Bluetooth mesh

Principles and Commissioning

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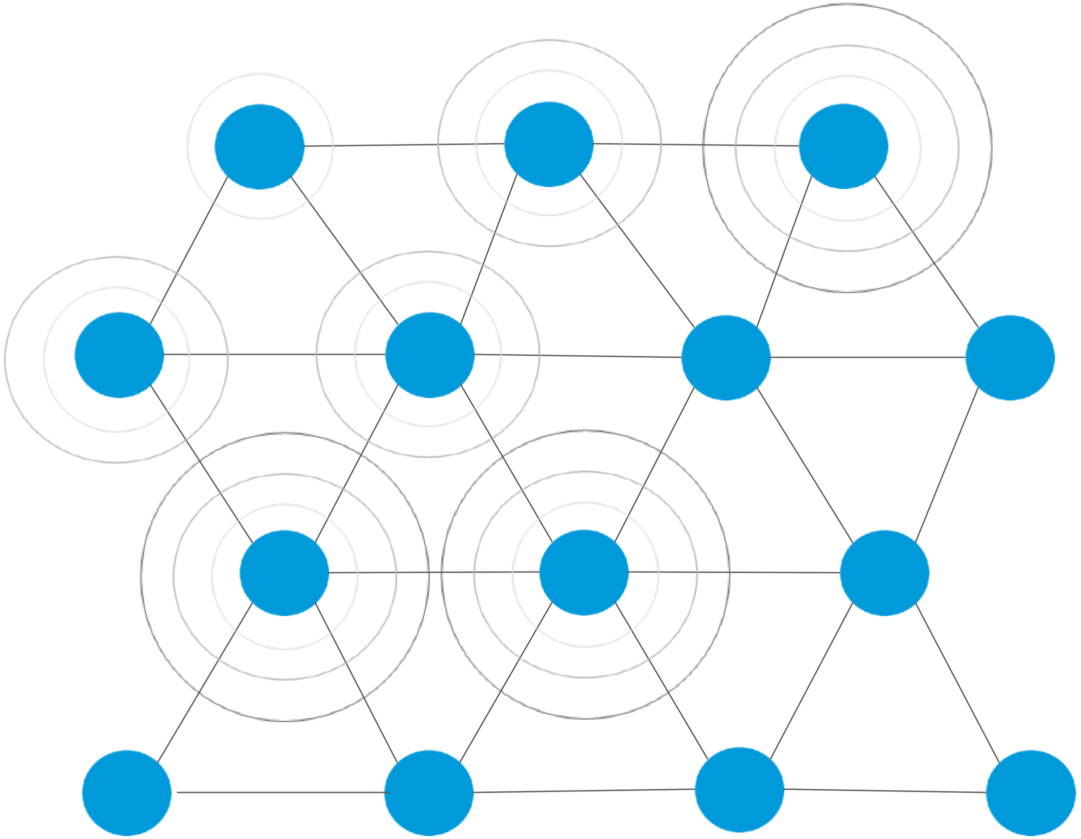
Bluetooth Asia 2018

Why we need mesh?

- **If we want to communicate with a device which is far away**
  - Enlarge the power of transmission?
- **What if there are some physical obstacle?**
  - Can we enlarge the power of transmission again?
- **If we want to communicate with multiple devices at the same time**
  - May be we can use multi-link?
  - Or we can use observer and broadcaster?
- **What if we want to communicate with lots of device which spread in an area?**
- **What if we want devices can communicate to each others? (decentralization)**

What Bluetooth mesh brings

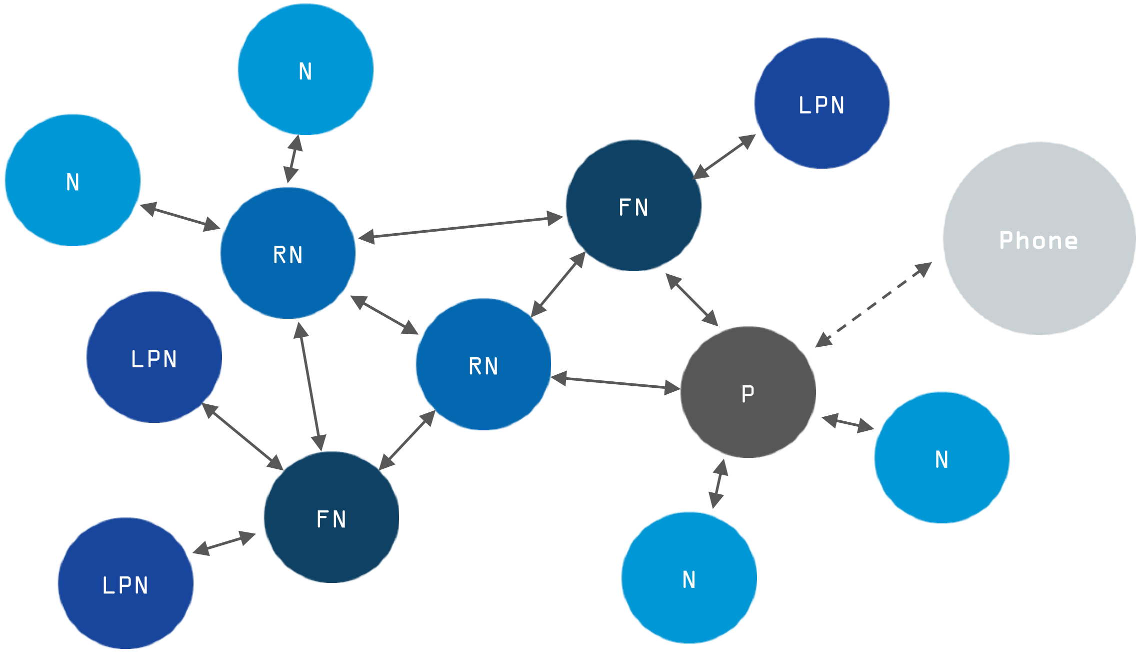
- Multi-hopping feature
  - Multi-hopping to avoid walls blocking radio signal
  - Extending the coverage
- From point-to-point to multi-point control
  - Every device can send/receive data to/from any other device
- Scenario
  - Sensor network
  - Building automation



Bluetooth mesh Specification

- The Bluetooth mesh specification is divided in three parts
  - Mesh Profile - Fundamental requirements for an interoperable mesh network based on Bluetooth LE
  - Mesh Model - Basic functionality of mesh network nodes
  - Mesh Device Properties - Device properties required for the Mesh Model specification.
- Based on Bluetooth v4.0
  - **Bluetooth mesh is not a wireless communications technology. It's a networking technology**
  - Compatible with any Bluetooth v4.0 controllers
  - Use of Bluetooth 5 feature will break the compatibility

Bluetooth mesh roles and topology



Node types:

- ● N: Node
- ● LPN: Low power node
- ● RN: Relay node
- ● FN: Friend node
- ● P: Proxy Node

⟷ ADV Bearer

<- - -> GATT Bearer

Mesh Key features highlights

- Managed flooding
  - Using managed flooding, easy to implement
  - Using "advertising" in Bluetooth LE for communication among mesh network
- Power consumption
  - Bluetooth LE radio. Low Power Nodes possible with Friend feature
- Grouping concept
  - Group addressing, identified at node level
- Built-in security
  - Security mechanism is not optional, is mandatory
  - Traffic encrypted by AES-128

Different kind of mesh ?

- Flooding mesh
  - All the devices are broadcasting data and also listening the broadcasting from the nearby devices
  - Easy to implement
  - Collision may happen when traffic is high

- Routing mesh
  - Maintain connection between devices
  - Possible to send data along a selected path
  - Single point of failure may happen

What if there is a better “flooding” ?

Bluetooth mesh is using “managed flooding”

Message Cache

- If a message has been received before, it will be store in the message cache
- Node checks the incoming message, if it already in the message cache, node will drop it simply
- **This prevent the duplicated relay message between nodes**

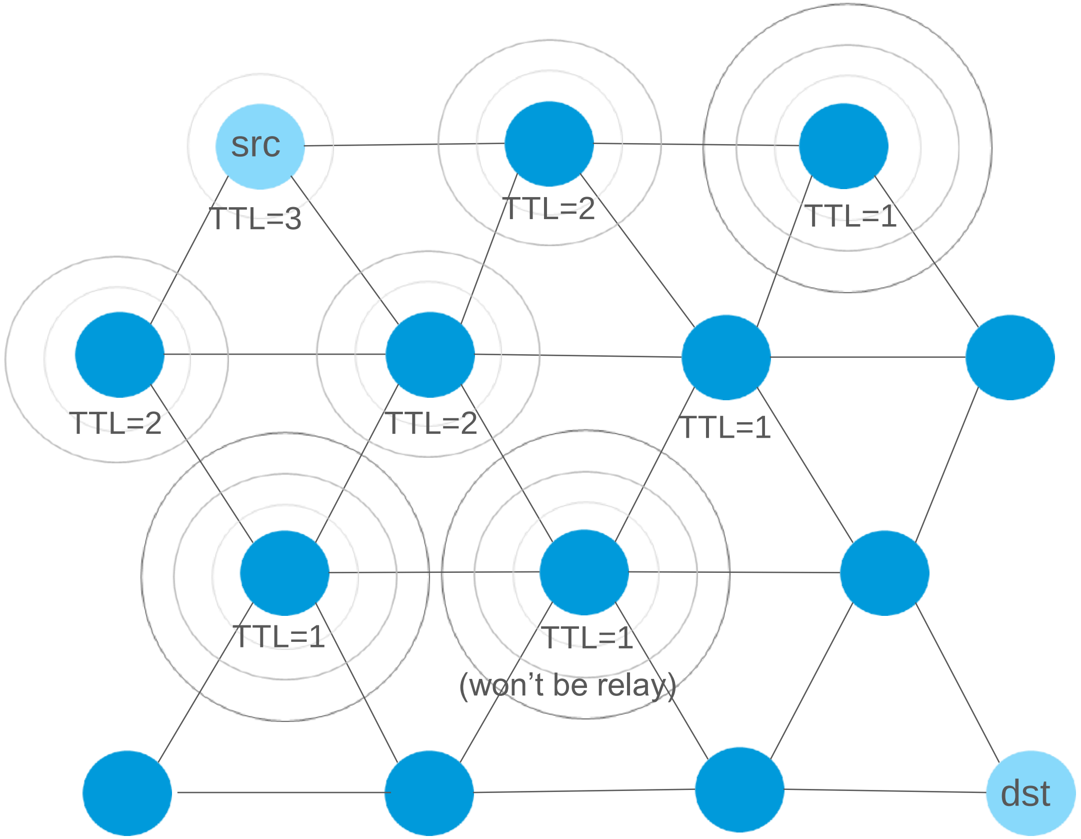
Time to Live

- There is a parameter “TTL” inside every packets
- The TTL range is from 0 ~ 127
- The TTL of one message will decrease every time when the message been relayed
- If TTL <= 1, message won’t be relayed
- **TTL can reduce the traffic loading for small area message transmission**

Different node features

- Not all the nodes relay messages
- Some nodes can **just listen** and **transmit the message when necessary**

How to choose the TTL value ?



