Topics

- Background
- What is Bluetooth low energy?
- Basic concepts
- Architecture
- Differentiation and comparison
- Markets and applications
Background
Background

2001:
- First ideas from Nokia: BTLite

2006:
- Nokia, Suunto, Nordic Semiconductor etc. form Wibree Forum to further develop the technology

June 2007:
- Bluetooth SIG together with Nokia agreed that the Wibree Forum is merged with the Bluetooth SIG

- Wibree addresses devices with very low battery capacity and as it could be easily integrated with Bluetooth technology, it will round out Bluetooth technology’s wireless Personal Area Networking (PAN) offering
Background

December 2009:
- First version of the core specification was released

July 2010:
- First version of the host specification was released

March 2011:
- First Bluetooth LE profiles adopted

2011:
- First Bluetooth low energy devices appear on the market
What is *Bluetooth* low energy?
What is Bluetooth low energy?

Bluetooth low energy is a NEW, open, short range radio technology

- Blank sheet of paper design
- Different to Bluetooth classic (BR/EDR)
- Optimized for ultra low power
- Enables coin cell battery use cases
  - < 20mA peak current
  - < 5uA average current
What is *Bluetooth* low energy?

However...

- Must reuse as much Bluetooth RF as possible
  - Same antenna and RF components
  - Can time division multiplex with *Bluetooth*

- Must reuse Bluetooth HCI
  - Same physical host interfaces: UART, USB and SDIO
  - Same HCI packet format
  - Same HCI OS drivers

- Must reuse Bluetooth L2CAP
  - A known packet multiplexing point
What is *Bluetooth* low energy?

Has same benefits as *Bluetooth* classic:

- Robust
- Interoperable
- Global
- Royalty free
- Small size
- Secure
- Connectivity to mobile phones and PCs

Except:

- Lower power
- Lower cost
Basic concepts
Basic concepts

Everything is optimized for lowest power consumption

- Short packets reduce TX peak current
- Short packets reduce RX time
- Less RF channels to improve discovery and connection times
- Simple state machines
- Single protocol
- Etc.

Why?

- Coin cell batteries will be the main source of power
  - < 20mA peak current
  - < 5uA average current
Basic concepts

Memory is expensive
- Memory requires silicon area, which costs money
- Memory increases leakage current and reduces battery life

So minimize memory requirements
- Short packets require less buffering
- Simple protocol requires less states
- Simple services require less memory
Basic concepts

Peripherals are simple and resource constrained
- Optimize peripherals

Central devices have more resources and power
- Not so critical to optimize
- e.g. mobile phones and PCs
Basic concepts

Design for success

- Ability to discover thousands of devices
- Unlimited number of slaves connected to a master
- State of the art encryption
- Security including authentication, authorization and privacy
- Robustness and data integrity
Architecture
Layered architecture

Profiles
- Application specific data

GAP
- Device discovery, connections

GATT
- Organization of data

ATT
- Data access protocol

L2CAP
- Multiplexer

HCI
- Interface between host and controller

Link layer
- Packets and radio control

Physical layer
- Transmission/reception of bits
Device modes

Dual mode
- Implements Bluetooth BR/EDR and Bluetooth low energy
- Can be used everywhere, where Bluetooth is used today

Single mode
- Implements only Bluetooth low energy
- Will be used in new devices / applications
Device modes

**BR/EDR stack**
- BT Profiles
- eSCO
- L2CAP
- HCI
- Link Manager (LM)
- Link Controller (LC)
- Physical Layer (PHY)

**Dual-mode stack**
- BT Profiles
- eSCO
- L2CAP
- UL Network Control
- Admission Control
- HCl + Extension
- LM
- LC
- Physical Layer (PHY)

**Single-mode stack**
- BT ULP Profiles
- L2CAP
- HCI
- Link Layer (LL)
- Physical Layer (PHY)
Physical layer

2.4 GHz transceiver
- Industrial Scientific Medical (ISM) band
- 2400 MHz to 2483.5 MHz
- License free

GFSK modulation
- Modulation index 0.5
- \( \rightarrow \) Improve SNR and therefore better range

Bandwidth
- 1 Mbps

40 channels
- 2 MHz channel spacing
- 2402 MHz to 2480 MHz
Physical layer

Minimum transmit power
- 0.01mW (-20 dBm)

Maximum transmit power (regular limit)
- 10mW (+10 dBm)

Minimum receiver sensitivity
- -70 dBm (Bit Error Rate 0.1%)

Range
- 0dBm TX power and -70dBm RX sensitivity
- ~ 30 meters
- 10dBm TX power and -90dBm RX sensitivity
- 100+ meters

