Portal: Transparent Cross-technology Opportunistic Forwarding for Low-power Wireless Networks

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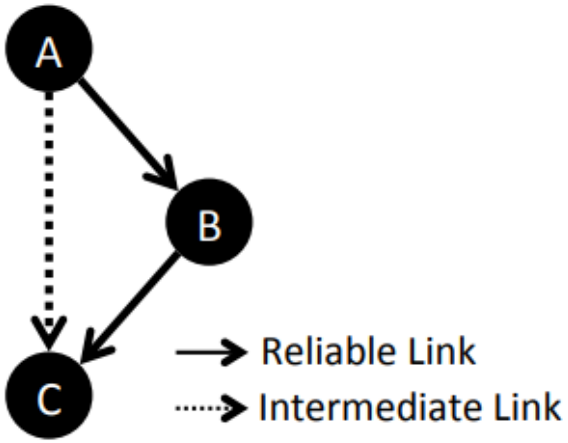
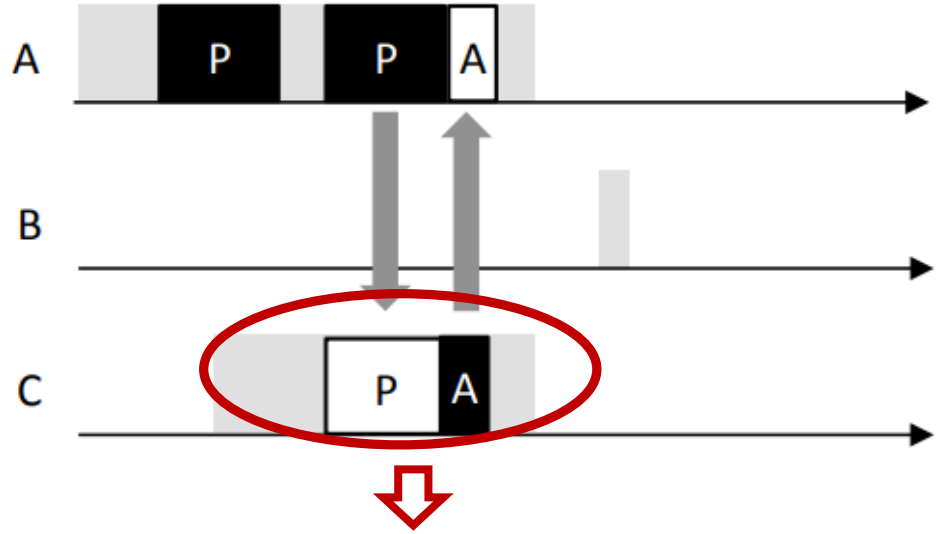
Low-power Wireless Networks

- Duty cycling: Low Power Listening
- Opportunistic Forwarding (OF)
  - Reduce the delay and energy consumption

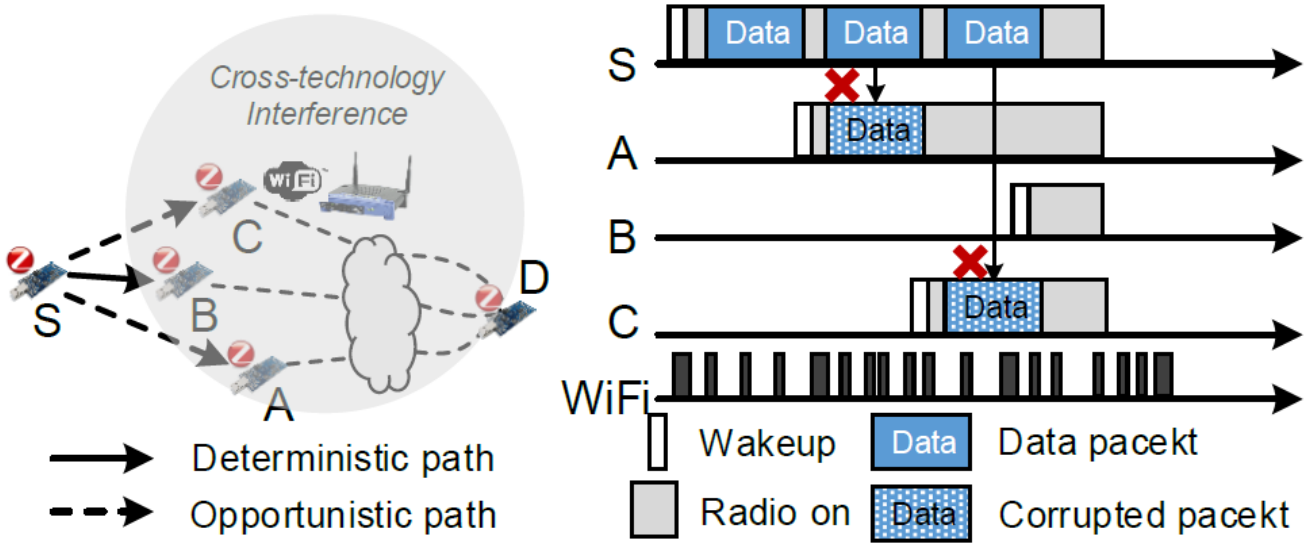




The node wakes up earlier and helps to forward packets

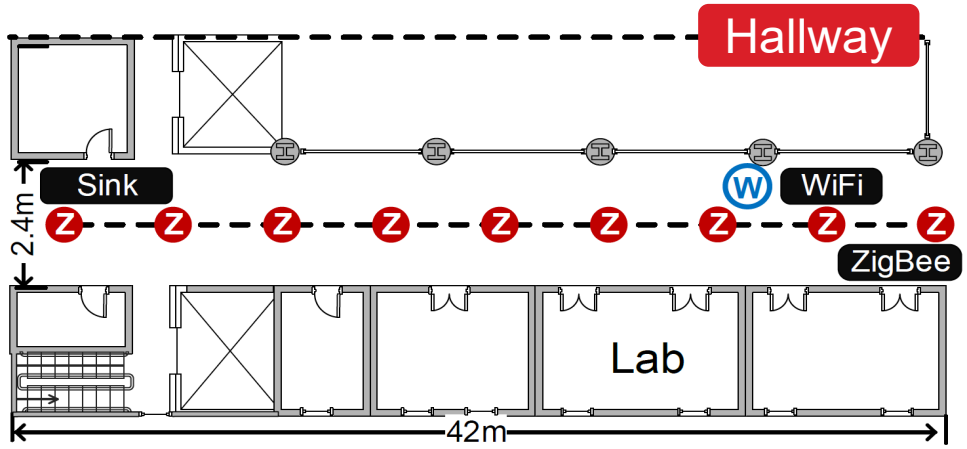
Cross-Technology Interference (CTI)

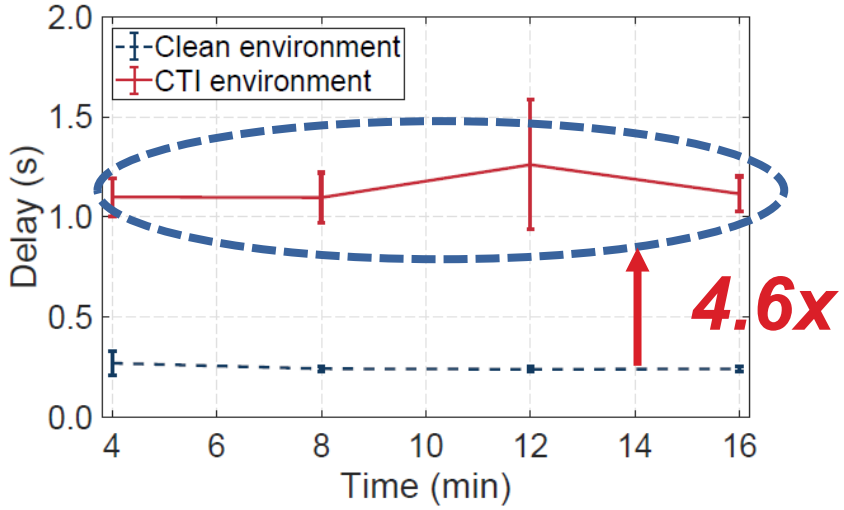
- Coexistence of heterogeneous devices
- Contention for the shared frequency resource
  - Corrupt the link diversity
  - Large delay, low PRR, low channel utilization ratio



