Physical-Layer Cross-Technology Communication via Emulation

BEST Paper Award @ MobiCom 2017

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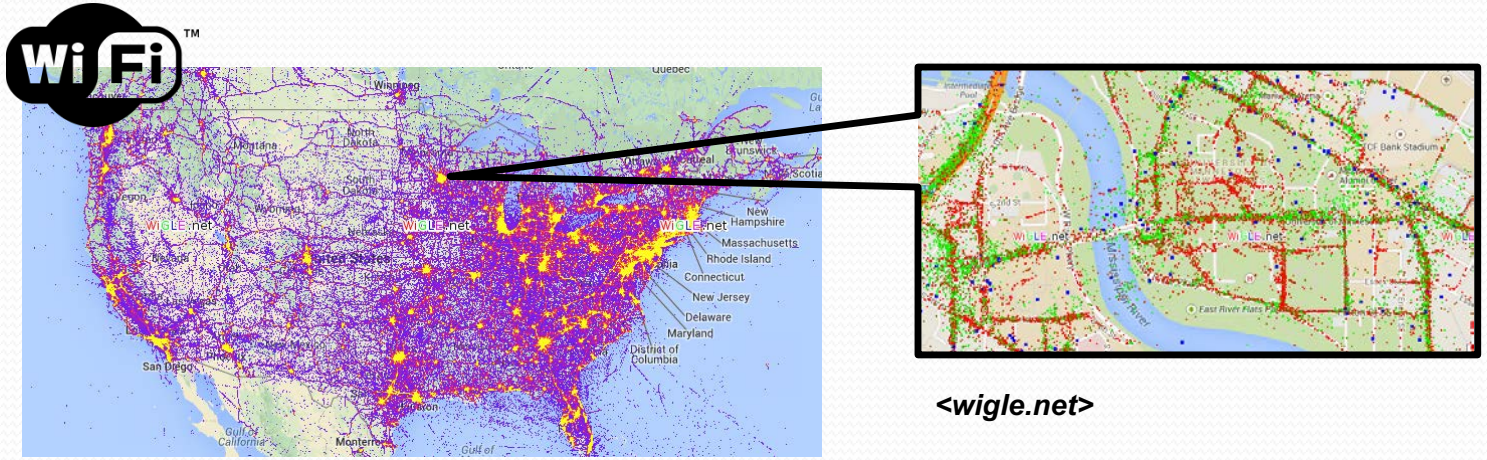
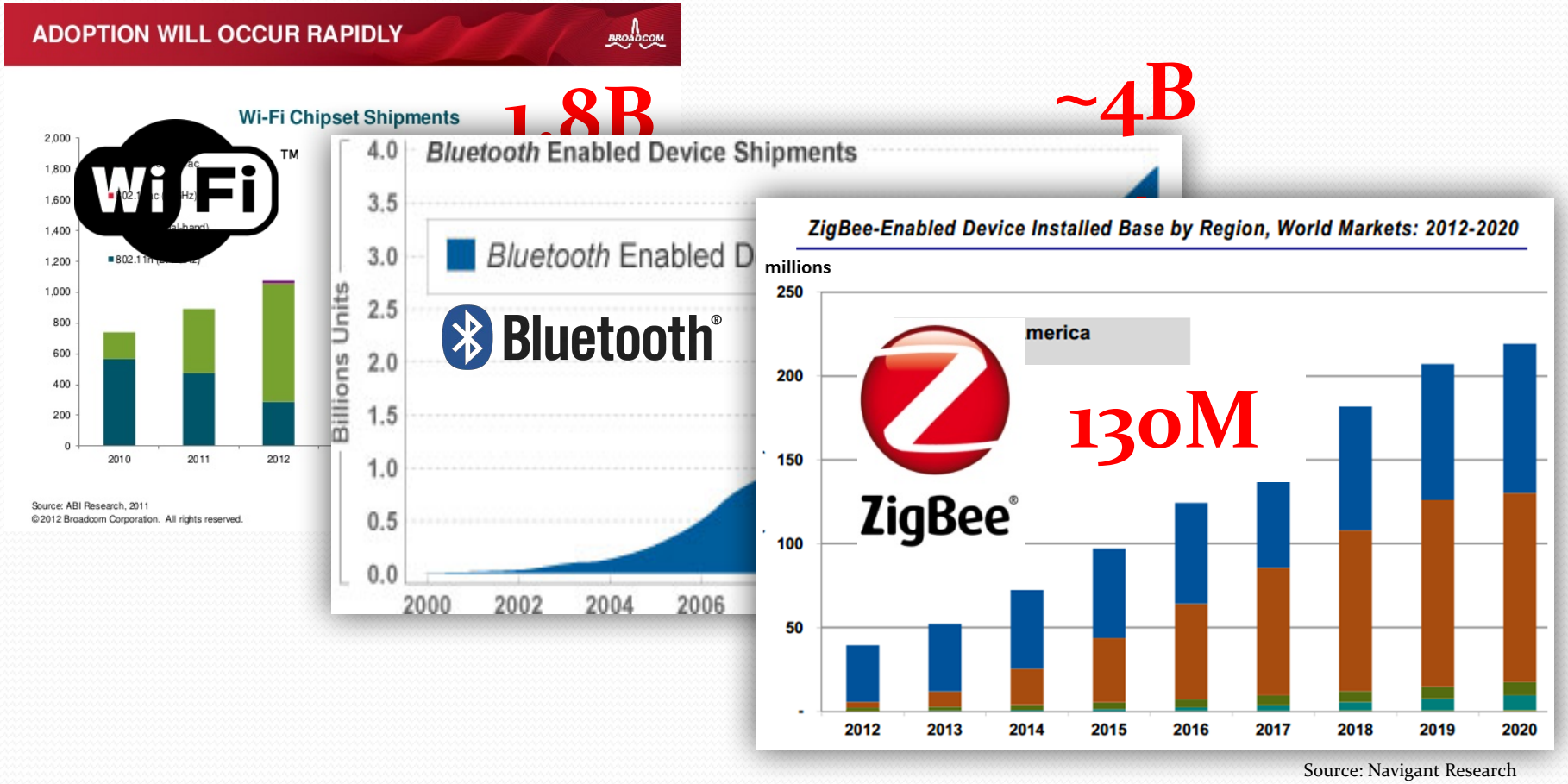
Wireless is Everywhere