If TTL is too small, the message cannot reach destination

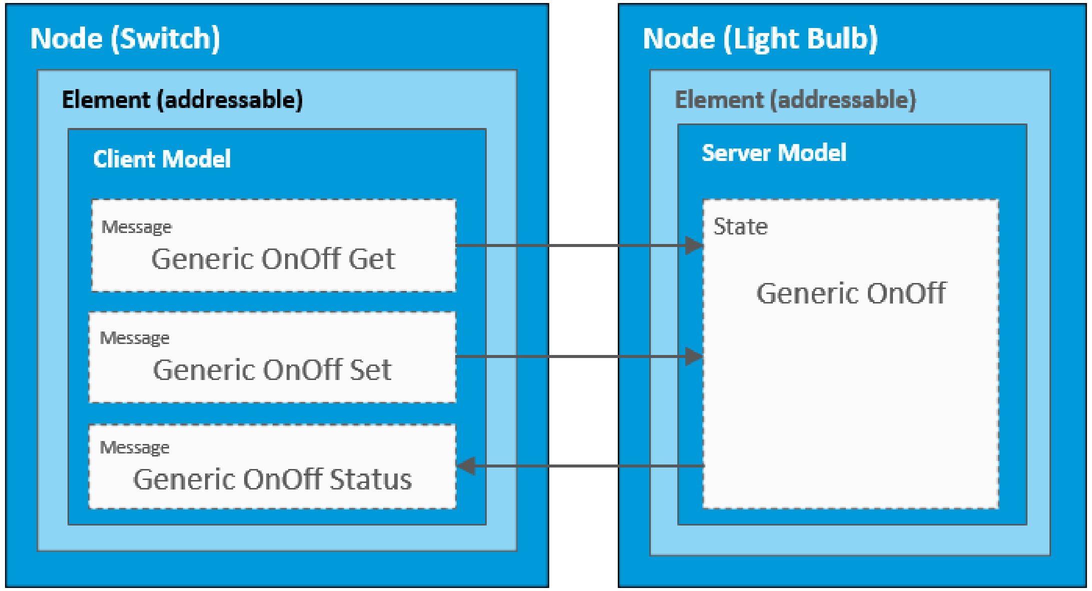
- We can set the TTL number with a fixed value
  - If TTL is too small, the message will not be able to reach the destination
  - If TTL is too large, the mesh traffic will become heavy
- "Heartbeats" message can do help!
  - Can be sent periodically
  - Provide TTL information from source to destination
  - Possible to optimize the TTL

Be careful of “traffic jam”

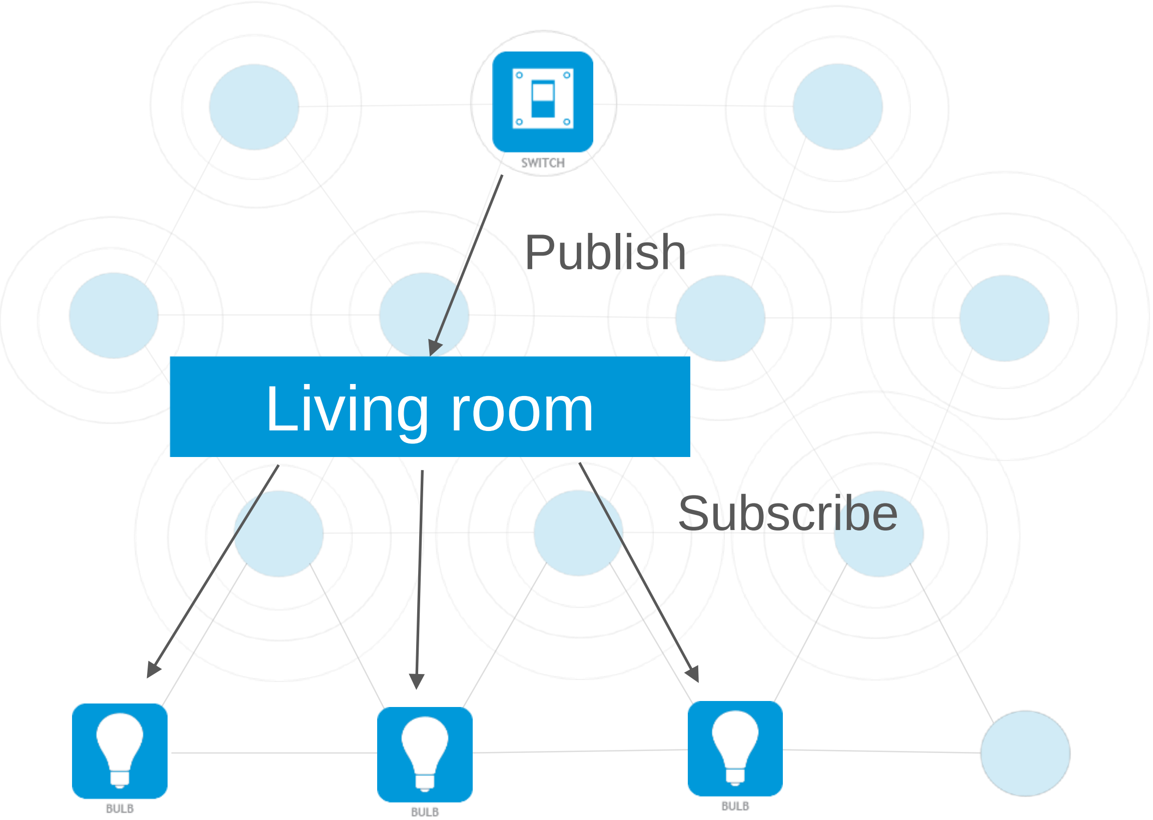
- Bluetooth mesh uses advertising channels to exchange information
  - Only 3 channels are used (channel 37, 38, 39)
  - Channel congestion in case of heavy traffic (e.g. dense network)
  - Additional Wi-Fi or other 2.4 GHz signals interference
- Once the traffic is saturated or interference happens
  - The communication latency will increase
  - Some messages may be lost
- We need to use some mechanisms to solve this
  - using Acknowledge Message in the access layer
  - Setting a filter to focus on advertising packet with mesh types

How device “talk” to each other

- Client-Server model
  - Equivalent to GATT profiles
  - Everything is a **state**
  - Using **publish/subscribe** to exchange information
  - Foundation models:
    - Configuration model
    - Health model
  - Model specification
    - Generic on/off
    - Lighting
    - Sensors

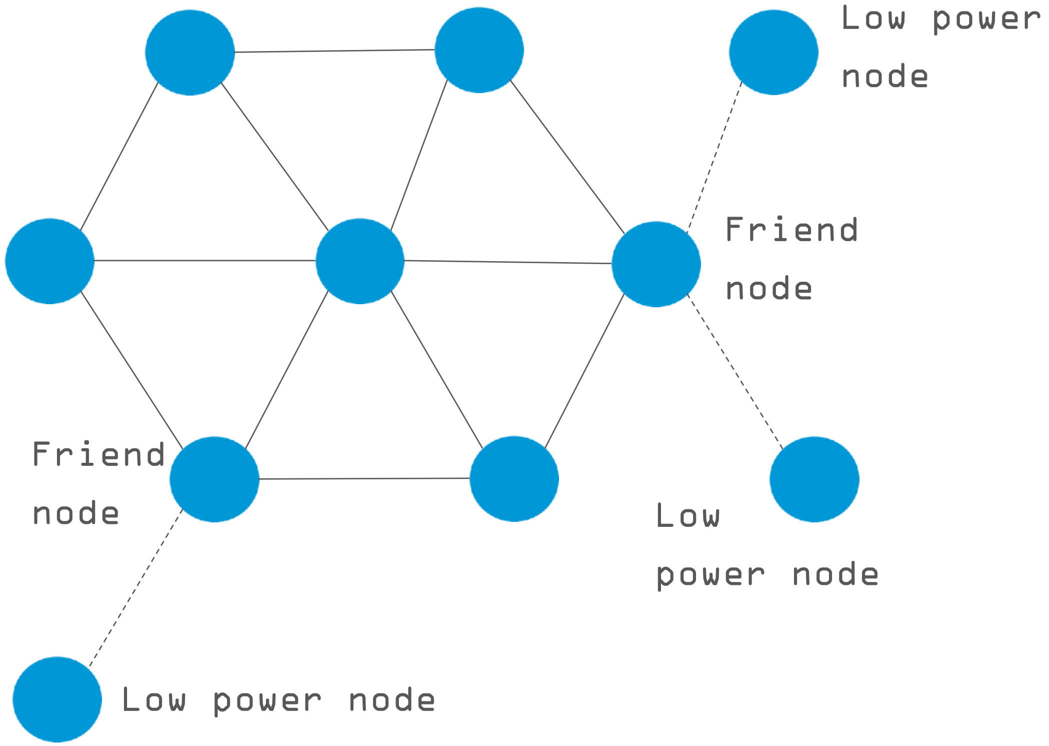


Group addressing



- Built-in group and virtual addressing
- Publish to a group address
- Subscribers receives the message
- Easier to replace nodes

Power consumption and management

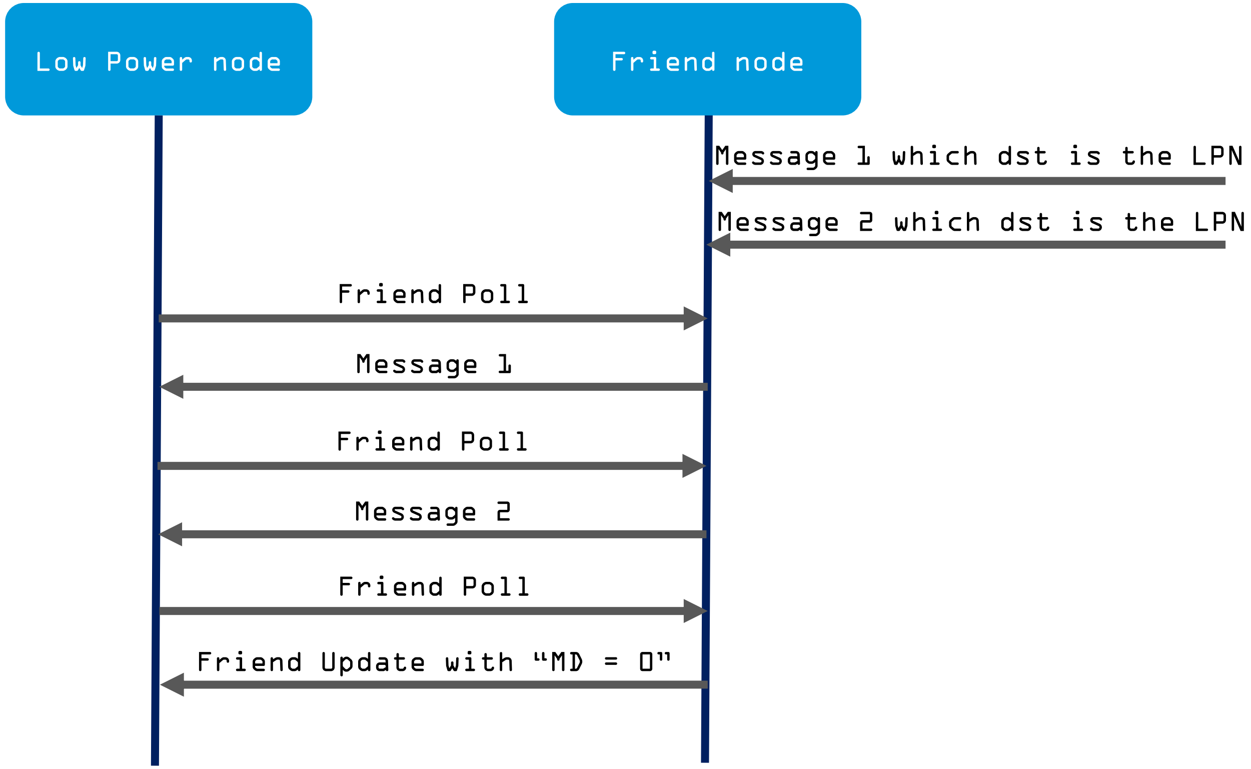


- Nodes continuously in RX
- Normally mains powered
- Friend feature for low power operation
- Friend caches and forwards
- Low power nodes sleep

How friendship works?

