IoT with Multihop Connectivity

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Contents

Introduction

- **2008 - ZigBee based smart metering**
- **2010 - Smartphone based IoT**
- **2012 – Telcos such as AT&T, Verizon, USsprint started IoT services**
  - Smart Lighting
- **Home control market: growth of 60% per year**
- **Number of connected devices**
  - 2015 - 15 billions, 2020 – 50 billions forecasted by WSJ
- **[Multihop] Smart factory, environment monitoring, smart grid, price tagging**

Introduction

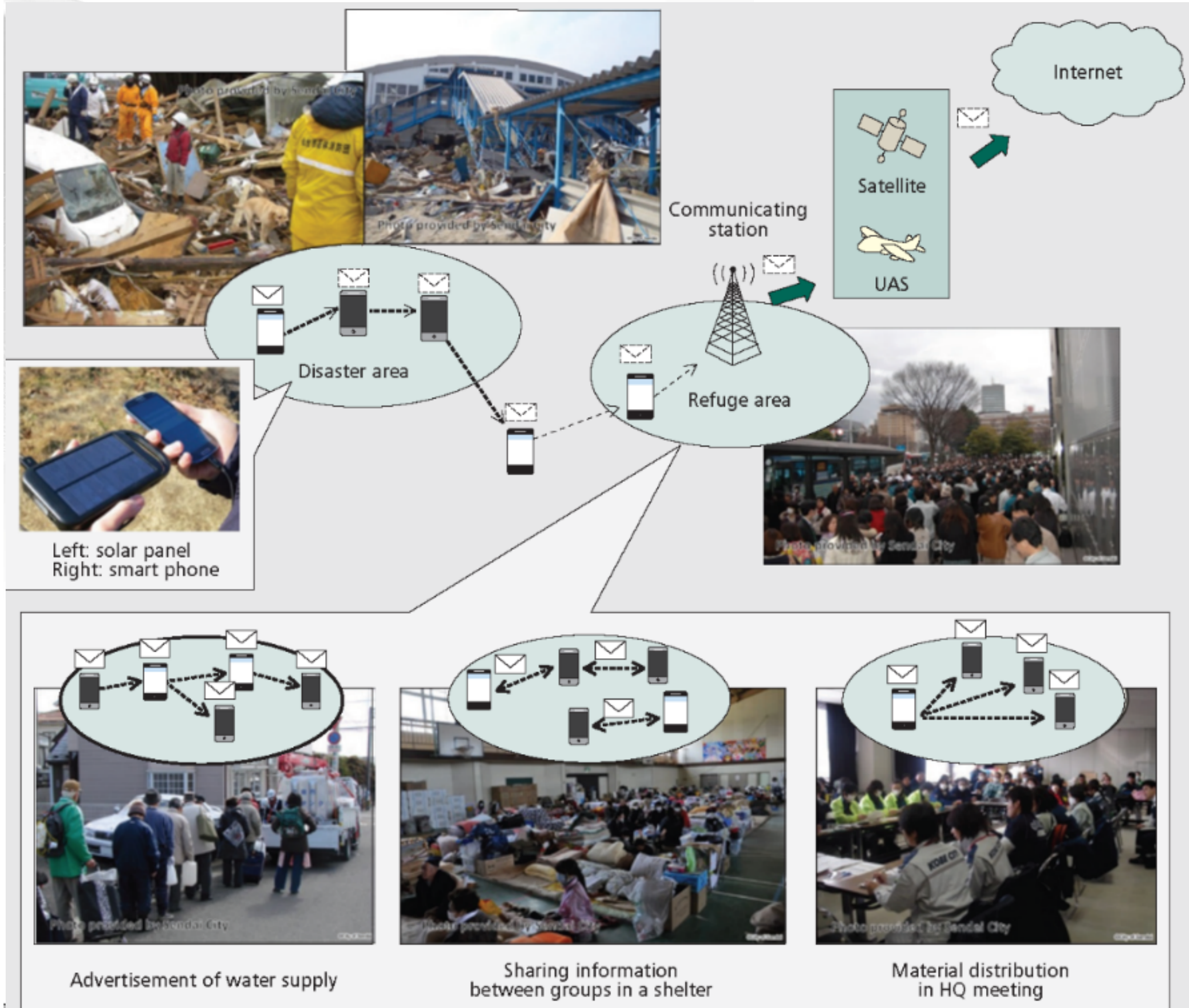
- **Internet of Things (IoT)**
  - Technical megatrend to provide Internet connectivity to resource constrained devices

- **Low power and Lossy Network (LLN)**
  - Wireless network with resource constrained devices
  - Candidate link layer protocols
    (**BLE, IEEE 802.15.4**, Z-wave …)

- **Routing Protocol for LLN (RPL)**
  - IPv6 routing protocol for LLN from IETF
  - Foundation to construct multi-hop LLN

Scenario of multi-hop D2D services

- **Disaster network**

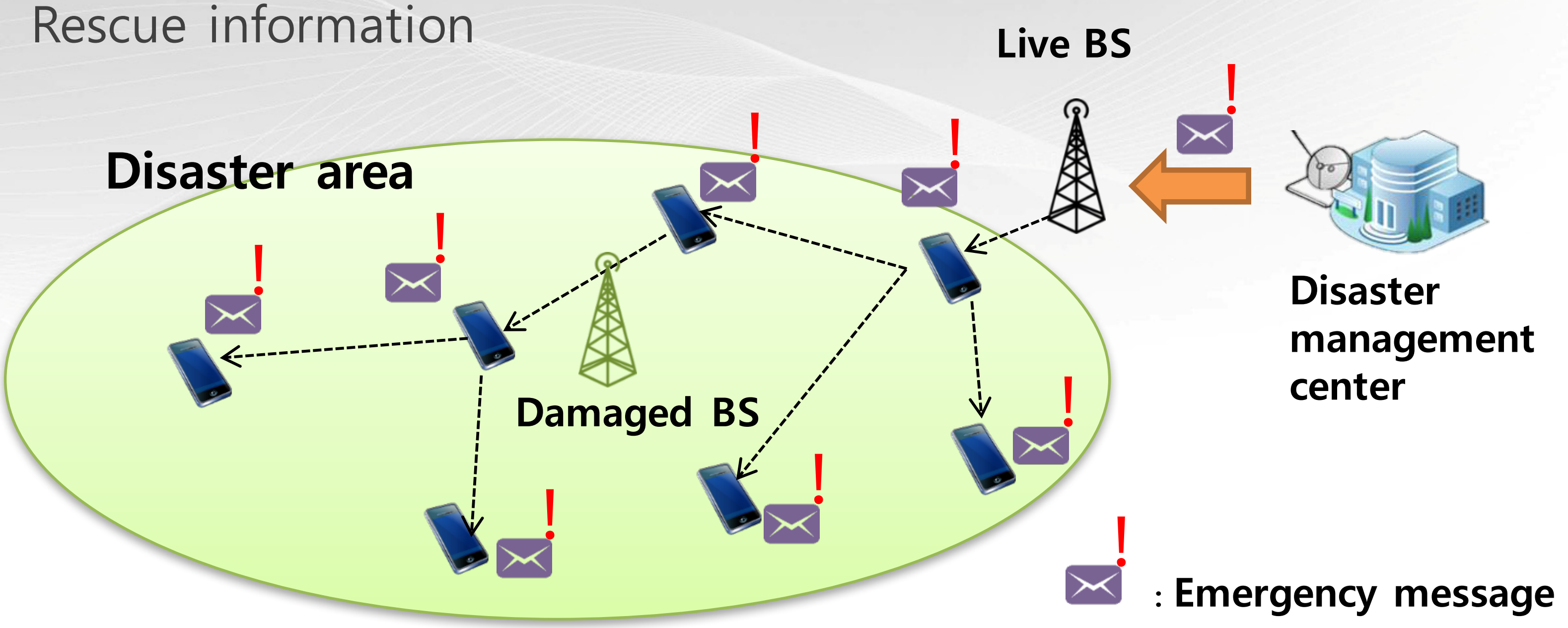


"D2D communications can be used for emergency information transmission and information exchange in a local area in a disaster area."

H. Nishiyama, M. Ito, and N. Kato, "Relay-by-Smartphone: Realizing Multihop Device-to-Device Communications", IEEE Communications Magazine, pp.56-65, Apr. 2014.

Example (2/2)

- **Disaster Communication**
  - In a disaster situation, the management center floods emergency messages related to disaster response.
    - Disaster state information
    - Rescue information



ZigBee

ZigBee and IEEE 802.15.4

- PHY layer remains as a major standard.
- Various MAC/Network protocols have been developed to replace ZigBee

IEEE 802.15.4 (PHY layer)

Modulation	O- QPSK, DSSS
Channel sensing	Clear channel accessment (CCA)
Data rate	256 kbps
Transmission power	< 1mW
Packet length	< 128 bytes
Bandwidth	2 MHz
Error check	CRC check

IEEE 802.15.4 (MAC layer)

Beacon mode

Superframe architecture
Duty cycle (superframe interval)
Hybrid MAC: CSMA and TDMA

Non- beacon mode

No duty cycle
CSMA

Network association

Association mechanism,
Orphan procedure

ZigBee (Network layer)

Address allocation

Distributed address allocation mechanism (DAAM),
Stochastic address allocation mechanism (SAAM)

