ECEN 5823-001 / -001B

Internet of Things Embedded Firmware

Lecture #24

16 November 2017

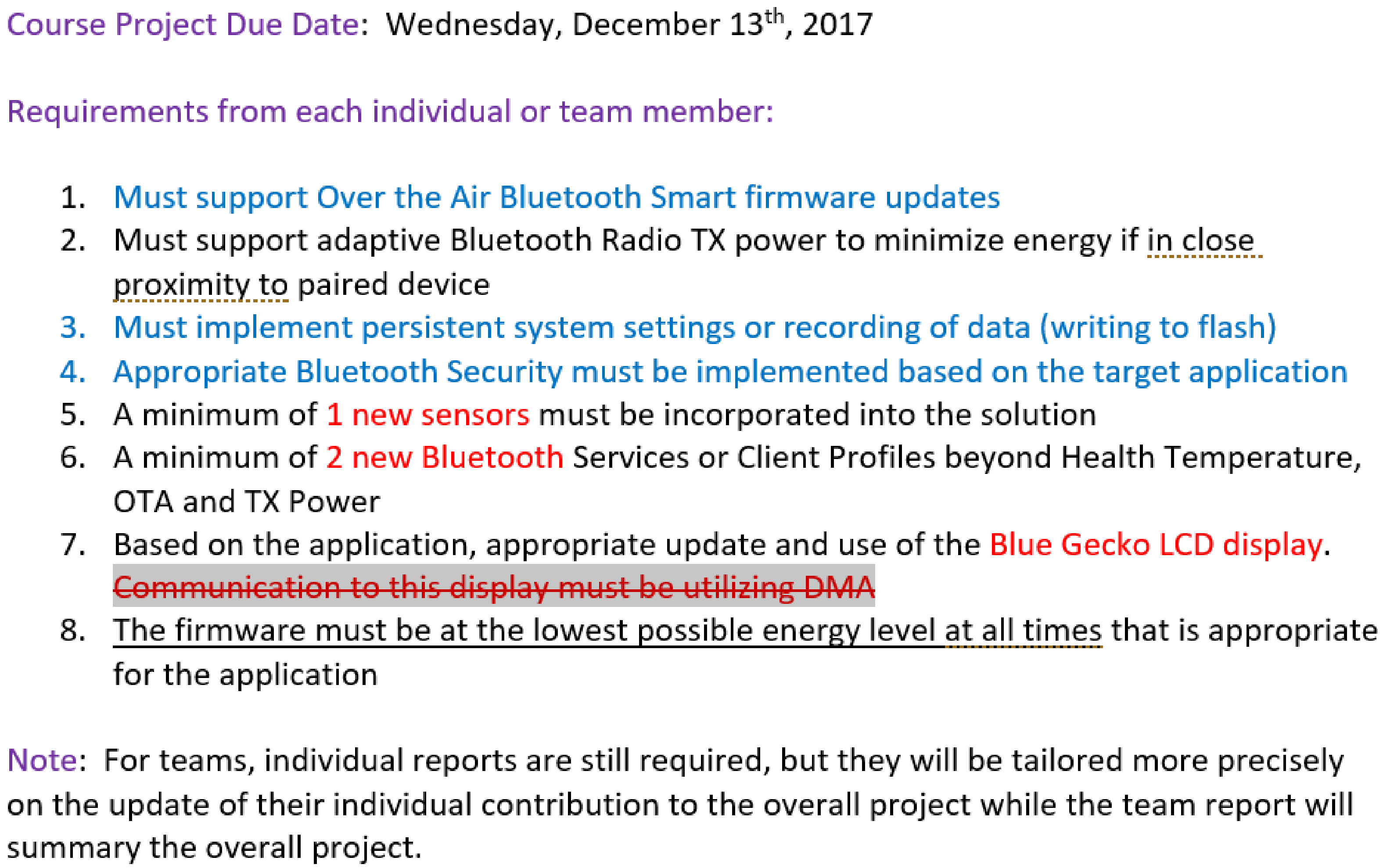
Agenda

- Class announcements
- Course Project update
- Bonus opportunity #4 – ???
- Bluetooth Mesh

Class Announcements

- Quiz #9 is due at 11:59pm this Sunday, November 26th, at 11:59pm
- Course Project Update #1 is due at 11:59pm this Saturday the 18th
- Bonus #3, Persistent Data, is due by 11:59pm this Saturday the 18th
  - Since it is a bonus, it must be done during a convenient time for the instructing team and do not expect to get a time at 11:59 on the 18th to demo your OTA bonus assignment
  - This will not be used an excuse to request an extension
- Bonus #4, ???, is due by 11:59pm on Saturday, December 2nd
- Any questions regarding the Course Project?
- Any questions regarding Bluetooth Mesh?

Course Project Update



Course Project Due Date: Wednesday, December 13th, 2017

Requirements from each individual or team member:

1. Must support Over the Air Bluetooth Smart firmware updates
2. Must support adaptive Bluetooth Radio TX power to minimize energy if in close proximity to paired device
3. Must implement persistent system settings or recording of data (writing to flash)
4. Appropriate Bluetooth Security must be implemented based on the target application
5. A minimum of 1 new sensors must be incorporated into the solution
6. A minimum of 2 new Bluetooth Services or Client Profiles beyond Health Temperature, OTA and TX Power
7. Based on the application, appropriate update and use of the Blue Gecko LCD display. ~~Communication to this display must be utilizing DMA~~
8. The firmware must be at the lowest possible energy level at all times that is appropriate for the application

Note: For teams, individual reports are still required, but they will be tailored more precisely on the update of their individual contribution to the overall project while the team report will summary the overall project.

Course Project Update

3. Implementing Control Points into the Server where a Client Profile can specify behavior of the Server
4. Demonstrating DMA operations to the SPI LCD or other appropriate usage. A DMA of one byte will not be considered a good example. Good examples are:
    a. DMA of characters to the LCD
    b. Multiple byte payloads across a communication bus on a regular basis such as LEUART, I2C, SPI, etc.
    c. Multiple byte reads or writes from / to sensors

Course Project – 4th Bonus Opportunity

- Implementing LCD and fully implementing scheduler
- Opportunity is worth 1% towards your final grade!
- You will need to end application usage on the LCD and walking through code to demonstrate the proper minimal coding within Interrupt Handlers and using a scheduler to service the interrupts.
- Requirements to get the extra credit:
  - Must demo to one of the three instructing team members by Saturday, December 2nd, at 11:59pm
  - By being a bonus, you must demo during convenient instructing team availability and not expect availability at 11:58pm on December 2nd
  - For distant students, the demo should be arranged over video chat, skype, etc.

Bluetooth Mesh: States

- States are values representing conditions of node elements
  - When an element is exposing a state (value) representing the condition of the element that element is called a Server and implements the Server Model
  - When accessing a state of an node element the accessing node is called a Client, which implements the Client Model
- There are three different methods for controlling element states
  - A state-changing message which is sent to a Server
  - An asynchronous event from the scheduler
  - A local event such as pressing a button

Bluetooth Mesh: Scenes

- Bluetooth Mesh stores states of elements as a Scene
  - A Scene register is a 17-element, zero-based, indexed array of 16-bit values
  - The “handle” of the state is the index into the scene array to state storage containers in which the associated state information is stored

