Performance Evaluation of Deployable Bluetooth Low Energy Mesh Network for Monitoring System

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Master thesis seminar

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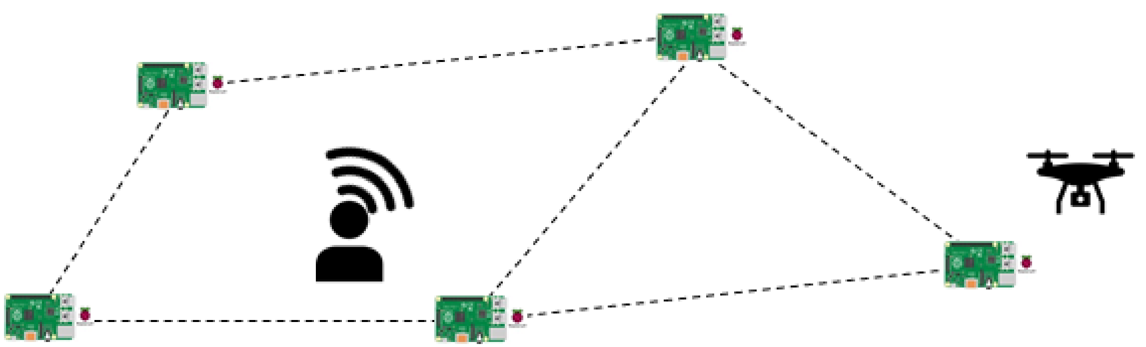
Contents

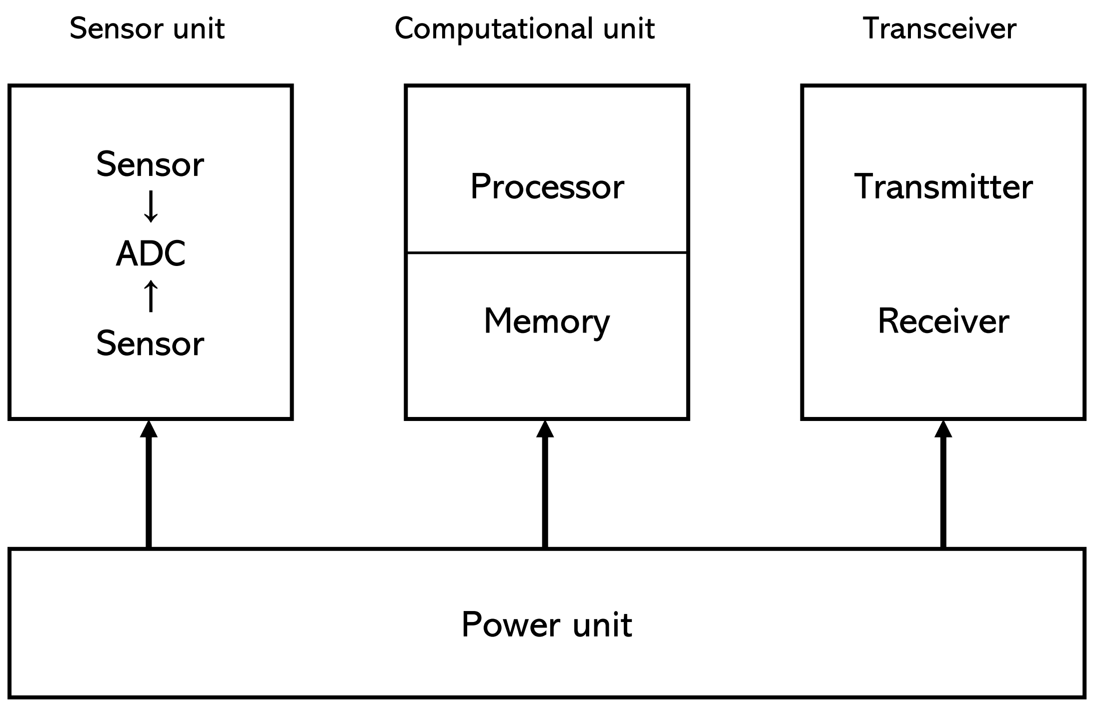
Introduction

- This thesis built a BLE Mesh network using PIR and acoustic sensors to detect the presence of people in the network coverage area. Once the people presence is detected, their voice samples are recorded and a feature vector from each person's voice is computed in the nodes for speaker identification.
- Performance in communication, power and memory is evaluated by several experiments.



