SoftBLE: An SDN Framework for BLE-Based IoT Networks

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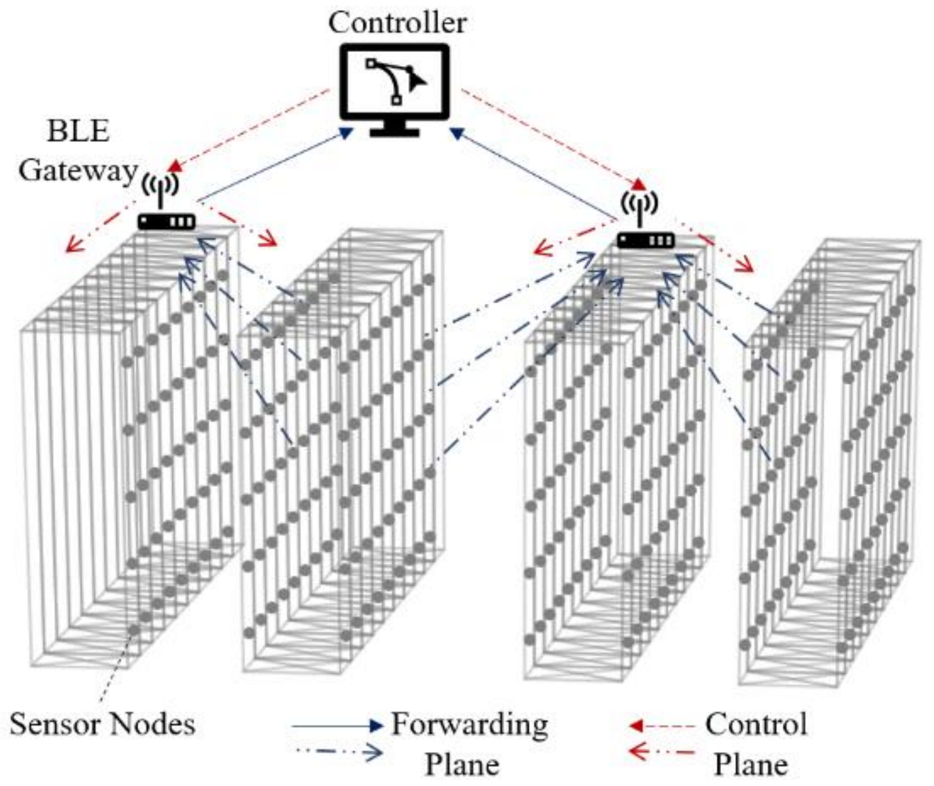
Problem

- Dense IoT Device Network are difficult to work with
  - Dropped packets, high congestion, power wasted
- Dense sensor networks shown to have ‘GoodPut’ down $\emptyset(1/n)$ as ‘n’ devices increases
  - ‘GoodPut’ ability to successfully receive sensor data
- Example Problem:
  - Temperature sensors in a server room