Bluetooth Mesh: Initial, Present and Target States

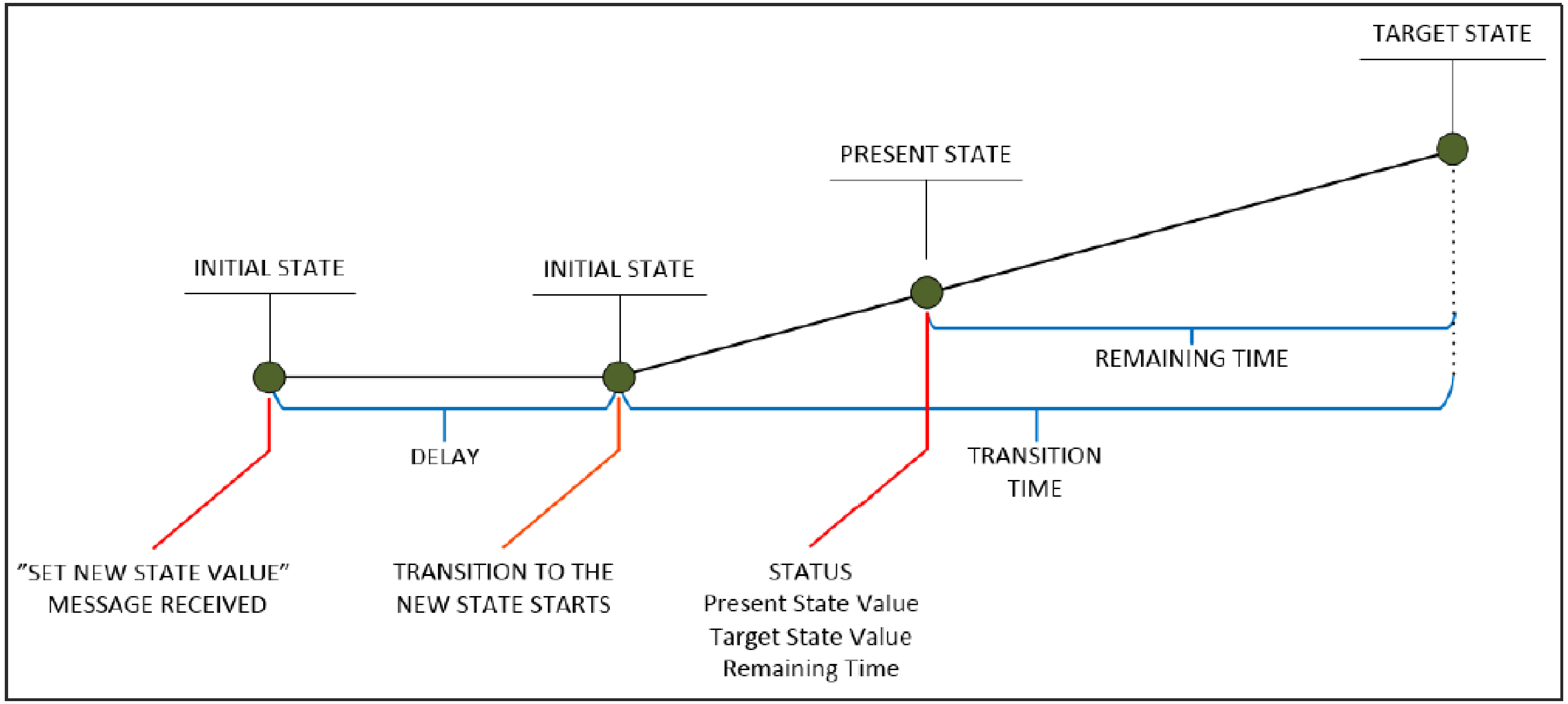
- States can change instantaneously or within a certain time period, this time period being called Transition Time
- The change begins from an Initial State ending to the Target State
- The Present State is the current state of an element.
- Bluetooth mesh defines a flexible method for defining how states can be changed using several different parameters and has a selection of specially optimized commands for various applications such as lighting control, sensors etc.

Bluetooth Mesh: Initial, Present and Target States

- The user can utilize a default transition time or alternatively define the time by changing the appropriate field in the related message
- One can also add a Delay which defines the length of time between the receipt of the message and the actual start of the state transition
  - This is useful for synchronizing actions with multiple receivers

Bluetooth Mesh: Initial, Present and Target States

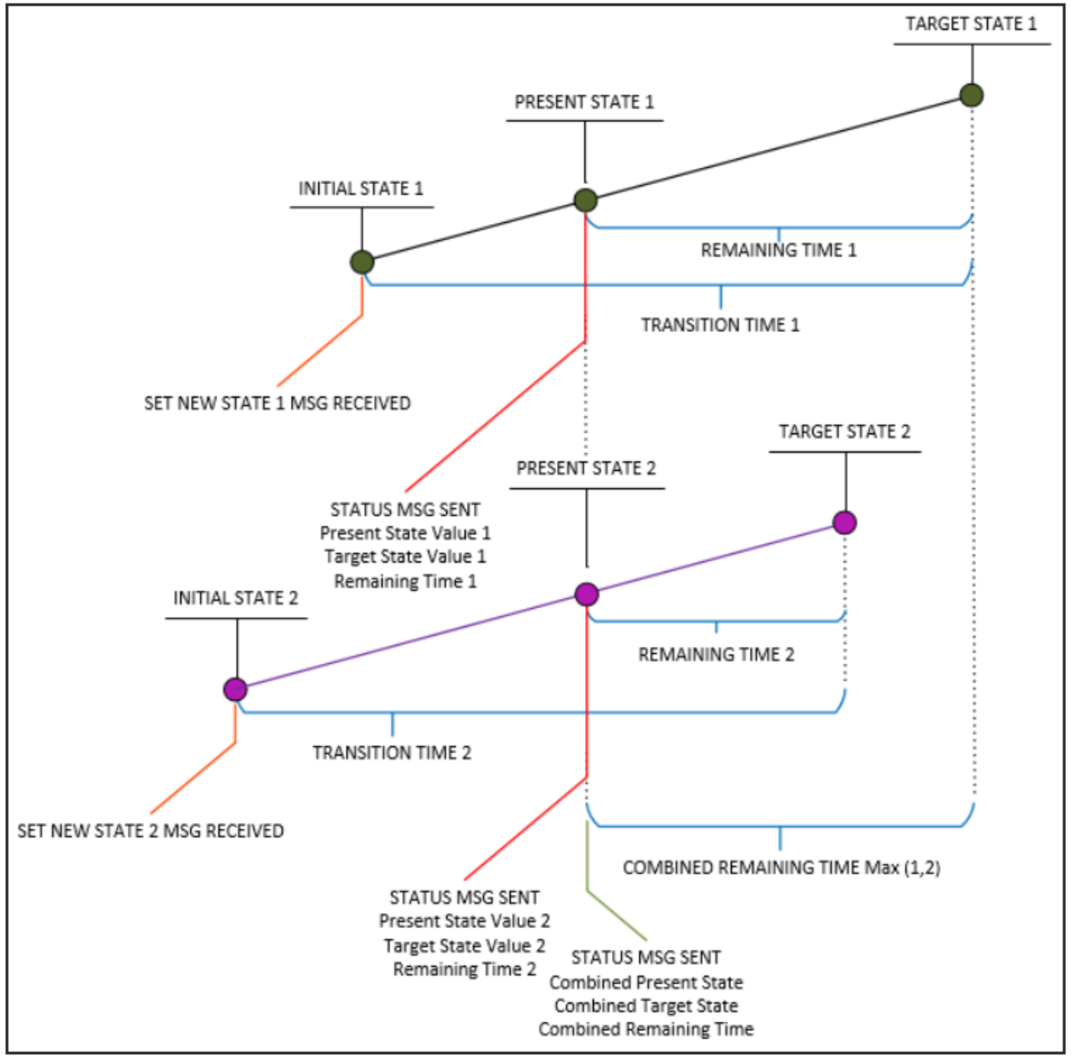
- Some states messages can be used to report the state of the transition, either the present state, or including both the present and target states together with the remaining time when the target state will be reached



State change using delay and transition time with related status info

Bluetooth Mesh: Initial, Present and Target States

- States can be one-dimensional or multi-dimensional
- For example, in light control applications one might be interested in controlling the hue, saturation and lightness



Bluetooth Mesh: Bound States

- States can also be bound together in which case a change in any of the states bound to each other will result in a change in the other states bound together
  - An example from lighting applications would be a case in which the light is dimmed to zero which will then cause the On/Off state to change to off-state
- It should be noted that bound states do not need to be from the same model nor do they have to be related to the same element
- Binding can be defined as bi-directional or uni-directional
  - This gives a lot of freedom for creative application development.

Bluetooth Mesh: Composite States

- To make the detection of changes in states as flexible as possible the user can group together multiple states
  - These kind of groups are called Composite States
  - As an example, consider the Light Lightness state, which is actually composed of three states name the Light Lightness Actual State, the Light Lightness Last State and the Light Lightness Default State
- If an indication of a change in any of the listed three states is required one can just refer to the Light Lightness state instead of referring to all three states separately.