Typically devices have:
- 0-4 dBm TX power
- -85 to -90 dBm sensitivity
# Physical layer

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>LL</th>
</tr>
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<tbody>
<tr>
<td>2402 MHz</td>
<td>37</td>
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<td>2478 MHz</td>
<td>37</td>
</tr>
<tr>
<td>2480 MHz</td>
<td>38</td>
</tr>
</tbody>
</table>
Link layer

A simple state machine

Channels
- Advertising and data channels

Packets
- Advertising and data packets

Link layer procedures
- Advertising
- Scanning
- Initiating connections
- Connected

Topologies
- Point-to-point
- Star

Link layer security
Link layer state machine

- **Scanning** (Role: scanner)
  - Stop scanning
  - Start scanning

- **Standby**
  - Stop advertizing
  - Start advertizing
  - Connection lost / Disconnection
  - Connection received (Role: slave)
  - Connection successful (Role: master)
  - Start advertizing
  - Stop advertizing

- **Initiating**
  - Start connection

- **Connected**
Link layer channels

3 advertising channels
- Used for discoverability and connectability
- Used for broadcasting
- Avoid known 802.11 frequencies

37 data channels
- Used to reliably send application data in a connection
- Use Adaptive Frequency Hopping for co-existence and robustness
Link layer

Frequency (MHz)

- 2402 MHz
- 2404 MHz
- 2406 MHz
- 2408 MHz
- 2410 MHz
- 2412 MHz
- 2414 MHz
- 2416 MHz
- 2418 MHz
- 2420 MHz
- 2422 MHz
- 2424 MHz
- 2426 MHz
- 2428 MHz
- 2430 MHz
- 2432 MHz
- 2434 MHz
- 2436 MHz
- 2438 MHz
- 2440 MHz
- 2442 MHz
- 2444 MHz
- 2446 MHz
- 2448 MHz
- 2450 MHz
- 2452 MHz
- 2454 MHz
- 2456 MHz
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- 2464 MHz
- 2466 MHz
- 2468 MHz
- 2470 MHz
- 2472 MHz
- 2474 MHz
- 2476 MHz
- 2478 MHz
- 2480 MHz

Link layer (LL)

- 37
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- 37
Link layer packets

Single packet format
- Preamble used to synchronize AGC
- Access address identifies advertising PDUs or device pairs
- PDU contains application data
- 24-bit CRC protects against errors
  - Better than Bluetooth BT/EDR
Link layer packets

Advertising PDUs
- Used to find devices, get additional information or open connections
- 7 PDU types

Data PDU
- Carries application data reliably
Device address

Public Device Address

Random Device Address
Link layer: Passive scanning

Scanner

Advertised Device

Advertisement

Advertisement

Advertisement

Advertiser
Advertising

Advertising data
- "I’m connectable and bondable"
- "My transmit power is 0 dBm"
- "I support heart rate, manufacturer and battery services"

Why advertise?
- Takes around 1.5 ms of time
- 20 x lower power than Bluetooth classic
Link layer: Active scanning
Active scanning

Active scanning used to get more data from the advertiser

Scan response data

- Device name is "Indoor thermostat"
- Device supports thermometer and battery services
Link layer: Connection

- Initiator
  - Advertisement
  - Connect Request
- Advertiser
  - Total time < 3 ms
- Master
  - "poll"
  - Data
  - ack
  - LL Terminate
  - ack
- Slave
- Advertising Channels
- Data Channels
Connections

- **Master always transmits at known “anchor points”**
  Known as connection interval
  Starts a connection event
  From 7.5ms to 4.0s

- **Slave is able to listen / communicate**
  Slave latency allows slave to save power if it has nothing to send
  Slave can skip N anchor points

- **Automatically extends when**
  More data bit set by either device

- **Automatically ends when CRC errors received**
  Move to another channel at next connection event
Link layer: Topologies

- Master
- Slave
- Advertiser
- Scanner

Advertisements flow from Master to Slaves and from Slaves to Advertiser.
Link layer: Topologies
Link layer: Topologies

- Master
- Slave
- Connected
- Advertiser
- Scanner
- Advertiser
A single master can address $2^{31}$ slaves

- ~ 2 billion addressable slaves per master

**Max Connection Interval = 4.0 seconds**

- Can address a slave every ~ 5 ms (assuming 250 ppm clocks)
- ~ 800 active slaves per master

**Note:**
Devices RAM may limit the number of connections
Link layer security

AES-128 is the encryption engine of choice
- Used by most other secure wireless standards

Link Layer uses CCM (Counter Mode CBC-MAC) (RFC 3610)
- Encryption and Authentication of Data
- MIC added to end of payload to authenticate data
- Authentication does not have to be done in real-time
  - Saves power