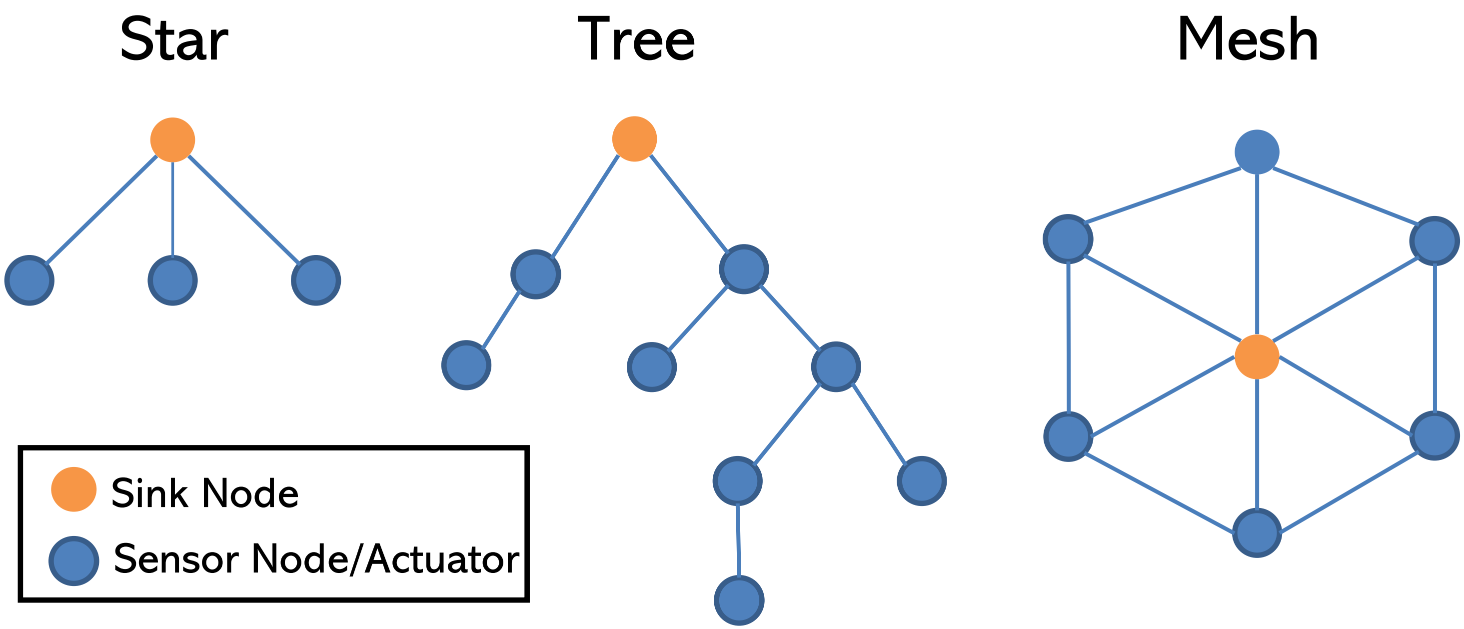
Background: Wireless sensor network

- Wireless sensor networks (WSNs) are built to collect data and information from the environment by deploying many sensor nodes in the area over a wireless link.



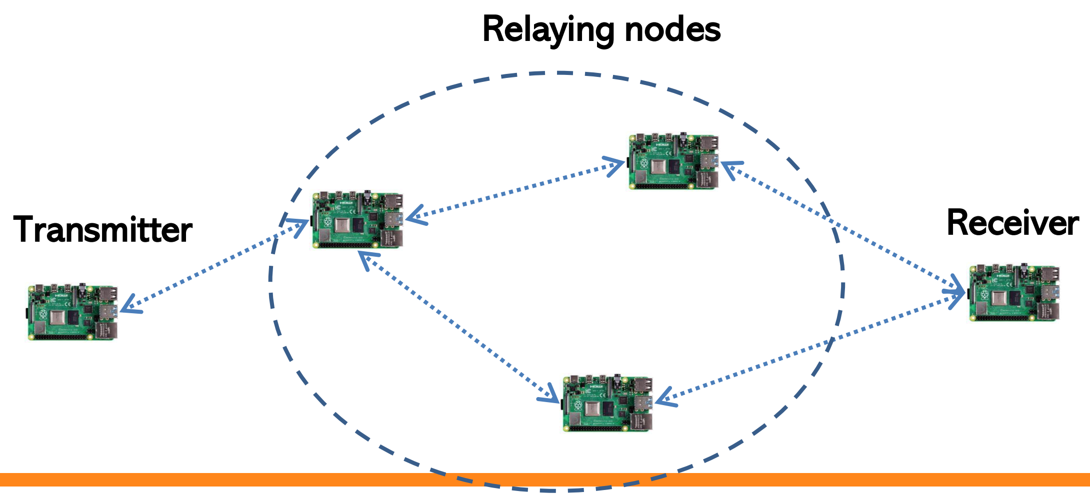
Background: Wireless sensor network

- A sensor node can also function as a clusterhead, a sink, or a gateway.
- Typical topologies: star, tree, and mesh



Background: Mesh Network

- Mesh topology have the ability of self-organization and self-configuration. It has higher flexibility, easier node deployment and configuration, and higher fault tolerance.
- Nodes can communicate over multi-hop paths by relaying nodes between the transmitter and receiver nodes. This extend the communication range and improve the stability.
- The mesh architecture can reduce WSN deployment costs.

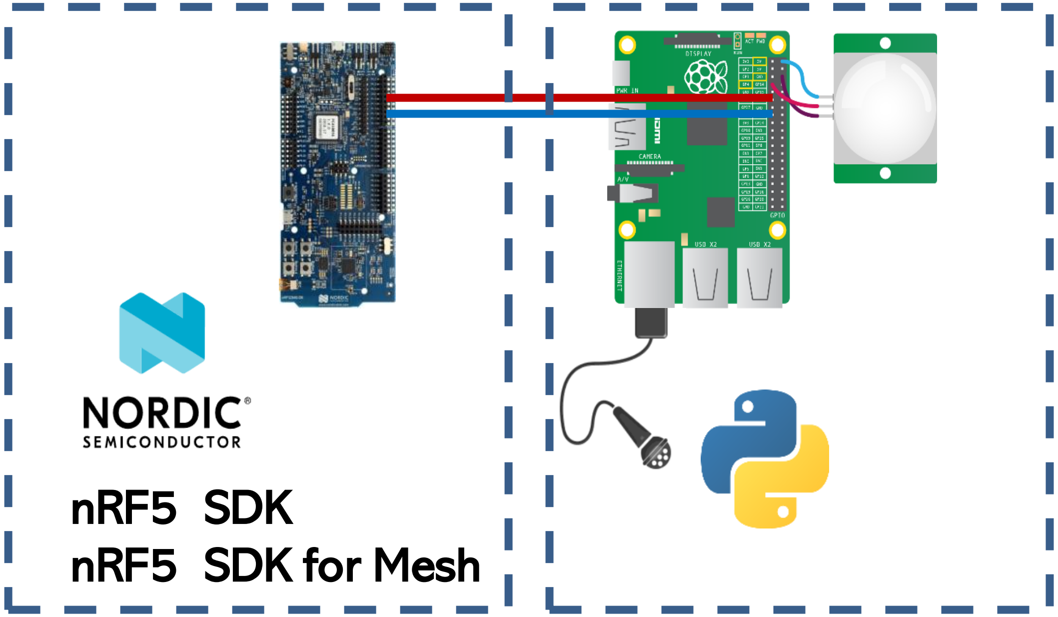


Background: BLE Mesh

- In 2017, Bluetooth SIG released the *Bluetooth Mesh profile specification* [1]. It enables a many-to-many mesh and suitable for large-scale systems.
- It has high reliability, scalability and security.
- It provides full-stack implementation to bring convenience to developers