Bluetooth Mesh: Scenes

- Bluetooth mesh includes a useful feature called Scene with which it is possible to recall a set of States for a group of Nodes
  - A practical example for a home application utilizing Scenes would be a light control by which a parent can control the lights in all of the children's bedrooms to the desired level
  - For example, in the evening the user could set all the lights in the bedrooms off except for a dimmed comfort light which slowly dims and finally switches off completely

Bluetooth Mesh: Messaging

- All communication in a Bluetooth mesh network is based on sending messages which operate on states
  - All states have a defined set of messages supported by a Server
  - Clients can use these same messages for requesting the value of state or to change the value of a state
- Information on states and/or the changing of states may be sent by a Server without any external request
- Messages consist of an opcode and related parameters
  - Single octet size messages are used with special messages when maximum payload size is required
  - Two octet messages are standard messages
  - Three octet messages are reserved for vendor-specific messages.

Bluetooth Mesh: Messaging

- Messages are either acknowledged or unacknowledged
  - Acknowledged messages require a response
  - Unacknowledged messages do not require a response
- Set, Clear, Recall, and Store messages can be either acknowledged or unacknowledged
  - Even though their semantics are the same their opcodes are different

Bluetooth Mesh: Messaging

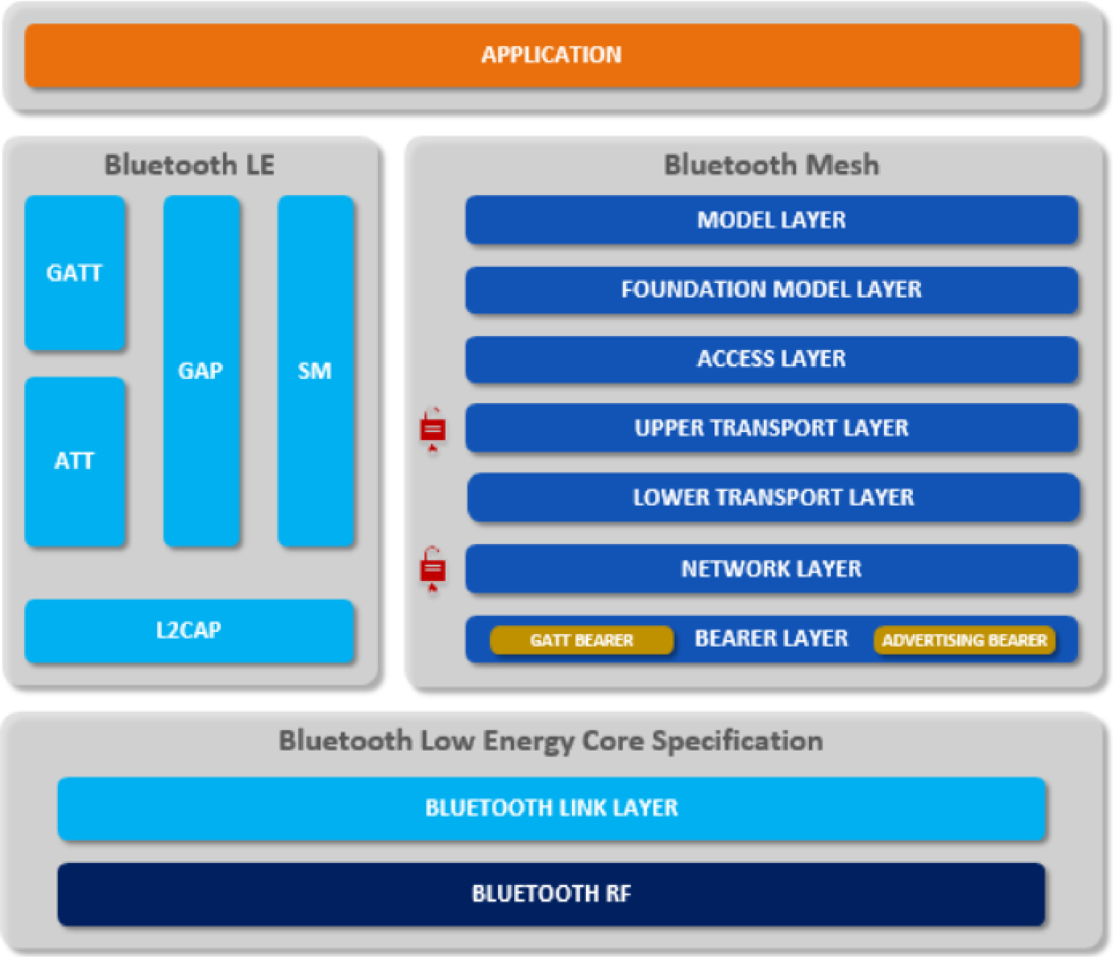
- Broadcast messages to all nodes listening at any time are based on the Advertising Bearer using BLE non-connectable advertising
- Messages are sent using broadcast channels
- Point-to-point messages are based on the GATT Bearer using BLE connections and standard GATT service
- Any node may support either or both bearers

Bluetooth Mesh: Segmentation & Reassembly

- The Transport Layer defines the total message size
    - Segmentation and Reassembly (SAR) can be used
    - In an optimal case only a single segment is used
    - With Segmentation and Reassembly a maximum message of 32 segments which translates to a maximum message of 384 octets
- With a single octet opcode this means that 379 octets are available for parameters, and with two or three octets 378 or 377 octets
- Bluetooth mesh messages are sent inside models using opcodes and element addresses

Bluetooth Mesh: Segmentation & Reassembly

- With large PDU’s, Protocol Data Unit, exceeding the maximum size the Lower Transport Layer of the transmitting node takes the PDU from the Upper Transport Layer and segments it by splitting the PDU into several Transport PDU’s
- When the receiving node receives these PDU’s the Lower Transport Layer reassembles the original PDU and then passes it upward to the Upper Transport Layer in the receiving node



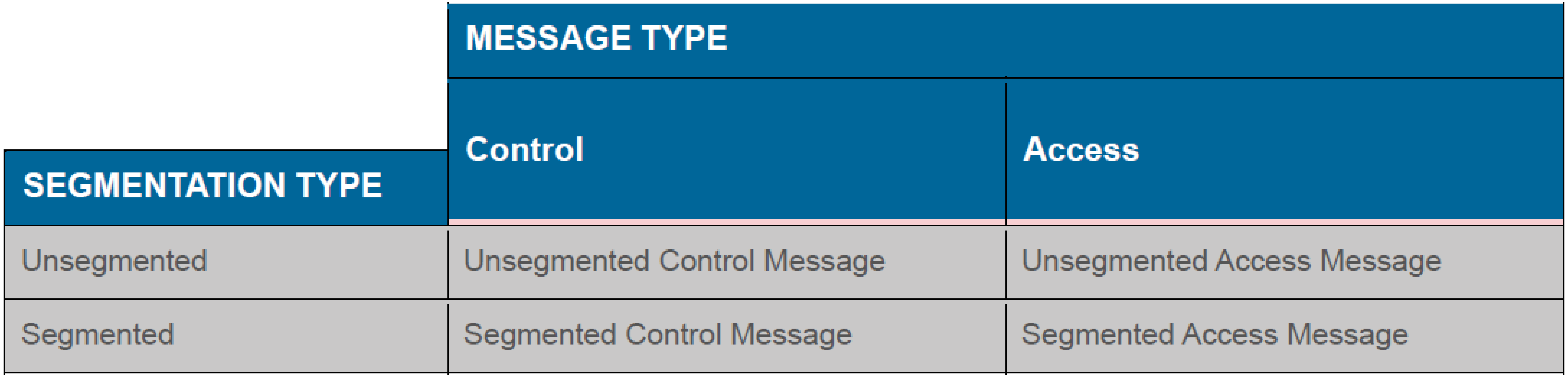
Bluetooth mesh architecture (right) with Bluetooth LE architecture (left)

Bluetooth Mesh: Segmentation & Reassembly

- Segments are identified by using a Segment Offset Number (SegO) where the first segment has the value 0, the second has the value 1 and so on
- The offset of the last segment needs to be also defined with the Last Segment Offset Number (SegN).
- For example, if the message consists of four segments the value to use for SegN would be 3
- In addition each message is identified by using a Sequence Authentication (SeqAuth) value which is used to encrypt or authenticate the access message
- The normal procedure would be to use the Sequence Number (SEQ) of segment number 0

Bluetooth Mesh: Segmentation & Reassembly

- There are four different message types defined for segmentation and reassembly



	MESSAGE TYPE	
SEGMENTATION TYPE	Control	Access
Unsegmented	Unsegmented Control Message	Unsegmented Access Message
Segmented	Segmented Control Message	Segmented Access Message