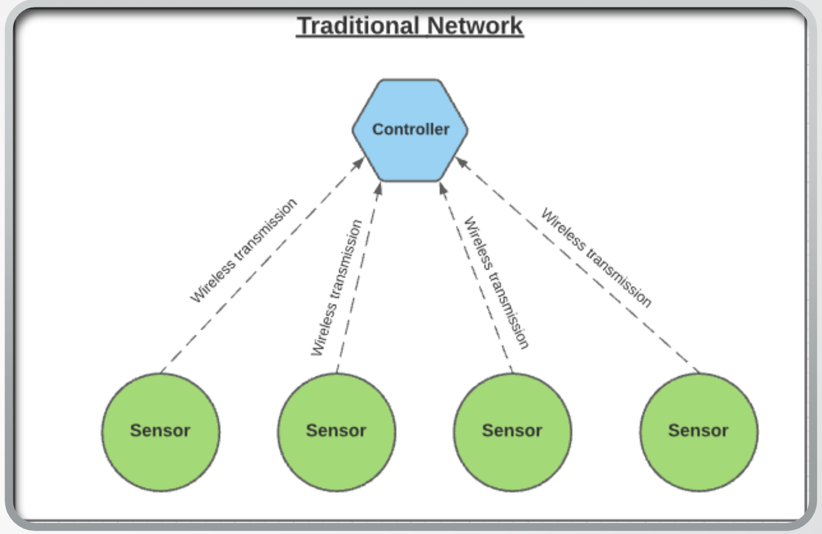
Goal

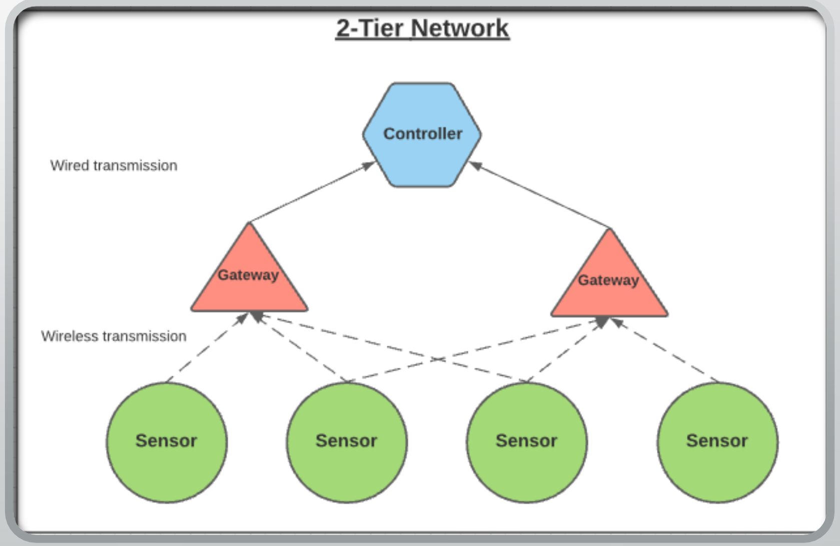
Increase Packet Reception Rate (PRR)

Decrease Power Consumption (PWR)

Hierarchical Networks (2-Tier Networks)

- Benefits:
  - Reduce traffic to controller
  - Decrease latency with gateway closer to sensor and wired connection to controller
- Problems:
  - Without customizability, lacks the ability to scale with more devices and handle dynamic changes in traffic





SoftBLE Solution

- What if we can control and customize BLE traffic AT RUN TIME to create an optimal network?
- A Software Designed Network (SDN) that provides controllability for BLE Based 2-Tier Networks
- **Contributions:**
  1. An SDN designed as an overlay on a two-tier network forwarding plane
  2. Two orchestration algorithms for optimized scanning parameters on the gateway and advertising parameters on the sensor

Brief BLE Background

- Bluetooth Low Energy is a wireless personal area network that is similar to Bluetooth, but emphasizes low energy consumption while sacrificing some bandwidth and connectivity features

BLE Background

- Light-weight and power efficient
- Uses 40 possible channels with only **3 for advertising**
- Has 5 possible states, but SoftBLE only utilizes 3 of them
  - Connected and Initiated are too power hungry