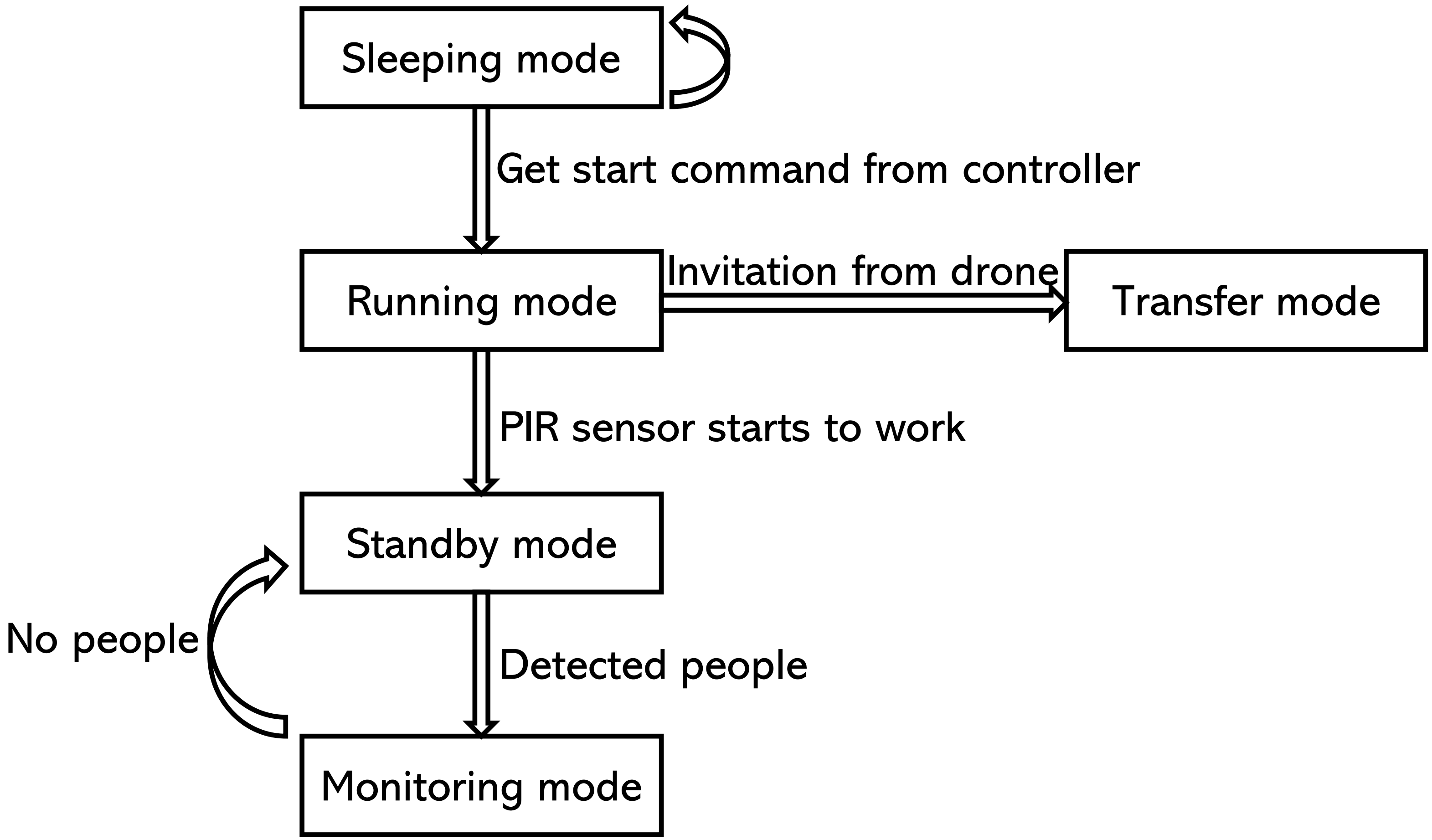
[1] B. SIG, "Mesh profile version 1.0," https://www.bluetooth.com/specifications/mesh-specifications, 2017.

Developed Architecture: Node hardware and software



- Radio module (nRF52840) for mesh connection
- Raspberry Pi 4 Model B for programming and processing
- PIR sensor (HC-SR501) for people detecting
- Acoustic sensor for voice collection