Limits:
- 13.5 Terabytes / connection
- ~12 years at maximum data rate
Host Controller Interface

Transport layer
- UART
- USB
- SDIO
- 3 wire UART

Functional layer
- HCI commands
- HCI events
- Data

New commands added for Bluetooth LE
L2CAP

Logical Link Control and Adaptation Protocol

Acts as a protocol multiplexer
- Segmentation and reassembly of packets

All application data is sent using L2CAP

Three fixed channels for Bluetooth LE
- Attribute protocol
- LE L2CAP signalling protocol
- Security Manager protocol
Security Manager

Used for pairing and key distribution

Use distributing key model
- Slave generates and distributes key information to master
- Master can use this key information when reconnecting

Pairing
- Authentication based on their capabilities / security requirements
- Side effect is encrypted link / key distribution

Signing Data
- Signing allows authentication of sender without encryption

Uses several keys
- Short term key
- Long term key
- Identity resolving key

Bonding
- GAP concept – device save keys for bonded devices
Security Manager

Phase 1: Exchange IO Capabilities

Phase 2: Authenticate

Link Layer Encryption

Phase 3: Key Distribution
Attribute Protocol (ATT)
Attribute Protocol (ATT)

The only protocol used in Bluetooth low energy

Uses client server architecture
- servers store data
- clients request data from server
- clients writes data to server

Protocol Methods
- Client to server: Read, write
- Server to client: Notify, indicate
Attribute Protocol

The data is exposed as attributes

- Attributes have values
- 0 to 512 octets
- Fixed or variable length

Attributes have handles

- Used to address individual attributes

Read 0x0022 -> 0x04

<table>
<thead>
<tr>
<th>Handle</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x0009</td>
<td>0x54656d70657261747572652053656e736f72</td>
</tr>
<tr>
<td>0x0022</td>
<td>0x04</td>
</tr>
<tr>
<td>0x0098</td>
<td>0x0802</td>
</tr>
</tbody>
</table>
Attribute Protocol

Attributes have a type
- Identified by UUIDs
- UUIDs are 16-bit (Bluetooth SIG assigned) or 128-bit (manufacturer proprietary)

Types are defined in specifications
- Characteristics specifications
- Generic Access Profile
- Generic Attribute Profile

<table>
<thead>
<tr>
<th>Handle</th>
<th>Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x0009</td>
<td>«Device Name»</td>
<td>0x54656d70657261747572652053656e736f72</td>
</tr>
<tr>
<td>0x0022</td>
<td>«Battery State»</td>
<td>0x04</td>
</tr>
<tr>
<td>0x0098</td>
<td>«Temperature»</td>
<td>0x0802</td>
</tr>
</tbody>
</table>

0x54656d70657261747572652053656e736f72 = “Temperature Sensor”
Attribute Protocol

Attributes have permissions:
- Readable / not readable
- Writeable / not writeable
- Readable & writeable / not readable & not writeable

Attribute values may require:
- Authentication to read / write
- Authorization to read / write
- Encryption / pairing to read / write

These are defined in Bluetooth LE profile specifications
Attribute Protocol

Attribute Protocol is stateless

Transactions:
- Request -> Response
- Command
- Notification
- Indication -> Confirmation

Attribute Protocol is sequential
- Only one request at a time

Simple!
Attribute Protocol

- **Attribute operations: notify**
  Server sends the data when it changes

- **Attribute operations: indicate**
  Server sends the data when it changes
  Client confirms that it has received the data
Attribute Protocol

- **Attribute operations: read**
  Client requests data when it needs it
  Client polls server for attribute value
  - This may be inefficient if data doesn’t change often
  - Shouldn’t be used for frequently changing data that you are monitoring

- **Attribute operations: write**
  Client can set attributes to configure a server
  - E.g. set the room temperature to 22ºC
Generic Attribute Profile (GATT)
Generic Attribute Profile

GATT defines concepts of
- Service group
- Characteristic group
- Declarations
- Descriptors

Same client server architecture as in ATT, except:
- Data is encapsulated in services
- Data is exposed in characteristics
GATT: Generic Attribute Profile

- Attribute Protocol is just a flat structure
  Profiles require hierarchical structures

- GATT defines how to group attributes
  Groups of attributes in a “Service”
  Groups of attributes within a “Service” – Sub-Services
  Groups of attributes by client
Generic Attribute Profile (GATT)

A service is:
- A collection of characteristics
- References to other services

Primary Service
- A primary service is a service that exposes primary usable functionality of this device. A primary service can be included by another service