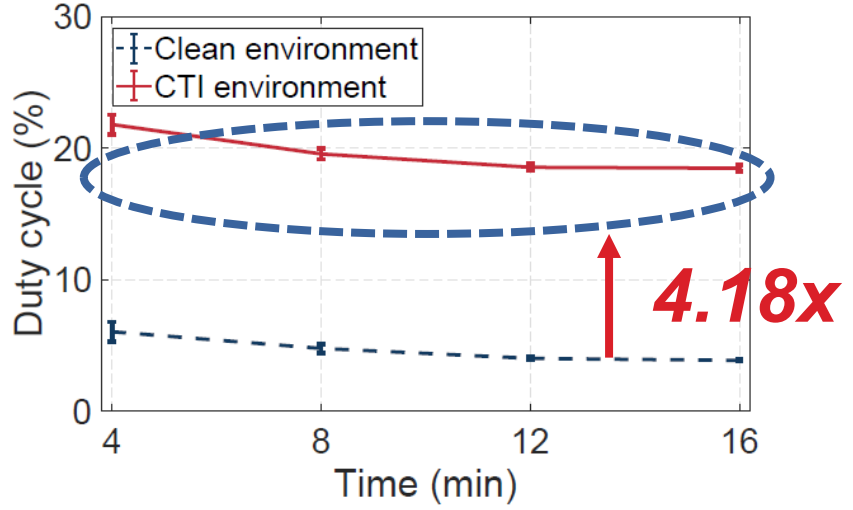
Impacts of CTI on *OF*

- Preliminary experiments
  - **ZigBee:** Implement ***ORW*** [1]
    - ✓Channel: 26 and 23
    - ✓Sleep interval: 2048ms





(a) End-to-end delay



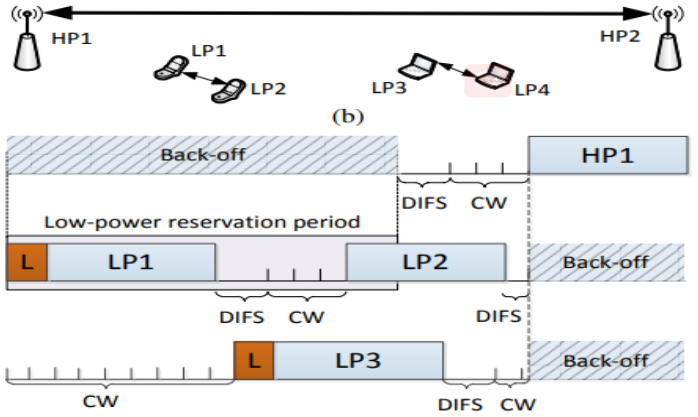
(b) Duty cycle

– CTI has a serious impact on low-power opportunistic forwarding.

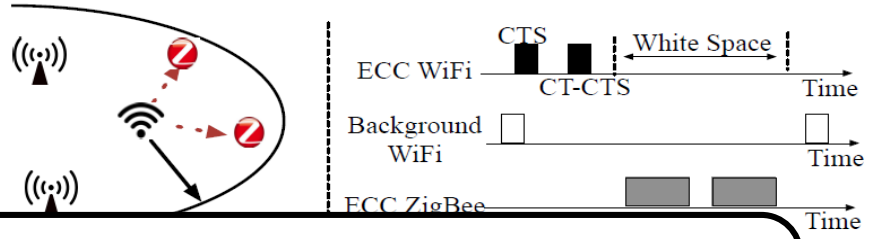
Existing methods

- Weeble
  - Intentionally jamming the high-power CTI
  - To reserve the channel for low-power devices
- ECC
  - Exploit CTC to coordinate the channel usage
  - Politely reserve the channel for ZigBee

Weeble [CoNEXT'12][2]



ECC [MobiSys'18][3]



– The best achievable performance of **channel reserving based methods** will not exceed the performance of OF running in clean environments.

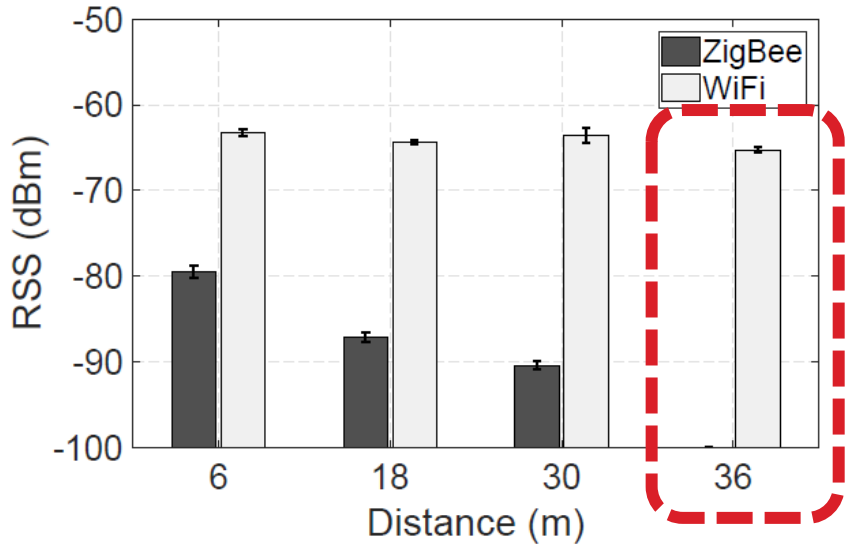
[2] Božidar Radunovic, Ranveer Chandra, Dinan Gunawardena. 2012. Weeble: Enabling Low-Power Nodes to Coexist with High-Power Nodes in White Space Networks. In Proceedings of CoNEXT.
[3] Zhimeng Yin, Zhijun Li, Song Min Kim, and Tian He. 2018. Explicit channel coordination via cross-technology communication. In Proceedings of ACM MobiSys.

Underutilized Coexisting CTI

- Friis transmission formula
  - Max Tx power: WiFi: 20dBm, ZigBee: 0dBm
  - WiFi theoretically has a ***4.5×*** longer communication range than ZigBee.

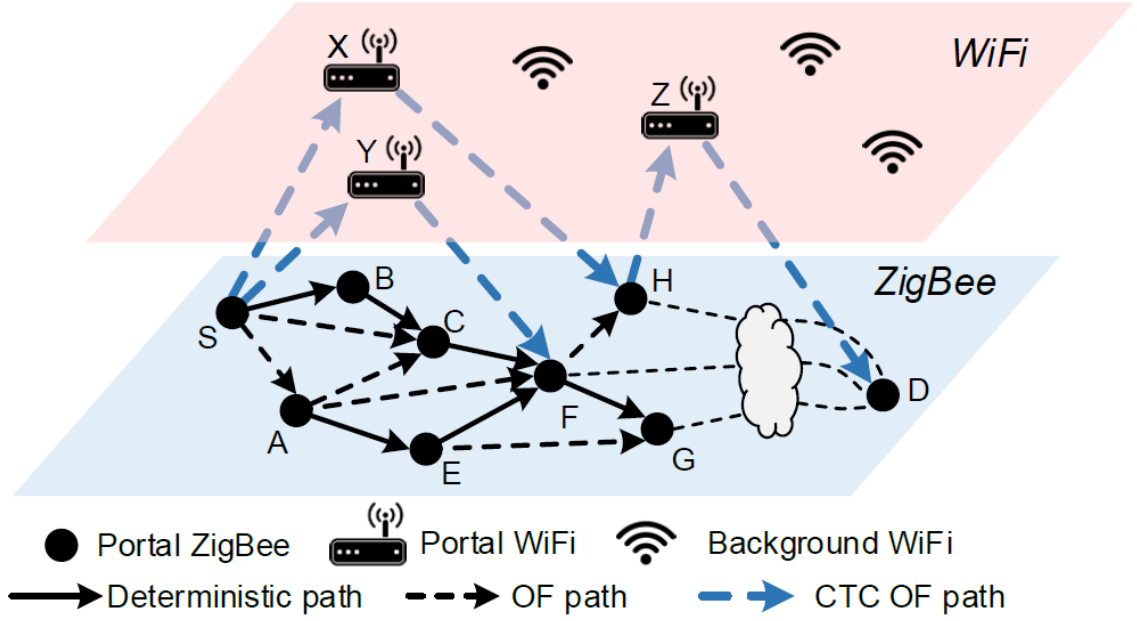
$$P_r(d) = \frac{p_t G_t G_r \lambda^2}{(4\pi d)^2}$$

- Experiment: RSS VS. distance
  - WiFi Tx power: 5dBm
  - ZigBee Tx Power: -15dbm



Underutilized Coexisting CTI

- Key insight
  - Leveraging CTI's superior communication capability to help the low-power opportunistic forwarding is better, for both low-power and high-power networks.