Routing

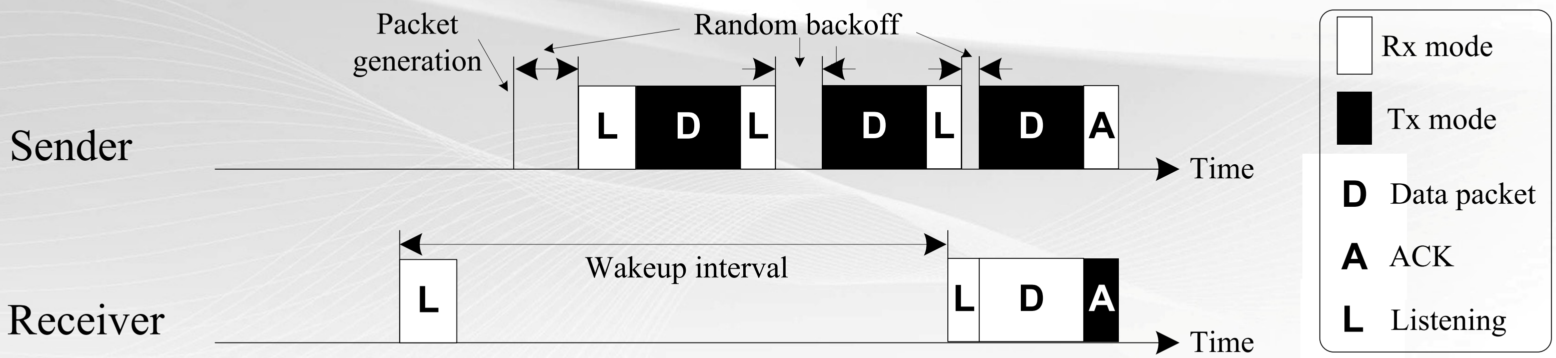
Tree- based hierarchical routing,
AODV
Passive ACK- based broadcast

Network association

Network discovery,
Parent selection,
Device type selection

MAC protocol over IEEE 802.15.4 PHY (1/2)

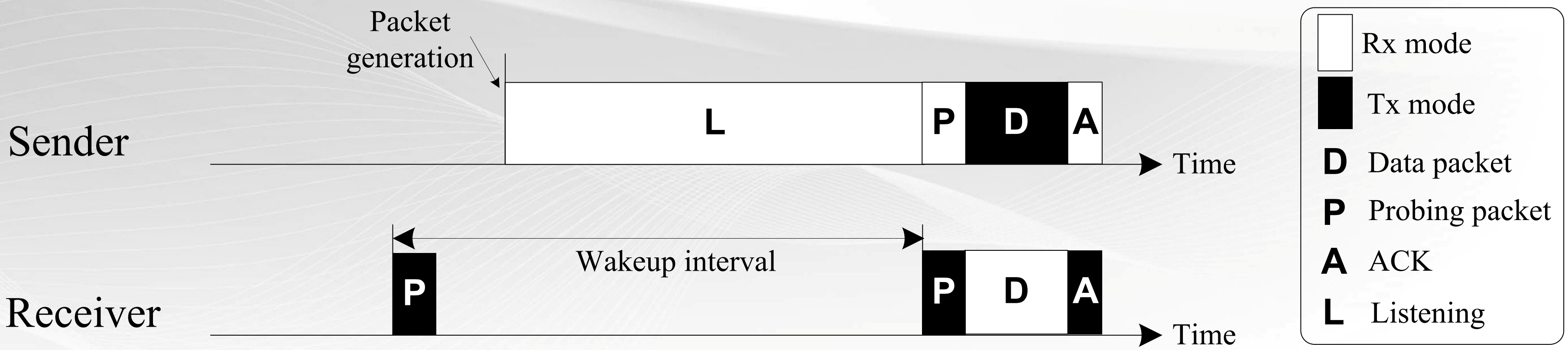
- **Low Power Listening (sender-initiated asynchronous MAC)**
  - B-MAC [SenSys'04], X-MAC [SenSys'06], BoX-MAC-2 [Stanford'08]



- **Approach 1: To solve congestion problem**
  - Burst forwarding [SenSys'11]: Consecutive transmission of all packets
- **Approach 2: To avoid false wake-up due to interference**
  - AEDP [IPSN'13]: Energy detection threshold adaptation
  - ZiSense [SenSys'14]: Interference detection by signal characteristics

MAC protocol over IEEE 802.15.4 PHY (2/2)

- **Low Power Probing (receiver-initiated asynchronous MAC)**
  - RI-MAC [SenSys'08], A-MAC [SenSys'10]

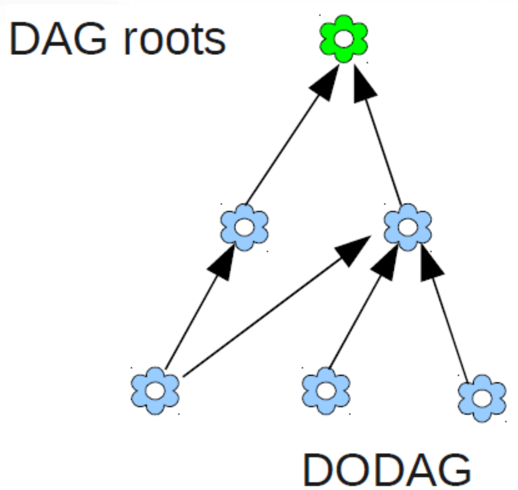


- **To avoid packet collision**
  - Strawman [IPSN'12]: Packet length-based best sender selection
  - Stairs [INFOCOM'14]: Improvement of Strawman (sender scheduling)
  - CD-MAC [SECON'15]: Packet timing-based sender scheduling

RPL over IEEE 802.15.4 PHY [2012] (1/2)

- ***de-facto* IETF standard (bi-directional, IPv6)**
- **RANK**
  - End-to-end Expected transmission count (ETX) toward the root
- **DODAG Information Object (DIO)**
  - Broadcasting message which contains routing information including RANK

→ Each node exchanges **routing information** with **DIO message,** and constructs **DODAG toward the root**



Destination-Oriented Directed Acyclic Graph (DODAG)

RPL over IEEE 802.15.4 PHY (2/2)

- **Key metrics**
  - $RANK(k) = Hop(k) + 1$, propagated via DIO message broadcast
  - $ETX(k, p_k) = \frac{\#\ of\ total\ tx.(k \rightarrow p_k)}{\#\ of\ succesful\ tx.(k \rightarrow p_k)}$, measured by child node k
- **Parent selection mechanism**
  - Parent candidate: $RANK(p_k) < RANK(k)$ and $ETX(k, p_k) < \delta$
  - Routing metric: $R(p_k) = RANK(p_k) + ETX(k, p_k)$
  - Best parent candidate: smallest $R(p_k)$
  - Parent change condition: significantly smaller $R(p_k)$ found
- **DIO broadcast period – Trickle Timer**
  - Low overhead: Double the period after every DIO transmission
  - Fast route recovery: Reset the period to the minimum when inconsistency is detected.

Network protocols over IEEE 802.15.4 PHY

- **RPL [2012]: *de-facto* IETF standard (bidirectional)**
  - Upward route optimization using RANK and link layer ETX
  - Downward route is **simply the reverse of upward route**
- **CTP [SenSys'09]: *de-facto* uplink routing protocol**
  - HELLO tx. period control via Trickle Timer (Low overhead and fast recovery)
  - Upward route optimization using end-to-end ETX
- **LOADng [2015]: IETF draft (Lightweight AODV)**
  - Only the destination is permitted to respond to a Route_REQuest
  - No intermediate Route_REPly nor unnecessary RREP
  - No precursor list maintained at routers

*** QU-RPL [SECON'15]: RPL variant**

- Traffic load or queue utilization-based (multi-)parent selection

*** MarketNet [SenSys'15]: RPL variant**

- Direct transmission by using high powered gateway

MarketNet

H. Kim, H. Cho, M. Lee, J. Paek, J. Ko, and S. Bahk
MarketNet: An Asymmetric Transmission Power-based Wireless System for Managing e-Price Tags in Markets, ACM SenSys 2015.

Price tag management

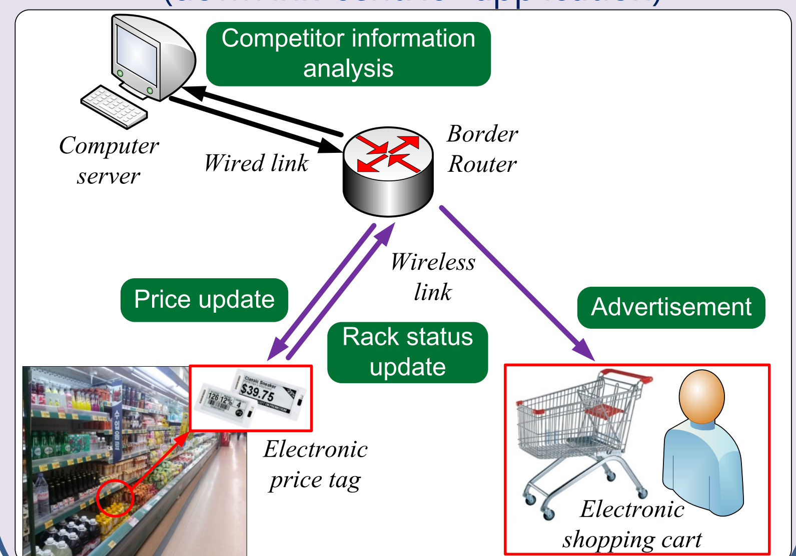
Various information

High density

Frequent update
(competitors, freshness, event)

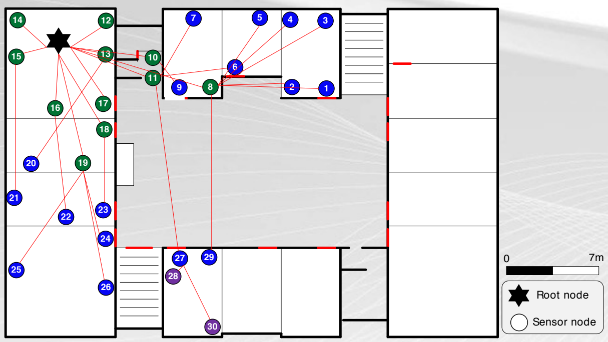
Manual update
(**labor cost**)

IoT-based automatic wireless update
(downlink-centric application)