Secondary Service
- A secondary service is a service that is subservient to another secondary service or primary service. A secondary service is only relevant in the context of another service.
### Generic Attribute Profile (GATT)

Attributes are flat

<table>
<thead>
<tr>
<th>Handle</th>
<th>Type</th>
<th>Value</th>
<th>Permissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x0001</td>
<td>«Primary Service»</td>
<td>«GAP»</td>
<td>R</td>
</tr>
<tr>
<td>0x0002</td>
<td>«Characteristic»</td>
<td>{r, 0x0003, «Device Name»}</td>
<td>R</td>
</tr>
<tr>
<td>0x0003</td>
<td>«Device Name»</td>
<td>“Temperature Sensor”</td>
<td>R</td>
</tr>
<tr>
<td>0x0004</td>
<td>«Characteristic»</td>
<td>{r, 0x0006, «Appearance»}</td>
<td>R</td>
</tr>
<tr>
<td>0x0006</td>
<td>«Appearance»</td>
<td>«Thermometer»</td>
<td>R</td>
</tr>
<tr>
<td>0x000F</td>
<td>«Primary Service»</td>
<td>«GATT»</td>
<td>R</td>
</tr>
<tr>
<td>0x0010</td>
<td>«Characteristic»</td>
<td>{r, 0x0012, «Attribute Opcodes Supported»}</td>
<td>R</td>
</tr>
<tr>
<td>0x0012</td>
<td>«Attribute Opcodes Supported»</td>
<td>0x00003FDF</td>
<td>R</td>
</tr>
<tr>
<td>0x0020</td>
<td>«Primary Service»</td>
<td>«Temperature»</td>
<td>R</td>
</tr>
<tr>
<td>0x0021</td>
<td>«Characteristic»</td>
<td>{r, 0x0022, «Temperature Celsius»}</td>
<td>R</td>
</tr>
<tr>
<td>0x0022</td>
<td>«Temperature Celsius»</td>
<td>0x0802</td>
<td>R*</td>
</tr>
</tbody>
</table>
## Generic Attribute Profile (GATT)

Grouping gives structure

<table>
<thead>
<tr>
<th>Handle</th>
<th>Type</th>
<th>Value</th>
<th>Permissions</th>
</tr>
</thead>
<tbody>
<tr>
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<td>«Primary Service»</td>
<td>«GAP»</td>
<td>R</td>
</tr>
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<td>0x0002</td>
<td>«Characteristic»</td>
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<td>R</td>
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<tr>
<td>0x0003</td>
<td>«Device Name»</td>
<td>“Temperature Sensor”</td>
<td>R</td>
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<tr>
<td>0x0004</td>
<td>«Characteristic»</td>
<td>{r, 0x0006, «Appearance»}</td>
<td>R</td>
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<tr>
<td>0x0006</td>
<td>«Appearance»</td>
<td>«Thermometer»</td>
<td>R</td>
</tr>
<tr>
<td>0x000F</td>
<td>«Primary Service»</td>
<td>«GATT»</td>
<td>R</td>
</tr>
<tr>
<td>0x0010</td>
<td>«Characteristic»</td>
<td>{r, 0x0012, «Attribute Opcodes Supported»}</td>
<td>R</td>
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<tr>
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<td>0x0003FDF</td>
<td>R</td>
</tr>
<tr>
<td>0x0020</td>
<td>«Primary Service»</td>
<td>«Temperature»</td>
<td>R</td>
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<tr>
<td>0x0021</td>
<td>«Characteristic»</td>
<td>{r, 0x0022, «Temperature Celsius»}</td>
<td>R</td>
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<tr>
<td>0x0022</td>
<td>«Temperature Celsius»</td>
<td>0x0802</td>
<td>R*</td>
</tr>
</tbody>
</table>
GAP: Generic Access Profile

Defines Profile Roles
- Broadcaster, Observer, Peripheral, Central

Defines Modes
- Discoverable: General discoverable, non-discoverable, limited discoverable
- Connectable: Connectable, non-connectable
- Bondable: Bondable, non-bondable

Privacy
- Non-Resolvable and Resolvable Private Addresses
Differentation & Comparison
Differentiation

- Simple star topology reduces implementation complexity significantly
- Very small silicon footprint and thereby very low cost
- Very robust through frequency hopping compared to other wireless technologies
- Very secure through 128 bit AES encryption
- Very low power – always OFF technology
- No competitors (*Bluetooth* is already in phones)
## Comparison