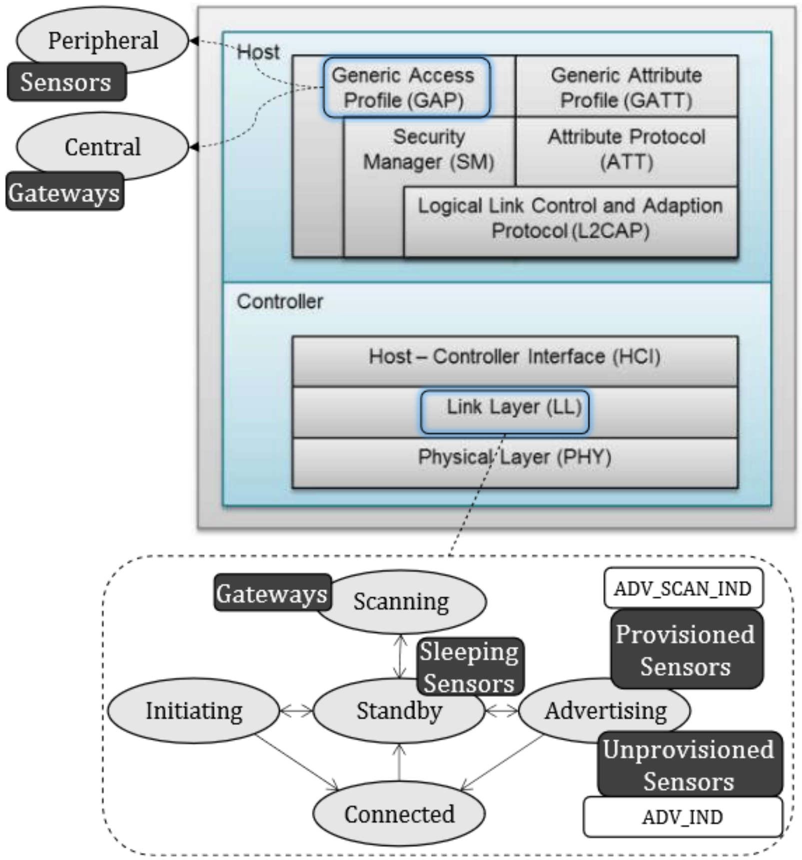


Figure 2: BLE protocol stack.

BLE Old Way

Sensors:

- Advertise for the "advertising interval" time + a "random delay"
- Can be configured via the following:
  - Advertising Channel Map
  - Advertising interval
  - TX power level
  - BLE Address (specifically Random Private Non-Resolvable) (Settable by the application)

Scanners:

- Scan on a channel map for a period of time called the scanning window
- Scan for a scanning interval then changes to next address on channel map
- Can be a passive scanner (scanning close to source)
- Can be an active scanner (accepts scan requests and connection requests form sensor)
- Can be configured to only scan a certain list of addresses

SDN – Software Designed Netowork

- SDN = Networking approach that uses software-based controllers with an emphasis on dynamic programmability for efficient networks
  1. **End User**: Sensor Nodes (generating data)
  2. **Flows**: Data ‘flows’ coming from sensors
  3. **SDN Switches**: BLE Gateways that forward flows
  4. **SDN Controller**: Central computer connected to gateways

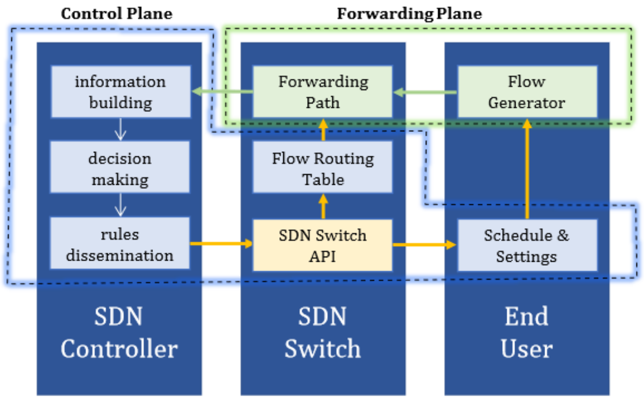


Figure 4: The components of SDN framework in a SoftBLE.

Provisioning of an End User (Sensor)

- Sensors start un-provisioned and continually send out provision requests
  - *'Please accept my data and let me into the network'*
- After a certain number of requests, the controllers configures the sensor and allows it in the network
  - *'Okay come on in, but here is your schedule and how you should act'*
- Upon provisioning an observation matrix is created

Sensor-Gateway Observation Matrix

Generated during provisioning

Many to Many matrix defining the RSS (Received Signal Strength) from the sensor to each gateway

$$O = \begin{bmatrix} o_{11} & \cdots & o_{1N} \\ \vdots & o_{ij} & \vdots \\ o_{M1} & \cdots & o_{MN} \end{bmatrix}, o_{ij} = \begin{cases} 1 & \text{if } \max\left(rss_j^i\right) > P_{sen} \\ 0 & \text{if } \max\left(rss_j^i\right) < P_{sen} \end{cases}. \quad (1)$$