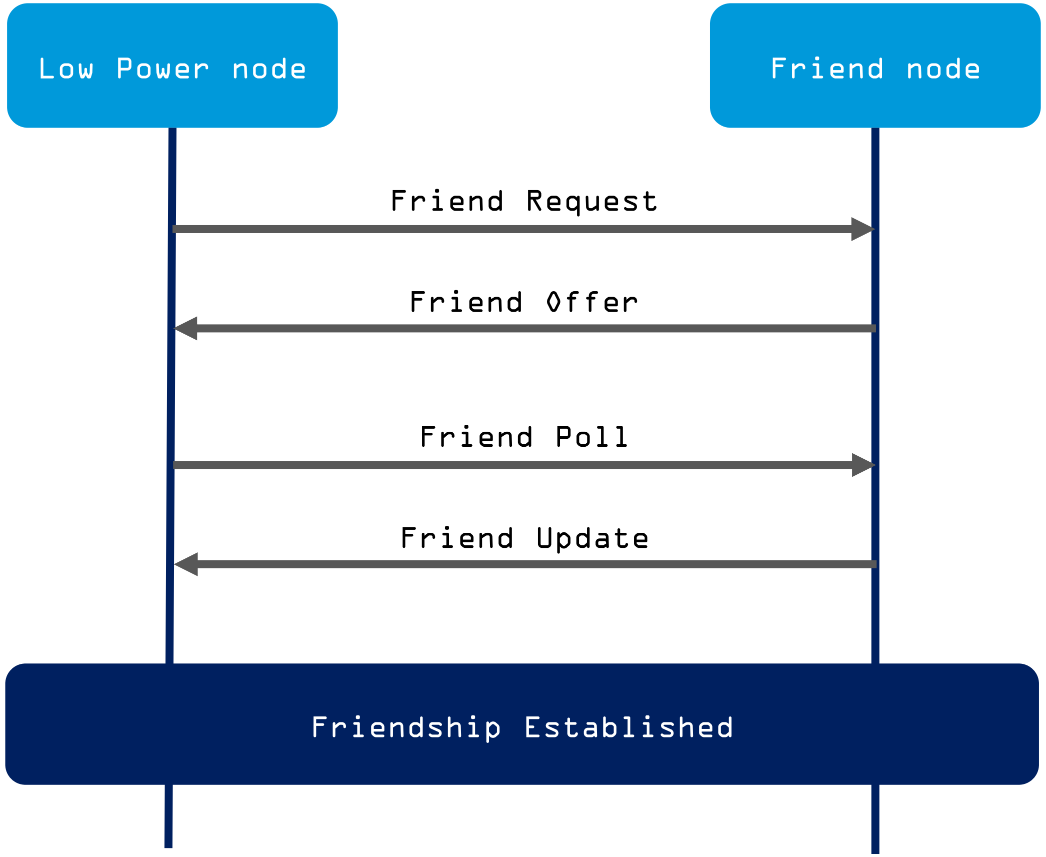
Once the friendship established

- The friend node will help low power node to keep the messages
- When the low power node wakes up
    - Low power node sends friend poll
    - Friend node sends the queued message
    - Low power node continue sends friend poll
    - When there's no message, friend node sends the "friend update" with "MD=0"


Low Power node
Friend node
Message 1 which dst is the LPN
Message 2 which dst is the LPN
Friend Poll
Message 1
Friend Poll
Message 2
Friend Poll
Friend Update with "MD = 0"

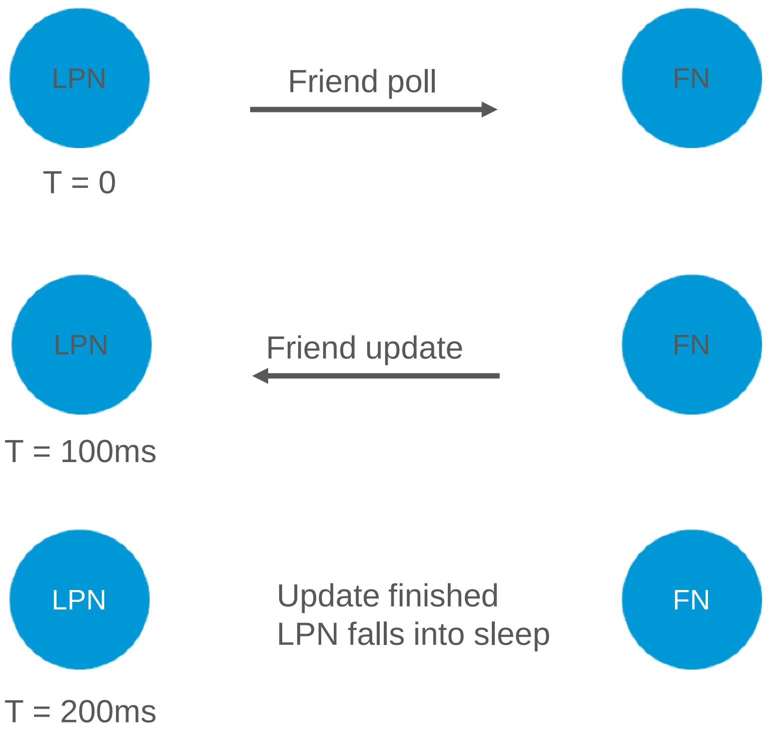
How to establish friendship?

- LPN send "**Friend Request**" to nearby friend nodes
  - Receive delay
  - Receive window
  - Poll timeout
- Friend send "**Friend Offer**"
  - Received window size supported
  - Message queue size available
  - Subscription list size available
  - RSSI
- LPN select the friend node by custom algorithm
- LPN send "Friend Poll" to the friend node
- Friend node replies "Friend Update"



How can low power nodes help ?

- For example:
  - If a low power node sends a "friend poll" to friend node to receive stored data every 15 minutes
  - And friend node responds after 100 ms, finishing the update in 100 ms
- The duty cycle for a day will be
  - 0.101 * (60/15) * 24 = 9.696 sec in a day
  - 0.01 duty cycle

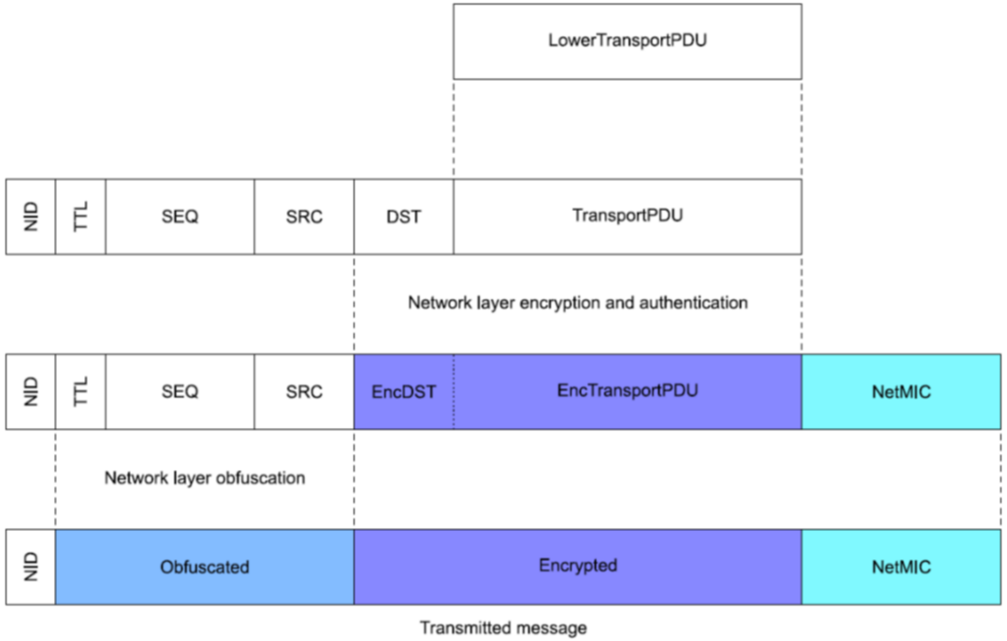


Built-in security

- All traffic encrypted with AES-128
- Only provisioned nodes can communicate
- Additional encryption per application
- Refresh procedures for encryption keys
- Additional protection against replay attacks and trash can attacks

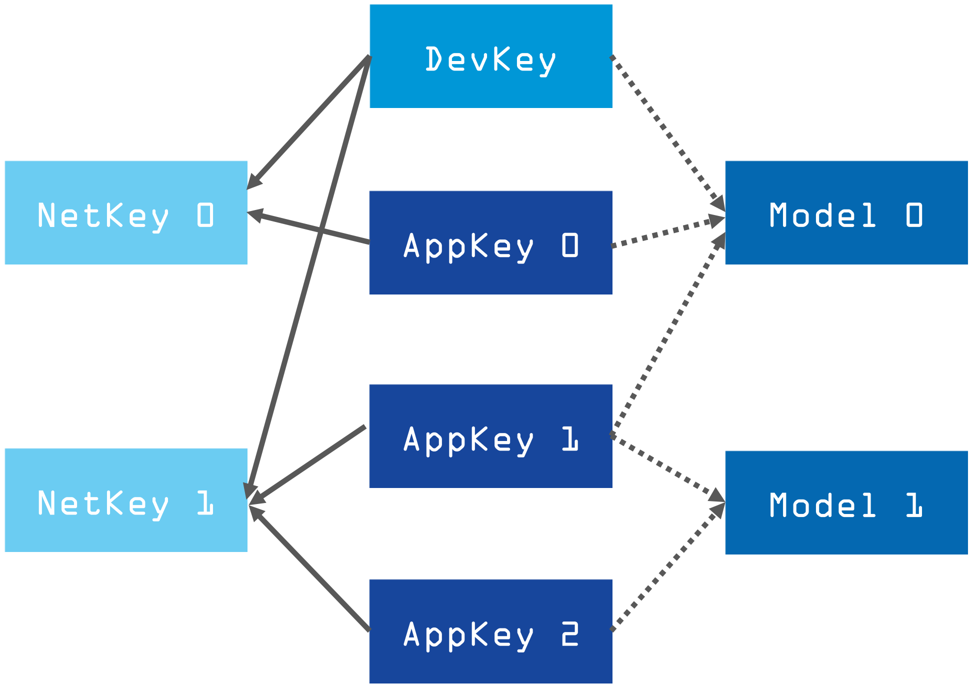
More deep about security

- Not every device can join a mesh network
  - Provisioning is necessary
- 2 layer data encryption using AES-128
  - Network layer - Network key
  - Access layer - Application key
- Split the application and configuration
  - Config client/server negotiated using Device key
- Key refresh and node blacklisting



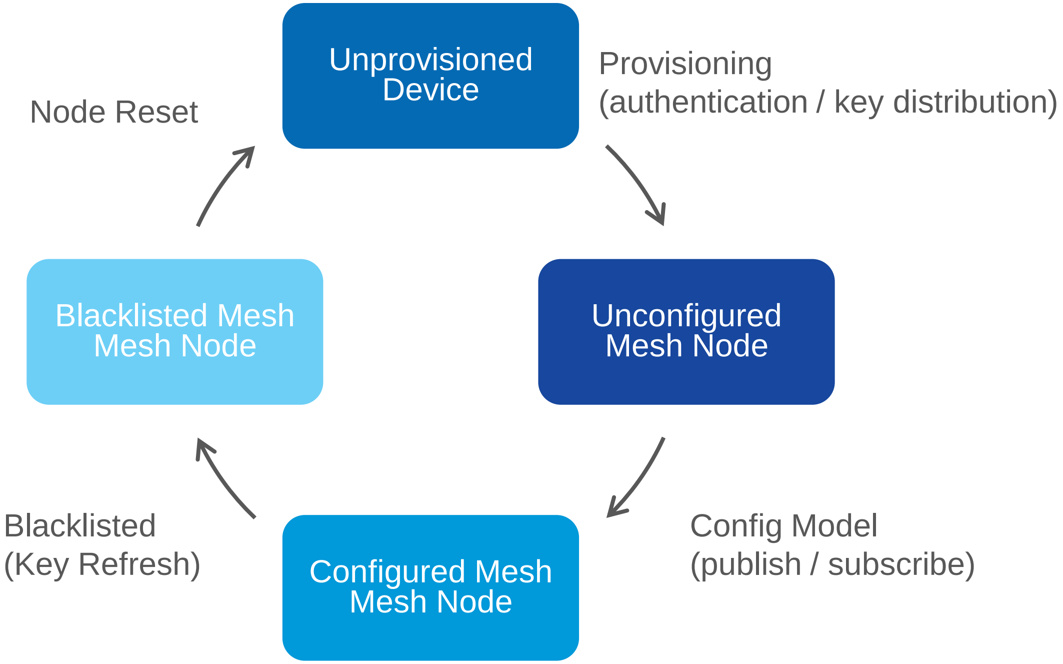
More deep about security

- Keys
  - Application key
    - Only the application with the correct key can access the data
    - You don't want your light bulb to be able to unlock your door
  - Network key
    - Only the message with correct network key can be relayed
    - If the network key is not correct, the packets will be discarded
  - Device key
    - Only the configuration client (provisioner) with correct device key can configure the nodes