Developed Architecture: Node Modes



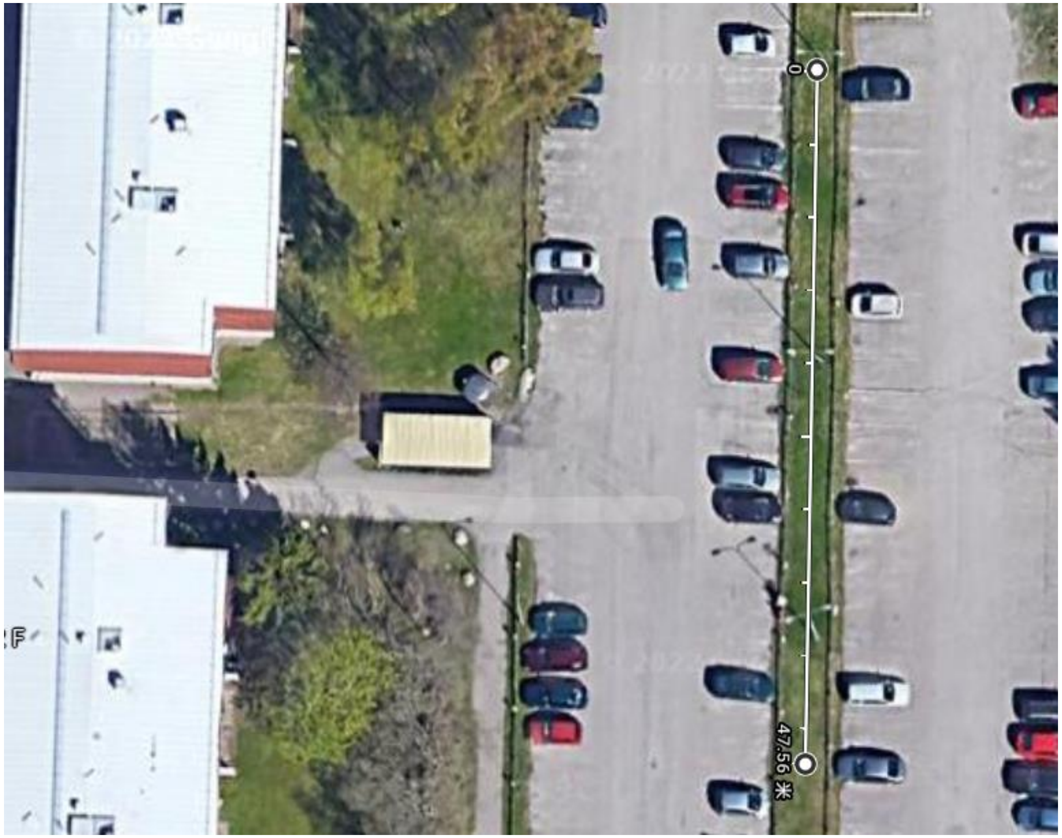
Developed Architecture: Speaker identification

In the monitoring mode, the nodes will:

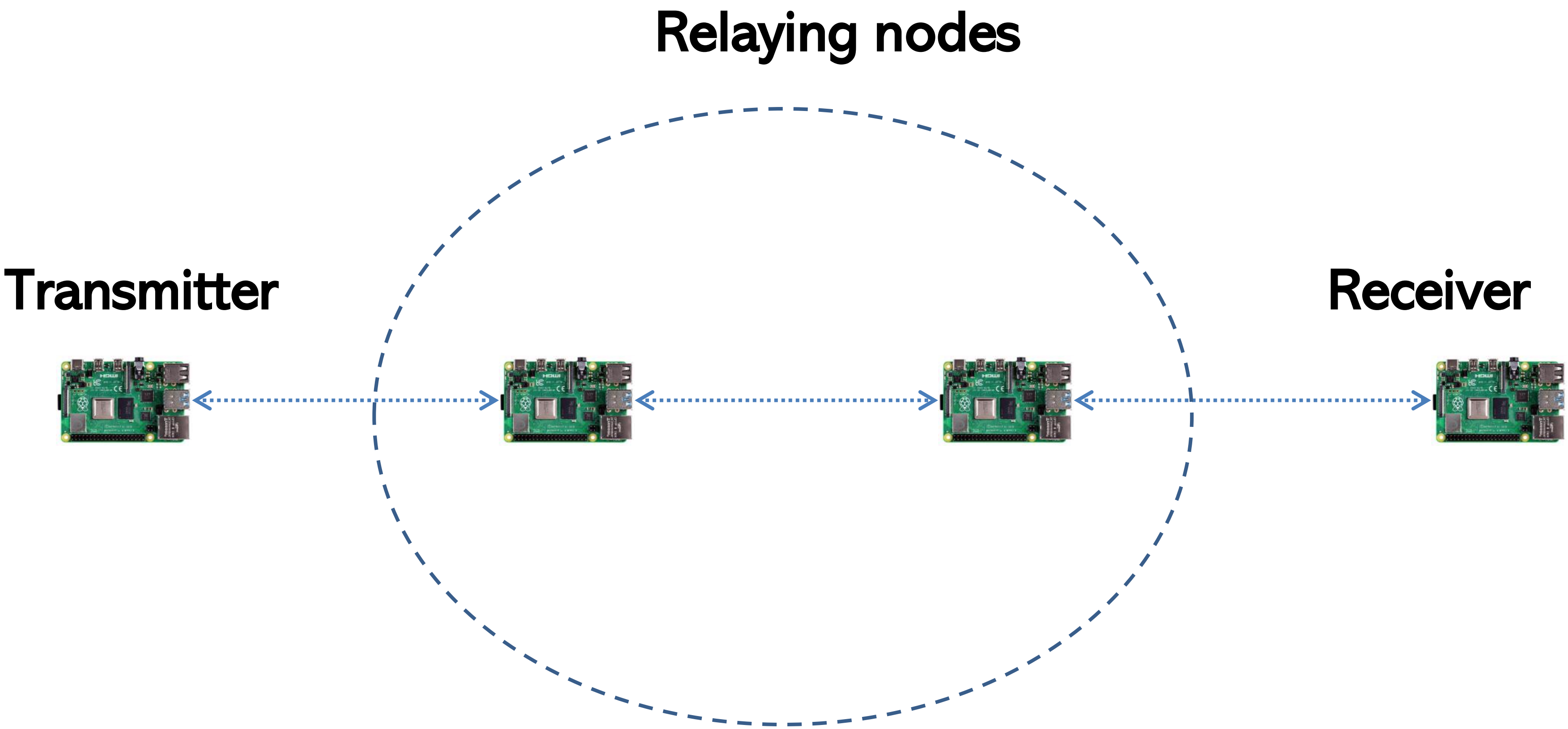
1. Start to recording when the PIR sensor detect the people.
2. Compute the feature vectors (Mel Frequency Cepstral Coefficients of each voice sample)