Bluetooth Mesh: Segmentation & Reassembly

- With segmented messages Bluetooth mesh defines a Segment Acknowledgement procedure which enables retransmission of segments which have not been received during the first try
- The mechanism allows indication of missed segments to make the source send only missed segments
- In case the receiving node is receiving messages on behalf of a defined Low Power node in a Friendship setup an OBO (On Behalf Of) acknowledgement message is used
- The Friend node which buffers the received message replies with the OBO on behalf of the Low Power node

Bluetooth Mesh: Addressing

- IoT use cases require that the user is able:
  - to control a single node
  - a group of nodes
  - Or, all of the nodes simultaneously
- This is provided in Bluetooth mesh by using:
  - unicast
  - virtual and group addressing
  - A special value representing an unassigned address not used in messages is also available
  - An element is an addressable entity

Bluetooth Mesh: Addressing

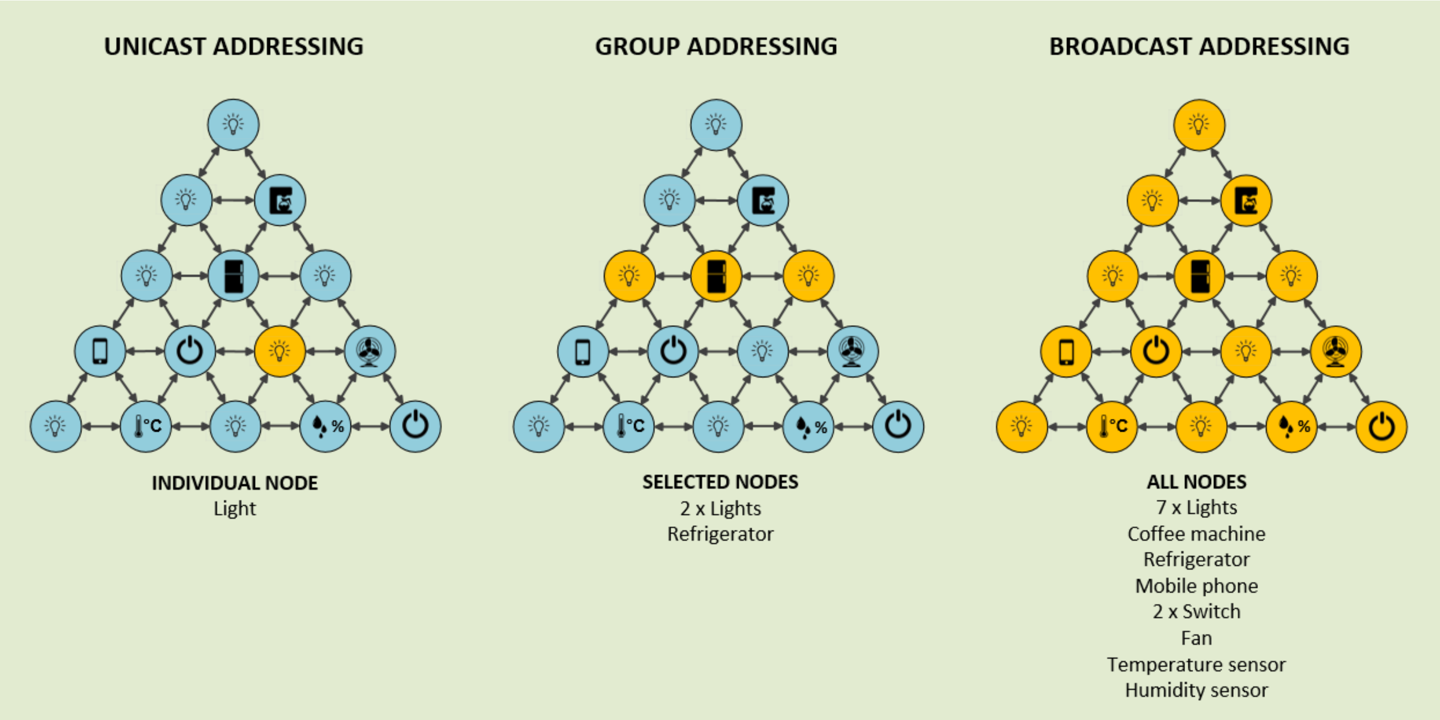
- An element is an addressable entity within a node and each node has at least one element called the Primary Element
- In addition to the Primary Element, a node may have one or more additional elements
  - This characteristic is stable throughout the lifetime of the node

Bluetooth Mesh: Addressing

- Unicast Addresses are allocated to Elements and they represent a single Element in a Node
  - A Bluetooth mesh network allows a maximum of 32767 unicast addresses
- A virtual address is a hash of a 128-bit Label UUID
  - Resulting in a very large amount of virtual addresses even if they are represented as 14-bit quantities in the network PDU’s
- Group addresses are also used for multicasting and may represent several Elements in one or more nodes
  - A mesh network offers 16384 group addresses.
  - The Bluetooth mesh standard defines a set of fixed group addresses which can be used to address a subset of all primary Elements of nodes of certain functionality
  - The rest are dynamically assigned group addresses and the user has 256 fixed group addresses and 16128 dynamically assignable groups

Bluetooth Mesh: Addressing

- Since each node in the mesh may contain one or more elements the Provisioner allocates each element with a unique unicast address
- In addition to the unicast addresses for each element the Provisioner also allocates group addresses
- important to note that Bluetooth mesh allows grouping of all kinds of devices to allow flexible grouping of mesh devices



Bluetooth Mesh: Security

- Bluetooth SIG has taken security concerns seriously and made security a mandatory feature of Bluetooth mesh
- All traffic is encrypted and sending of unencrypted messages is prohibited
- This fact alone makes the security model used in Bluetooth mesh stronger compared to BR/EDR and LE

Bluetooth Mesh: Encrypted Layers and Multiple Keys

- Achieving a high level of security is based on encryption and authentication both at network and transport layers
- Message Integrity Check (MIC) is applied to traffic of both layers
- All mesh messages are encrypted and authenticated using two different keys which are protected by using AES-128
  - Network traffic (Network Key)
  - Application data traffic (Application Key)
- Application specific keys provide effective isolation of applications and application data

Bluetooth Mesh: Encrypted Layers and Multiple Keys

- Authentication and confidentiality of all data in Bluetooth mesh is provided by using three different keys:
  - Device Key
  - Network Key
  - And, Application Key
- There are also some other keys derived from these three main keys which as a group are called Derived Keys

Bluetooth Mesh: Device Keys

- Each individual node of a mesh network has its own unique Device Key
- The value of the Device Key is calculated with the shared secret provided by the Elliptic Curve Diffie-Hellman key agreement between the two devices and is never transmitted over the air
- In theory only the Provisioner has knowledge of the Device Key except if the Device Key has been handed over to another device for configuration purposes

Bluetooth Mesh: Device Keys

- The Device Key is used to authenticate and encrypt communications between the Configuration Client and a single node
- Other nodes have no way of interpreting communication between the said two devices
- The Device Key is the most critical key in the mesh network since the Device Key is used to:
  - Read information about the node
  - Enable configuring how the node will communicate with other
  - The distribution of security credentials

Bluetooth Mesh: Network Key

- Mesh networking flexibility is provided by the fact that any node can be configured to be in one or multiple Mesh Networks
  - Requiring the ability to use one or multiple Network Keys simultaneously
- Similarly, a Mesh device can be in one or more subnet through the definition of Subnet Network Keys
- Subnets are groups of nodes able to communicate with each other at the Network Layer
- Alternatively a node may belong to two or more totally separate mesh networks
  - A good example of such a case would be a mobile phone which could be part of a home mesh network, an office mesh network and a vehicle mesh network