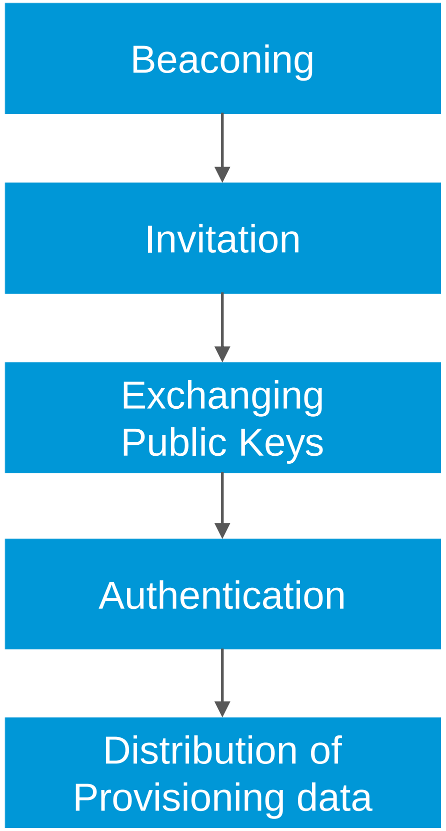
More deep about security

- Provisioning
  - Every device needs to be provisioned before joining a mesh network
  - Authentication is also performed during provisioning
  - ECDH based provisioning provides the protection from man in the middle attack
- Once the device needs to be removed
  - Key refresh procedure for preventing trash-can attack


Unprovisioned Device
Provisioning (authentication / key distribution)
Unconfigured Mesh Node
Config Model (publish / subscribe)
Configured Mesh Mesh Node
Blacklisted (Key Refresh)
Blacklisted Mesh Mesh Node
Node Reset

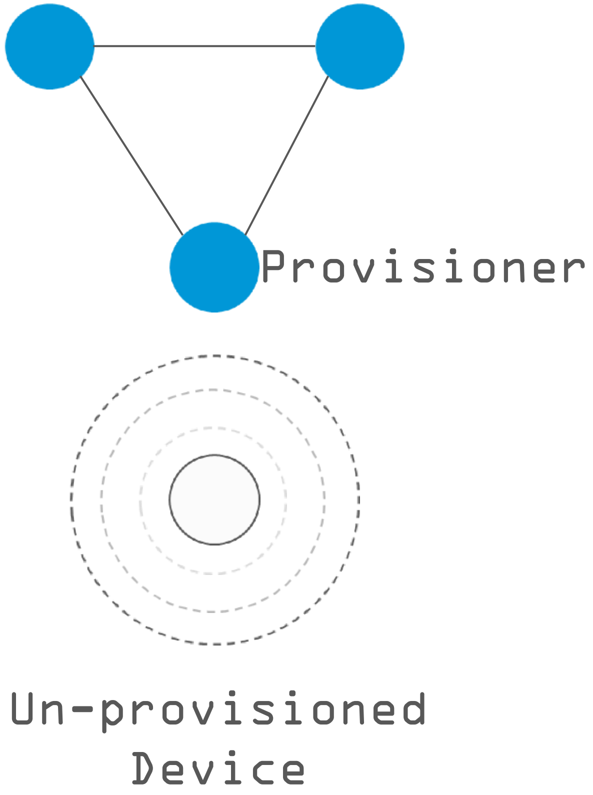
Provisioning

- Provisioning procedure in short:
- Provisioner listens for un-provisioned devices
- Provisioner initiates the Provisioning process by inviting the un-provisioned device
- Provisioner and device establish a secure tunnel for exchanging information and providing provisioning data
  - Unicast Address
  - Device Key



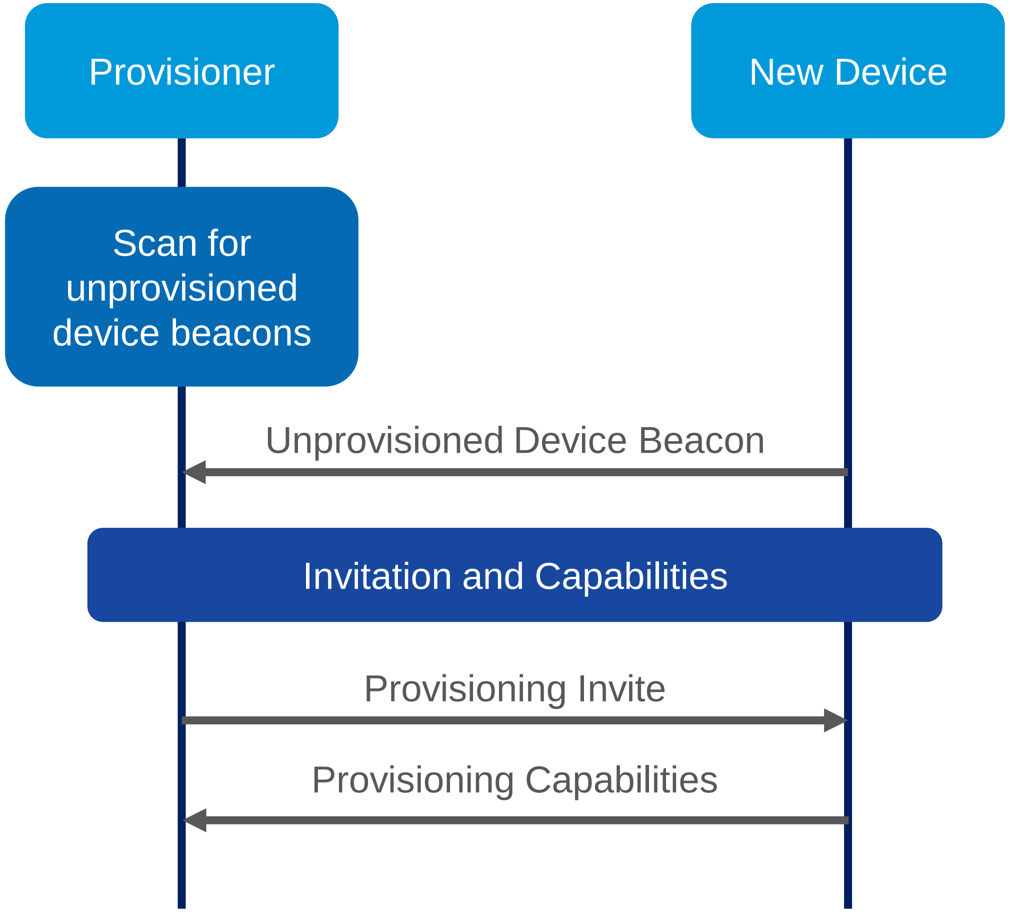
Beaconing

- The unprovisioned device should advertising a beacon signal
  - To indicate the provisioner for provisioning
  - The beacon signal may also contain the OOB information
    - QR code
    - Bar code
    - NFC
    - …



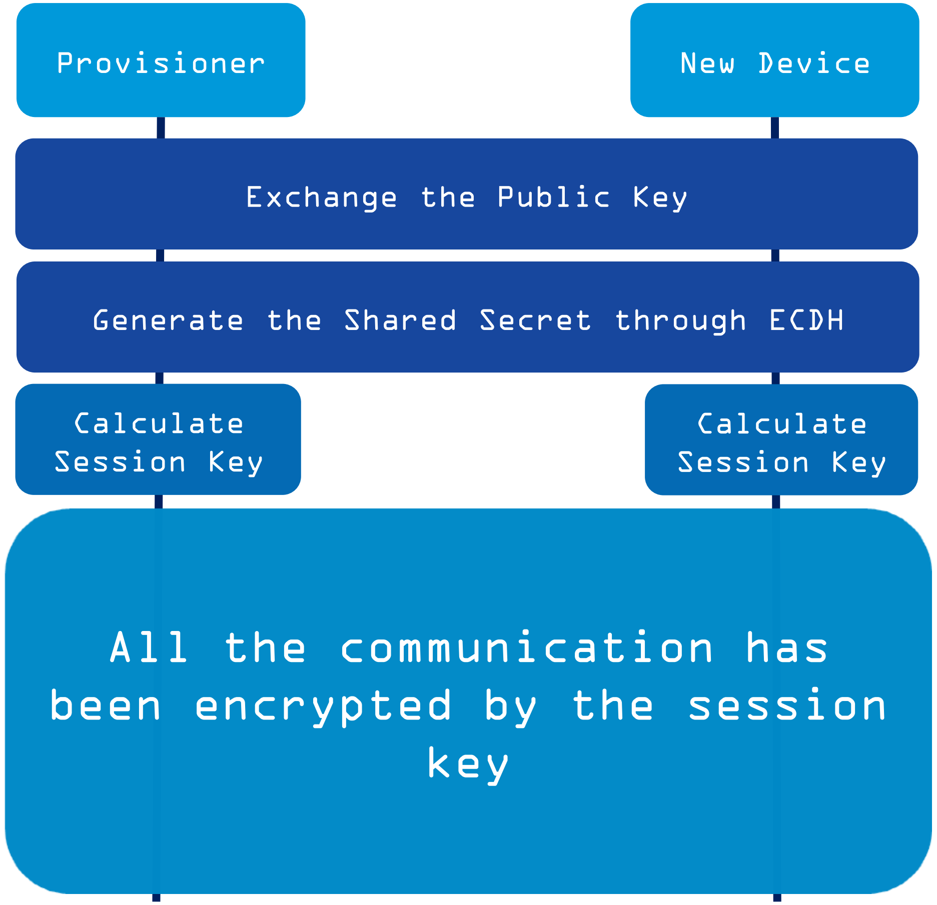
Invitation

- The provisioner can choose the interested device for provisioning
  - Provisioner will send the invitation
    to the device which contains
    - Attention Timer
    - The device should attract people's attention before time's up
  - The device should reply the IO capabilities
    - Like we see in the Bluetooth LE device pairing


Provisioner
New Device
Scan for unprovisioned device beacons
Unprovisioned Device Beacon
Invitation and Capabilities
Provisioning Invite
Provisioning Capabilities

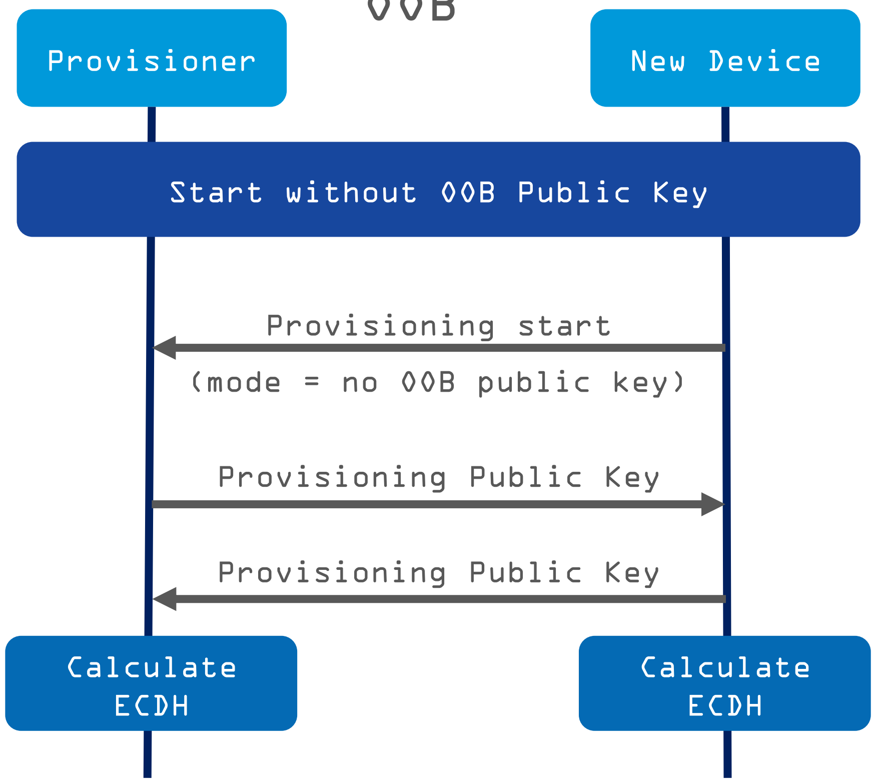
Exchange public keys

- Why we need this ?
- It is difficult to send the keys securely
  - Someone may sniff keys
- We can use asymmetric encryption to solve this problem
  - Bluetooth mesh use Elliptic Curve Diffie-Hellman (ECDH) to establish a shared secret over an insecure channel
  - Use this shared secret to create a session key for encrypting the