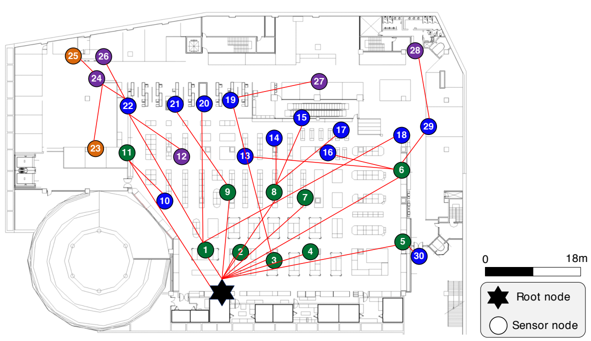


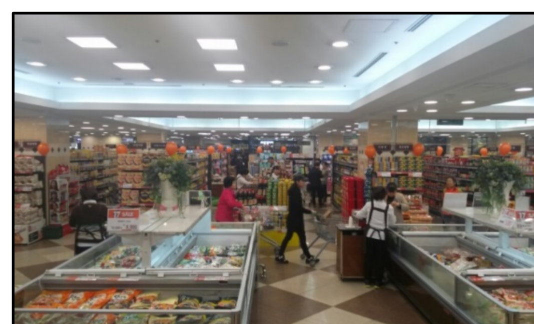
Real-world experiments

- Testbed construction (30 nodes, an indoor office building)



- Field deployment (30 nodes, an urban crowded market place)



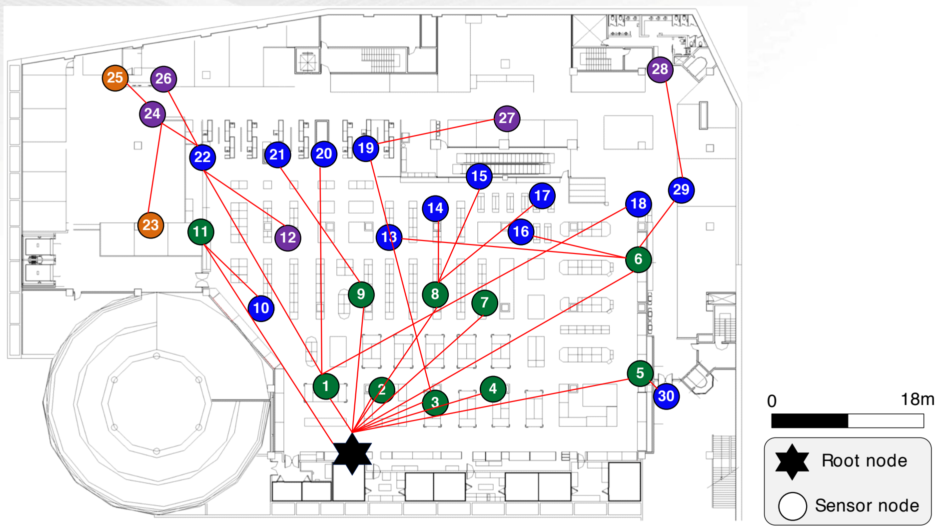


Our approach: Multi-hop LLN

- **Differentiation**
  - Vs. Conventional low power and lossy network (LLN)
    - Downlink centric application
    - Measurement study in a real-world crowded market place
  - Vs. Automatic price update with many single hop networks
    - Easy deployment (single gateway preferred)
- **Baseline protocol**
  - Transport layer: UDP
  - Routing layer: IETF Routing protocol for LLN (RPL)
  - MAC layer: Low power listening (LPL)
  - PHY layer: IEEE 802.15.4

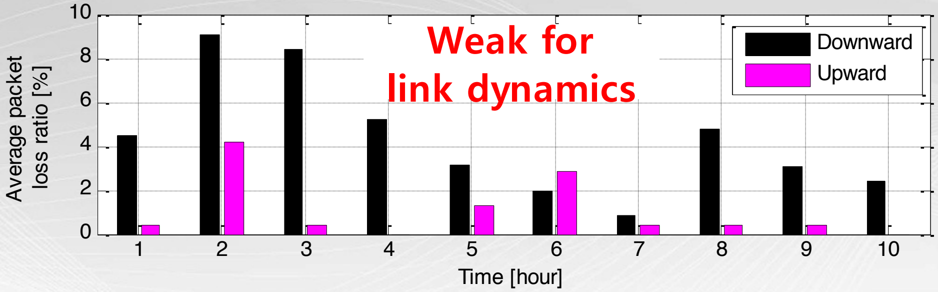
Experiment field – Urban market place

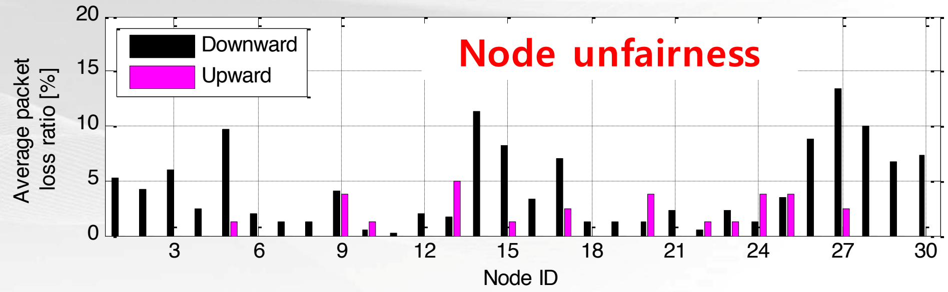
- >10k items, >5,000 customers/day, day time (11AM~9PM)
- 30 nodes, Tx. Power = -15 dBm/10dBm, Sleep interval = 2s
- Downward pac. interval = 90s, upward pac. interval = 450s



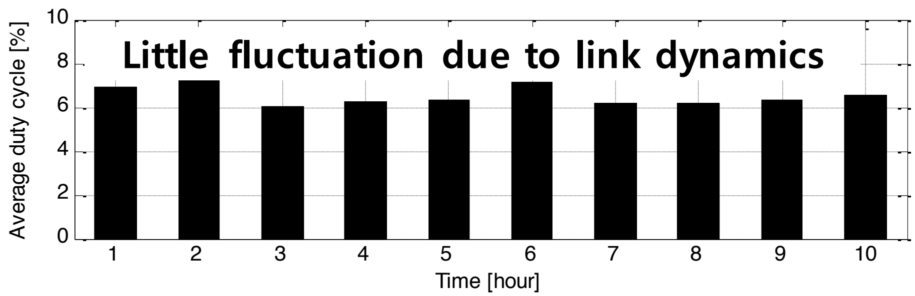
Motivation – Performance of RPL+LPL

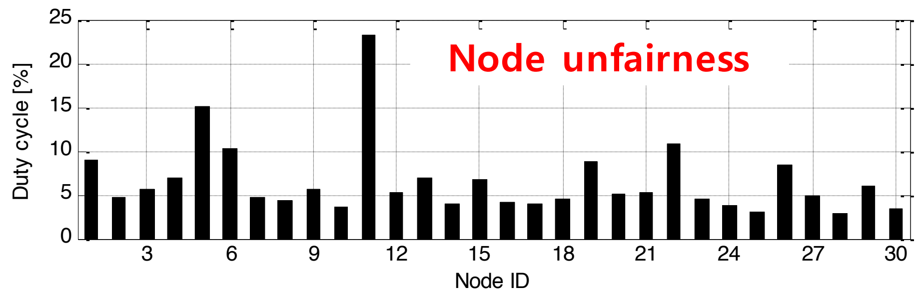
- Packet delivery performance (Downlink performance < Uplink performance)





- Energy consumption (severe unfairness among nodes)



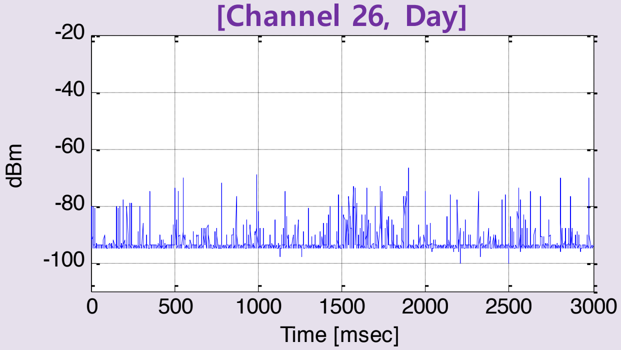


Motivation – Link characteristics

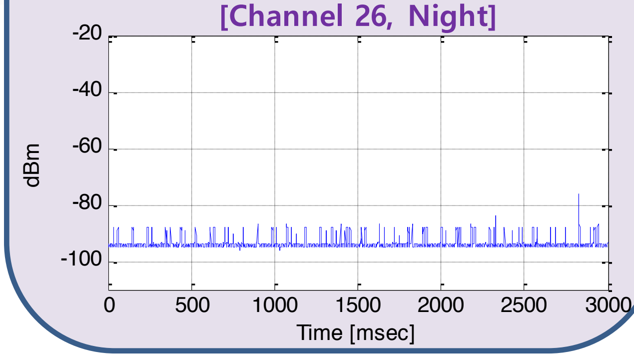
WiFi interference

WiFi occupies all 2.4 GHz bands in Korea

[Channel 26, Day]



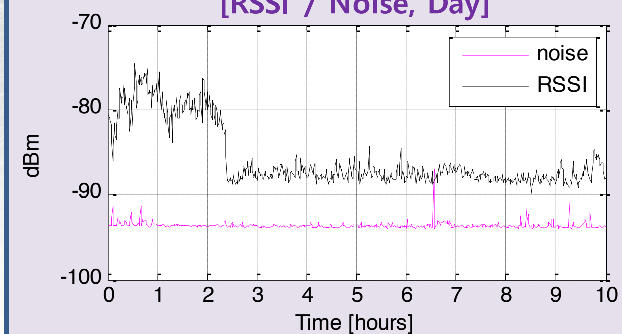
[Channel 26, Night]



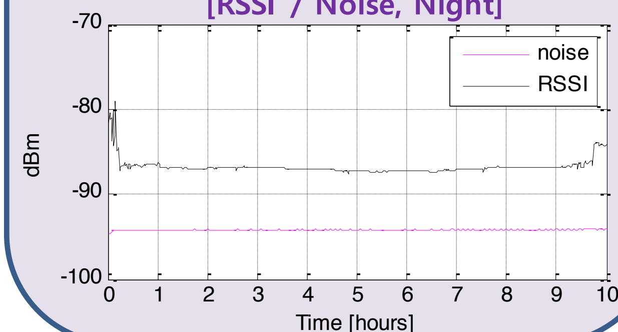
Human activity

Short term variance: Movement & WiFi
Long term variance: Item refilling events

[RSSI / Noise, Day]