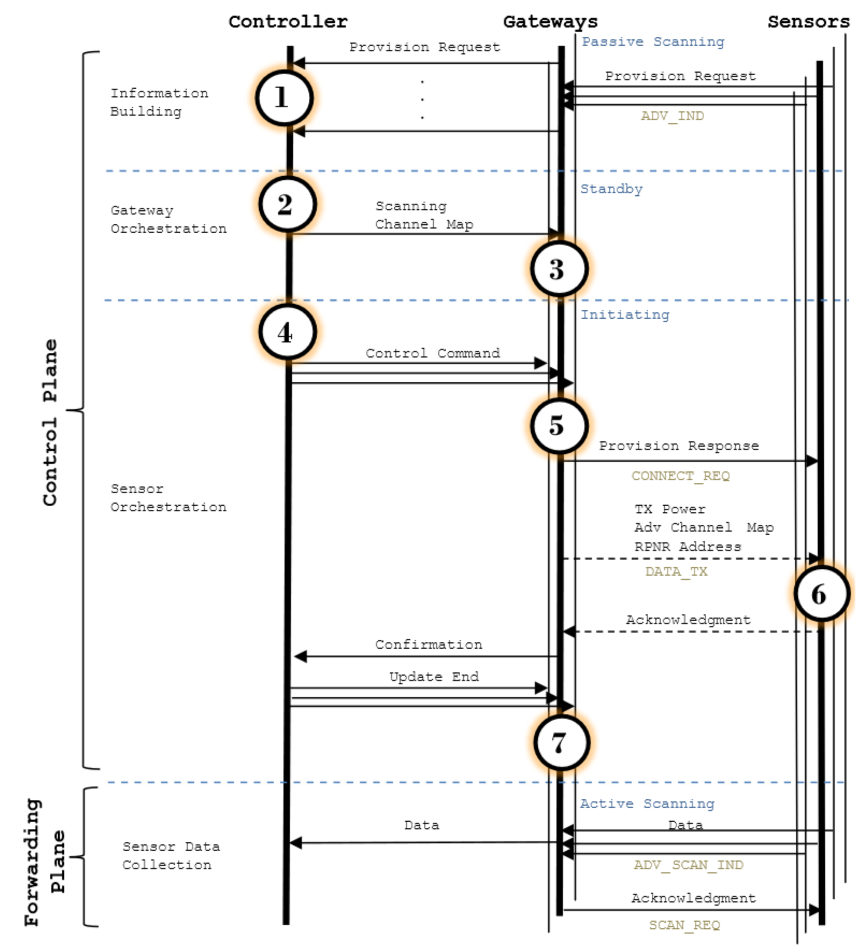
$$\forall i \in \{1,..,N\}, j \in \{1,..,M\}$$

What is configured in SoftBLE?

Channel Map of Sensors:	TX Power Level:	Advertise Address:	Channel Map of Gateway:	Whitelist of Gateway:
• What channels a sensor will broadcast to	• How powerful will the sensor broadcast	• What private address a BLE device will have when broadcasting	• What channels a gateway will listen to	• What 8 addresses will the Gateway listen to on that channel

Control Plane

- Sits on top of the forwarding plane
- Only job is to provision new sensors OR re-provision disconnected sensors
- Three Jobs
    1. **Information Building**: *'How strong is this sensor, what is our current sensor network'* (think observation matrix)
    2. **Gateway Orchestration**: *'Which channels are each gateway scanning and what is open'*
    3. **Sensor Orchestration**: *'Okay SENSOR you should broadcast this strong on this channel for this long and GATEWAY listen on this channel'*



Gateway Orchestration

- Gateway's only scan ONE channel, deciding what channel that should be is gateway orchestration
- Assign a Gateway channel such that the neighboring gateway has the least number of interfering sensors
- Max-Min Optimization Heuristic applied here to determine best channel:
  - Max: Find the gateway that has the max common sensors on the three channels
  - Min: Find the channel on that has the least number of common sensors and choose that one