Step	**Explanation**
Framing	Slice a time series into overlapping frames
Window	Hamming widow
FFT	Fast Fourier transform
Power spectrum	Retrieve a magnitude spectrogram
Mel filter	Create a Filterbank matrix to combine FFT bins into Mel-frequency bins
Mel-scaled spectrogram	Compute a mel-scaled spectrogram
DCT	Discrete Cosine Transform
log energy	Convert a power spectrogram (amplitude squared) to decibel (dB) units
Get Mel-cepstral coefficient	Add first- and second order temporal derivatives

Experiments: Outdoor Setup

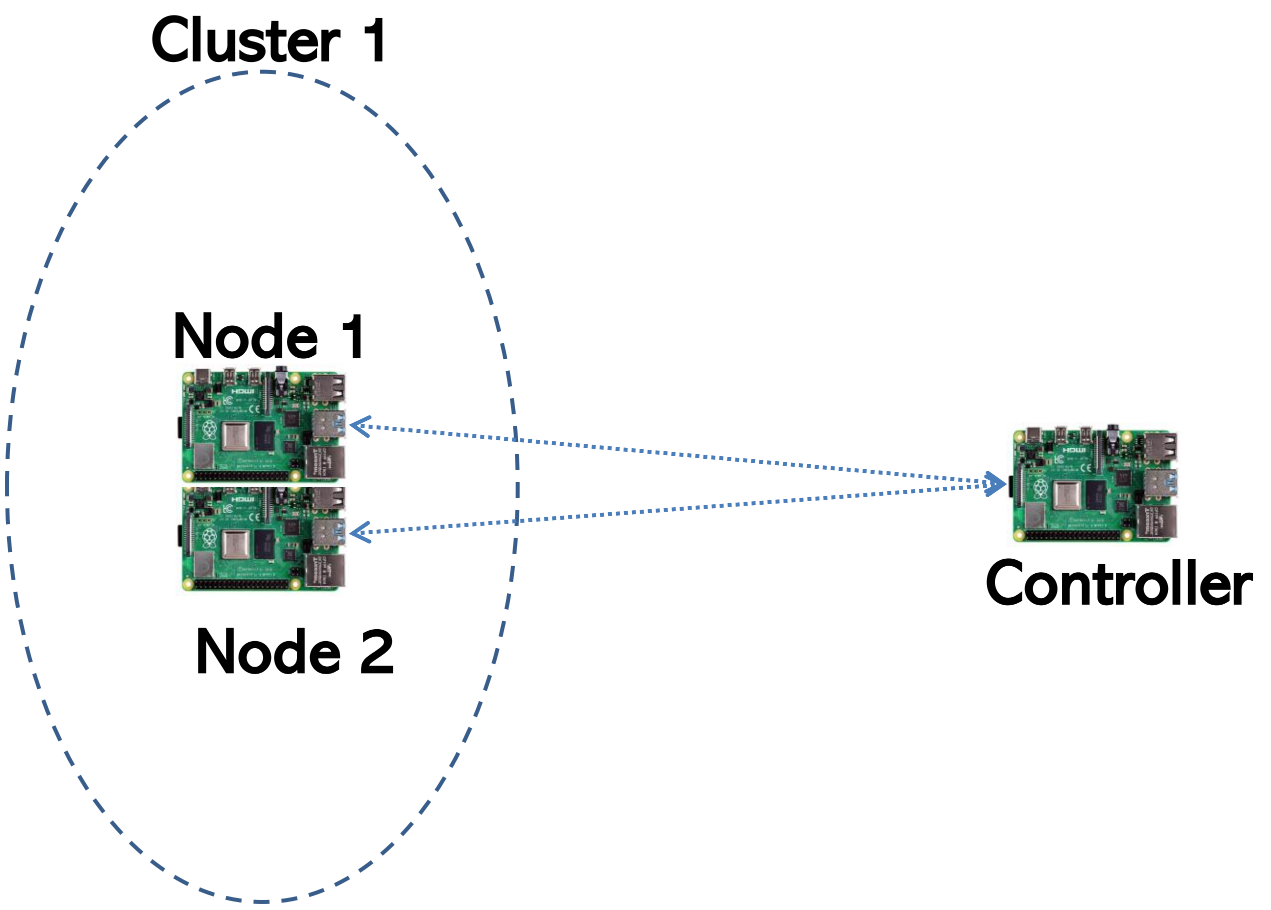


Experiments: Network Architecture



Single-hop and Multi-hop Architecture

Experiments: Network Architecture



Cluster Architecture

Experiments: Performance Evaluation Metrics

- Packet Delivery Rate (PDR)

$$\text{PDR} = \frac{N_{Received\ packets\ by\ receiver}}{N_{Sent\ packets\ by\ transmiter}}$$

In single-hop and multi-hop cases, PDR is the ratio of the number of received packets and sent packets. In cluster case, PDR is the ratio of the sum of received packets by the two nodes in the cluster and the sent packets.

