Analysis of Bluetooth Mesh Network Performance

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Outline

- Overview of Bluetooth Mesh
- Project Motivation
- Experiment Setup
- Results and Analysis
Bluetooth Mesh Overview
Bluetooth Mesh Overview

- Released in July 2017
- Great compatibility
  - Share the link and physical layer with Bluetooth 4.2
- High scalability
  - Support m-to-m communication
- Target applications
  - Wireless sensor network
  - Smart home automation

https://blog.bluetooth.com/introducing-bluetooth-mesh-networking
Bluetooth Mesh Network Components

● Provisioner
  ○ All devices join the mesh network through the provisioner
  ○ Phase 1: adding device to network and exchange keys for data encryption.
  ○ Phase 2: provisioner also configures the functionality of new devices and the network topology

● Relay nodes
  ○ Re-transmit received messages by flooding
  ○ Messages can traverse the whole mesh network by making multiple hops
  ○ Time to Live (TTL): limits the number of hops a message can take to prevent over-flooding
Bluetooth Mesh Network Components

- Server Nodes - defines a set of states
- Client Nodes - can get, set, and acquire the states of server nodes
More complex topology
How Bluetooth Mesh Works

Bluetooth Mesh enables the \textit{m-to-m communication} through the broadcasting and scanning mechanism of Bluetooth Low Energy

- Devices within radio range - directly receive advertisement packets in one of 3 channels of 2.4GHz band (37 38 39)
- Devices outside radio range - relay nodes will re-transmit received messages (flooding)
- Each device will be identified by the address called unicast address
Broadcast and Scan

Broadcast and Scan

● Scan window
  ○ How long does the radio stay active for listening to incoming packets

● Scan Interval
  ○ The period of triggering scanning activity

● Broadcast Event
  ○ Sending out packets in three channels (37 38 39) one by one
  ○ The order can set to random
Advertise(Broadcast) and Scan for BLE

Scanner scan interval = 50 ms
Scanner scan window = 25 ms

Scanning on channel 37
0 ms 25 ms

Scanning on channel 38
50 ms 75 ms

Scanning on channel 39
100 ms 125 ms 150 ms

Advertising on 37, 38 and 39
Advertiser Advertising Interval = 20 ms

Bluetooth Mesh Communication Basics

Scan interval = Scan window (Radio for RX is always active)

Project Motivation
Motivation

- **Bluetooth Mesh is newly released**
  - Experimental features
  - Insufficient documentation
- **Has not been widely used**
  - Proof-of-concept applications
- **Lack of guidelines**
  - Performance evaluation
  - Reliability - flooding mechanism
  - Power consumption
- **Goals**
  - Evaluate performance of a Bluetooth Mesh network with different topologies and parameters
Experiment Setup
Experiment Setup - Hardware

- nRF52 DK
  - nRF52832 SoC
  - JTAG debugger
- Customized PCB
  - BT832 (Bluetooth Module)
  - USB port
- Laptop
  - Run-time configuration
Experiment Setup - Software

- Software Development Kits
  - nRF5 SDK for Mesh
  - nRF52 Development Kit for BLE
- J-Link - logger
  - Events
  - Clock counts
- Python scripts
  - Data processing
  - Data visualization
Experiment Setup - Inputs and Outputs

● Input
  ○ Distance
  ○ TX power
  ○ Random channel
  ○ Scan interval
  ○ Number of clients
  ○ Number of servers
  ○ Number of relay nodes

● Output - Performance and Reliability
  ○ Packet-drop-rate (PDR)
  ○ Round-trip-time (RTT)
Experiment Design

- Packet transmit interval: 1000 ms
- Sample size: 100

\[
PDR = \frac{\text{No. of packets sent} - \text{No. of acknowledgements}}{\text{No. of packets sent}} \times 100\%
\]

\[
RTT = \frac{(RT_{C_{\text{send}}} - RT_{C_{\text{ack}}}) \times 1000}{f_{\text{clk}}}
\]
Experiment Design - Topology

Clients \( (n_{\text{client}}) \)

Relay Nodes \( (n_{\text{relay}}) \)

Servers \( (n_{\text{server}}) \)
Result and Analysis

\[ [\text{nClient}, \text{nRelay}, \text{nServer}] = [1, 0, 1] \]
\[ \text{Distance} = 0 \]
Packet Drop Rate vs Scan Interval

- No apparent relation
- High drop rate: range from 15% to 30%
- Interference?
Packet Drop Rate vs Scan Interval

- Range from 10% to 20%
Packet Drop Rate vs Scan Interval

- Randomization improves PDR
- Peculiarly high PDR for scan interval around 800-1000
RTT vs Scan Interval

- Two separate groups of samples for each scan interval
- Mainly below 50 ms
RTT vs Scan Interval

- Two separate groups of samples for each scan interval
- Mainly below 50 ms
Percentage of RTTs over 150 ms

- Result unclear

![Graph showing the percentage of RTTs over 150 ms with two lines representing 'Random Channel Disabled' and 'Random Channel Enabled' with varying percentages over a scan interval ranging from 200 to 1000 ms.]
Conclusion and Takeaways

- Minimum 10% packet drop rate
- Unstable delay (about 15% chance to be higher than 250)

Bluetooth Mesh is not suitable for applications that have hard real-time deadlines or require high reliability