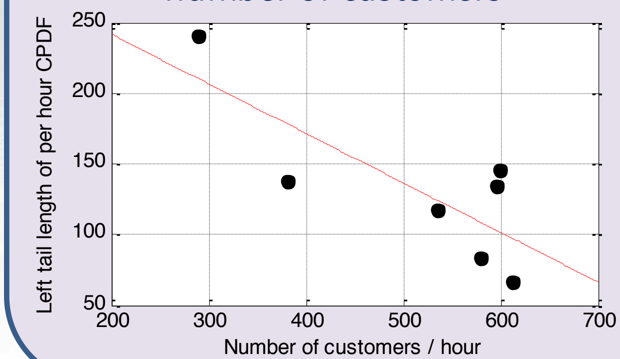


[RSSI / Noise, Night]



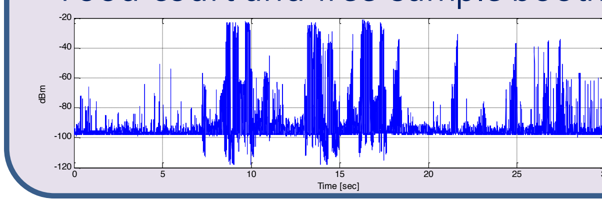
Dynamic link burstiness

Positive burstiness decreases with the number of customers



Microwave oven

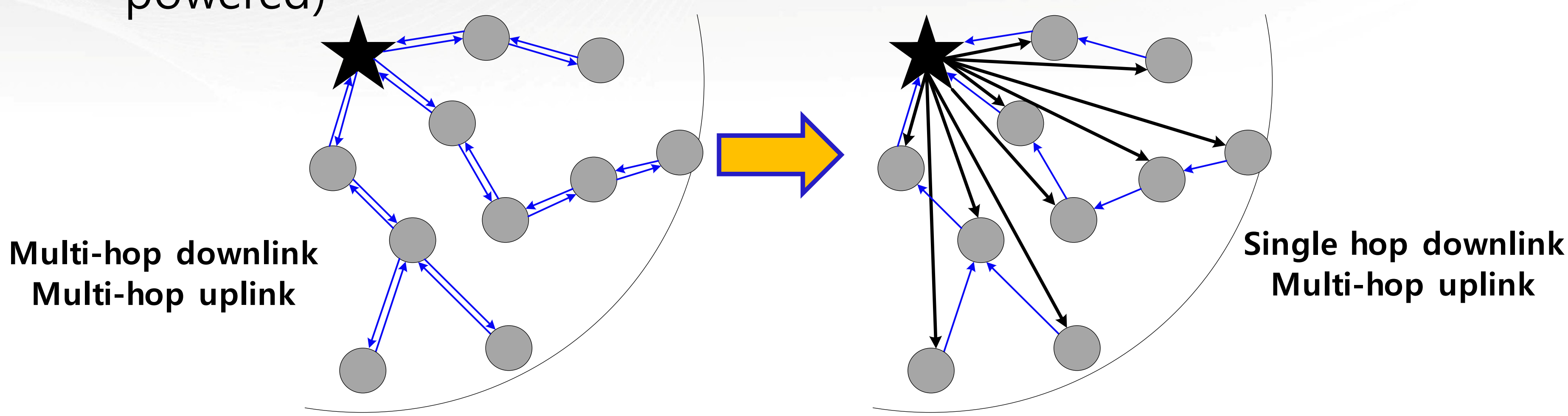
Food court and free-sample booth



Baseline of our approach – APN

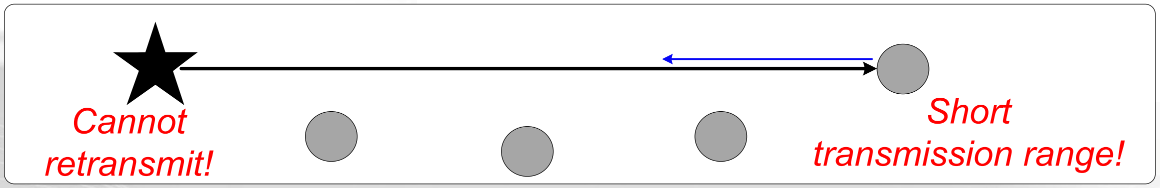
- **Challenges**
  - Market place has dynamic link characteristics
  - RPL focuses on upward packet delivery and shows bad downlink performance
- **How about removing downward routing rather than improving it?**
  - High power root (wall-powered) and low power nodes (battery-powered)

Asymmetric transmission **P**ower-based **N**etwork



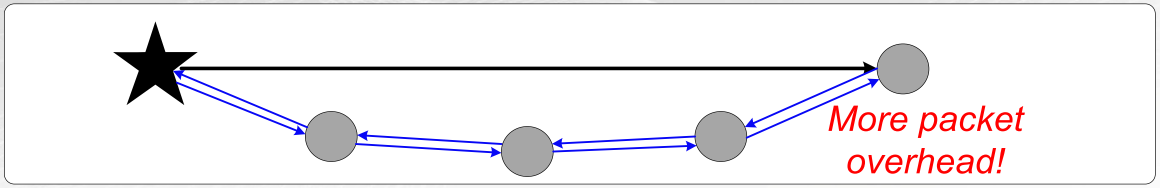
Our approach for MarketNet – SHDP

- **Problem of APN 1: Low power nodes cannot transmit ACK to the root**

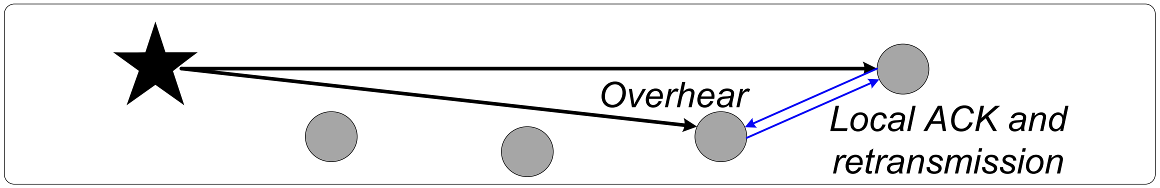


Single
Hop
Downlink
Protocol

- **Problem of APN 2: Multi-hop ACK delivery increases packet overhead**



- **Our solution (SHDP): Local ACK and local retransmission**



Our approach for MarketNet – NSA

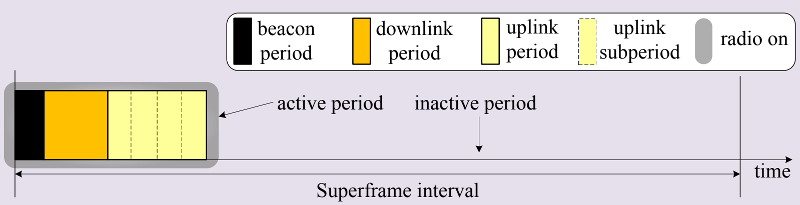
- **Problem of SHDP: Lack of spatial reuse due to high power signal from root**

Network-wide
Superframe
Architecture

- **Our solution (NSA): Network-wide synchronization with high power root**

Network-wide superframe structure

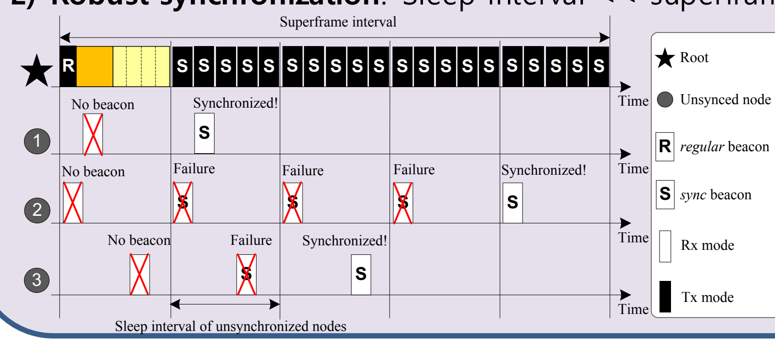
1) **Low tx. Overhead:** No repetitive tx. as LPL using synchronous MAC
2) **Spatial reuse:** Up/downlink Separation in a TDD manner
3) **Collision avoidance in uplink period:** Uplink period partitioning



All nodes in the network shares a single superframe
Only high power root transmits beacon

(Initial) synchronization mechanism

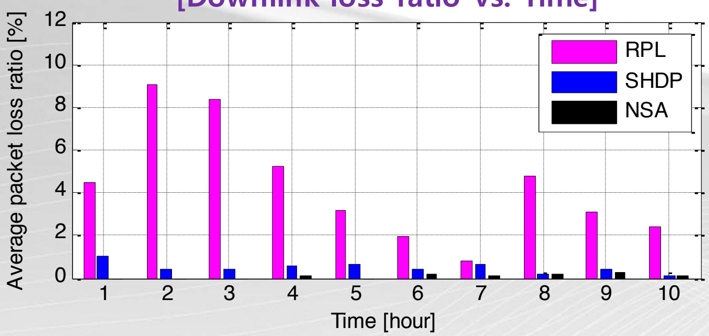
1) **Low tx. overhead:** Only root node transmits sync beacon
2) **Robust synchronization**: Sleep interval << superframe interval



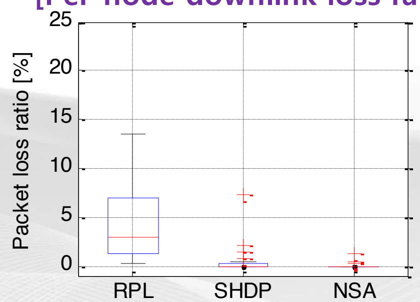
Field test – Packet delivery performance

- SHDP and NSA significantly improve downlink performance

[Downlink loss ratio vs. Time]