Bluetooth Mesh: Network Key

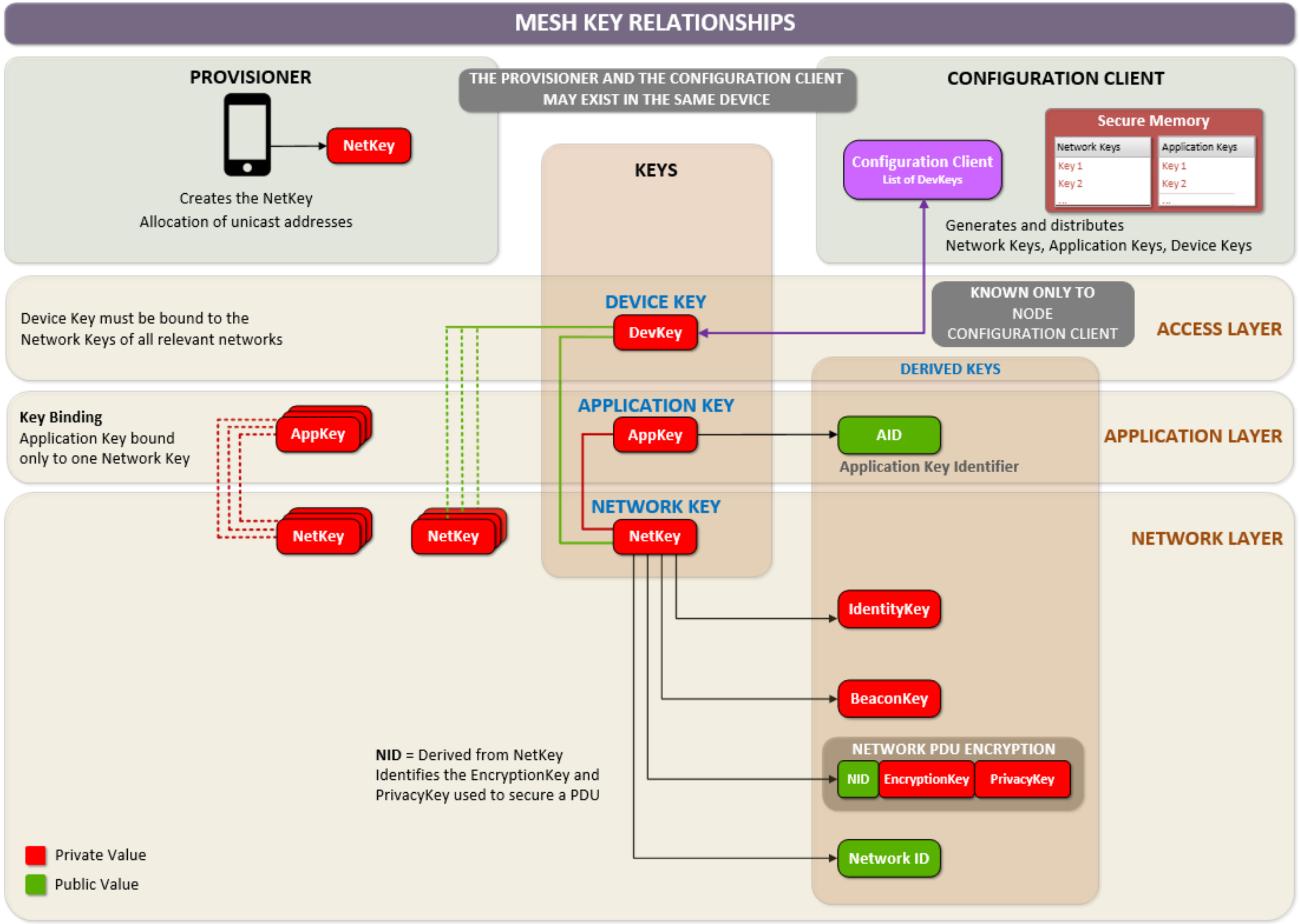
- The maximum number of different Network Keys in any installation is 4096 which makes it possible to create secure partitions inside a network when required
    - There is no direct use for the Network Key
    - It is used to derive encryption and other keys using AES-CMAC hashing

Bluetooth Mesh: Application Key

- A mesh network can contain one or more application domains each with a unique Application Key
- Nodes which are configured with a particular Application Key can receive and transmit messages related to the said application while messages originating from nodes part of different application domains are just relayed
- The above solution allows compartmentalization of applications which increases security
  - As an example consider a home with a wireless doorbell and an electrically controllable door lock
  - Having separate application domains for these two devices increases security since a compromised doorbell would still not make it possible to hack the door lock
- One can think of application domains as virtual security areas which belong to a larger security area provided by the mesh network itself

Bluetooth Mesh: Derived Keys

- Due to the nature of the Device Key and the fact that it is not used directly requires that we have other keys
- These are established from the Device Key using a Key Derivation Function (KDF) as defined by the Bluetooth SIG
- The idea here is to protect the Device Key even though a Derived Key is compromised for any reason
- The relationship of Derived Keys with the three basic keys is shown in the figure on next page.



MESH KEY RELATIONSHIPS

Creates the NetKey
Allocation of unicast addresses

THE PROVISIONER AND THE CONFIGURATION CLIENT MAY EXIST IN THE SAME DEVICE

Generates and distributes
Network Keys, Application Keys, Device Keys

Device Key must be bound to the Network Keys of all relevant networks

KNOWN ONLY TO NODE CONFIGURATION CLIENT

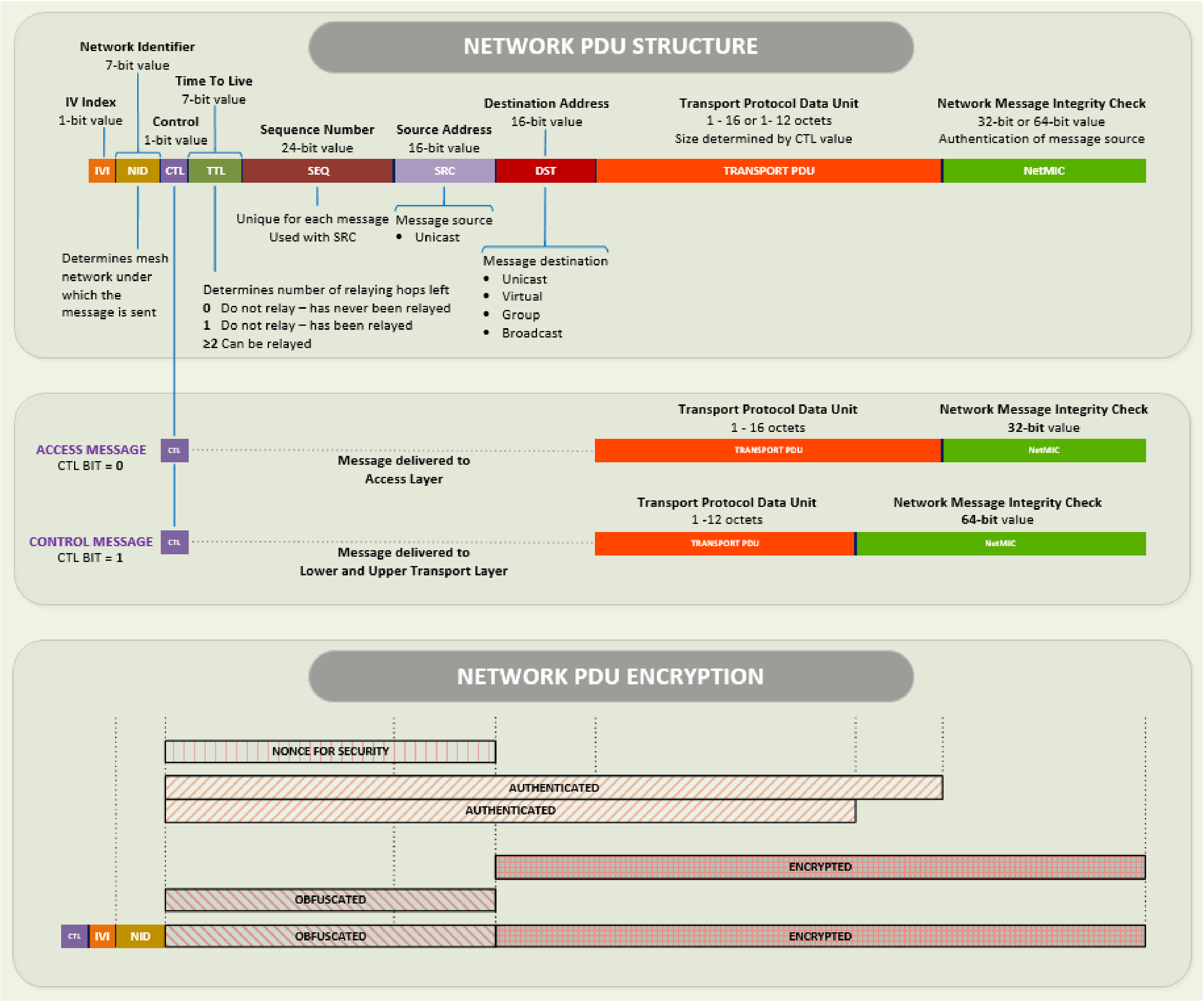
Key Binding
Application Key bound only to one Network Key