- ✓ For low-power networks:
  - longer opportunistic paths
  - break through the performance limit
- ✓ For high-power networks:
  - forward data out of local area faster
  - reduce the local competitors

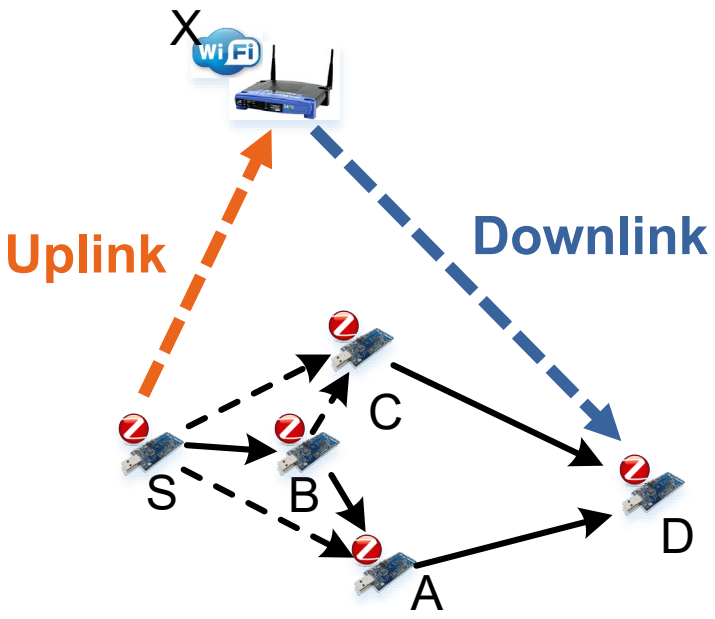
Challenges

- Enable transparent cross-technology forwarding
  - Radio incompatibility between CTI
  - How to enable WiFi forwarders overhear the ZigBee packets
  - How to forward the packet back into ZigBee networks without affecting original OF
- Make beneficial forwarding decisions with limited information
  - In-network routing metric is NOT available for WiFi forwarders
  - Minimize the influence on WiFi's own traffic
- Forward the ACKs in the reverse direction
  - ACK is necessary to stop redundant opportunistic transmissions
  - Asymmetric communication causes ACK failures

Roadmap

- Background
- Motivation
- **Design of Portal**
- Evaluation
- Conclusion

Portal: Cross-technology Rebroadcasting (CTR)



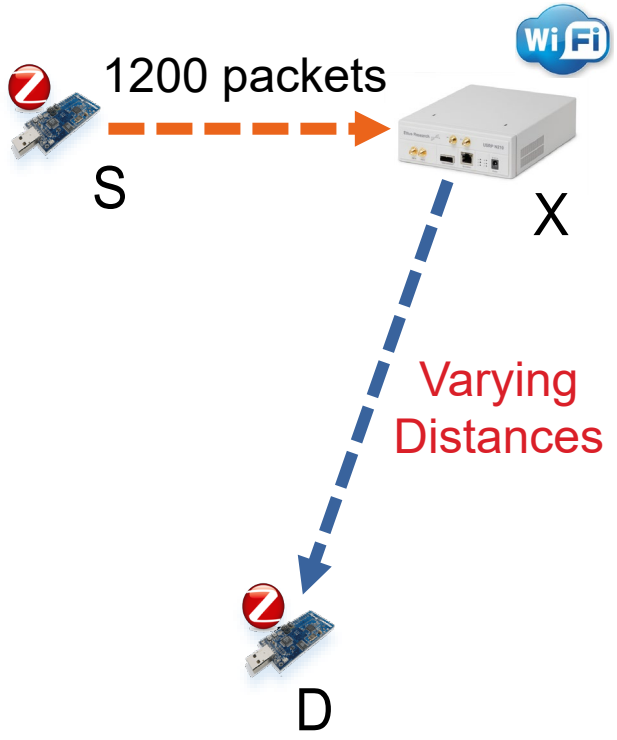
- Uplink (LEGO-Fi)
  - Reuse the long preamble detection module of WiFi to detect SFD of a ZigBee packet.
  - Moving correlation of the received signal r_n and SFD template x_k

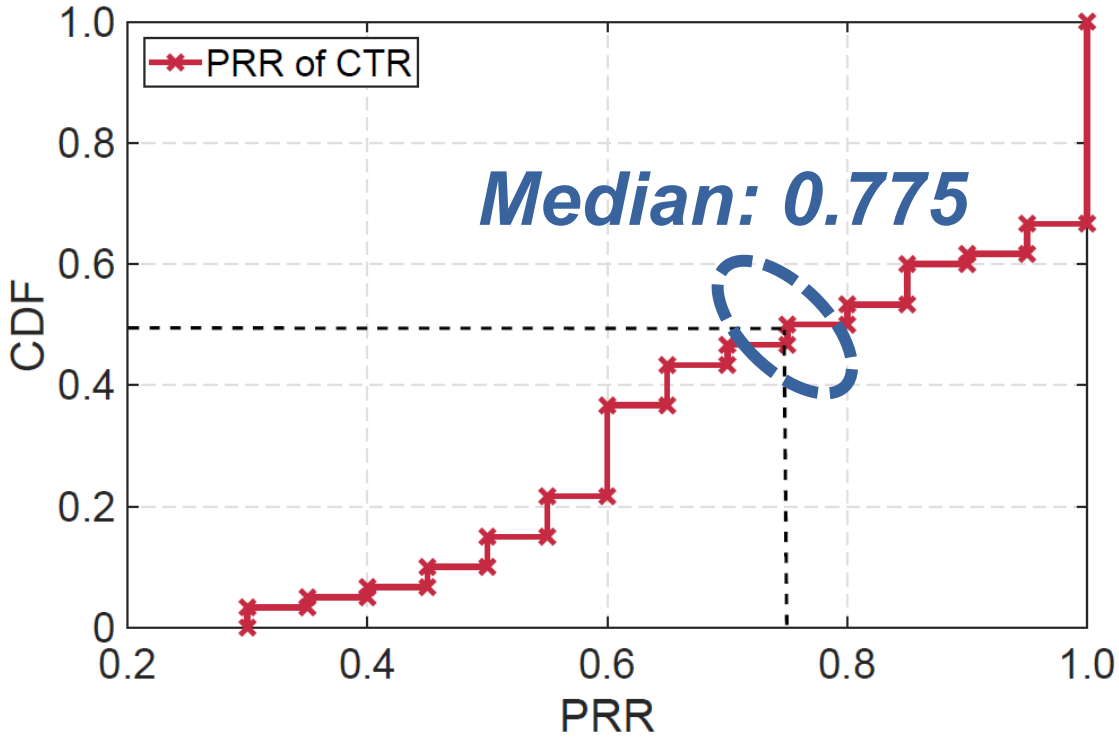
$$corr_i = \sum_{k=0}^{127} r_{i+k} x_k^*, i = 1,2, \dots, n - 127$$

- Downlink (WEBee)
  - Use the recorded ZigBee as the template to generate the WiFi signals that contain the interested ZigBee signals.