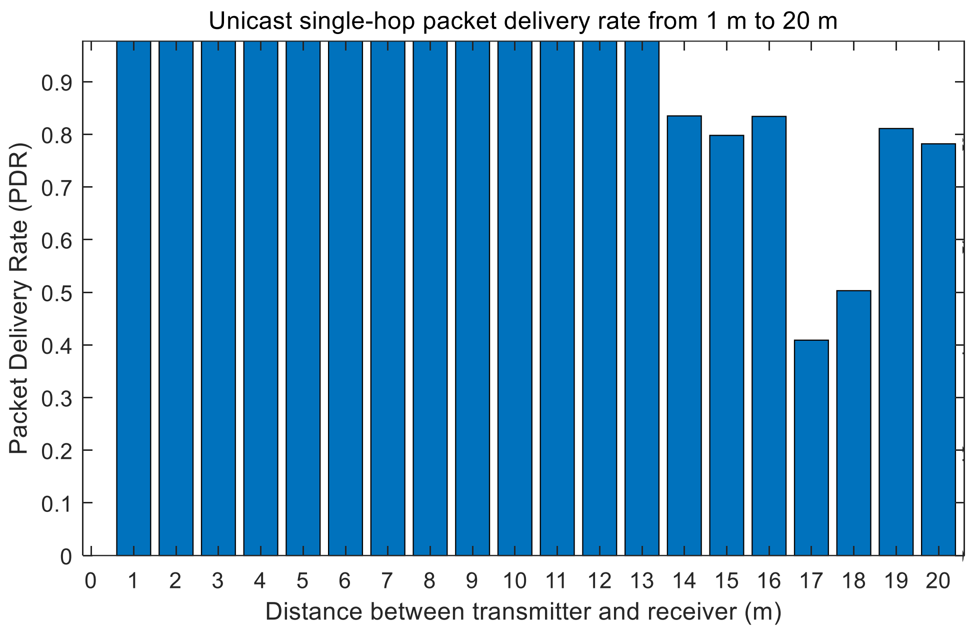
- Round Trip Time (RTT)

$$RTT = T_{transmitter\ get\ the\ acknowledgment} - T_{transmitter\ start\ sending}$$

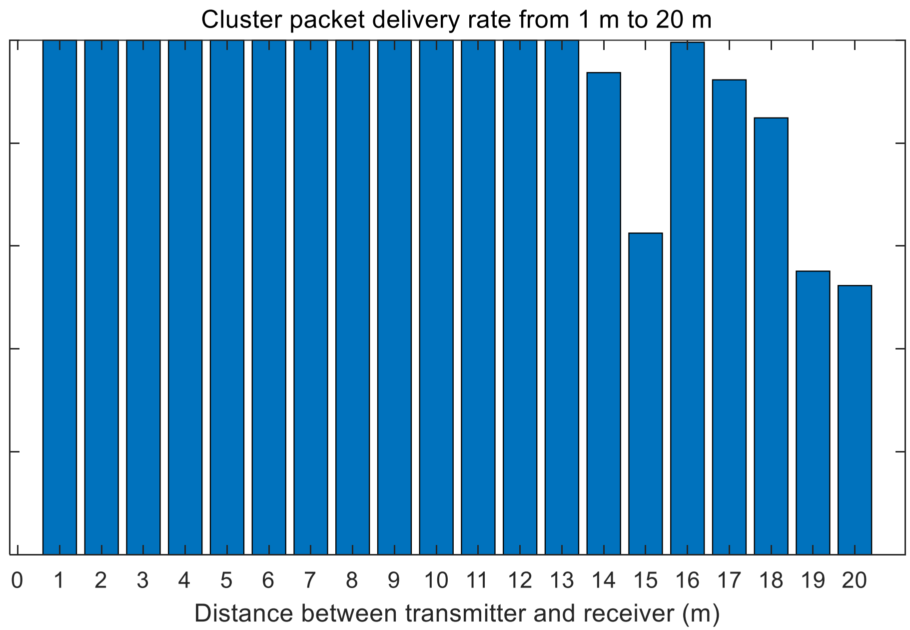
RTTs are only tested in 100% PDR distance because if the transmission fails, the time will be the timeout I set, which is meaning less.