Sensor Orchestration

- Sensors can advertise on any of the three channels at varying transmission power levels
- But:
  - More channels, more traffic, lower PRR
  - Higher Tx, more power, more traffic, lower PRR
- Sensor orchestration is attempting to find that happy medium

$$E[PRR]_s = 1 - (1 - \hat{prr}_s)^R.$$

$$\begin{aligned} E[PWR]_s &= \sum_{r=1}^{R} \frac{1}{\delta} \cdot E_s^{adv} \cdot E[PRR]_s (1 - E[PRR]_s)^{(r-1)} \\ E_s^{adv} &= P_s^{tx} \cdot \left\| C_s^S \right\| \cdot \left(\frac{|DATA|}{\mu} + P_{ifs} \right) \\ &\quad + P_{rx} \cdot \left(\frac{|SR|}{\mu} \right) + P_{ifs} + P_s^{tx} \cdot \left(\frac{|SS|}{\mu} \right) \\ P_s^{tx} &= P_{tx} \cdot 10^{(TX_s/10)}, \end{aligned} \tag{13}$$

Sensor Orchestration Factors

- Expected PRR:
  - Broken down into a Per Gateway PRR
  - Solving for this, want higher PRR
- Interference counter:
  - Number of potentially colliding sensors
- Traffic Load:
  - Sum of transmissions in a region
- Expected Number of Retransmissions:
  - Estimated number of times data must be re-transmitted
- Expected Power:
  - Solving for this, want lower power

Sensor Orchestration

- The final algorithm for sensor orechestration is a simple nested for-loop running in O(c) time
- First loop through all possible channel combinations (37,38,39), (37,38) etc.
  - For each channel combination loop through all 13 power configurations
    - Check for the lowest E[pwr] and highest E[prr]

Algorithm 2: TX power optimization on the sensors

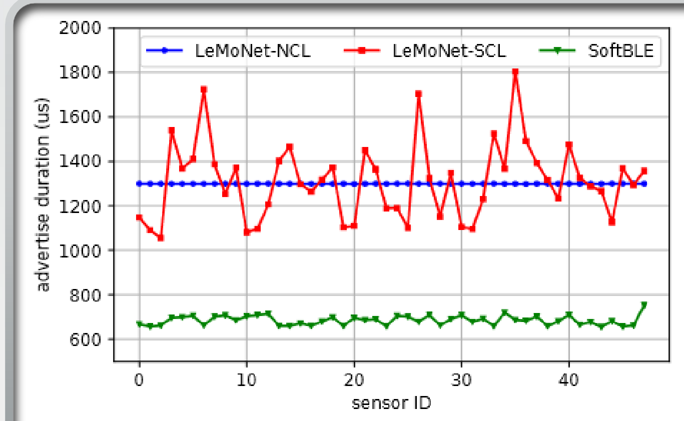
```
input  : sensor ID (s), observation matrix (O), RSS of provision
         requests received from s (rss_s)
output : assigned advertising channel map (C_s^S) and TX power
         (TX_s^S) to sensor s
PTX ← {−21, −18, −15, −12, −9, −6, −3, 0, 1, 2, 3, 4, 5}
bestC ← {37, 38, 39};
bestP ← 5;
bestPWR ← ∞;
for C ← Subsets of {37,38,39} do
    for p ← 1 to 13 do
        TX ← PTX[p];
        Estimate E[PRR_s] based on C, TX, rss_s, O using (5);
        Estimate E[PWR_s] based on E[PRR_s] using (13);
        if E[PRR_s] > T and E[PWR_s] < bestPWR then
            bestC ← C;
            bestP ← PTX[p];
            bestPWR ← E[PWR_s];
C_s^S ← bestC;
TX_s ← bestP;
```