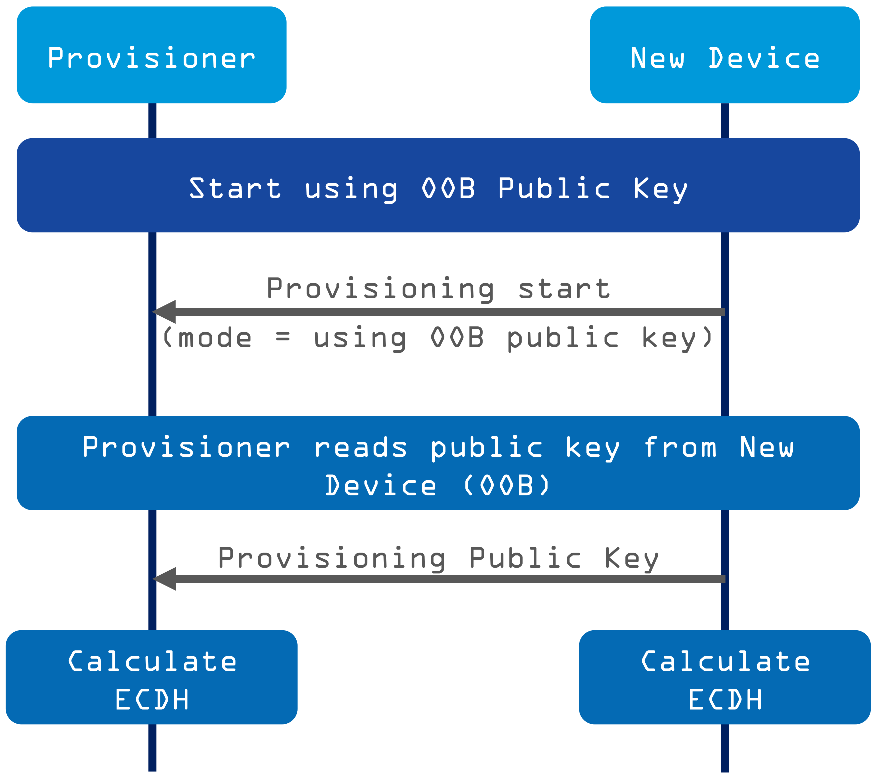

Provisioner
New Device
Exchange the Public Key
Generate the Shared Secret through ECDH
Calculate Session Key
Calculate Session Key
All the communication has been encrypted by the session key

Exchange public keys

Exchange public key without OOB

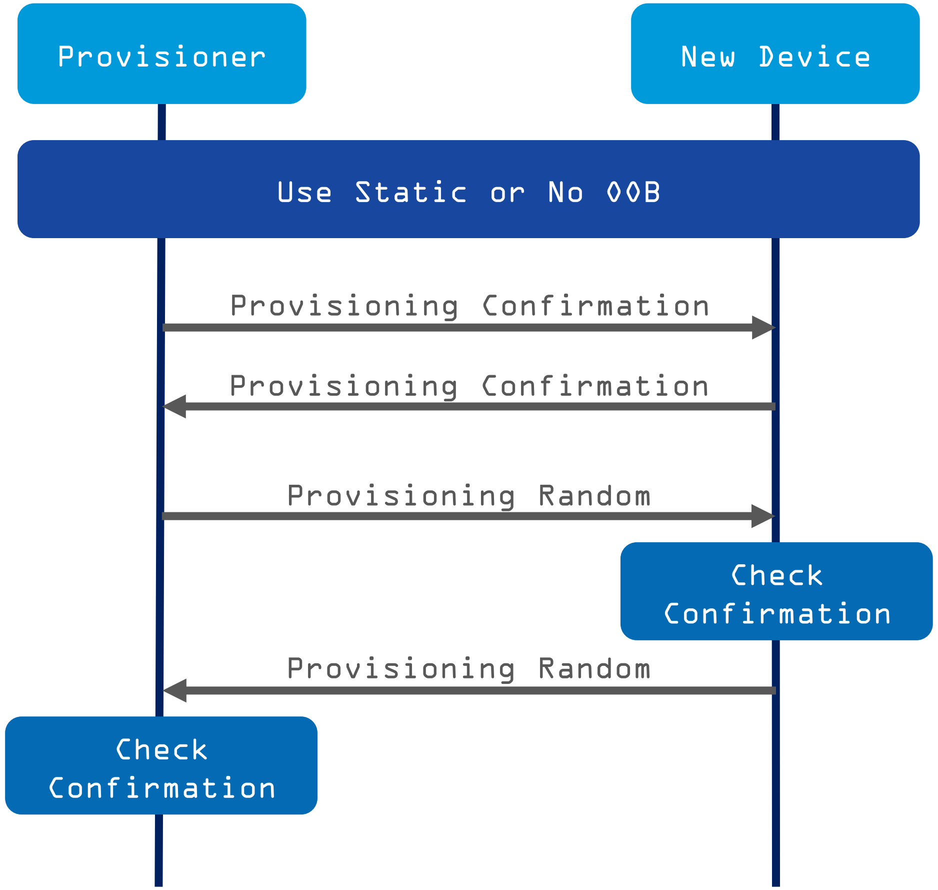


Exchange public key in OOB


Provisioner
New Device
Start using OOB Public Key
Provisioning start
(mode = using OOB public key)
Provisioner reads public key from New Device (OOB)
Provisioning Public Key
Calculate ECDH
Calculate ECDH

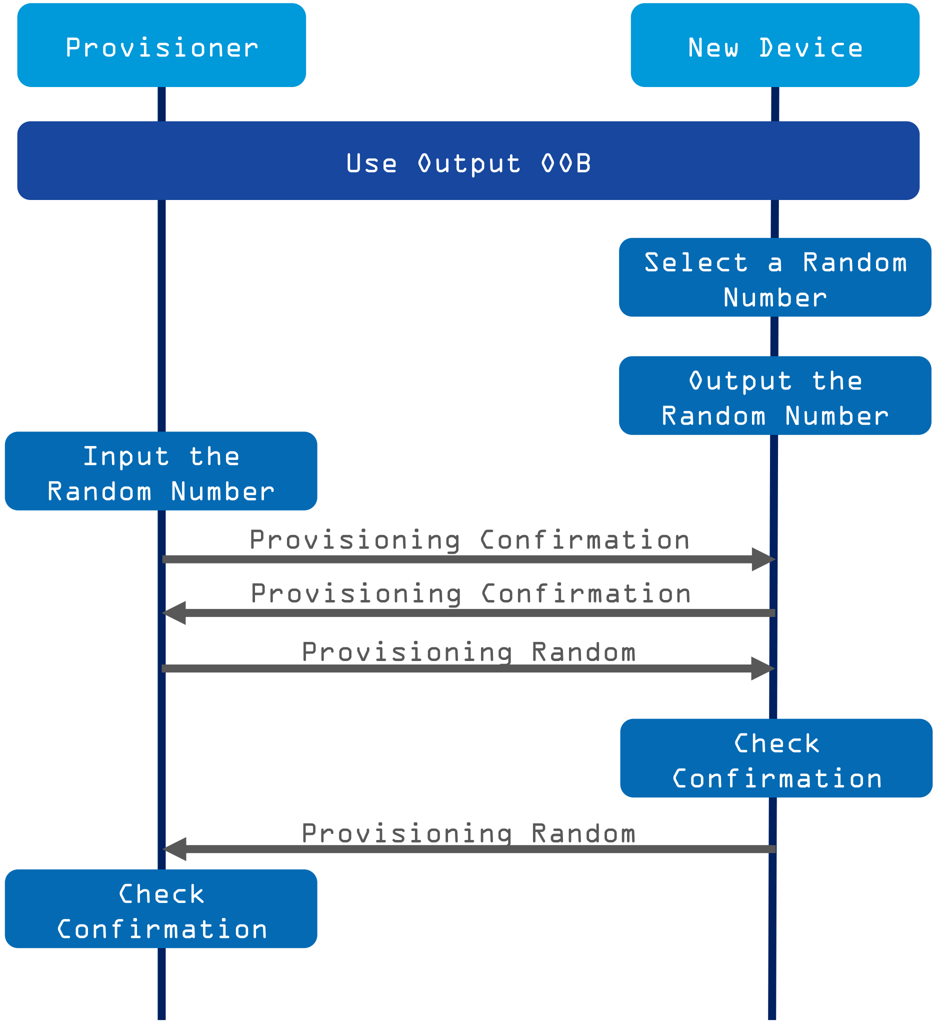
Authentication - Static method

- We need to make sure the device which we are provisioning is the correct one
- Since the device has sent the IO capabilities to the provisioner, the provisioner can choose the way to authenticate the device
- There are three ways to authenticate the device
  - Static
  - Input (perspective of device)
  - Output (perspective of device)



Authentication - Output method

- If device has the output interface, and provisioner has the input interface
  - Device generates a random number
    - LCD shows that random number
    - Blink that LED random times
    - Beep the buzzer
  - User needs to input what he/her saw on the provisioner
    - Push the button several times
    - Enter the number if key pad exists
  - Both of the provisioner and device will use a complex procedure to calculate the result generated by the random number, and confirm with each other



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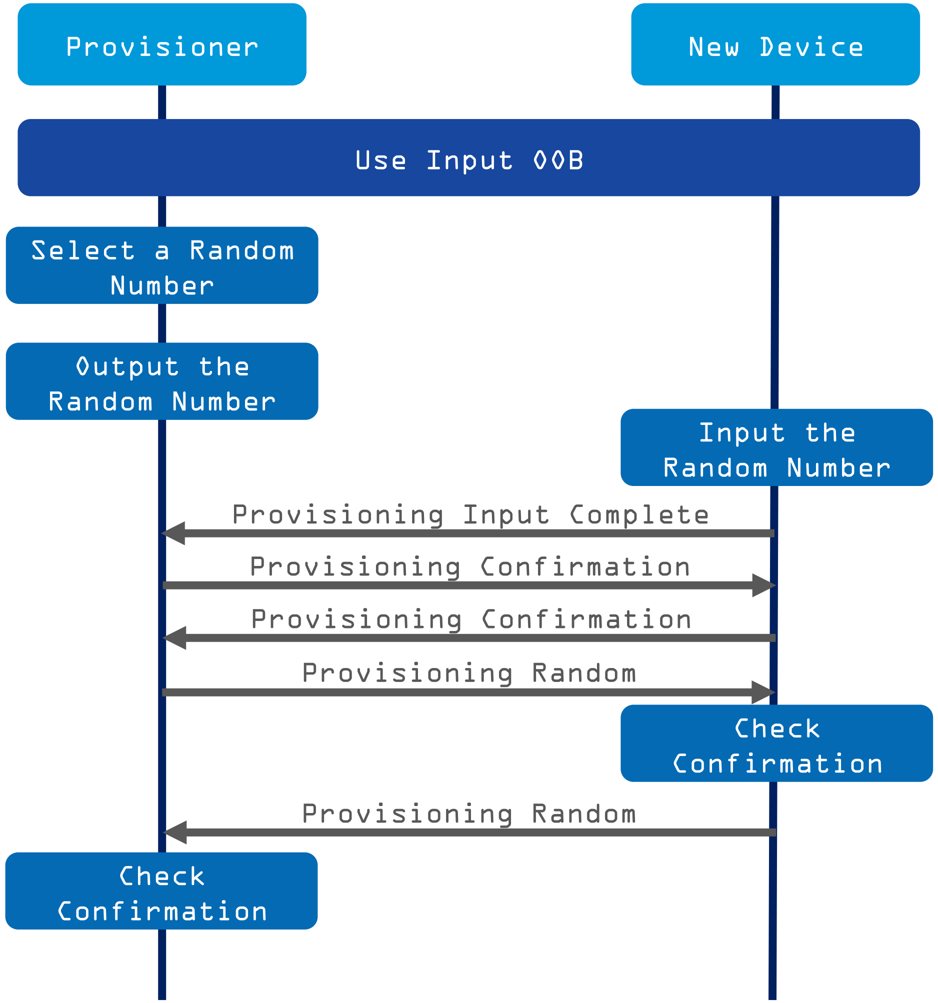
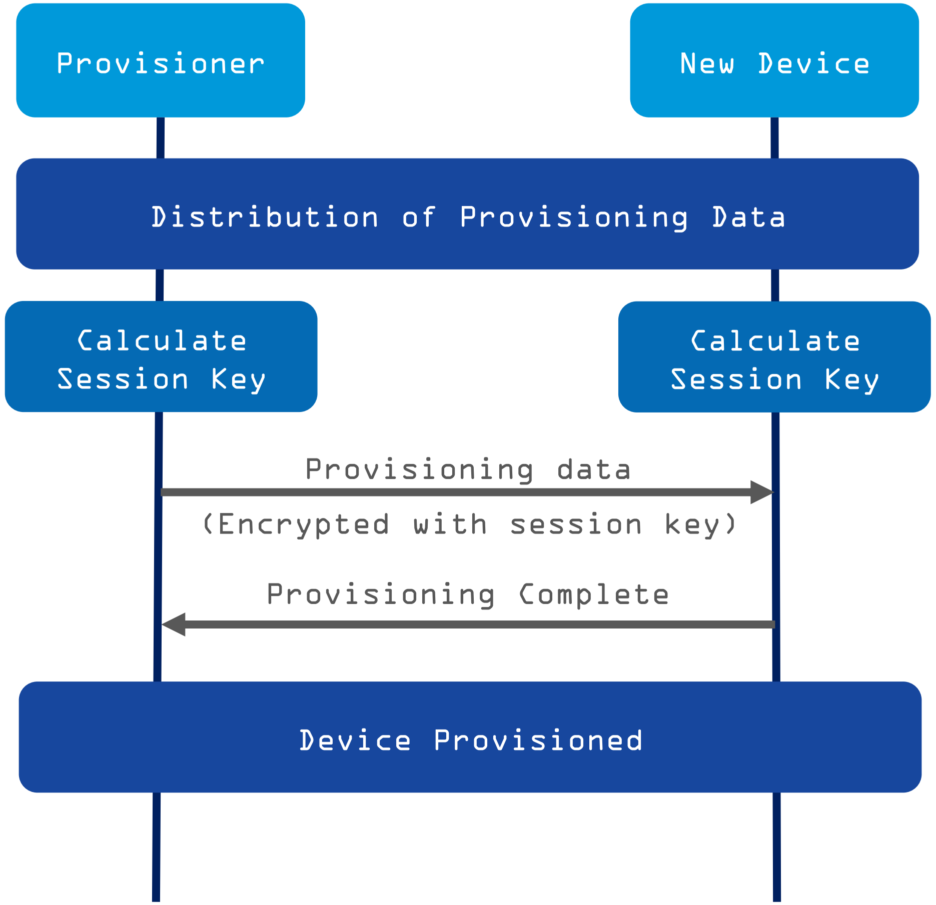