Portal: Cross-technology Rebroadcasting (CTR)

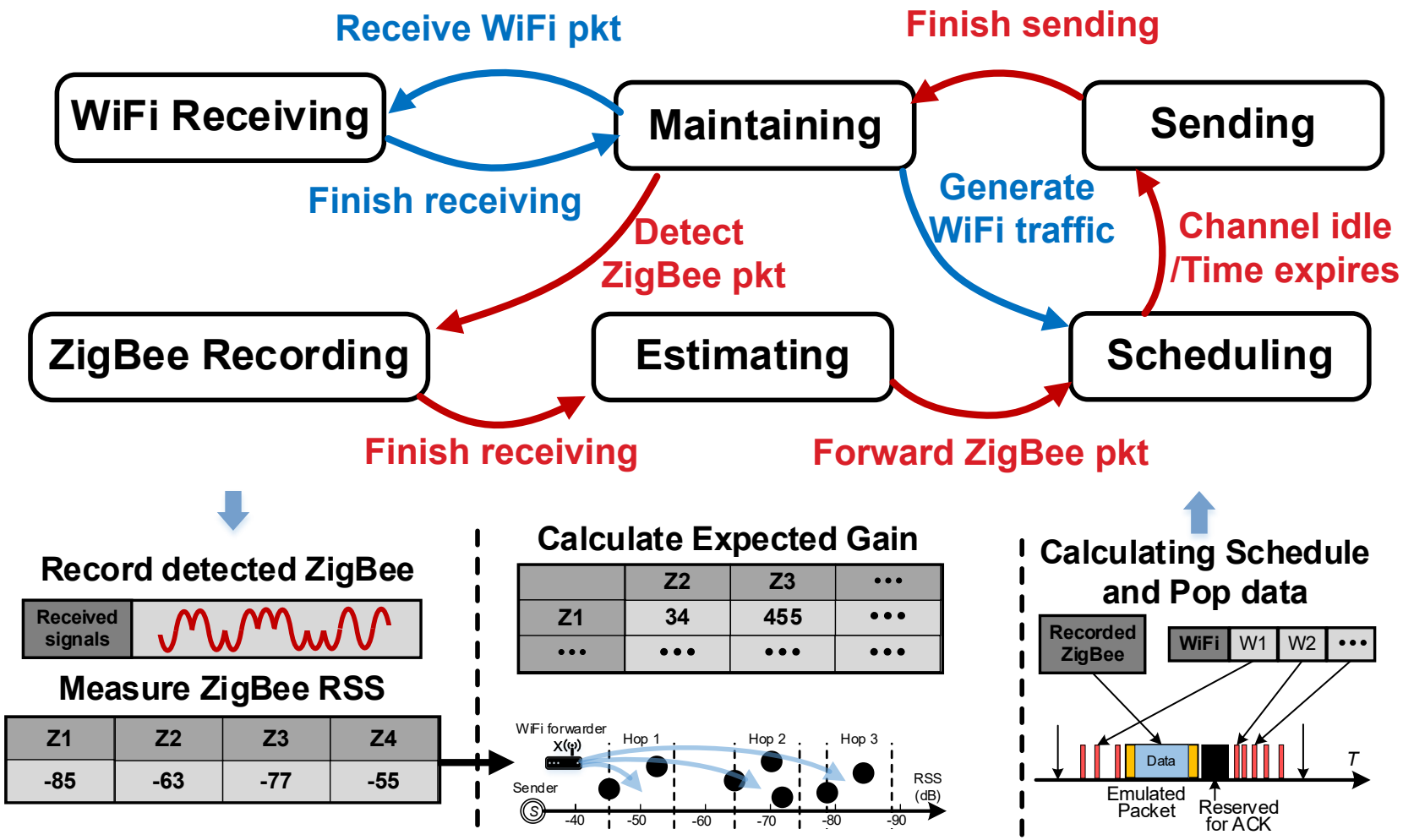
- Effectiveness of CTR
  - Median PRR of rebroadcasting once is 0.775, which is good enough for CTC





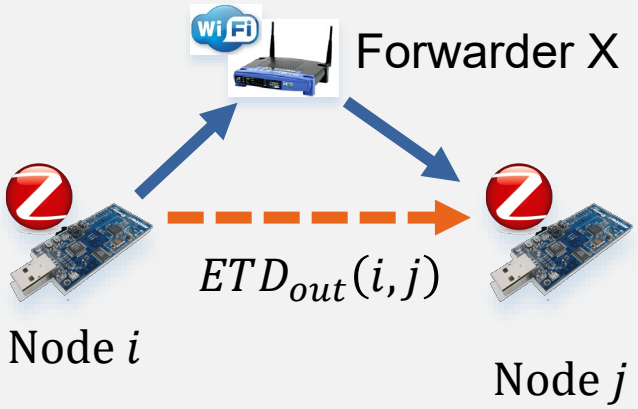
Portal: Forwarding Protocol

- Overall Procedure



Forwarding Protocol: Estimation State

- Performance gain



Delay of one wake-up

$$ETD_{in}(i,j) = (EDC_j - EDC_i) \cdot \left(\frac{T_s}{2} + T_x\right)$$

- T_s: Sleep interval
- $T_s/2$: Expected waiting time for one wake-up
- T_{tx}: Packet transmission time

Uplink delay, Scheduling delay, Downlink delay, Waiting delay

$$ETD_{out}(i,j) = T_{tx} \cdot \frac{1}{p_{iX}} + T_{wait} + T_{re} \cdot \frac{1}{p_{Xj}} + \frac{T_s}{2}$$

- T_{re}: Packet rebroadcasting time for WiFi forwarder
- P_{Xj} : PRR from X to j, P_{iX} : PRR from i to X
- T_{wait}: Scheduled waiting time of X's rebroadcast

Performance gain of *X*: $Gain_x(i,j) = ETD_{in}(i,j) - ETD_{out}(i,j)$

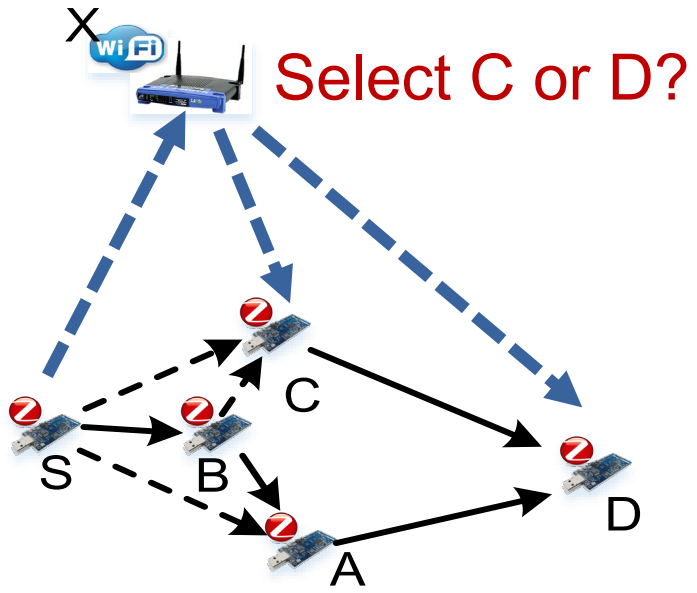
Forwarding Protocol: Estimation State

- Find the beneficial candidate set *C*
  - Nodes that reply ACKs to the WiFi forwarder before the local homogenous forwarder are the beneficial candidates. $\boldsymbol{Gain_x(i,j) = ETD_{in}(i,j) - ETD_{out}(i,j)}$
- Estimate the in-network progress
  - $ETD_{in}(i, c_m)$ is highly related to the hop distance between node i and c_m, $c_m \in C$
  - RSS-based in-network progress estimation

$$ETD_{in}(i, c_m) = ETD_{in}(i, c_{ref}) + K(c_{ref}, c_m) \cdot \frac{T_s}{2} + \delta \cdot \frac{T_s}{2}$$

Largest RSS, baseline

Hop difference



Forwarding Protocol: Estimation State

- Estimate the in-network progress
  - Start from c_{ref} and group the nodes by an RSS window:

    $$RSS_i - RSS_{ref} < th_{RSS}$$

  - $th_{RSS} = 3\text{dB}$, c_1 is c_{ref}
- Select the next-hop forwarders
  - Calculate the gain of each candidate
  - Select the top-2 ranked nodes as next-hop forwarders.

