail, not to mention chip geometry.
- ZigBee stack is light, but mesh networking costs complexity and power; the Bluetooth LE/GATT stack is even simpler. Staying on to listen within a mesh costs power.

Going forward:

- ZigBee has a lead on specifying applications and in marketing presence.
- Bluetooth low energy has even better low power technology
- Bluetooth has a commanding presence in several large existing markets: mobile phones, automobiles, consumer electronics, PC industry.

Upgrading “classic Bluetooth” (2.1, 3.0) to “dual mode” (4.0) devices will bootstrap this market very quickly.

IEEE

Bluetooth SIG and ZigBee Alliance + IEEE P802.15

The IEEE 802.15.4 committees & the ZigBee Alliance collaborate

- P802.15.4 writes the PHY and MAC specs – no testing or IP sharing
- The ZigBee Alliance writes all the higher layers.
- The ZigBee Alliance does limited testing and IP sharing

The Bluetooth SIG does all the essential administrative and technical work:

- Determine market needs
- Develop the entire stack of technical specifications
- Perform design Q/A on all the stack specification components by IOP testing, before they are Adopted
- Perform Qualification Q/A testing on the entire stack in each product – earning RANDZ IP rights

IEEE

Backup #2: phone and web app visuals

Everyday objects can become sensors

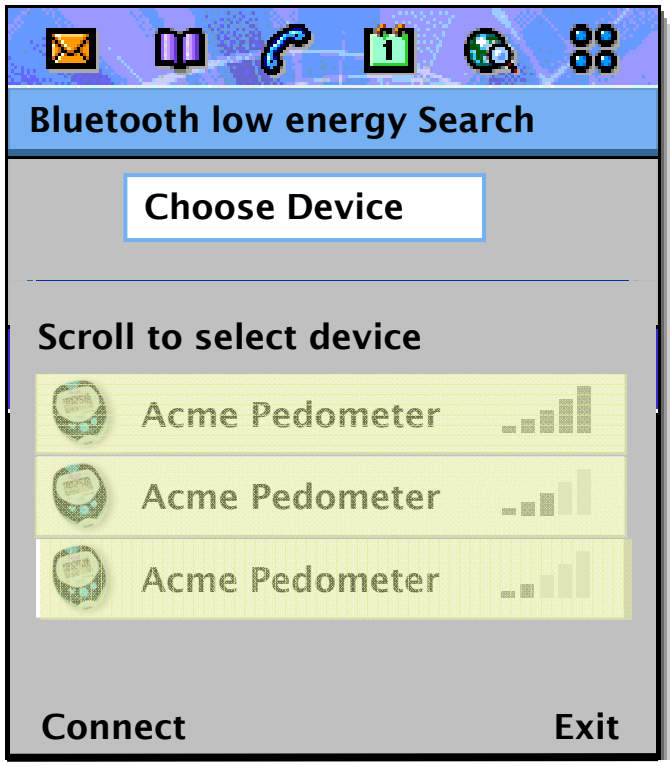
My pulse is…

My blood glucose is…

My temperature is…

…and monitor things unobtrusively

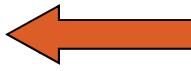
Connection works: start with a phone

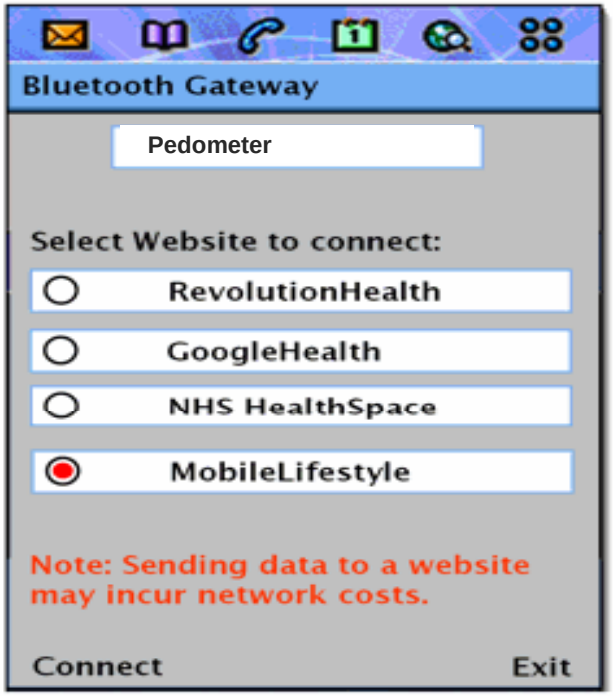


Devices ship with a web address…

www.patientslikeme.com

…using a generic app on your phone…





which connects them to the web app…

then automatically sends your data…

Or, tell the phone what they can do…

Pedometer
Acme Model XYZ
Steps per Minute
Total Steps
Calories Used
Find me an APP…

and the phone gets a tailored set of Apps

Easy to buy

=

More revenue