NID = Derived from NetKey
Identifies the EncryptionKey and PrivacyKey used to secure a PDU

🟥 Private Value
🟩 Public Value

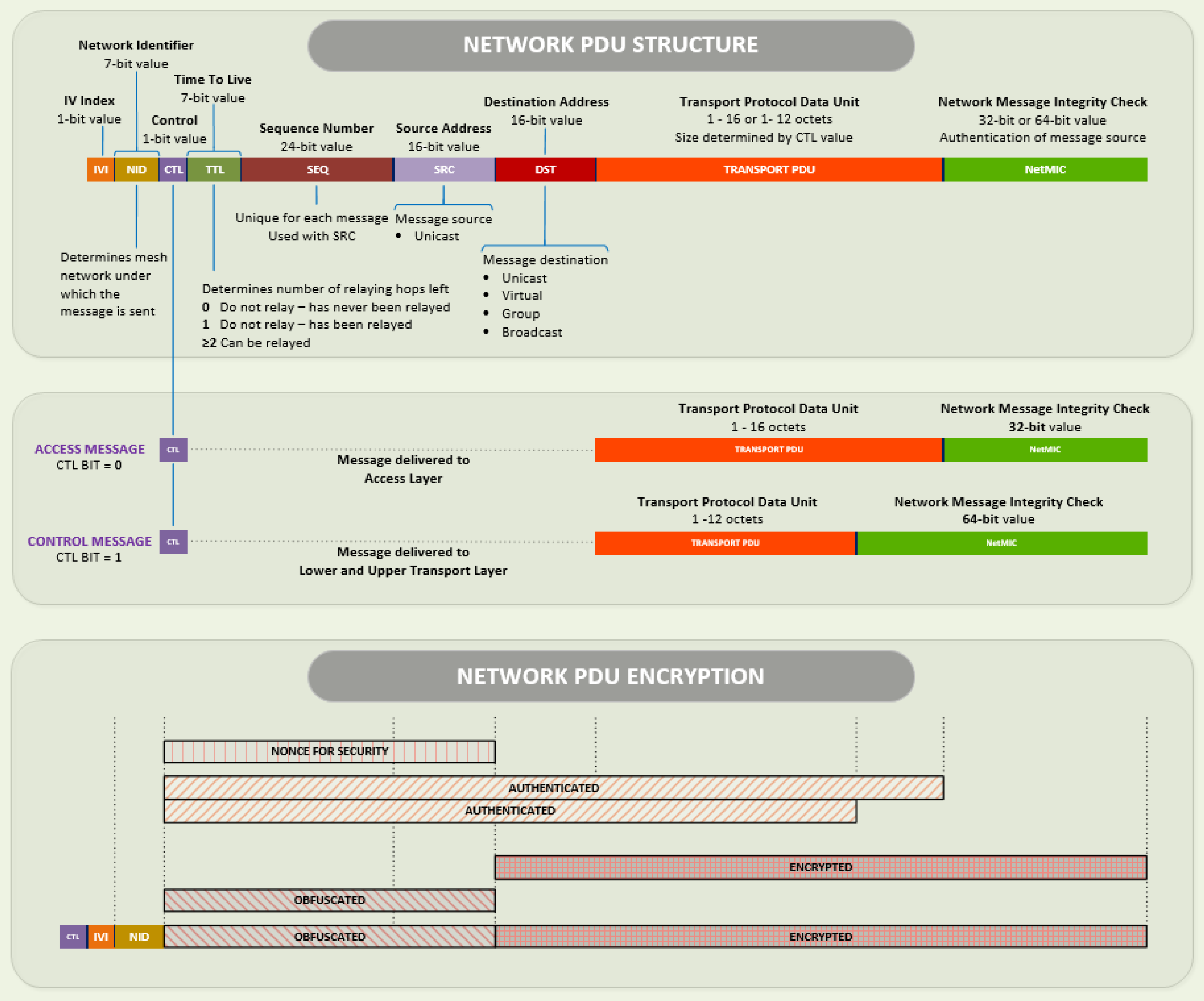
Bluetooth Mesh: Network PDU Obfuscation and Encryption

- The only plaintext parts of the Bluetooth mesh PDU are the IVI Index (IVI) and the Network Identifier (NID) at the start of the PDU package
- The rest of the PDU is obfuscated using AES-ECB or encrypted using AES-CCM
- This is to make passive snooping of the network structure next to impossible since the header, TTL, sequence number, source address etc. are not sent as plain text



Bluetooth Mesh: Network PDU Obfuscation and Encryption

- Nonce data is generated from sequence numbers and other network header information while message integrity is protected by a 32-bit or 64-bit MIC
- To keep track of individual messages each message has a unique 24-bit Sequence Number
- Replay protection is achieved by using message sequence numbering which the nodes keep track of based on source address



NETWORK PDU STRUCTURE

Network Identifier
7-bit value

Time To Live
7-bit value

IV Index
1-bit value

Control
1-bit value

Sequence Number
24-bit value

Source Address
16-bit value

Destination Address
16-bit value

Transport Protocol Data Unit
1 - 16 or 1- 12 octets
Size determined by CTL value

Network Message Integrity Check
32-bit or 64-bit value
Authentication of message source

IVI | NID | CTL | TTL | SEQ | SRC | DST | TRANSPORT PDU | NetMIC

Determines mesh network under which the message is sent

Unique for each message
Used with SRC

Message source
- Unicast

Determines number of relaying hops left
0 Do not relay – has never been relayed
1 Do not relay – has been relayed
≥2 Can be relayed