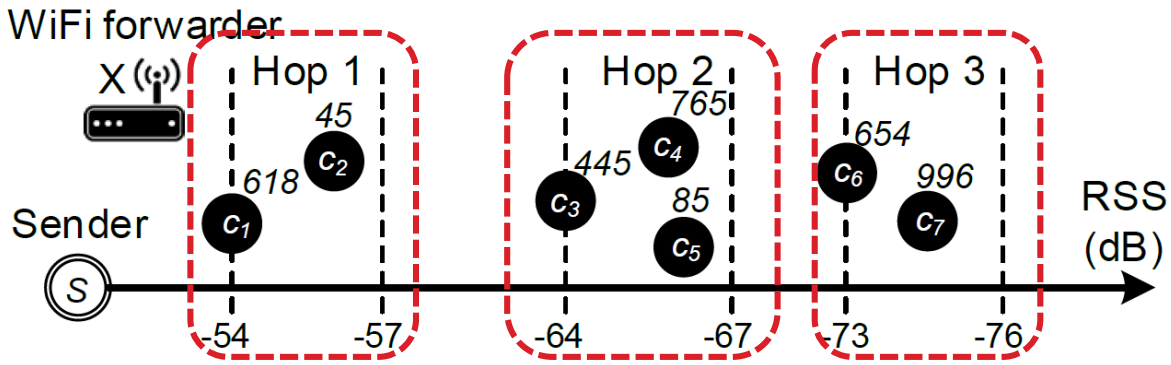


Table 1: Ranking of the candidate forwarders

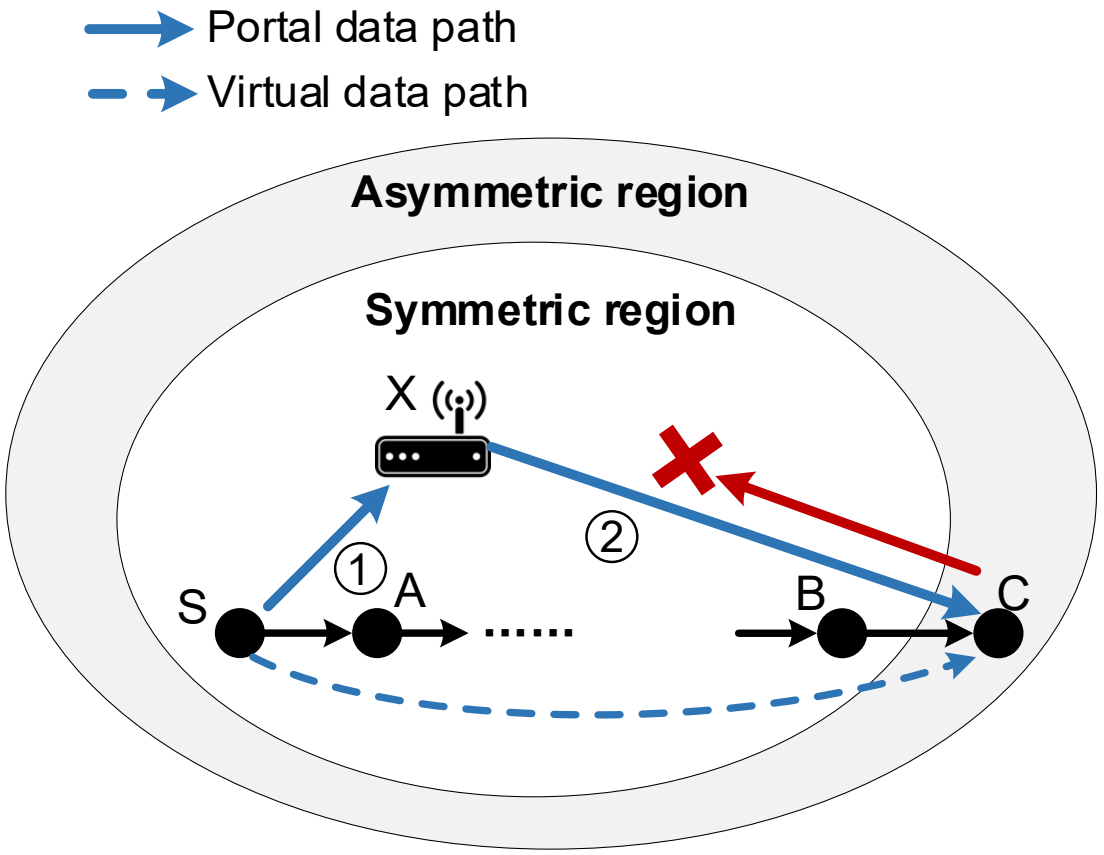
Ranking	Node	RSS (dB)	ETD_{in} (ms)	ETD_{out} (ms)	$Gain$ (ms)
1	c_5	-66	1000	85	915
2	c_6	-73	1500	654	846
3	c_3	-64	1000	445	555
4	c_7	-75	1500	996	504
5	c_2	-56	500	45	455
6	c_4	-65	1000	753	247
7	c_1	-54	500	618	-118

Portal: ACK Replying

① Concurrent overhearing

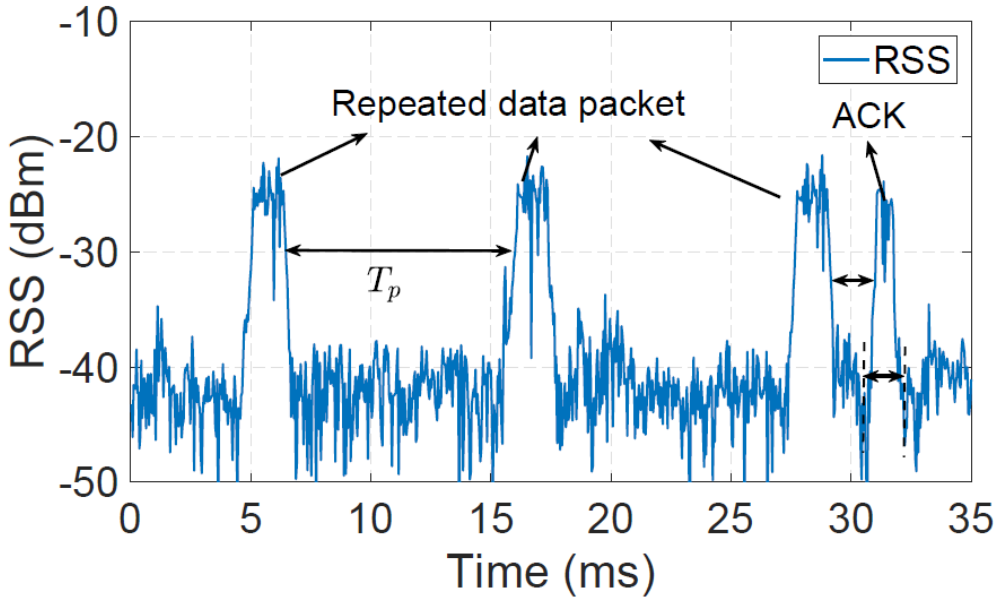
② Transparent forwarding

Asymmetric region: SINR at the WiFi forwarder will be too low to successfully rebroadcast the ACK!