Performance Analysis

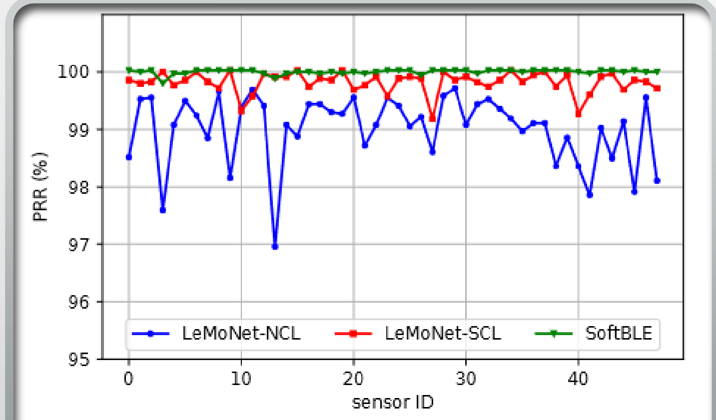
- Compared against LEMoNet
  - A static tiered network developed by this same research group
- LEMoNET vs. SoftBLE
  - In SoftBLE gateways only respond to sensors on their whitelist
  - RSS's are extracted directly from device and not estimated in SoftBLE
  - No NCL mode in SoftBLE
  - TX Power in Soft BLE is variable
- Run in two modes for LEMoNET:
  - Normal Connectionless Mode:
    - "Here is my data, take it if you want it"
  - Scannable Connectionless Mode:
    - "Here is my data, I will keep resending N times until someone sends a scan request confirmation that it was received"
- 48 sensors, 2 Gateways

Results

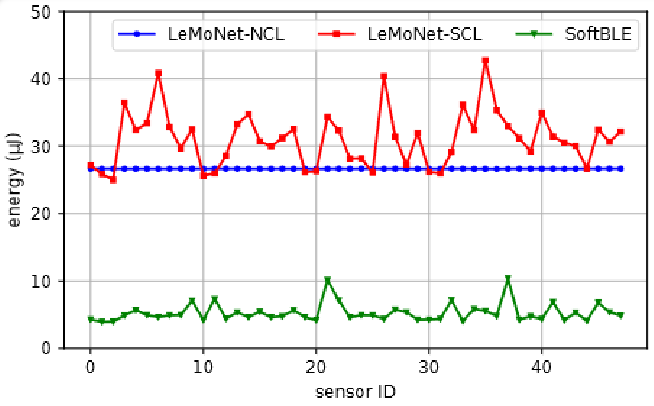
- Almost all sensors chose a single channel based on a higher RSS, but one device had a bad signal to both gateways and chose to broadcast on both channels
- PRR 99.9%
- PWR down 70%