Message destination
- Unicast
- Virtual
- Group
- Broadcast

ACCESS MESSAGE
CTL BIT = 0

CTL

Message delivered to
Access Layer

Transport Protocol Data Unit
1 - 16 octets

Network Message Integrity Check
32-bit value

TRANSPORT PDU | NetMIC

CONTROL MESSAGE
CTL BIT = 1

CTL

Message delivered to
Lower and Upper Transport Layer

Transport Protocol Data Unit
1 -12 octets

Network Message Integrity Check
64-bit value

TRANSPORT PDU | NetMIC

NETWORK PDU ENCRYPTION

NONCE FOR SECURITY

AUTHENTICATED

AUTHENTICATED

ENCRYPTED

OBFUSCATED

CTL | IVI | NID | OBFUSCATED | ENCRYPTED

Bluetooth Mesh: Key Management

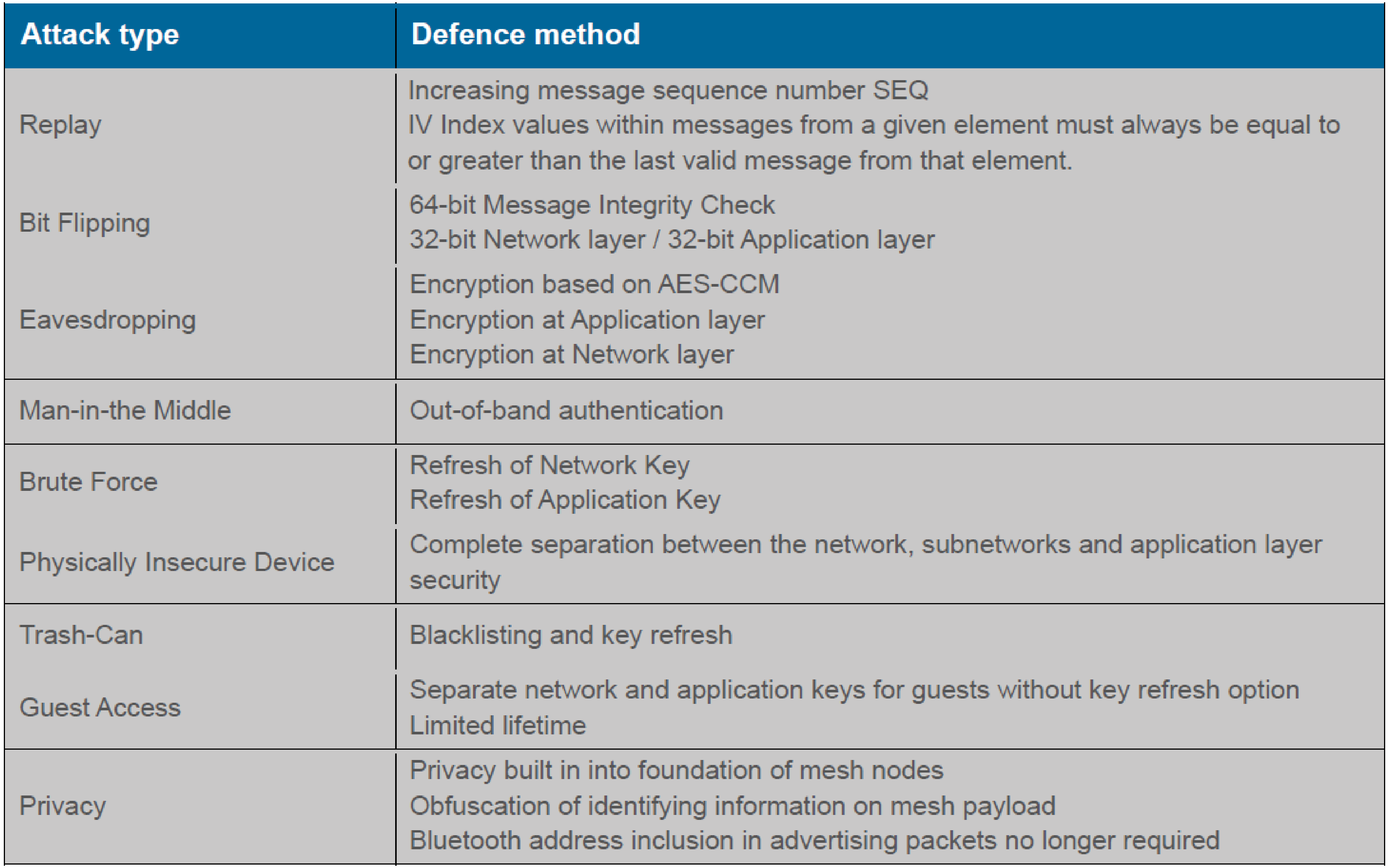
- The network, device keys, addresses, human friendly names related to nodes and groups are all saved into a Provisioning Database
- This solution enables the use of more than one Provisioner which is useful especially in large mesh networks
- Individual databases must then be compiled into a single database at a suitable time

Bluetooth Mesh: Key Refresh and Blacklisting

- To ensure security a Bluetooth mesh network needs to have its keys refreshed on a regular basis
- Whenever a node is removed from a Bluetooth mesh network intentionally, or should a network node become compromised for any reason, the keys must be to be refreshed!
- Bluetooth mesh provides a Key Refresh procedure
  - The Provisioner/Configuration client can utilize this feature to decrease the likelihood of security problems by performing a key refresh of all known acceptable devices on a regular basis such as once a week

Bluetooth Mesh: Minimizing Security Threats

- Bluetooth SIG has designed the security features of Bluetooth mesh to provide protection against many different types of security threats and attack methods.



Attack type	Defence method
Replay	Increasing message sequence number SEQ IV Index values within messages from a given element must always be equal to or greater than the last valid message from that element.
Bit Flipping	64-bit Message Integrity Check 32-bit Network layer / 32-bit Application layer
Eavesdropping	Encryption based on AES-CCM Encryption at Application layer Encryption at Network layer
Man-in-the Middle	Out-of-band authentication
Brute Force	Refresh of Network Key Refresh of Application Key
Physically Insecure Device	Complete separation between the network, subnetworks and application layer security
Trash-Can	Blacklisting and key refresh
Guest Access	Separate network and application keys for guests without key refresh option Limited lifetime
Privacy	Privacy built in into foundation of mesh nodes Obfuscation of identifying information on mesh payload Bluetooth address inclusion in advertising packets no longer required

Bluetooth Mesh: Practical Security Guidelines

- Bluetooth mesh provides various means to maximize security
- Applications should be configured with individual Application Keys which will limit problems if a node is compromised
- Pairwise Application Keys can be configured between nodes which need to exchange data only between each other
- Device Keys represent the most critical information in the network
  - If a mobile phone is used as a Provisioner, the Device Keys as well as Network Keys and Application Keys should be stored using secure storage API's available through the operating system of the mobile device
  - A lost mobile phone would then not present risks regarding the security of the mesh network
- For embedded devices security credentials should be stored in secure memory elements

Bluetooth Mesh: Practical Security Guidelines

- In device provisioning using out-of-band input or output the user should use at the minimum a 6-octet numeric or alphanumeric value but the longer the value the stronger the security
  - Alternatively a device may use other non-Bluetooth data transfer methods available
- When devices are removed from the mesh the Provisioner should initiate a Key Refresh procedure throughout the whole mesh network for both the network and the Application Key
- The removed device should also be blacklisted
- There is also a need to refresh the above mentioned keys periodically to help maintain the strength of the obfuscation
- Bluetooth SIG recommends this to be done every 14 days

Bluetooth Mesh: Practical Security Guidelines

- In similar fashion a periodic refresh of the IV Index keeps the nonces applied to encryption and authentication fresh
  - Bluetooth SIG recommends the same 14 day period for IV Index refreshing
- Programming fixed Network Keys during device manufacturing is strongly discouraged since refreshing as recommended above would not be possible
- The Provisioning Database contains very sensitive information regarding the safety of a mesh network special attention to the transfer of the database is needed
  - Authentication using at the minimum 128-bit MIC is recommended
  - In addition using OOB methods will ensure that only intended devices can utilize the database

Bluetooth Mesh: Low Power

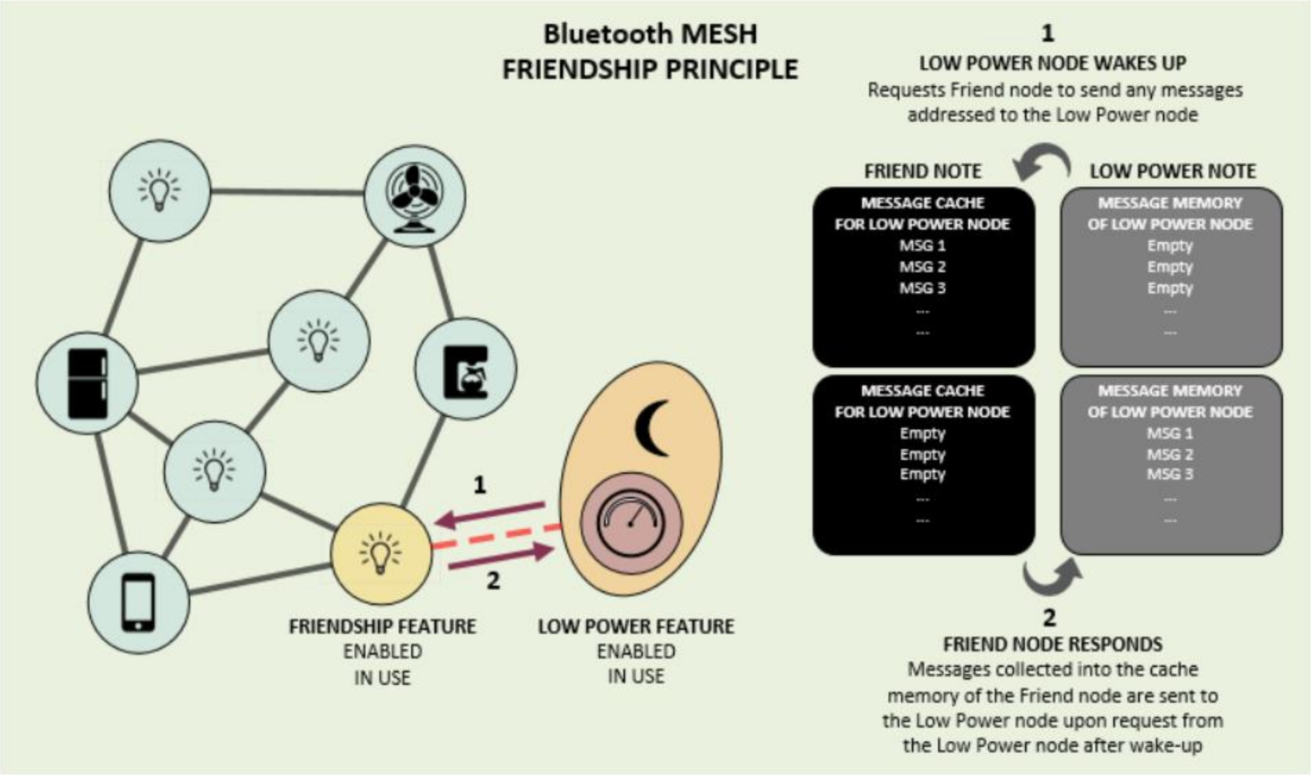
- Low sensors may be in deep sleep most of the time while gathering and saving data with the wireless radio circuitry switched off to save battery power
- How can the user be sure that messages addressed to dormant nodes will eventually reach the node?
  - In Bluetooth mesh this is managed by using the so called Friendship feature
  - A node which supports the Low Power feature must have the feature enabled
  - And, establish a friendship relationship with a Friendship node