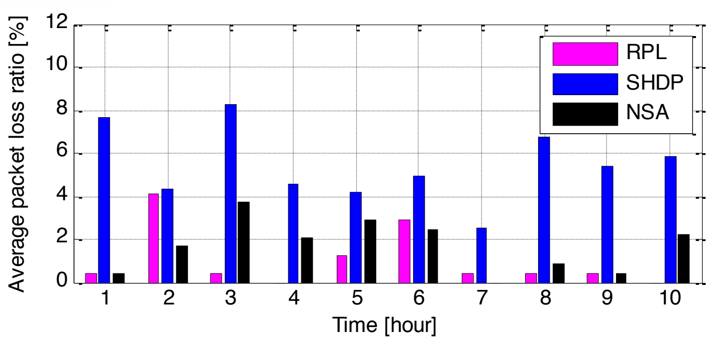
[Per node downlink loss ratio]



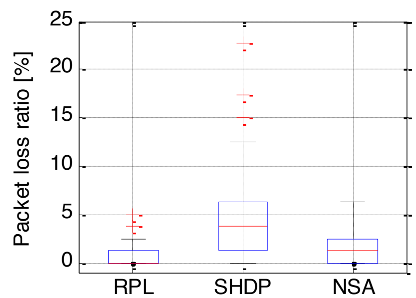
Average PRR: 99.9%
PRR for the worst node: 98.7%

- NSA provides uplink performance better than SHDP and comparable to RPL

[Uplink loss ratio vs. Time]



[Per node uplink loss ratio]

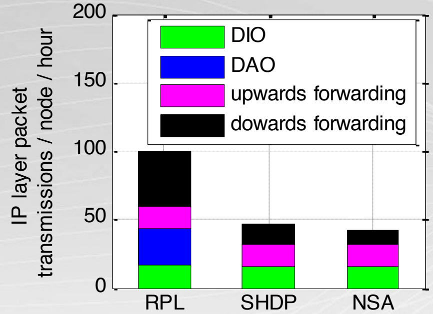


Average PRR: 98.3%
PRR for the worst node: 93.8%

Field test – Energy consumption

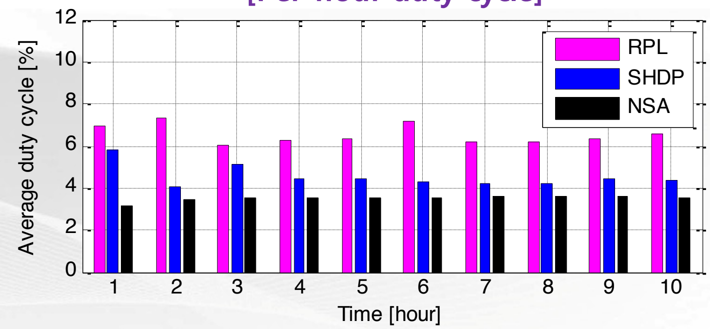
- Lower duty cycle (3.5%, lifetime of 3 months using AA battery)

[Transmission overhead]



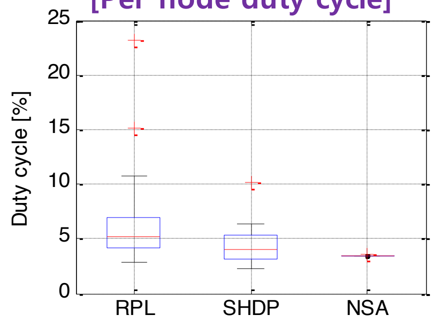
Low transmission overhead results in low energy consumption

[Per hour duty cycle]

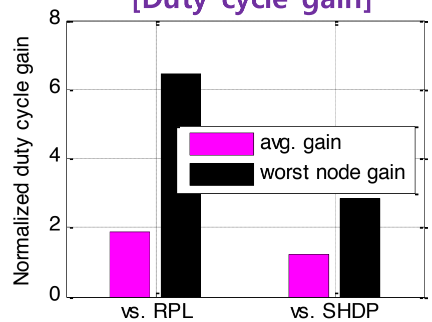


- Fairer duty cycle (100% fairness)

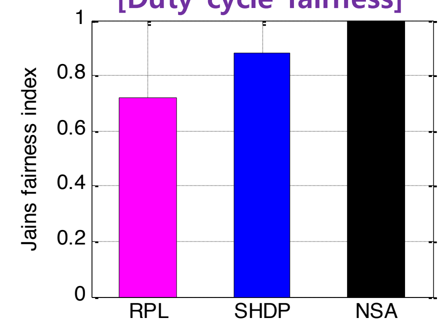
[Per node duty cycle]



[Duty cycle gain]



[Duty cycle fairness]



RPL over BLE

T. Lee, M. Lee, H. Kim, and S. Bahk,
“A synergistic architecture for RPL over BLE”, to appear in IEEE SECON 2016

BLE vs. IEEE 802.15.4

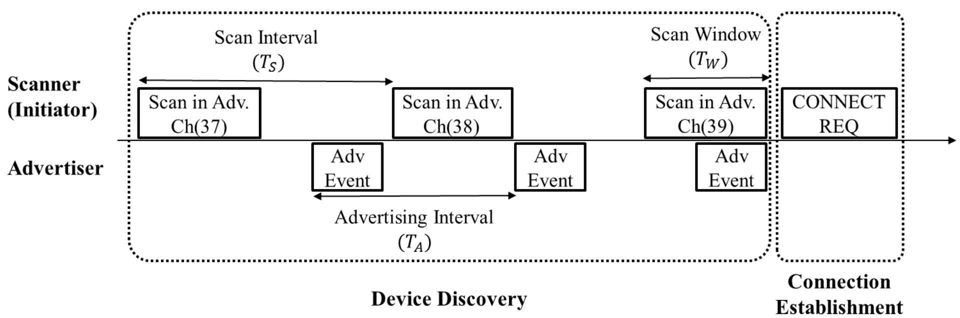
- **PHY rate**
  - BLE : 1Mbps
  - IEEE 802.15.4 : 250kbps
- **Packet delivery**
  - BLE : Synchronous MAC with a connection
  - IEEE 802.15.4 : Asynchronous MAC without a connection
- **Interference avoidance**
  - BLE : Adaptive frequency hopping
  - IEEE 802.15.4 : None
- **Accessibility & Usability**
  - BLE : Contained within today's smart phone
  - IEEE 802.15.4 : None

Characteristics of BLE

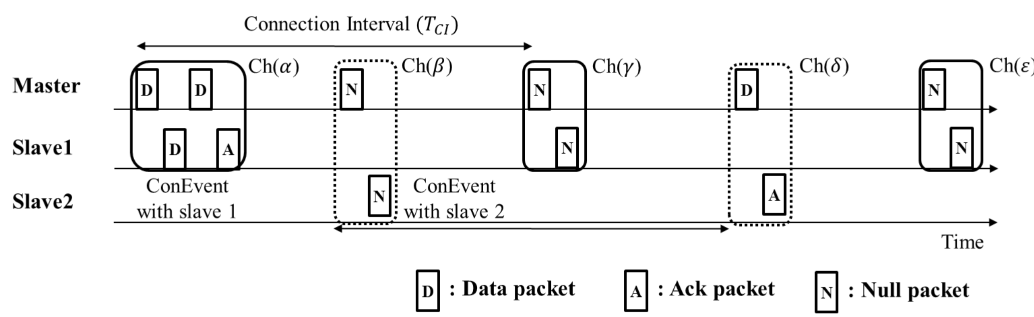
- **2.4Ghz ISM band**
  - 40 channels with 2Mhz bandwidth (3 advertising, 37 data channels)
- **Implemented on smart phones**
  - Advantage compared to other low power devices (such as Zigbee, Z-wave)
- **Low energy consumption compared to classic Bluetooth**
  - Simple connection setup → Low connection setup latency (Classic: 100msec, BLE: 3msec)
  - Low data rate (Classic:1~3Mbps, BLE: 1Mbps)
  - Low Tx power (Maximum output power- Classic: 100mW, BLE: 10mW)

BLE link layer operations

- **Advertising channel**
  - **Asynchronous** data exchange with **Advertising & Scanning**
  - **Connection establishment**
- **Data channel**
  - **Synchronous** data exchange with **Connection Event**
  - Interference mitigation with **frequency hopping**
  - Connection Event **scheduling with multiple slave nodes**



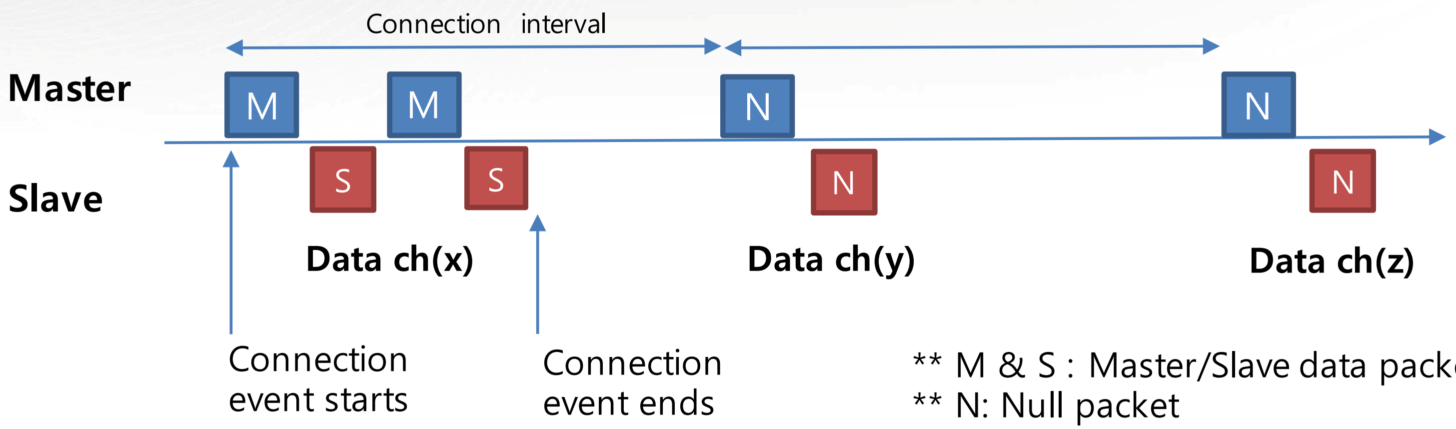
Advertising channel



Data channel

BLE Data transmission & Connection maintenance

- **Two cases of connection event termination**
  - Two consecutive CRC check error
  - No more data to send
- Supervision Time out & null packet transmission
- Channel hopping with every connection interval (7.5msec ~ 4sec)