Experiment 1: Packet Delivery Rate

Unicast single-hop



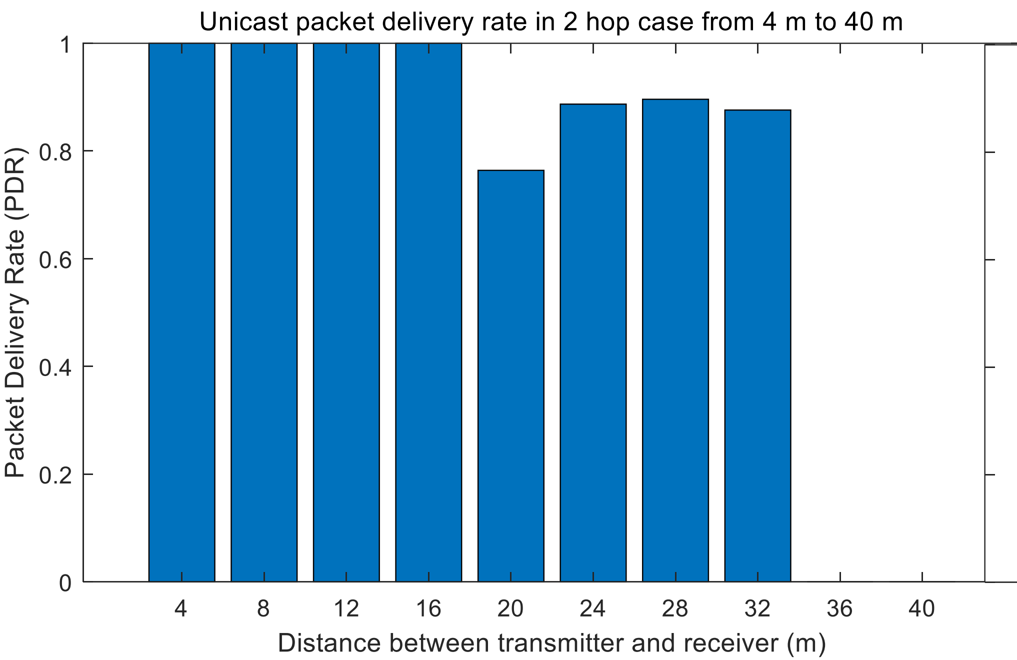
Cluster



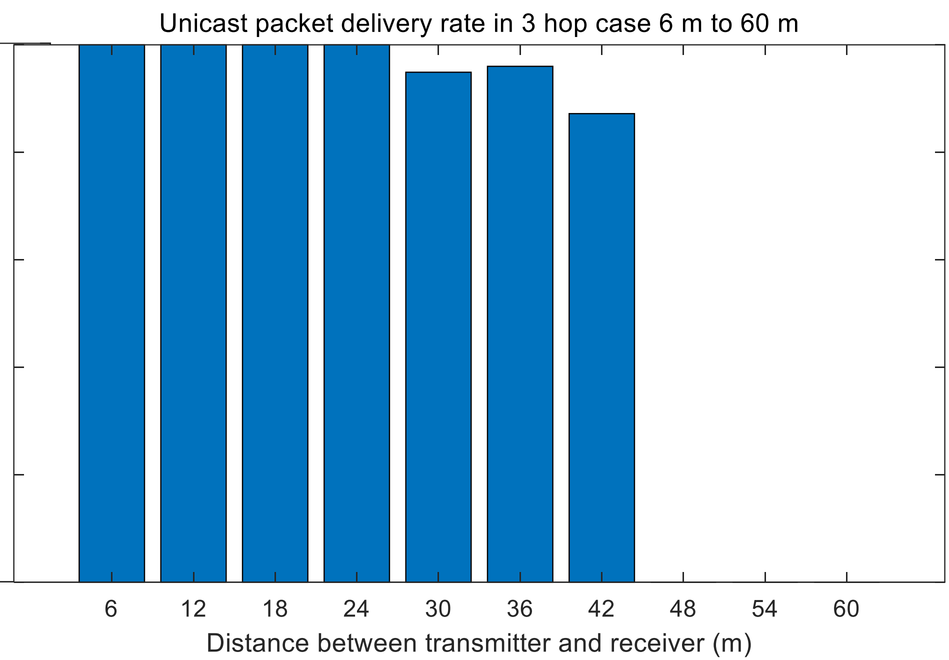
- Both have 100% reliability in 13 m.
- Irregularly distributed when the distance over 13 m

Experiment 1: Packet Delivery Rate

Unicast two-hop



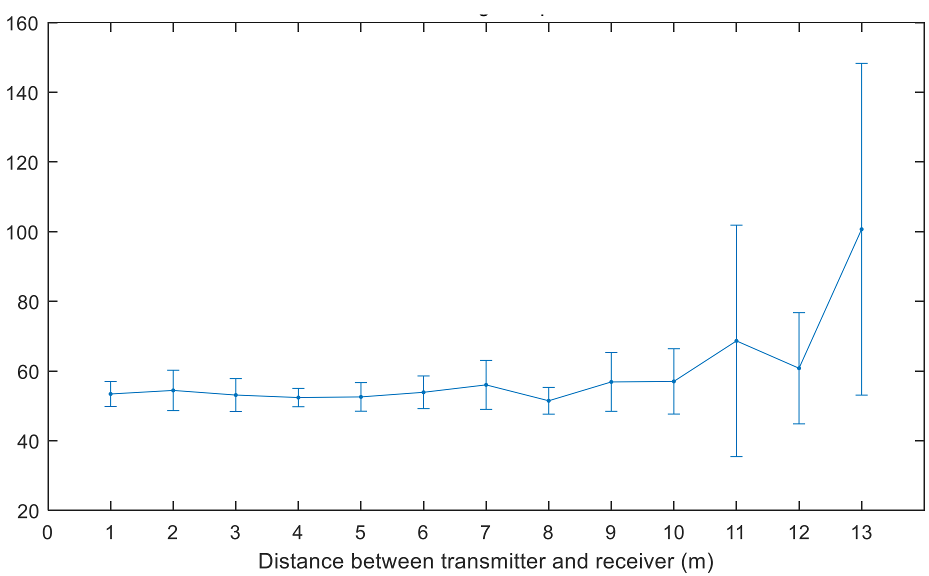
Unicast three-hop



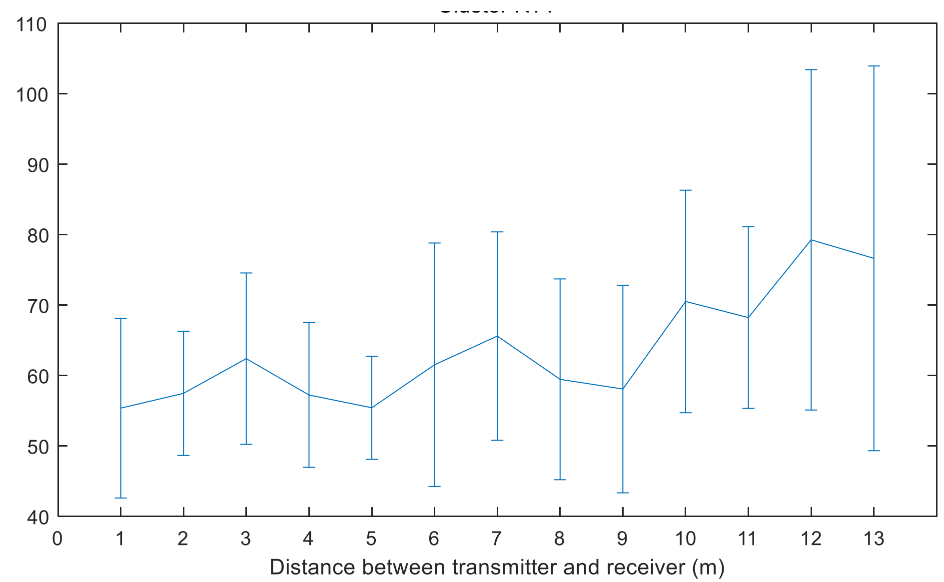
- Adding a relaying node between two nodes can indeed extend the communication distance between nodes but 100% reliability communication distance extension is limited.