Bluetooth Mesh: Low Power

- The Low Power feature reduces receiver duty cycles by allowing the Friend node to store messages intended to the Low Power node
- When the Low Power node wakes up it polls the Friend node for any messages stored on its behalf and can receive them “batch style”
  - How is this Low Power and Frienship node different in architecture compared to Bluetooth Low Energy?
- The Friendship node will need to be of the “Always on” type so that is can receive messages addressed to the Low Power node at any time

Bluetooth Mesh: Friendship

- Friendship is based on polling and there are some timing parameters defined at the setup of a Friendship connection which then are static until the connection is finally (if ever) cleared
- It should be noted that the Friendship device's power consumption may increase when messages are received acknowledged and stored and finally sent to the Low Power node


Bluetooth MESH FRIENDSHIP PRINCIPLE

1 LOW POWER NODE WAKES UP

Requests Friend node to send any messages addressed to the Low Power node

2 FRIEND NODE RESPONDS

Messages collected into the cache memory of the Friend node are sent to the Low Power node upon request from the Low Power node after wake-up

Relationship between a Low Power feature node and a Friend node.

Bluetooth Mesh: Sensor Cadence

- The user can configure the sensor to send measurement values as the value changes either up or down by more than a configurable delta value
- This feature saves energy since the sensor can be configured to report only when a value changes more than the configured delta value
- A more refined way of controlling how the sensor reports value changes is provided by Sensor Cadence state which controls when and how often the sensor reports using Sensor Status messages
- This state can be used to configure the sensor to send updated measurement values more often when the value changes more rapidly and vice versa
- The application can then be programmed to note the speed at which the value increases or decreases

Bluetooth Mesh: Lighting Control

- The simplest control method is related to turning a light source on or off or dimming a light
- For tunable white light sources the color temperature can be controlled by setting the actual color temperature value referenced to the black body curve together with a setting determining the set point distance from the black body curve
- In case the light type allows color changing in all three dimensions (hue, saturation and lightness) it is possible to set all three values independently

Bluetooth Mesh: Lighting Control

- The default model for color light control with mesh networks is generally based on the so called HSL (Hue, Saturation, Light) model instead of the RGB model typically used with computer monitors and printers
- If desired the HSL color space can be converted to e.g. RGB
- For professional lighting applications colors seen by the human eye are often represented using coordinates (x, y and Y) as defined in a color chart
- The coordinates of the color on the chart are defined by x and y whereas Y defines the luminance
- In mesh networks an xyL system is used instead where L corresponds to perceived lightness
- To enable accurate “fine-tuning” of a color source all light control states have 16-bit precision.

Bluetooth Mesh: General Location

- For widely dispersed mesh networks and/or networks with a multitude of sensors and other devices the location of
- any particular device is often mandatory information required by many applications
- Bluetooth mesh provides a generic state called Generic Location, which can be used to define the location of each device accurately
- Global Latitude and Global Longitude fields determine the coordinates (WGS84) of the device
- Global Altitude determines the altitude of the device above the WGS84 datum.

Bluetooth Mesh: General Location

- Local North and Local East fields can be used to describe the location of the device with reference to a local coordinate system on a predefined map with Local Altitude giving the altitude relative to the Generic Location
- There is even a Floor Number field which determines the floor on which the device is installed in.
- For devices which might be moved or move autonomously the Uncertainty field provides a way of defining that the device is either stationary or mobile

Bluetooth Mesh: Time and Scheduler

- Knowledge of time is the basis of scheduled and timed actions such as delayed switching or adjustment of certain settings linearly from an initial state to an end state in the defined time period etc
- However, what is also needed is the capability to store and recall device states when needed
  - Does this sound like Bluetooth Low Energy?
- The basis of time in Bluetooth mesh is the International Atomic Time (TAI) represented as seconds after 00:00:00 on 2000-01-01
- This information is passed on to all nodes in the network as long as one node has the time information

Bluetooth Mesh: Time and Scheduler

- States can be changed autonomously according to a programmed schedule based on the UTC time and an ISO 8601 calendar
- A register provides the means to set the time points at which a change of state is to be carried out

Bluetooth Mesh: Preventing Mesh Saturation

- Bluetooth mesh is based on flooding which is typically simple to implement but presents some issues regarding scalability as the network size and/or amount of traffic increases
- In flooding messages injected into the mesh network are potentially forwarded by all relays nodes which receive the message
- This may cause infinite retransmissions which will cause the mesh network to saturate
- Bluetooth mesh provides two methods, message caching and the Time-to-Live (TTL), to prevent the endless forwarding of messagesin the mesh.

Bluetooth Mesh: Preventing Mesh Saturation

- Network cache method
  - is designed to prevent forwarding of messages already received by the node
  - The node compares the received message to already stored messages in it's network layer cache
  - If the message has already been received the message is discarded
  - If the received message is new and intended for the receiving node it forwards the message to the higher architectural layers of the software in the node
  - If not the node simply relays the message forward to other nodes
  - List size is determined by the implementation

Bluetooth Mesh: Preventing Mesh Saturation

- Each message also includes a Time-to-Live (TTL) number
  - This number is originally determined by the source node but initially is assumed to be 64 (maximum value is 127)
  - TTL number limits the number of forwards allowed for that particular message
  - A node which forwards the said message also decrements the TTL value by one
  - Relay nodes forward only messages which have TTL values larger than 1
  - Thus the "lifetime" of a forwarded message as it hops along in the network can be effectively limited

Bluetooth Mesh: Monitoring Heartbeats

- Heartbeat messages can be used for checking whether a node is still active and for determining the distance to a node
- Heartbeat messages can be configured to be sent periodically a limited number of times or infinitely
- The destination address must be configured
- Received Heartbeat messages can be counted and the results are indicative of reliability
- Heartbeat messages also carry the TTL (Time-to-Live) value so that the number of retransmissions (hops) which can also be used to analyze reliability.
- This feature makes it possible to tune the TTL value to its optimal setting.

Bluetooth Mesh: Service Ratio

- When discussing mesh networks one of the most important factors determining performance is the service ratio
- Service ratio is the ratio of transmitted packets reaching their end destinations compared to the number of all transmitted packets
- Another important factor is Application layer packet delay
- Adding relays increases performance only to a certain point after which the mesh network will start to congest especially with high traffic densities
- Usually the more packets delivered successfully during the first or second hop the better

Bluetooth Mesh: Service Ratio

- One of the bottlenecks in Bluetooth mesh networks is related to the "first hop"
  - i.e. the injection of messages into the mesh in the first place
  - After a node has been able to inject the message into the mesh the nearby nodes are most likely able to send the message further on through the mesh because there are typically several paths available
- One method to help maximize performance is randomized advertising which can improve the service ratio even further.

Bluetooth Mesh: Summary

- Perhaps the most important technical points defined by the Bluetooth mesh specification are related to its security related features.
  - Separate network and application level encryption makes it possible to manage overlapping networks and overlapping applications
- Easy configurability of nodes through the subscribe-publish mechanism provides ease-of-use useful in end-user applications
- The inclusion of the GATT Bearer making it possible to use older Bluetooth devices as part of Bluetooth mesh networks will certainly speed up the adaptation of Bluetooth mesh technology
- Bluetooth mesh is by definition the most secure Bluetooth standard introduced so far and provides efficient security features for IoT applications