Portal: ACK Replying

- Feature-based ACK recognition
  - Interval between the data packet
  - Transmission period
  - An 11-Byte ACK (352μs) is transmitted 12 symbol periods (192μs) after receiving a packet.
  - Allowed error: 80μs



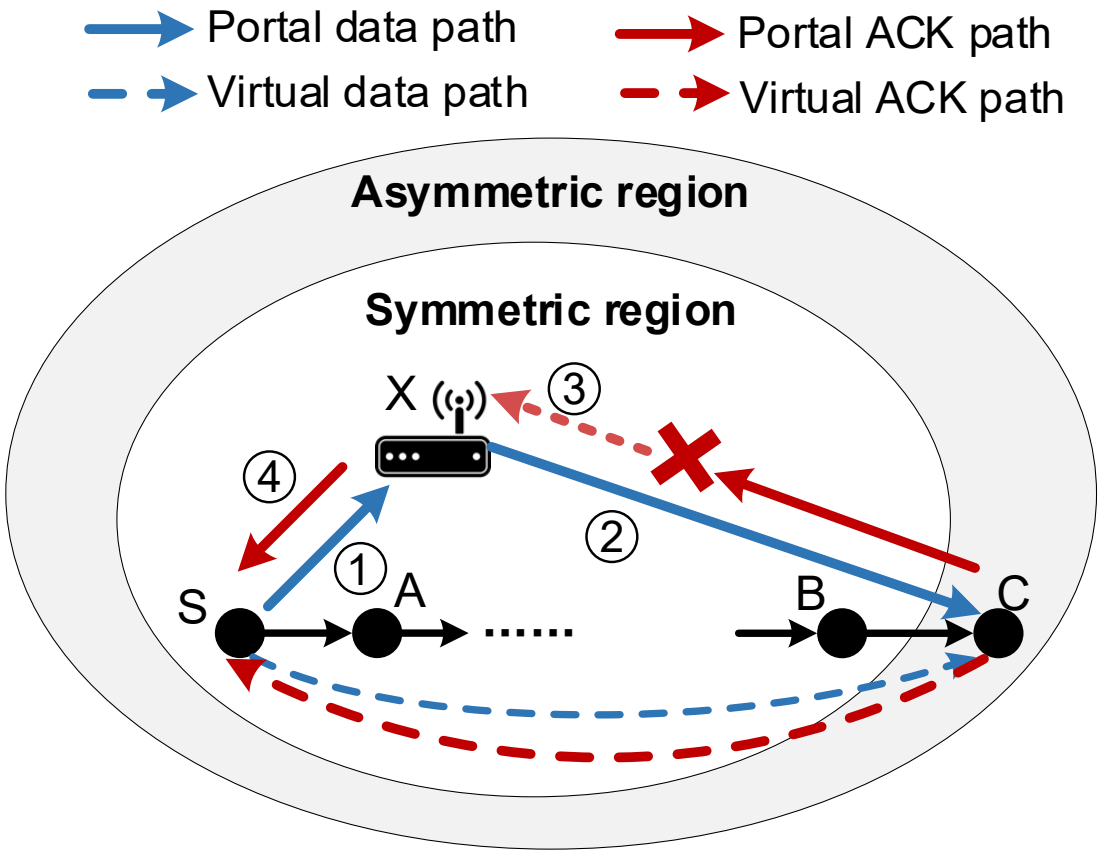
Portal: ACK Replying

① Concurrent overhearing

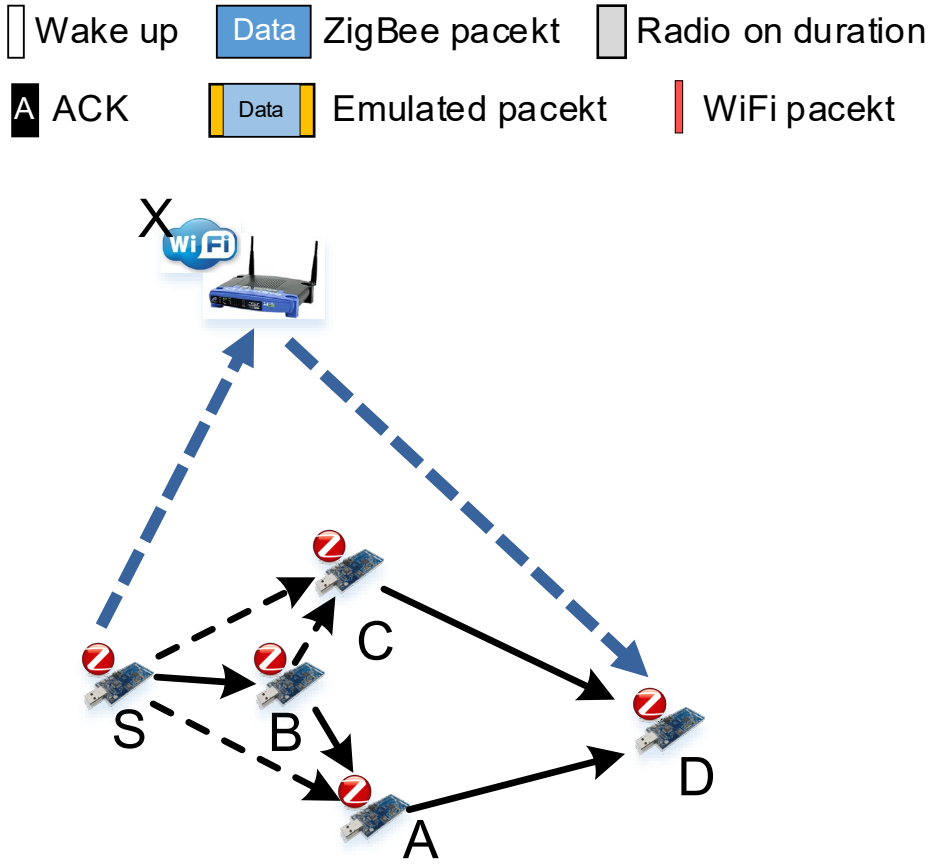
② Transparent forwarding

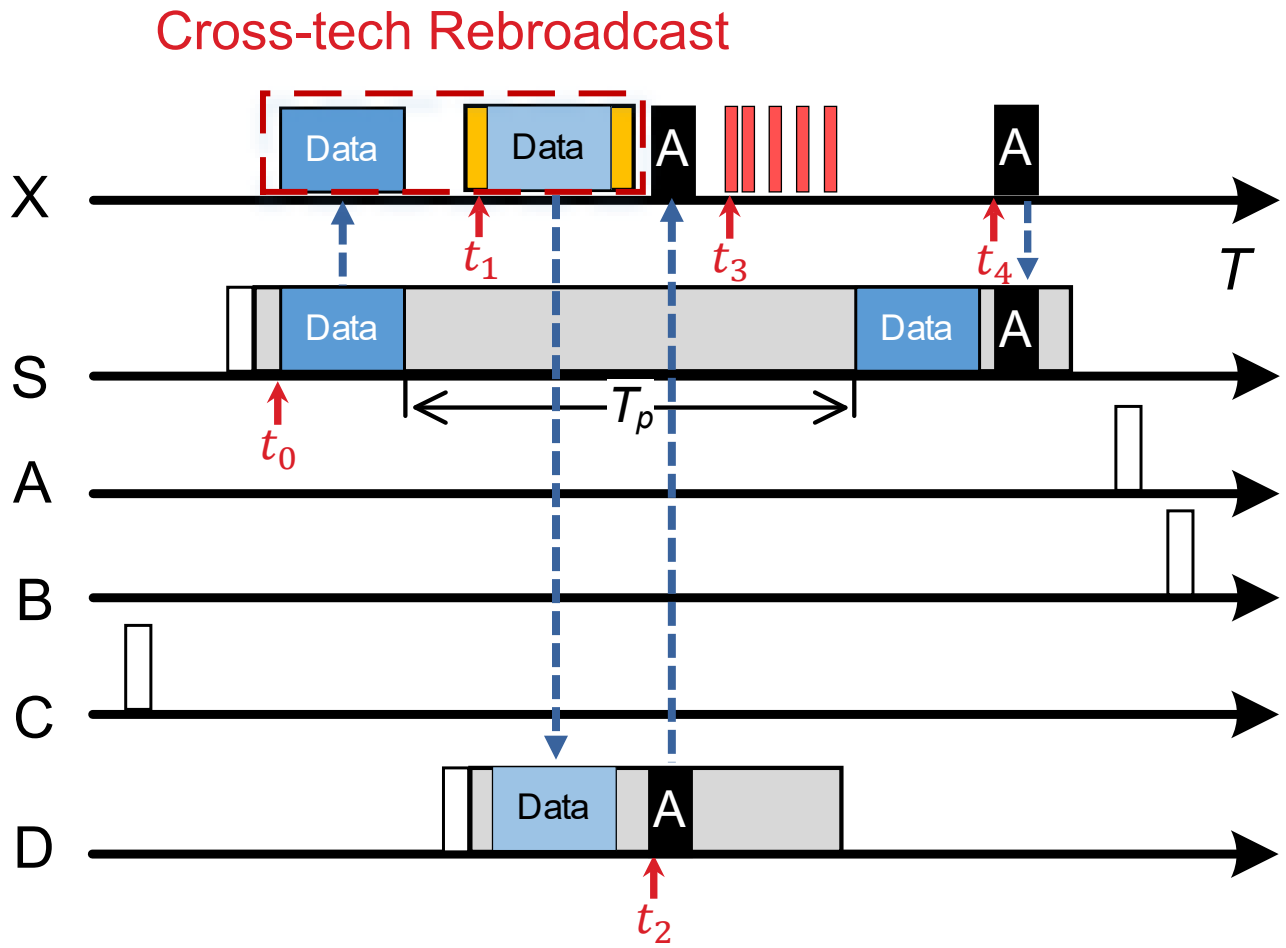
③ Feature-based ACK recognition

④ Jamming-based ACK replying



Portal: Overview





Roadmap

- Background
- Motivation
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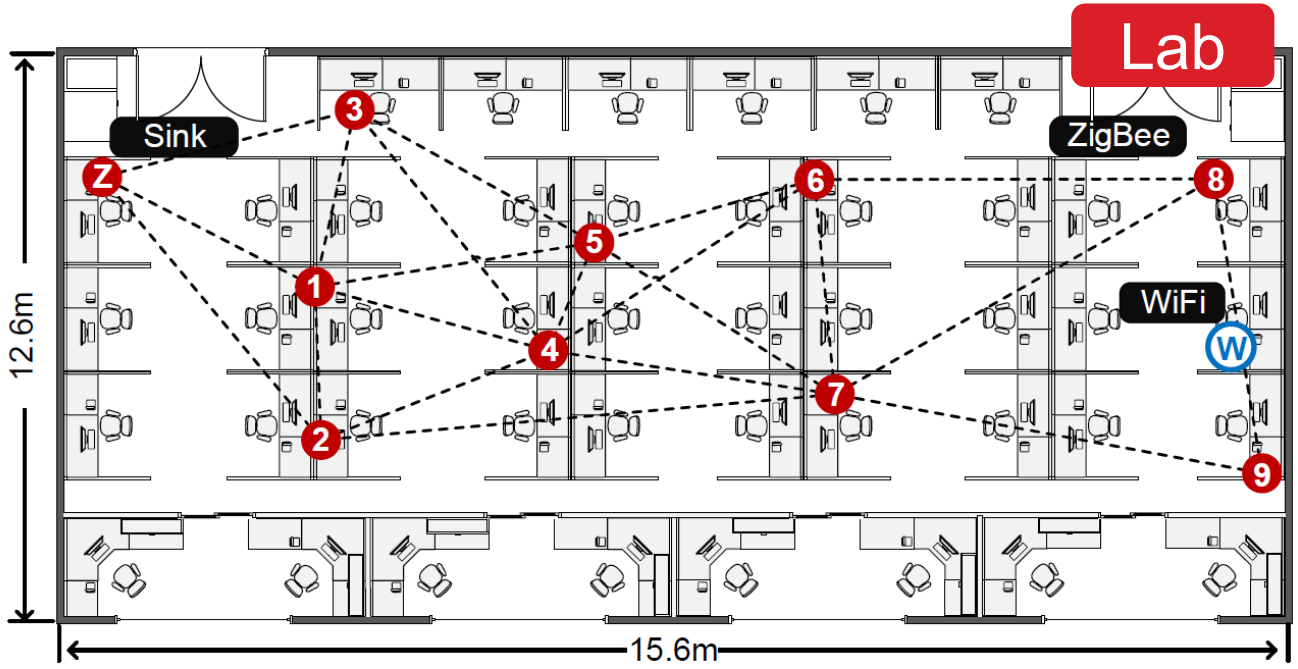