Experiment 2: Round Trip Time

Unicast single-hop



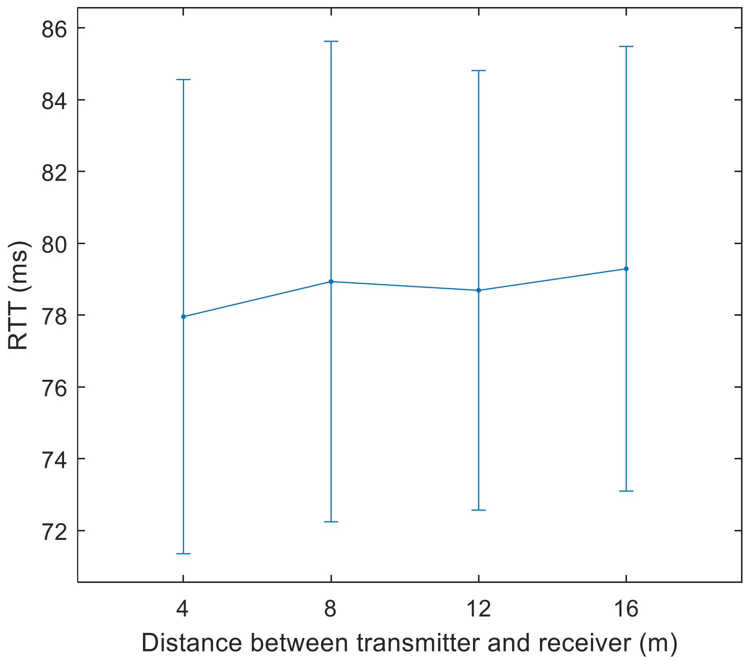
Cluster



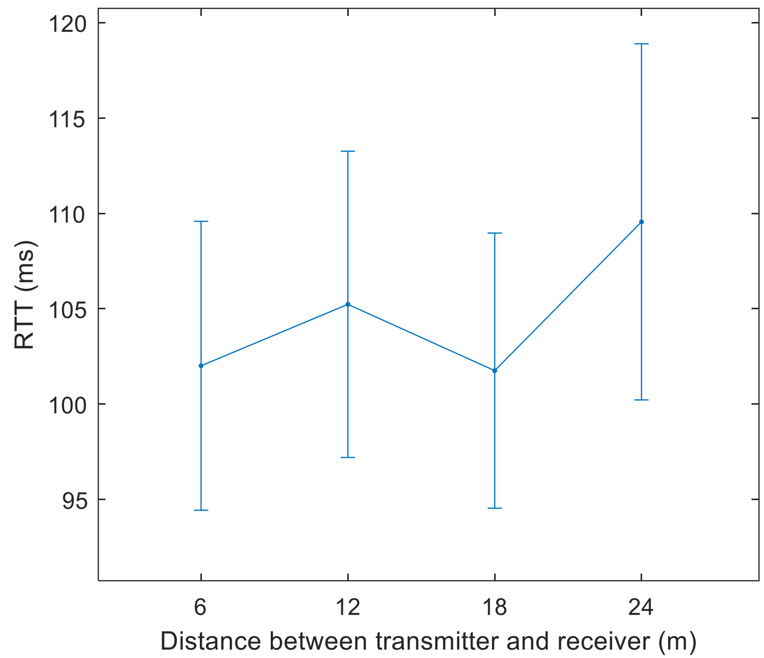
- The average RTTs in cluster case (58 ms) and unicast case (55 ms) has only a few milliseconds difference within 10 m.
- The standard deviation of RTT in cluster case is much larger.
- As the communication distance increases, both RTT and instability increase. The maximum RTT is up to 183 ms in unicast case and 140 ms in cluster case.

Experiment 2: Round Trip Time in Multi-hop cases

Unicast two-hop



Unicast three-hop



- In 2 hop case, the average $RTT \approx 78\ ms$, In 3 hop case, the average $RTT \approx 105\ ms$
- Deviations are similar in different distance
- The average RTT increase about 25 ms when the number of hops is increased by 1.

Experiment 3: Power and memory performance

The acoustic sensor record the voice for 7 seconds once and the sampling rate is 44.1 kHz. Each feature vector is 1×297 and has a memory footprint of 5.60 KB.

Parameter	**Test 1**	**Test 2**	**Test 3**	**Test 4**
Temperature (°C)	-8 ~ -2	-8 ~ -3	0 ~ 2	3 ~ 7
Feature vector number	4451	4400	4967	4949
Operating time (h)	9.44	9.34	10.55	10.51
Average computation time (ms)	238.8	240.9	240.4	239.5
Total memory (MB)	24.930	24.642	27.824	27.716

Conclusions

1. In unicast and cluster architecture, the nodes had 100% PDR up to 13 meters, similar average RTT (55 ms in unicast, 58 ms in cluster). but the unicast RTTs had smaller standard deviations than those of cluster RTTs.
2. Extensive and more reliable communication could be obtained by multi-hop communication paths by deploying relaying nodes in the network. However, as the number of hops increased by 1, the RTT also increased about 25 ms in the experiments.
3. Each node has sufficient power for over 9 hours even in low temperature environment and sufficient memory for more than 5000 feature vectors.

Limitations and Future work:

1. Lack of sensing performance:

- PIR sensing: the PIR sensor we used now (HC-SR501) perform well indoor, but the accuracy will be greatly reduced outdoor. The reasons will be analyzed, and other sensors should be taken into consideration.
- Acoustic sensing: The implementation of similarity comparison between feature vectors and speaker identification.

2. One-way latency is also need to be tested. Time synchronization will be implemented.

Thank you !