** M & S : Master/Slave data packet
** N: Null packet

BLE mesh network

- **Three candidates of BLE mesh networks**

Flooding in advertising channel

- CSR (Qualcomm 2015)
- Simple solution for small networks
- Not scalable (Latency & traffic load)
- MAC layer modification is needed for reliability and energy efficiency of data transmission
- Waste of 37data channels

Routing in advertising channel

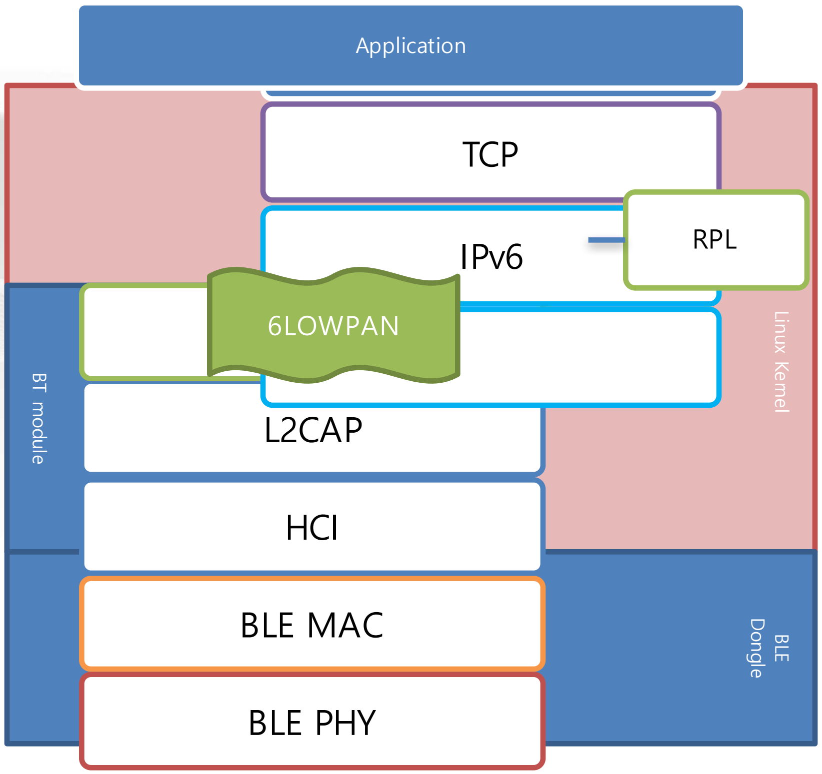
- NXP semiconductor & Broadcom
- Scalable compared to Flooding
- More Flash and RAM compared to Flooding
- MAC layer modification is needed for reliability and energy efficiency of data transmission
- Waste of 37data channels

Routing in data channel

- Silicon Labs
- Scalable compared to the other candidates
- No MAC layer modification for reliability and energy efficiency of data transmission
- Compatible with 6lowpan and IPv6
- More Flash and RAM compared to the other candidates

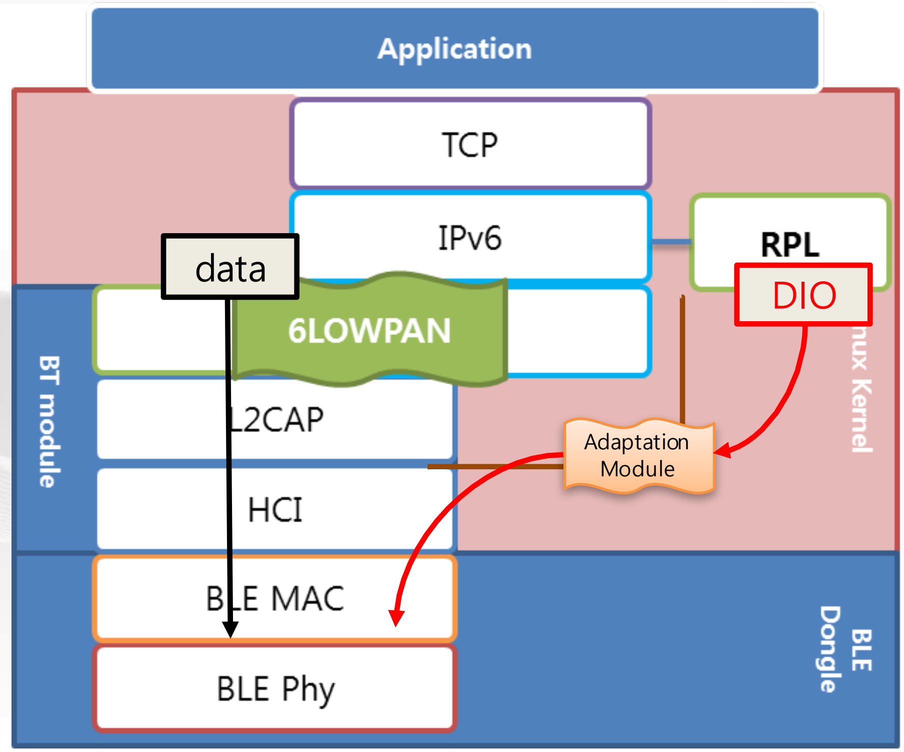
BLE multi-hop routing in data channel

- **Bluetooth 6lowpan**
  - IP header compression
  - Master-slave connection based
- **Linux RPL**
  - RFC 6550 from IETF
  - not standard code (Contiki RPL modified by João in IETF ROLL)



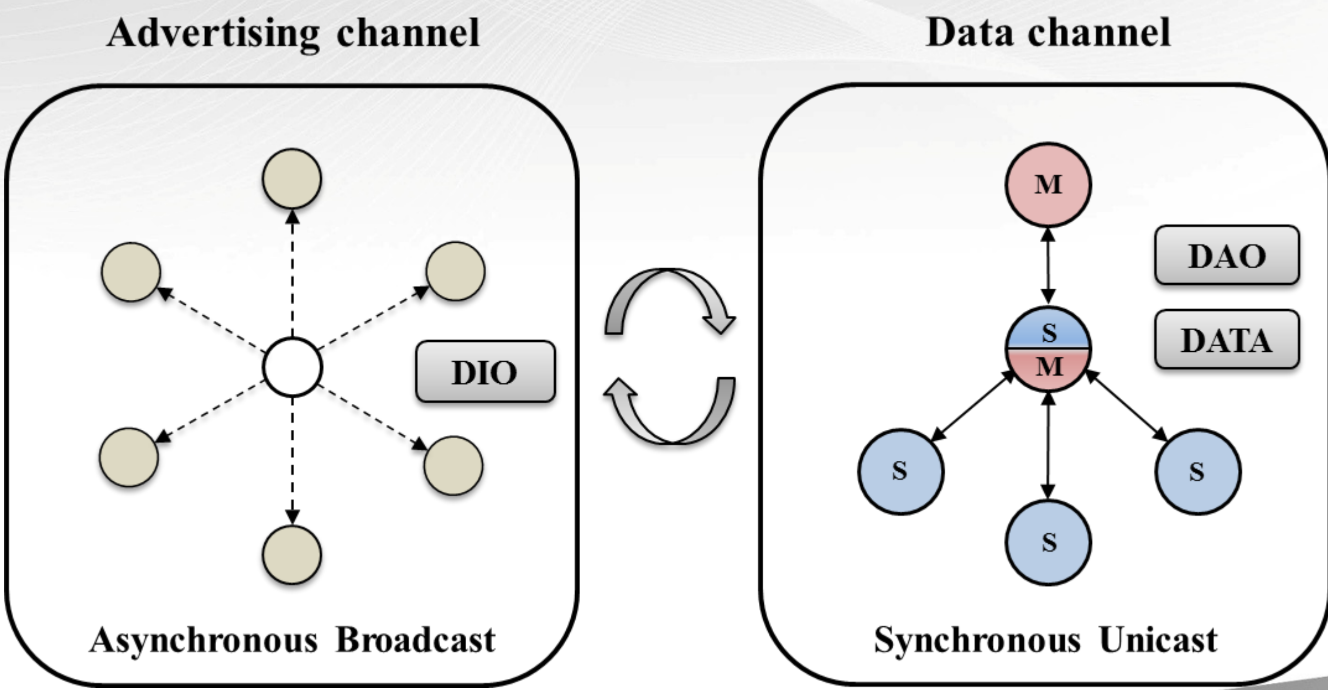
Implementation Issues

- **Data packet transmission**
  → Data channel
- **RPL control packet transmission**
  → Advertising channel
  - BLE 6LoWPAN layer only provides connection-based links.
  - RPL control frame cannot be transmitted via BLE 6LoWPAN module
    → New adaptation layer supporting HCI advertisement for RPL control frames