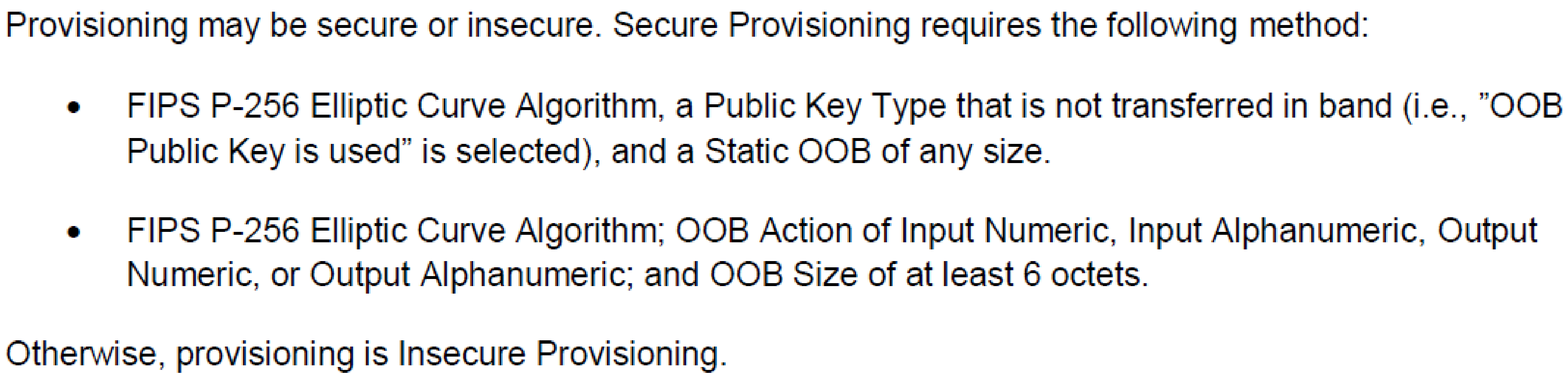
Distribution of provisioning data

- After the confirmation is finished
  - We can use the "**shared secret**" which generated by ECDH to get a session key through the KDF (key derivation function)
  - For now, both of the provisioner and device need to use the session key to encrypt/decrypt the provisioning data
    - Network key
    - Device key
    - IV index
    - Unicast address



The best security set for provisioning

- How to reach the best security set?
  - Since man-in-the-middle (MITM) attack may happen
  - The specification provides a suggestion like this:

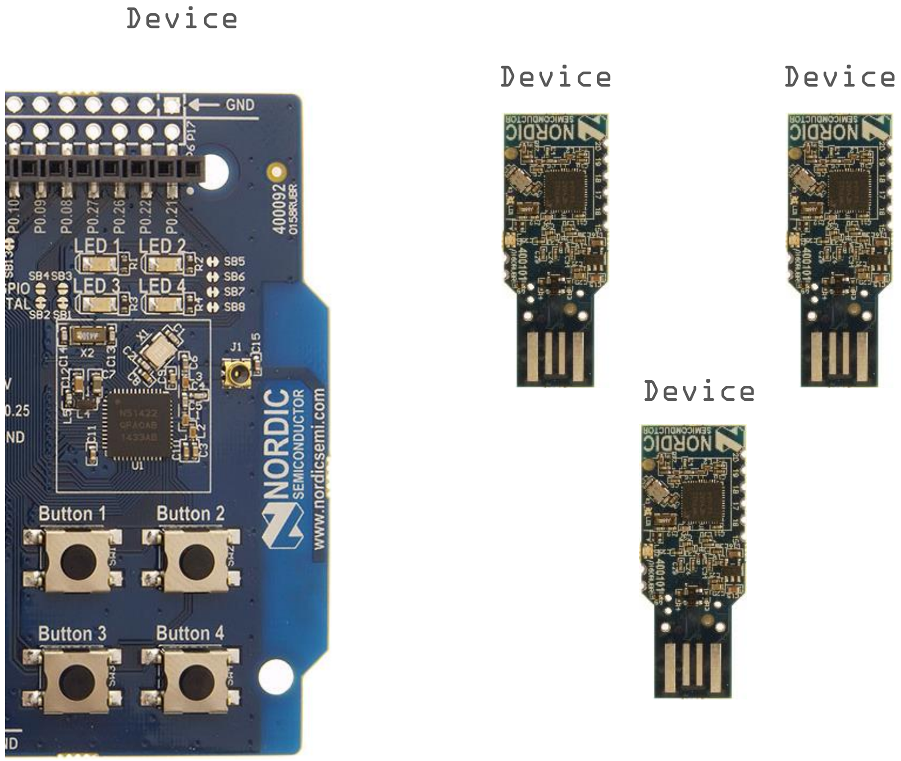


Provisioning may be secure or insecure. Secure Provisioning requires the following method:

- FIPS P-256 Elliptic Curve Algorithm, a Public Key Type that is not transferred in band (i.e., ”OOB Public Key is used” is selected), and a Static OOB of any size.
- FIPS P-256 Elliptic Curve Algorithm; OOB Action of Input Numeric, Input Alphanumeric, Output Numeric, or Output Alphanumeric; and OOB Size of at least 6 octets.

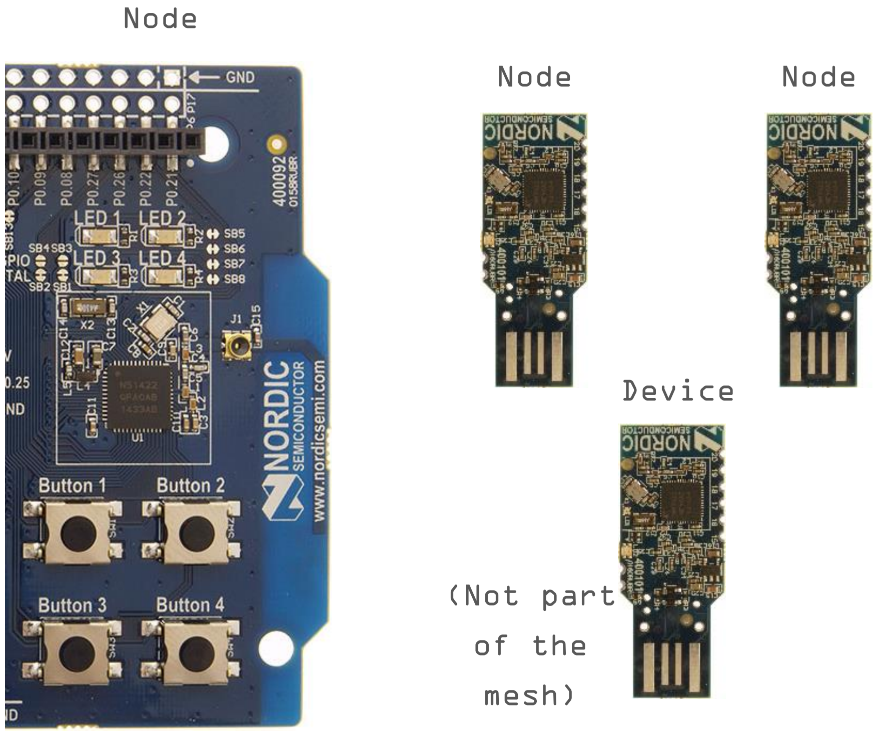
Otherwise, provisioning is Insecure Provisioning.

Working example



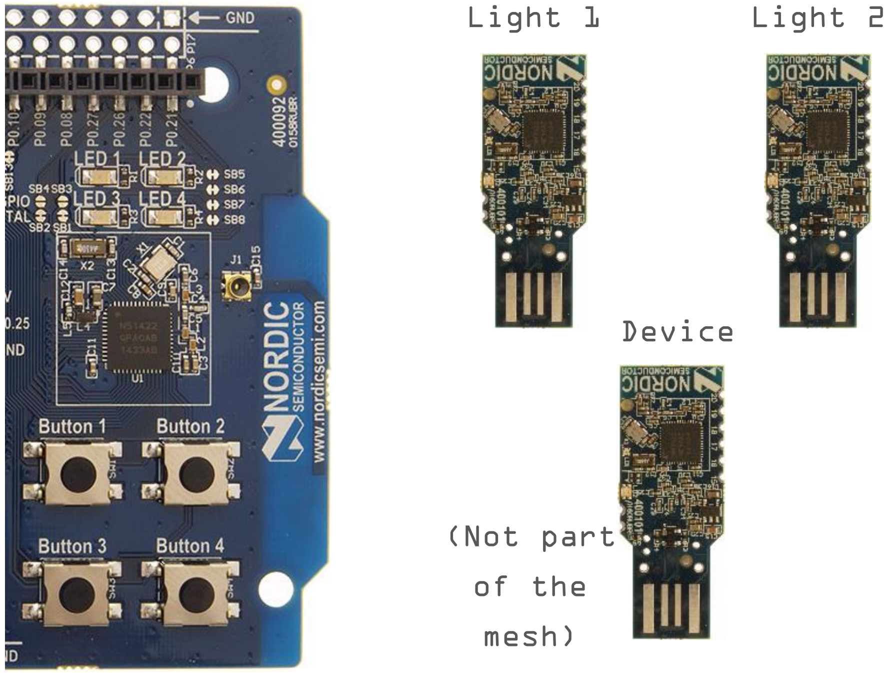
- Entities capable of being provisioned are called devices.
- Devices advertise a beacon signal.
- Devices can be provisioned by a provisioner.
- The technical meaning of provisioning is to distribute addresses and encryption keys

Working example



- Provisioned devices are called nodes.
- Nodes part of the network share the same address space.
- An addressable entity is called an element.
- Node has one or more elements.