<table>
<thead>
<tr>
<th>Technology</th>
<th>Classic Bluetooth technology (BR/EDR)</th>
<th>Bluetooth low energy technology</th>
<th>ZigBee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio Frequency</td>
<td>2.4 GHz</td>
<td>2.4 GHz</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>Distance / Range</td>
<td>10 to 100 meters³</td>
<td>10 to 100 meters³</td>
<td>10 to 200 meters⁴</td>
</tr>
<tr>
<td>Over the air Data Rate</td>
<td>1-3Mbps</td>
<td>1Mbps</td>
<td>250kbps at 2.4 GHz.</td>
</tr>
<tr>
<td>Application Throughput</td>
<td>0.7-2.1 Mbps</td>
<td>0.2 Mbps</td>
<td>&lt;0.1 Mbps</td>
</tr>
<tr>
<td>Nodes/Active Slaves</td>
<td>7 / 16777184⁵</td>
<td>Unlimited⁶</td>
<td>6553⁵</td>
</tr>
<tr>
<td>Security</td>
<td>64b/128b and applications layer</td>
<td>128b AES and application layer</td>
<td>128b AES and application</td>
</tr>
<tr>
<td>Robustness</td>
<td>Adaptive fast frequency hopping, FEC, fast ACK</td>
<td>Adaptive fast frequency hopping</td>
<td>layer user defined</td>
</tr>
<tr>
<td>Latency (from a non connected state)</td>
<td></td>
<td></td>
<td>DSSS, Uses only 16 ch. in ISM band, optional mesh topology has long recovery time</td>
</tr>
<tr>
<td>Total time to send data (det.battery life)</td>
<td>100ms</td>
<td>&lt;3ms</td>
<td>&lt;10ms</td>
</tr>
<tr>
<td>Government Regulation</td>
<td>Worldwide</td>
<td>Worldwide</td>
<td>Worldwide</td>
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<tr>
<td>Certification Body</td>
<td>Bluetooth SIG</td>
<td>Bluetooth SIG</td>
<td>ZigBee Alliance</td>
</tr>
<tr>
<td>Voice capable</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Network topology</td>
<td>Scatternet</td>
<td>Star-bus</td>
<td>Star or Mesh</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>1 as the reference</td>
<td>0.01 to 0.5(depending on use-case)</td>
<td>2 (router) / 0.1 (end point)</td>
</tr>
<tr>
<td>Peak current consumption (max 15 mA to run on coin cell battery)</td>
<td>&lt;30 mA</td>
<td>&lt;15 mA</td>
<td>&lt;15 mA</td>
</tr>
<tr>
<td>Service discovery</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Profile concept</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Primary Use Cases</td>
<td>Mobile phones, gaming, headsets, stereo audio streaming, automotive, PCs, consumer electronics, etc.</td>
<td>Mobile phones, gaming, PCs, watches, sports &amp; fitness, healthcare, automotive, consumer electronics, automation, industrial, etc.</td>
<td>Fixed location industrial, building &amp; home automation, AMI/SmartEnergy</td>
</tr>
</tbody>
</table>
Markets

Sports and Fitness  Health  Home  Office  Automotive  Watch
Sports & fitness

- Heart rate
- Cadence
- Watches
- Pedometers
Assisted living

- **Sensors**
  - Temperature
  - Humidity
  - Alarms

- **Collectors**
  - Collect information from sensors
  - Display information to user
Consumer medical

- Weight scales
- Blood pressure meters
- Blood glucose meters
Entertainment

- Remote controllers
- Gaming controllers
Automation

- **Industrial automation**
  - Robots
  - Motors
  - Processes

- **Home automation**
  - Temperature
  - Humidity
  - Lights
Security

- Key fobs
- Proximity monitors
- Electrical keys
- Mobile phone keys
Broadcast advertising

- Information points
- Indoor GPS
- Advertisements
- Maps of facilities
- Fire exits
Summary
Summary

*Bluetooth* low energy is a new technology
- Blank sheet of paper
- Optimized for low power

*Bluetooth* low energy is designed to be low power
- 10-20 times less power consumption compared to *Bluetooth* classic
- Low silicon area and memory requirements
- Enables coin cell battery use cases

*Bluetooth* low energy is designed for new applications
- Health
- Fitness
- Automation
- Security
- Watch
Summary

*Bluetooth low energy is designed to be secure and robust*
- AES-128 with CBC/MAC
- Simple pairing
- Privacy support
- Adaptive Frequency Hopping
- Reliable connections

*It’s still Bluetooth!*
- Reuse of RF, HCI and L2CAP
- Royalty free
- Developed and driven by Bluetooth SIG (~14000 members)
- Bluetooth already in mobile phones and PCs
- Qualification and interoperability
- ~3 billion sold devices already
Questions?

www.bluegiga.com