- **Evaluation**
- Conclusion

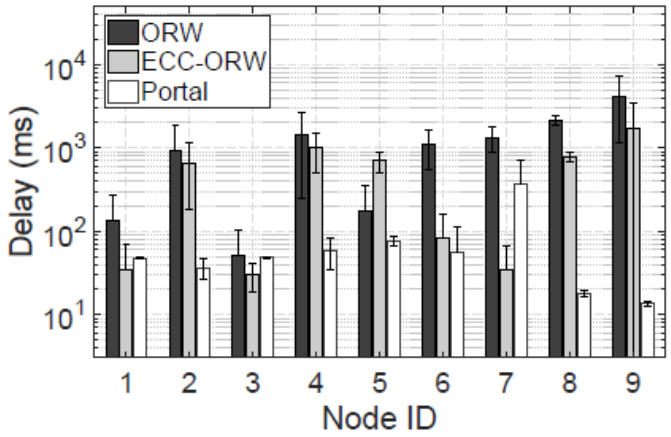
Experiment Setup

- Implementation
  - TelosB, TinyOS 2.1.2
  - USRP N210
- Compared schemes
  - Portal
  - ORW
  - ECC-ORW: stop the WiFi when there is ZigBee transmission.

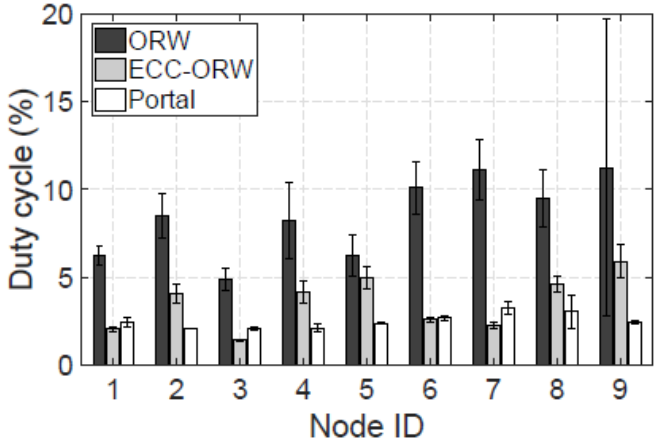


Performance in Real Environments

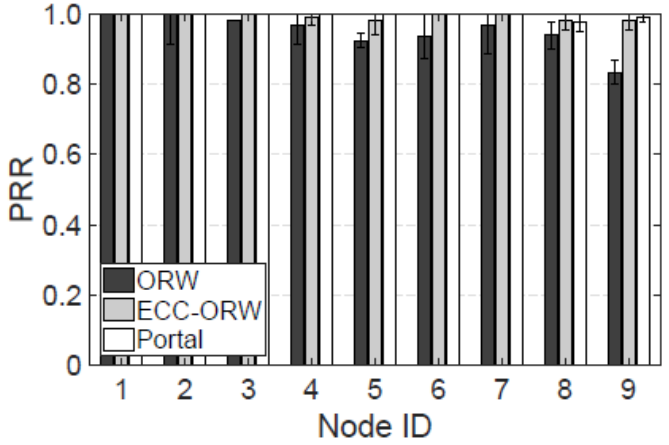
- Setting
  - **ZigBee**: channel 23, Tx power: -22dBm, sleep interval: 1s, packet rate: 30s/packet
  - **WiFi:** Tx power: 5dBm
- Portal
  - Average delay: 13.74ms, which is 304× and 125× faster than ORW and ECC-ORW
  - Duty-Cycle: 2.5%, which is 70.2% and 30.6% smaller than ORW and ECC-ORW