Working example - configuration



Lighting control

Light 1

Light 2

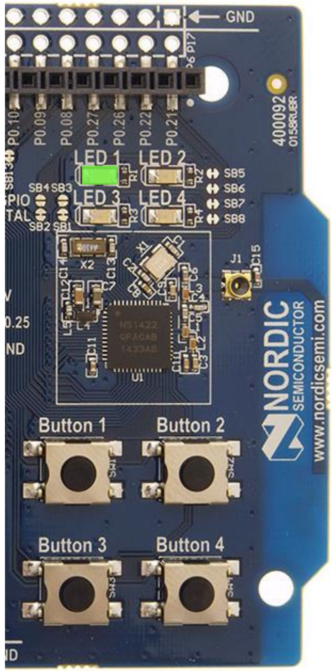
Device

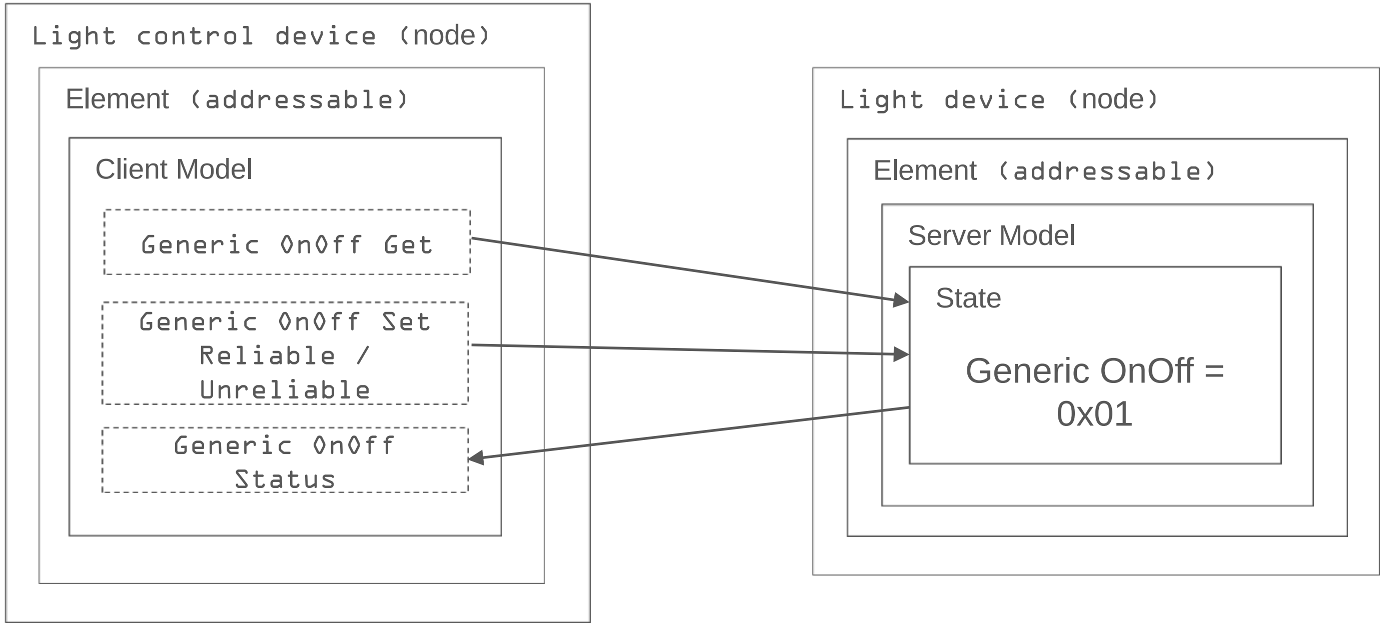
(Not part of the mesh)

- Provide application keys
- Configure how nodes do
  - Publish
  - Subscribe

Working example - Controlling a lighting

Lighting control




Light control device (node)

Element (addressable)

Client Model

Generic OnOff Get

Generic OnOff Set Reliable / Unreliable

Generic OnOff Status

Light device (node)

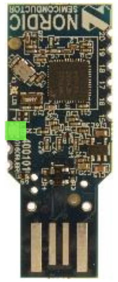
Element (addressable)