Design : RPL over BLE

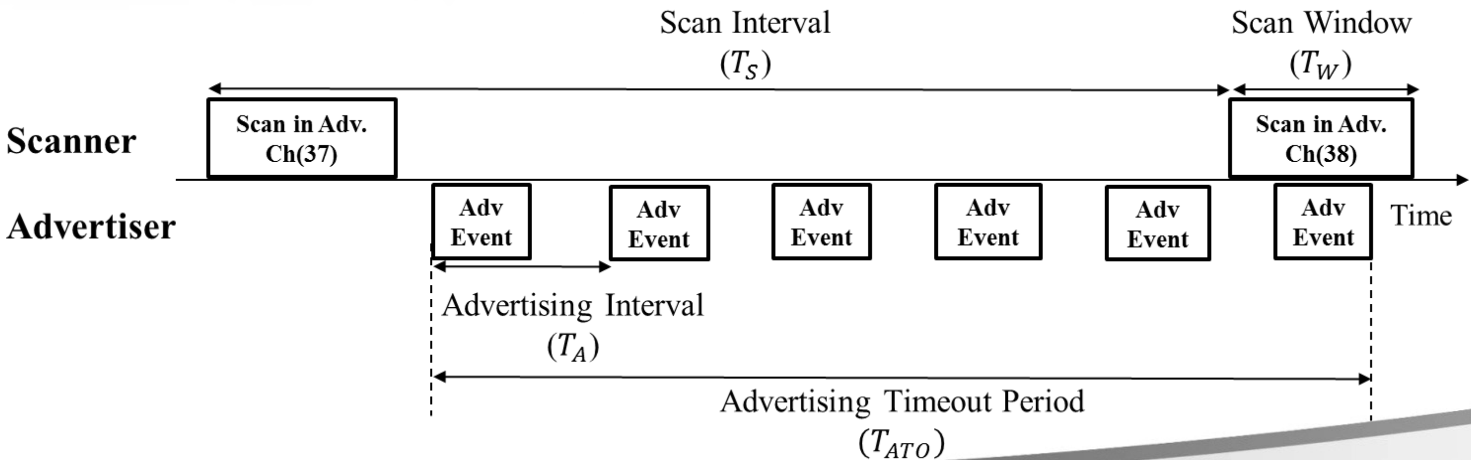
- **DIO message exchange in Advertising channel**
  - **Asynchronous** Broadcast
- **Data exchange in data channel**
  - **Synchronous** unicast



Design issue1: DIO broadcast over advertising channel

- **Parameters about asynchronous data exchange in advertising channel**
  - Scan Interval (T_S), Scan Window (T_W), Advertising timeout period (T_{ATO}), Advertising Interval (T_A)
- **Parameter tuning for reliable and energy-efficient DIO exchange**
  - **Condition for reliable DIO exchange**: $T_{ATO} \geq T_S$, $T_A \leq T_W$
  - **Objective function** (power consumption of BLE node for DIO exchange)

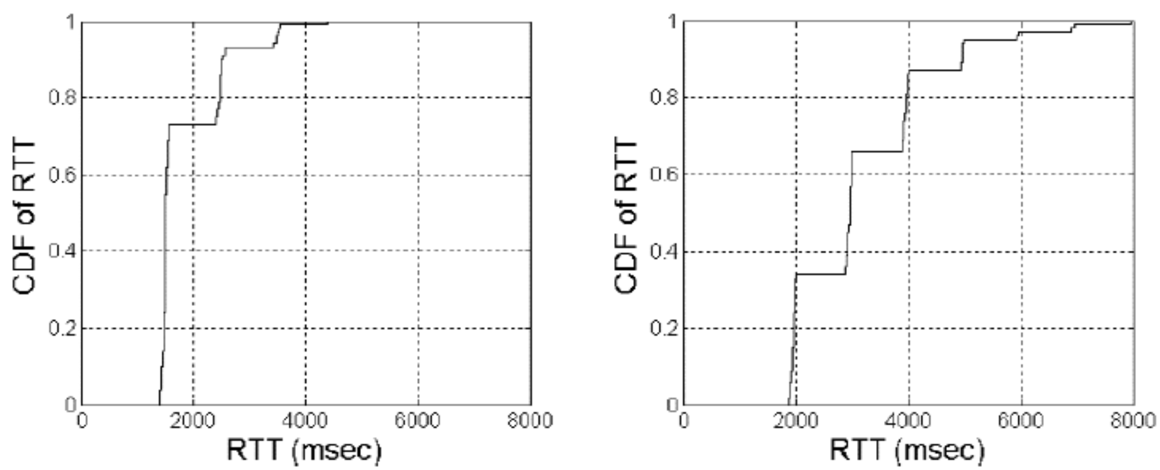
$$P = \left(\frac{T_W}{T_S}\right) I_s V + \left(\frac{3T_a T_{ATO}}{T_A} \times \frac{1}{T_{DIO}}\right) I_a V$$



Design issue2: Routing metric

- **Conventional routing metric for RPL over 802.15.4**
  - End-to-End ETX (expected transmission count)
    → **BLE link layer** does **not provide this information** to upper layer.

- **Routing metric for RPL over BLE**
  - In BLE link layer, each packet **retransmission increases RTT** by one Connection Interval
  - End-to-End **ECI** (Expected number of Connection Interval)
    → we can infer the ECI value from RTT of ping packet



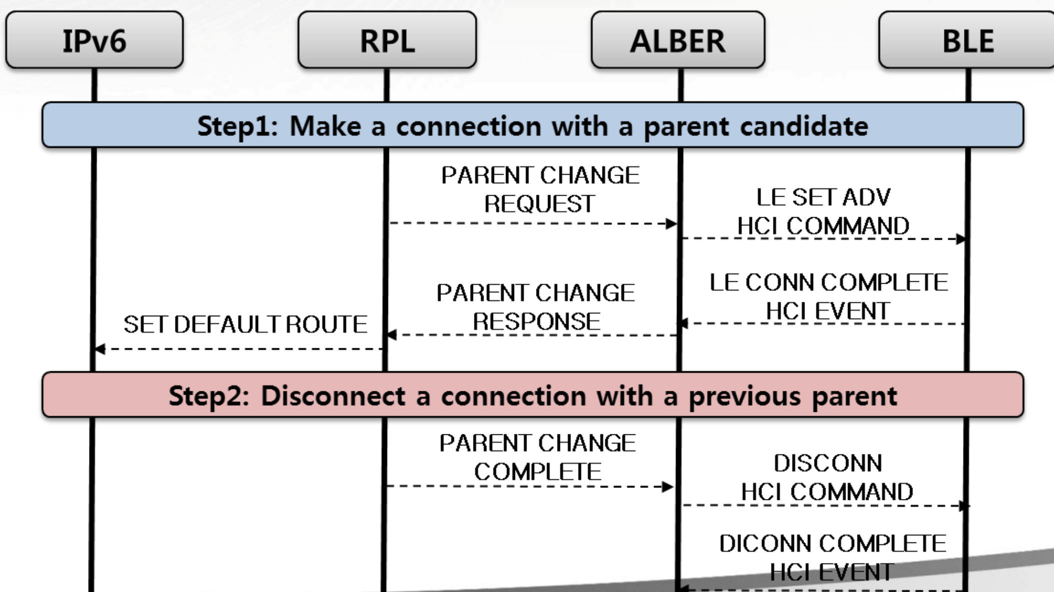
(a) LOS link with 10 m distance (b) NLOS link with 10 m distance

Design issue3: Parent change with BLE connection management

- **Parent change in RPL over 802.15.4**
  - No connection between child and parent nodes
  - Just modify routing table.

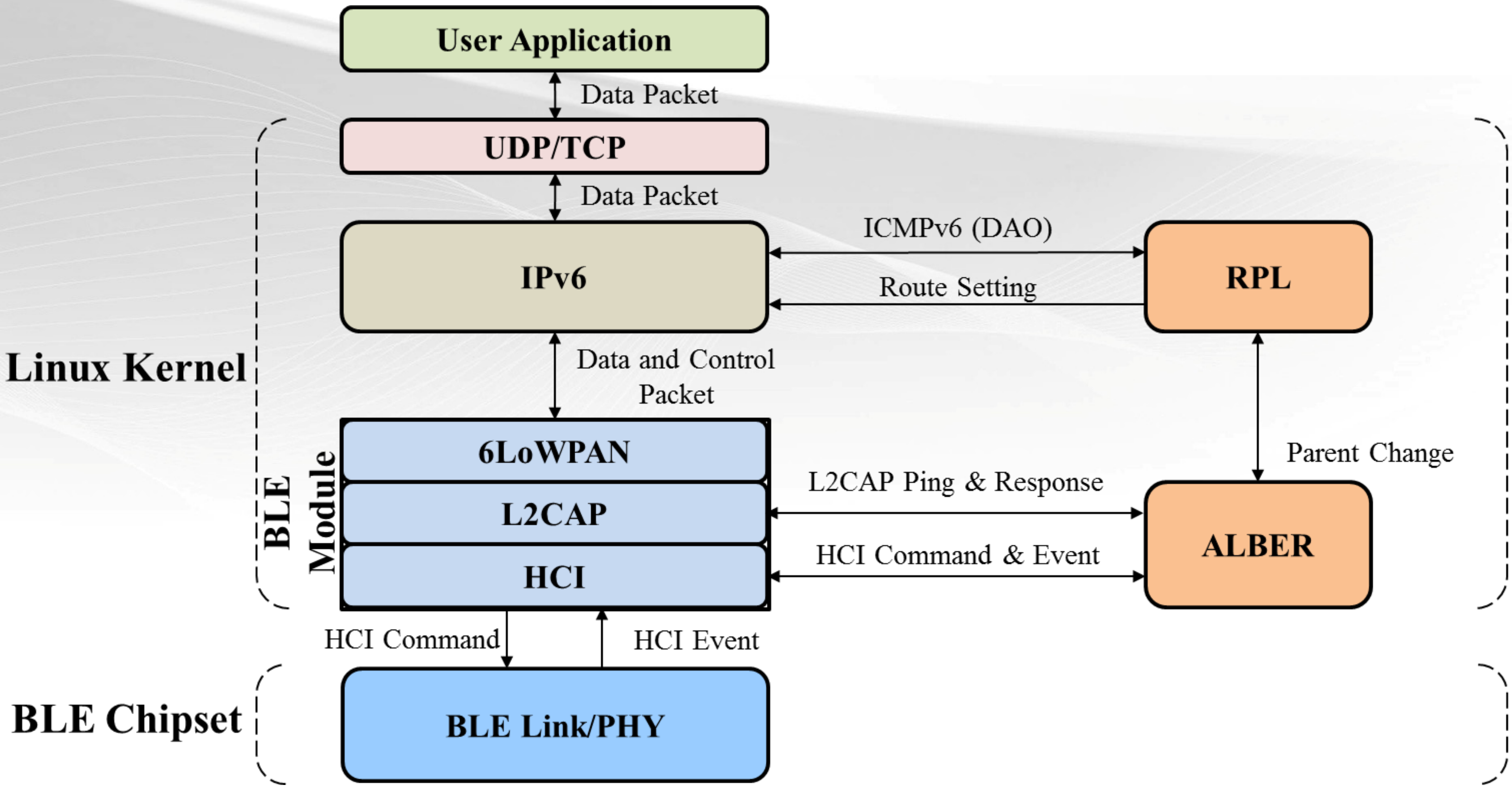
  → In RPL over BLE, parent change without considering connection management incurs **packet loss** in 6lowpan layer.