(c) Advertise duration per duty cycle



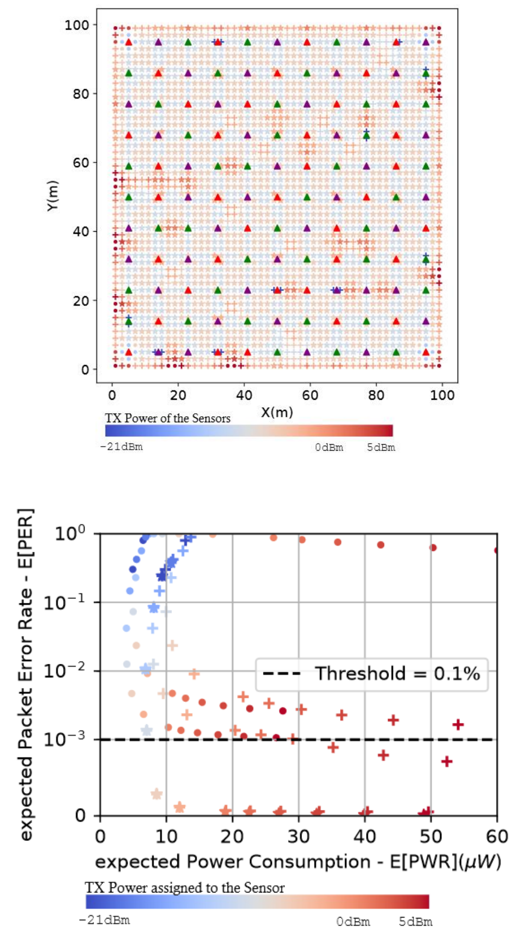
(b) Packet Reception Rate



(d) Mean energy consumption for TX per duty cycle

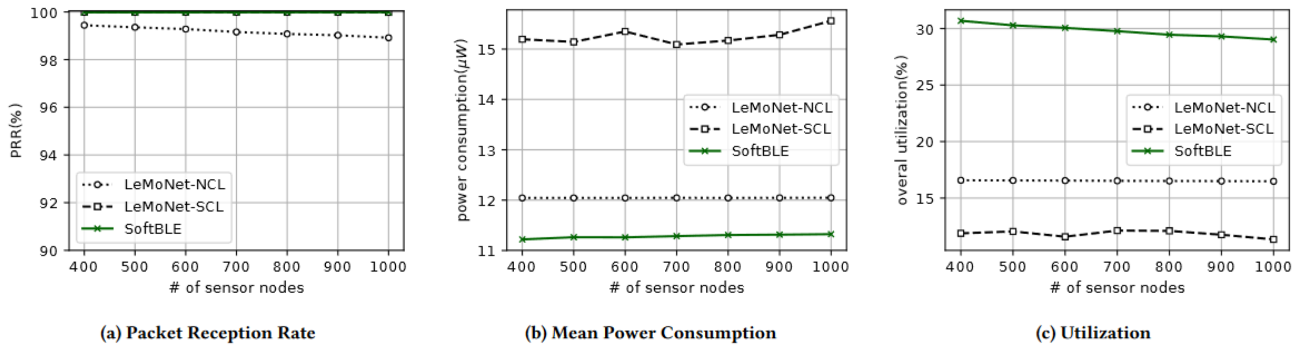
Simulation Study

- They also simulated a much larger network to test scalability:
  - Performance at Scale: How do 2500 sensors perform in network
  - Parameter Study: How do devices get configured in large networks
- See tradeoff in power and PER
- Notice how center sensors broadcast on 3 channels at low power and edge sensors broadcast on one channel at high power



Scalability + Duty Cycling Device

- SoftBLE scales very well
- Changing Duty Cycle (or how often data is pushed out) is able to be handled well by SoftBLE



igure 11: Effects of the number of sensors on the performance of SoftBLE. The sensors are deployed randomly in a $50m \times 5($
rea. Duty cycles of all sensors are set to 5s.

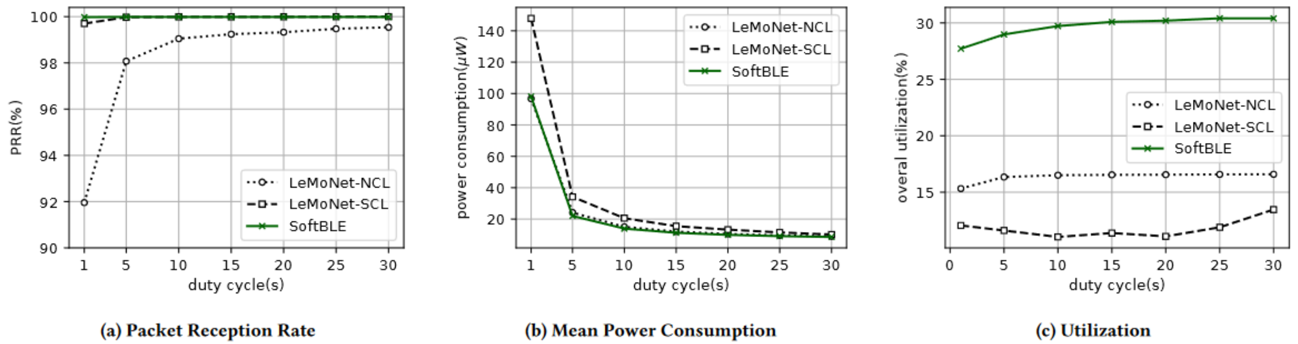


Figure 12: Effects of duty cycle on the performance of SoftBLE. 600 sensors are deployed randomly in a $50m \times 50m$ area.

Questions

- What if they worked on parameter tuning the advertising interval?
  - Could this lead to more efficiency or a lower PRR?
- How do you scale Gateways, since they are limited to 8 sensors per?
- Is it really necessary to choose the min-max algorithm or should gateways just choose channels that are not like their neighbor?