Server Model

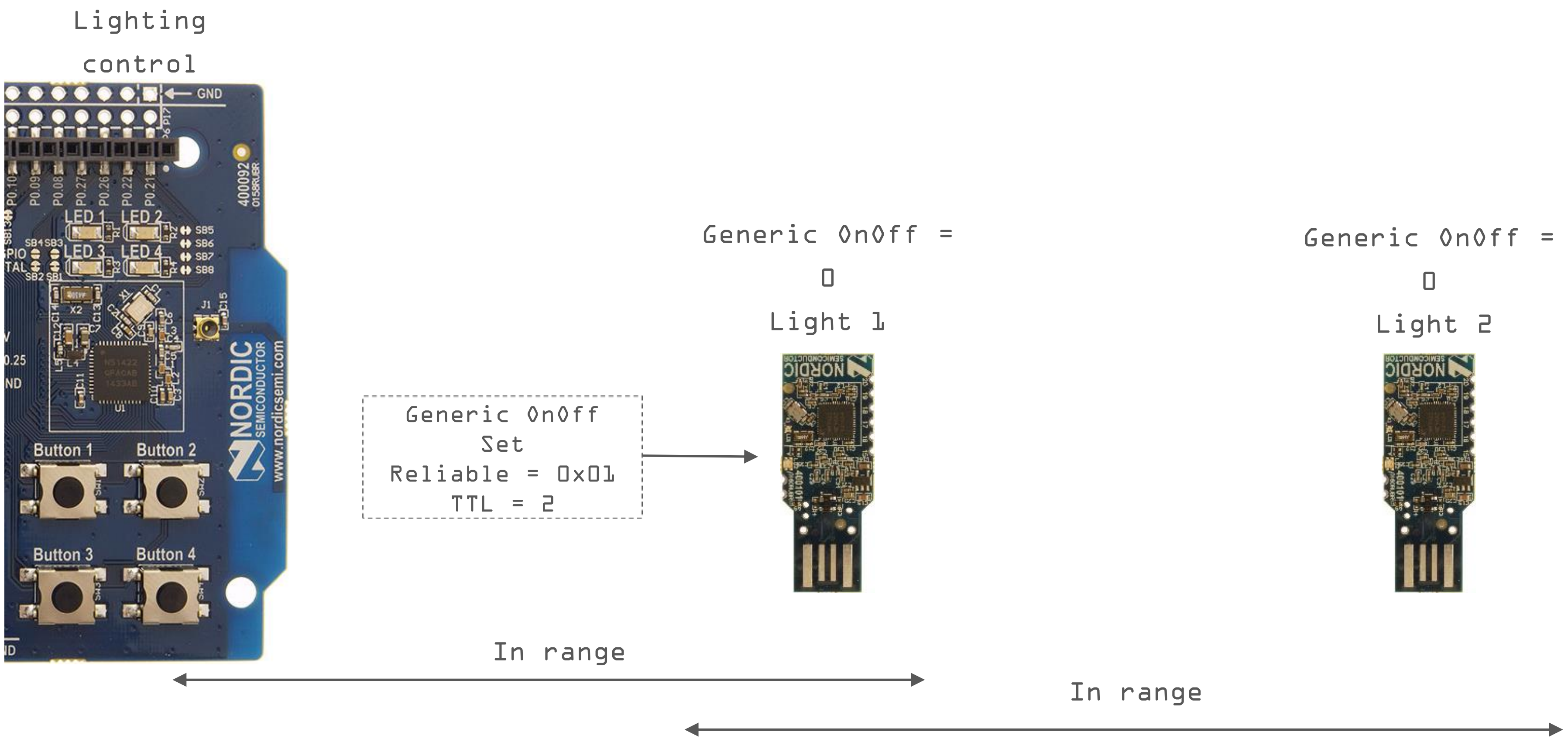
State

Generic OnOff = 0x01

Light



Working example - message transmission



Lighting control

Generic OnOff Set
Reliable = 0x01
TTL = 2

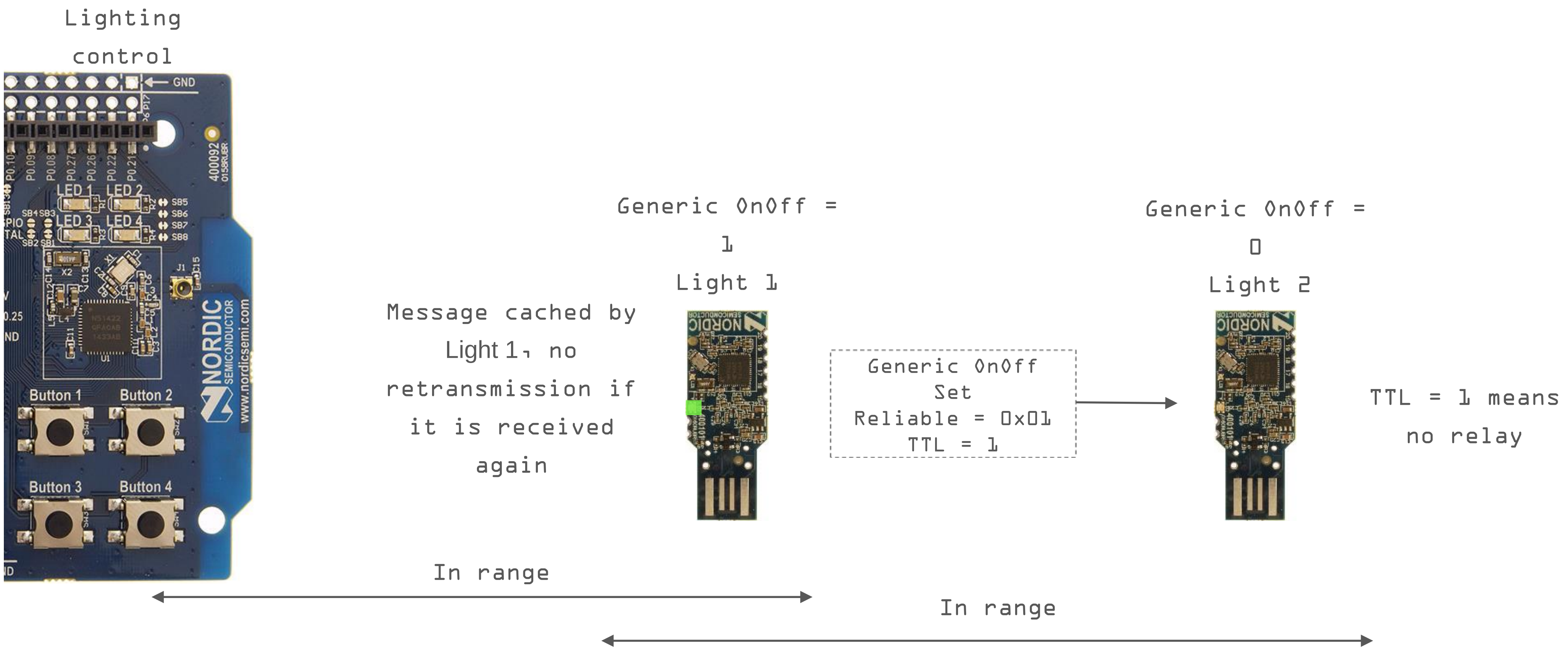
Generic OnOff = 0
Light 1

Generic OnOff = 0
Light 2

In range

In range

Working example - message transmission



Lighting control

Message cached by Light 1, no retransmission if it is received again

Generic OnOff = 1

Light 1

Generic OnOff Set
Reliable = 0x01
TTL = 1

Generic OnOff = 0

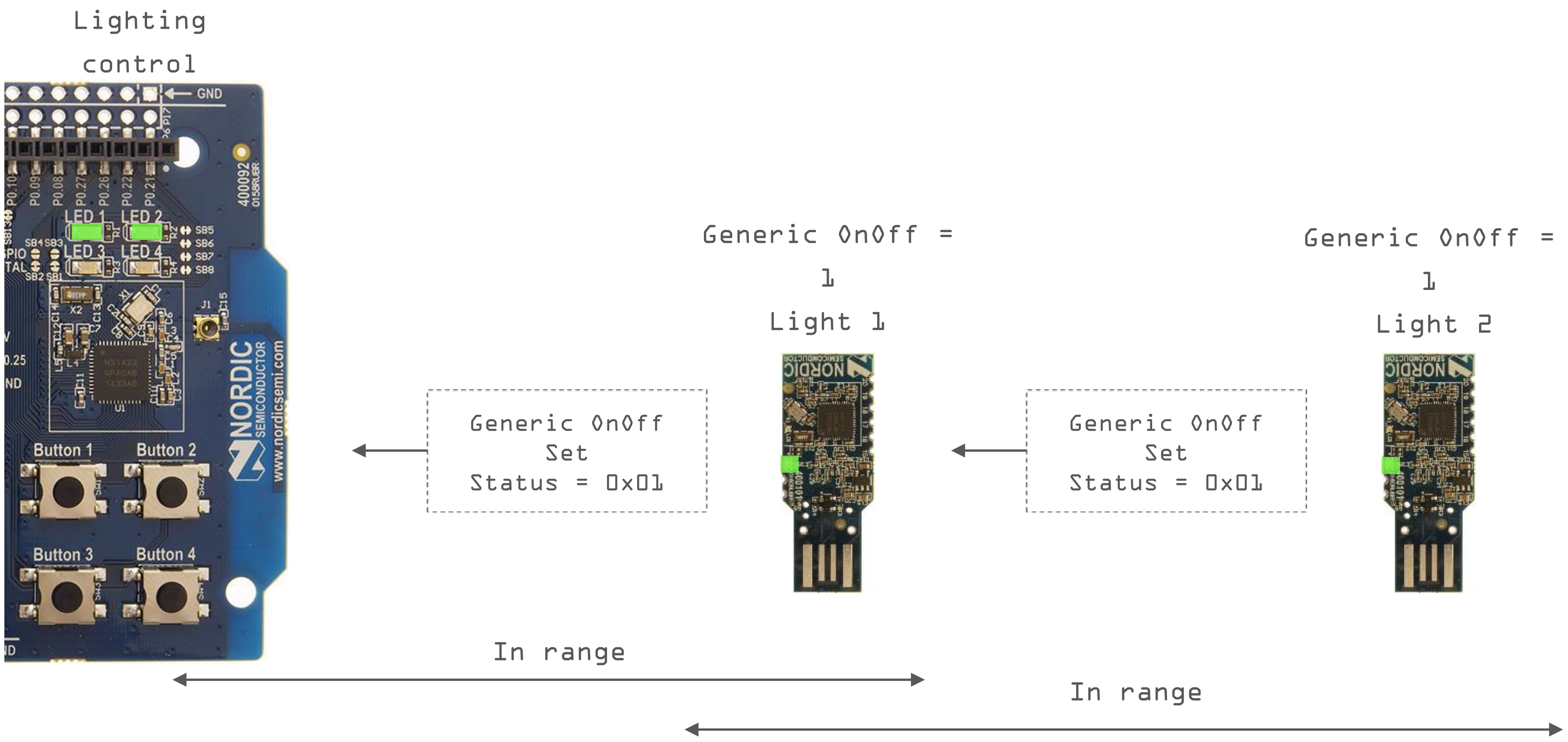
Light 2

TTL = 1 means no relay

In range

In range

Working example - message transmission



Lighting control

Generic OnOff = 1

Light 1

Generic OnOff = 1

Light 2

Generic OnOff Set
Status = 0x01

Generic OnOff Set
Status = 0x01

In range

In range

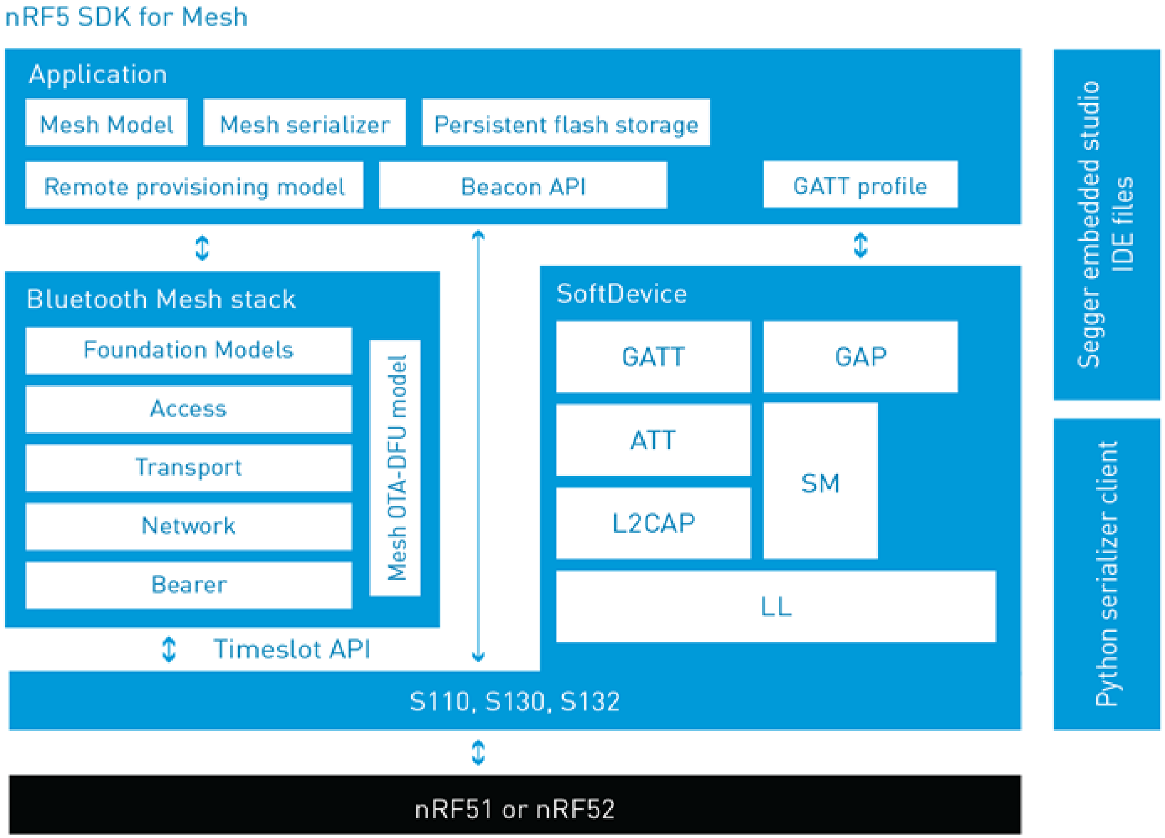
Some key parameter for Bluetooth mesh

- The maximum configuration of TTL is 127
  - If TTL = 1, the message will not be relayed
- 32767 elements in a mesh network
  - The unicast address space is 2^{15}
- 16384 group addresses in a mesh network
  - The group address space is 2^{14}
- 70 trillion virtual addresses in a mesh network
- 340 undecillion (2^{128}) mesh networks
- 4096 applications per mesh network

nRF5 SDK for Mesh

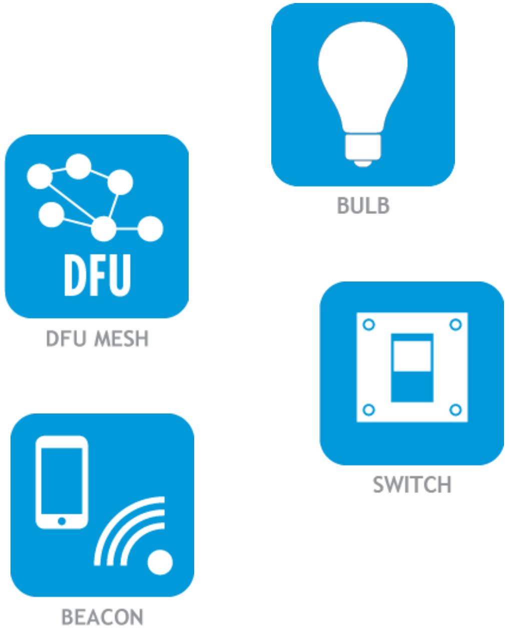
Bluetooth mesh from Nordic Semiconductor

nRF5 SDK for Mesh



- Source code release
- Mesh examples
- DFU solution
- Serialization solution
- Python tools

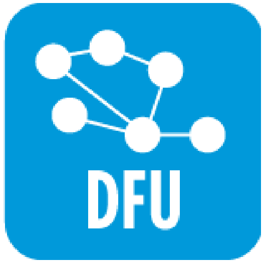
Bluetooth mesh examples



- Light control
  - With/without proxy features
  - PB-ADV provisioning
  - PB-GATT provisioning
- Serial interface
  - With interactive Python interface
- PB-Remote provisioning
- Beaconing
- DFU example

Mesh DFU solution

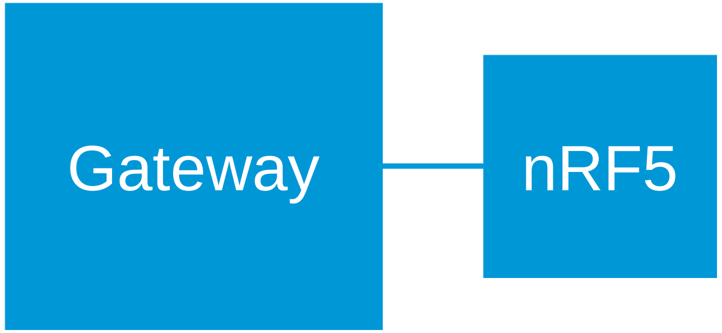
- Update mesh nodes with new firmware image
- Background mode: No interruption of service
- Nordic specific feature



DFU MESH

Mesh serial interface

Gateway



Gateway

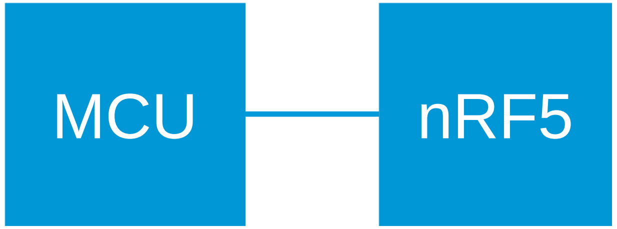
nRF5

Gateway to Internet

Ethernet or WiFi capable

Application processor

3rd party MCU/CPU



MCU

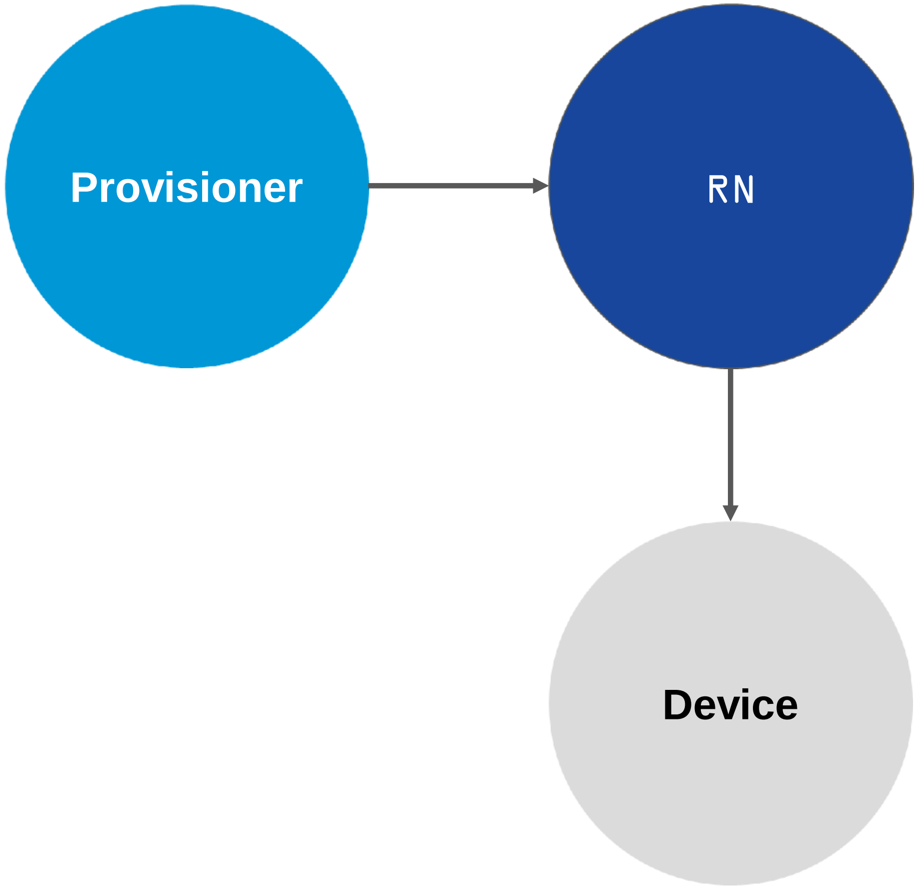
nRF5

Existing or specialized application

DALI, DMX, 0-10V

General Purpose MCU

PB-Remote - Remote provisioning



- Provision device across the mesh network
- No need to have device in range of the provisioner
- Automate large installation
- Nordic specific feature

nRF5 SDK for Mesh and other resources

- Available now at
  - https://www.nordicsemi.com/eng/Products/Bluetooth-low-energy/nRF5-SDK-for-Mesh
  - Or search "nRF5 SDK for Mesh"
- **All the documents are "open", no NDA needed**
  - https://infocenter.nordicsemi.com
- For any technical discussions, we invite you to join our DevZone
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Bluetooth mesh

Principles and Commissioning

Rick Chung

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Bluetooth Asia 2018