(a) End-to-end delay



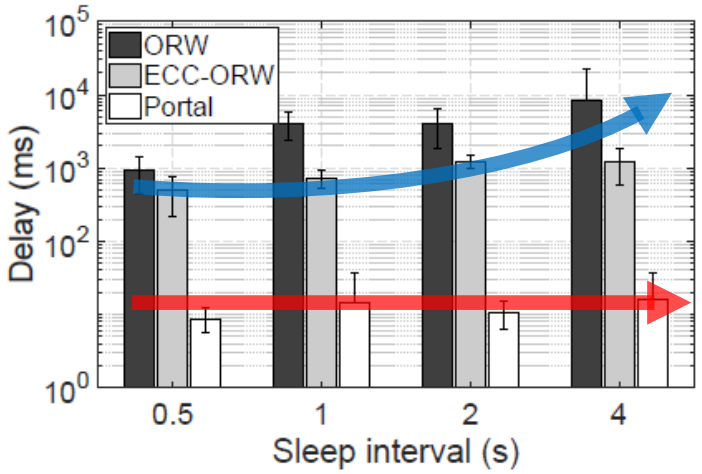
(b) Duty cycle



(c) PRR

Different Sleep Intervals

- Setting
  - ***Sleep interval: 0.5~4s***



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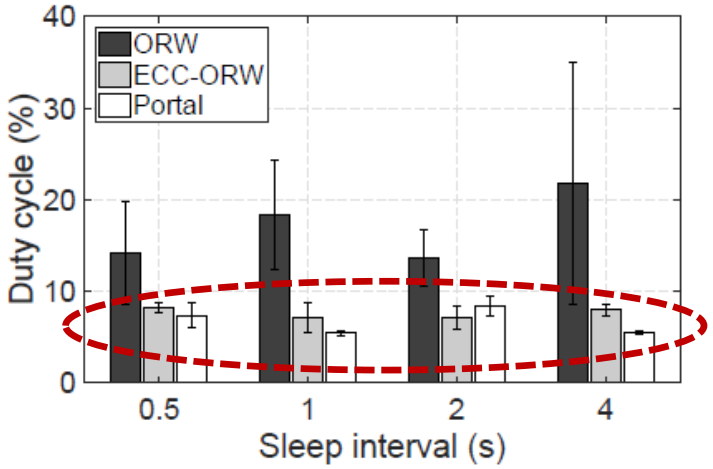
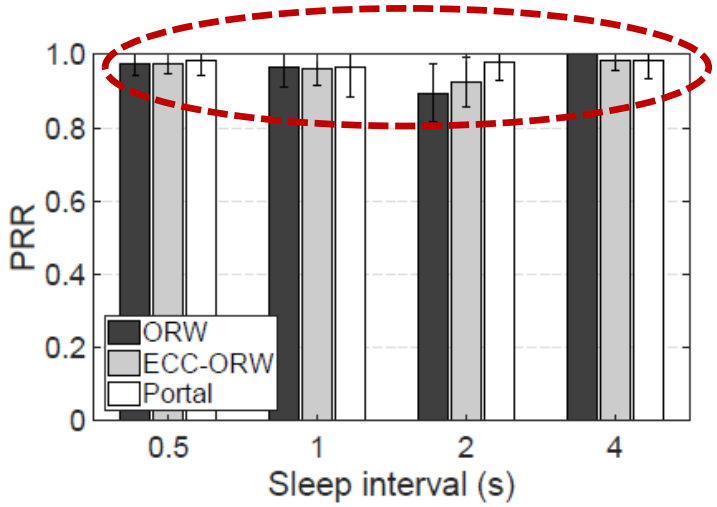


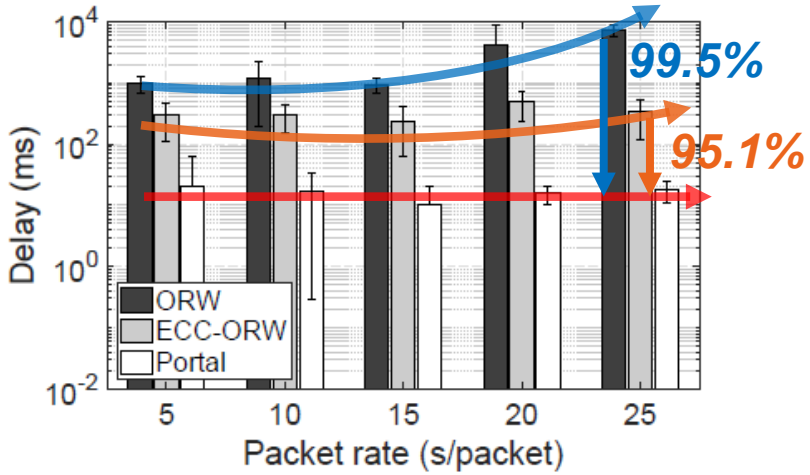
(b) Duty cycle



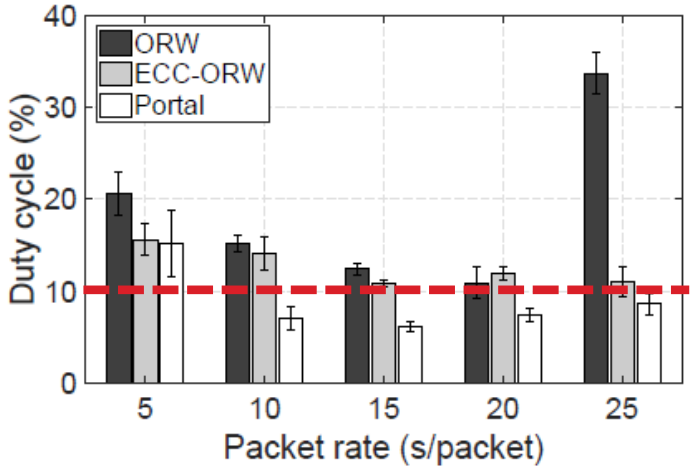
(c) PRR

Different Packet Transmission Rates

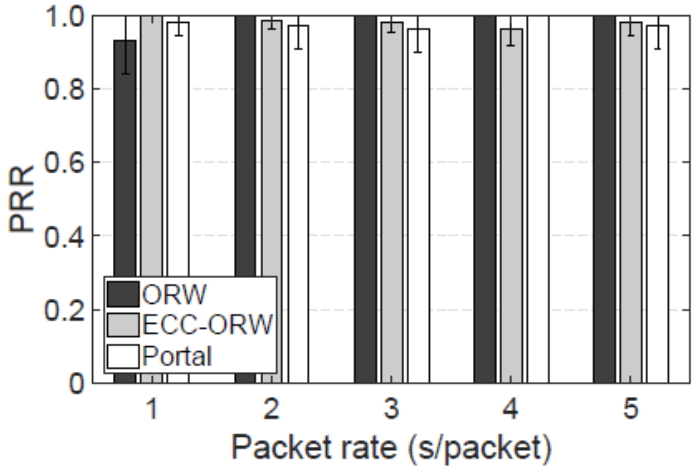
- Setting
  - ***Packet transmission rate: 5~25s/packet***



(a) End-to-end delay



(b) Duty cycle



(c) PRR

Conclusion

- Portal: a new paradigm for low-power opportunistic forwarding in CTI environments
  - Turn the enemy into friends: explicitly include the CTI devices into the forwarding process as the heterogeneous forwarder
  - Not only solve CTI problem, but also breaks through the performance limit by exploiting the superior capability of CTI devices

- Achieve ***125×*** faster end-to-end delay than ECC-ORW, the representative channel reserving based forwarding method.

THANKS!

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https://xiaolongbupt.github.io/

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