- **Parent change in RPL over BLE**
  - Adaptation Layer BLE and RPL (ALBER) controls seamless parent change.



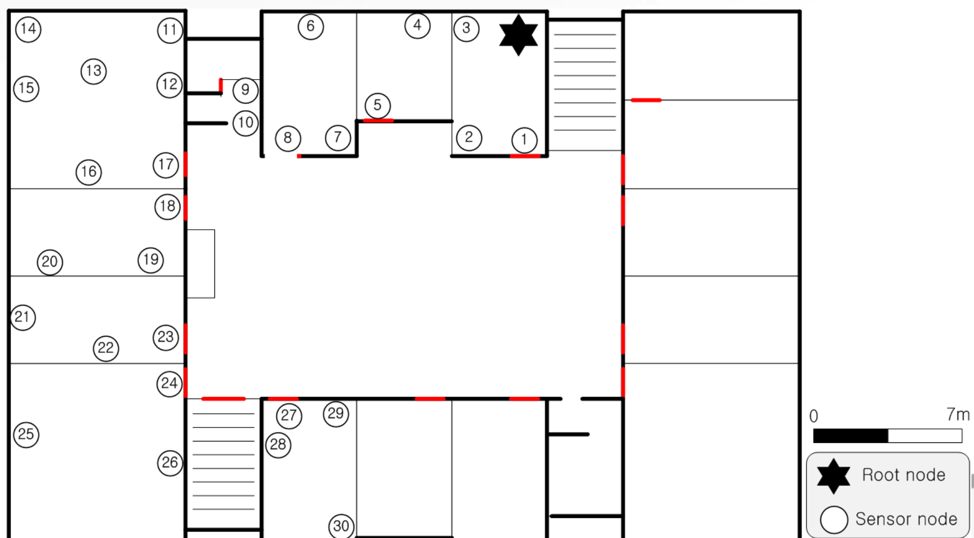
Overall structure of RPL over BLE

- **Protocol stack of RPL over BLE including ALBER**



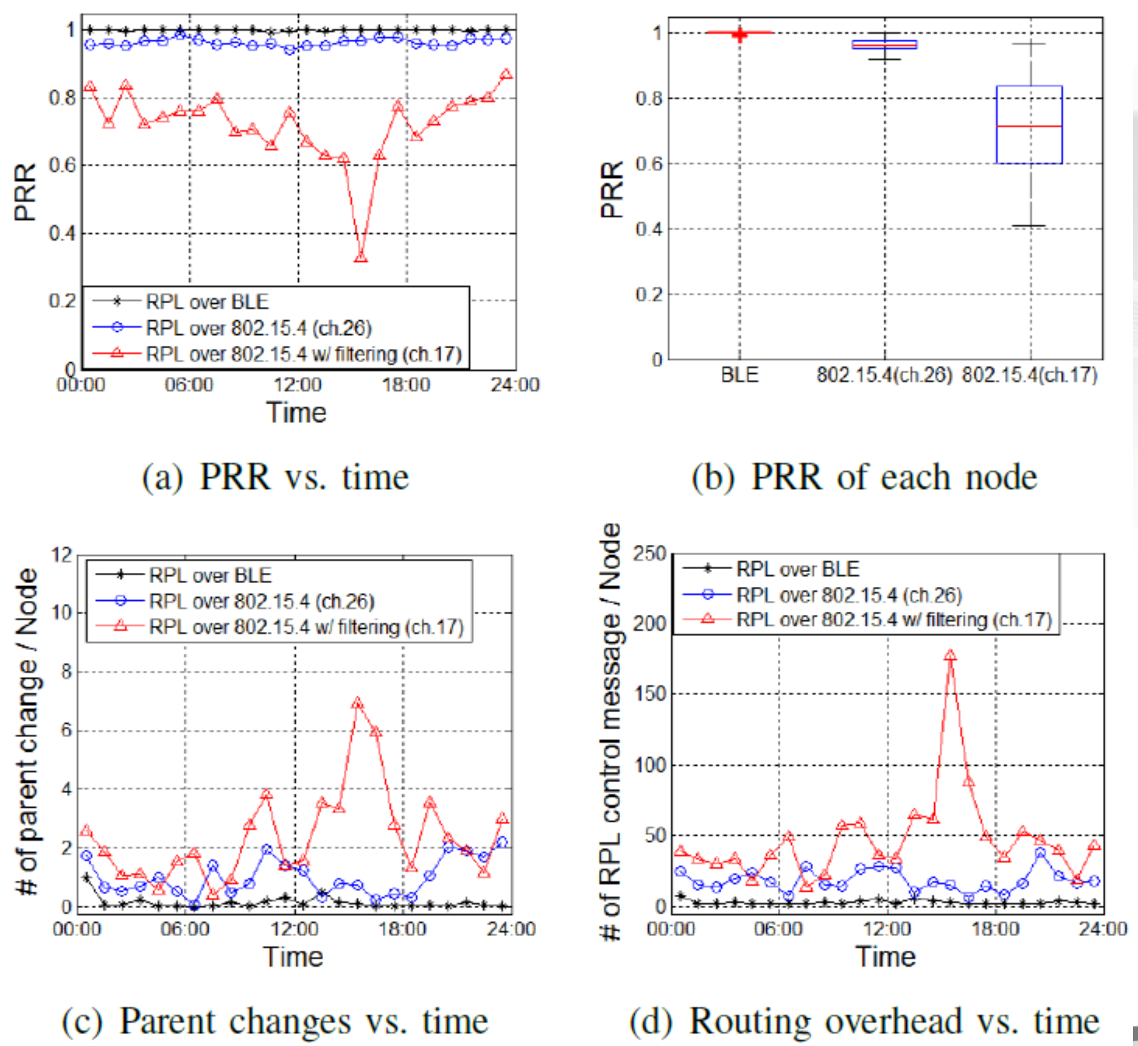
Performance evaluation: Testbed setup

- **Testbed topology**
  - Indoor office environment
  - 31 nodes (30 leaf nodes, 1 root node)
- **Node setup**
  - IEEE 802.15.4 : TelosB with MSP430 microcontroller and CC2420 radio (ContikiRPL and ContikiMAC)
  - BLE : Raspberry Pi device with Linux kernel 3.17 and BCM4356 BLE chipset (Modified ContikiRPL for RPL over BLE)



Performance Comparison against 802.15.4 (1/2)

- **Impact of link dynamics**
  (packet interval = 5minutes/packet/node, duration= 24hours)



(a) PRR vs. time

(b) PRR of each node

(c) Parent changes vs. time

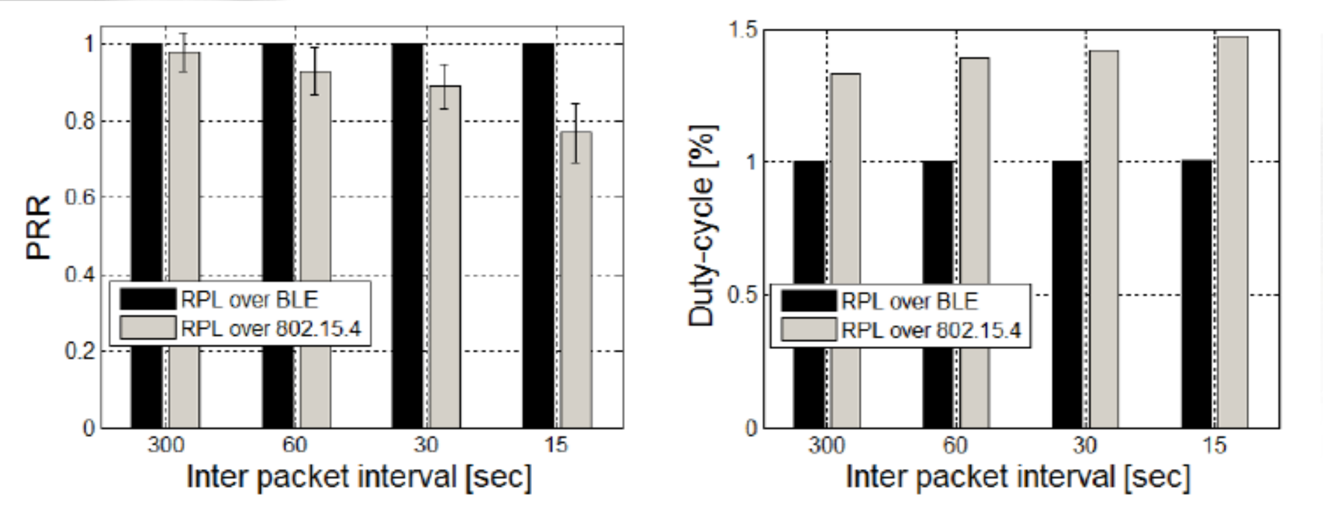
(d) Routing overhead vs. time

BLE shows stable DAG maintenance with almost perfect PRR owing to:

- Interference mitigation with **frequency hopping**
- Collision avoidance with **connection event scheduling**

Performance Comparison against 802.15.4 (2/2)

- **Impact of traffic load**
  (Sleep interval of ContikiMAC= BLE connection interval = 50msec)



(a) PRR vs. traffic load

(b) Duty-cycle of a leaf node (node 30) vs. traffic load

→ RPL over BLE achieves **higher PRR and lower duty-cycle** compared to RPL over 802.15.4

Conclusion

- **IoT Connectivity technologies**
  - BLE, ZigBee, Z-Wave, WiFi, Cellular IoT, NFC,
- **[Multihop] ZigBee vs Bluetooth Low Energy (BLE)**
  - MarketNet (variant of RPL over IEEE 802.15.4)
  - BLE over RPL (new approach)
- **On-going work**
  - Coexistence & Scalability
  - Reliability
  - Mobility

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