… and Increases Rapidly

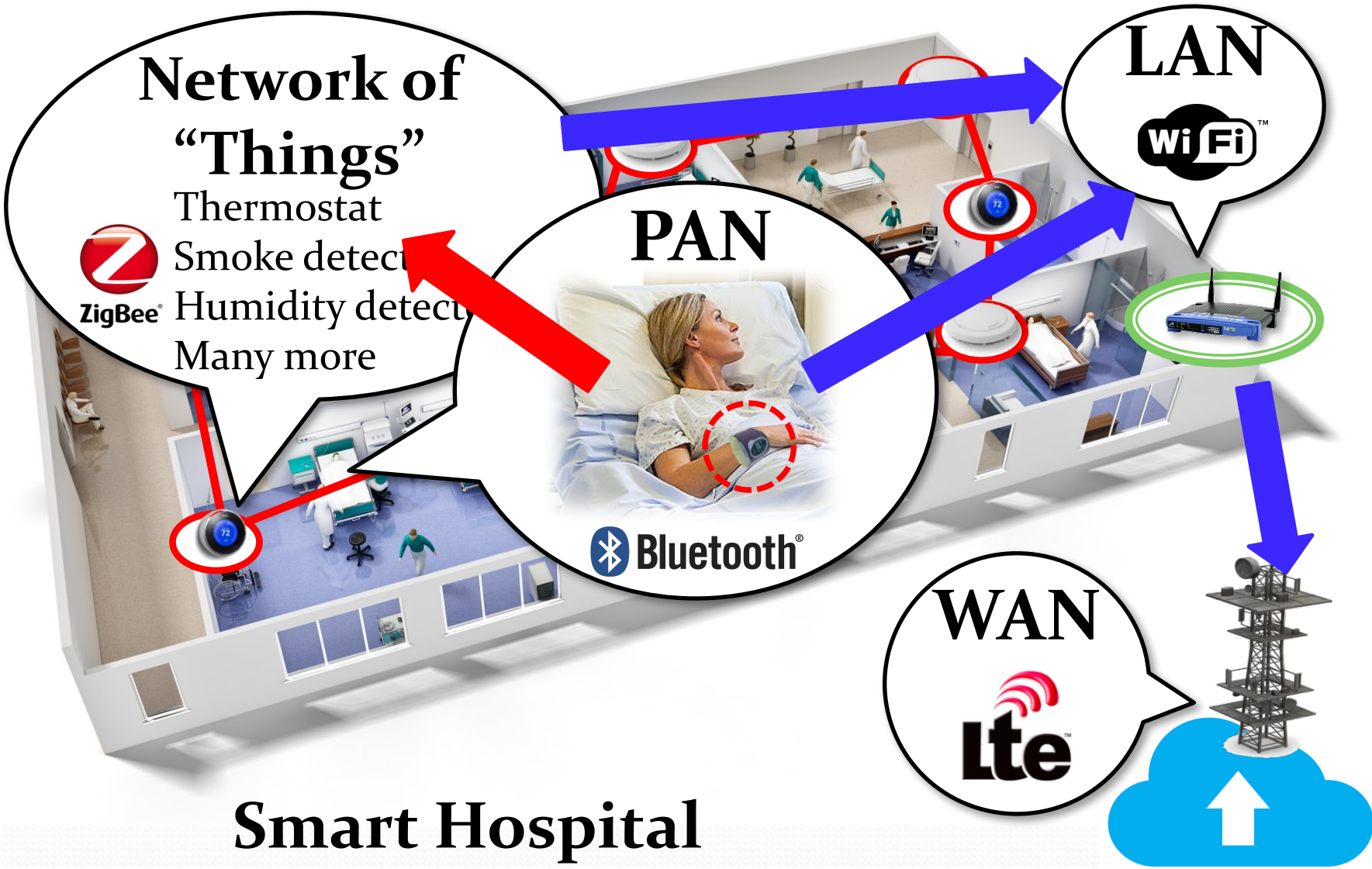


Source: Navigant Research

Gartner predicts 20 billion IOT devices by year 2020

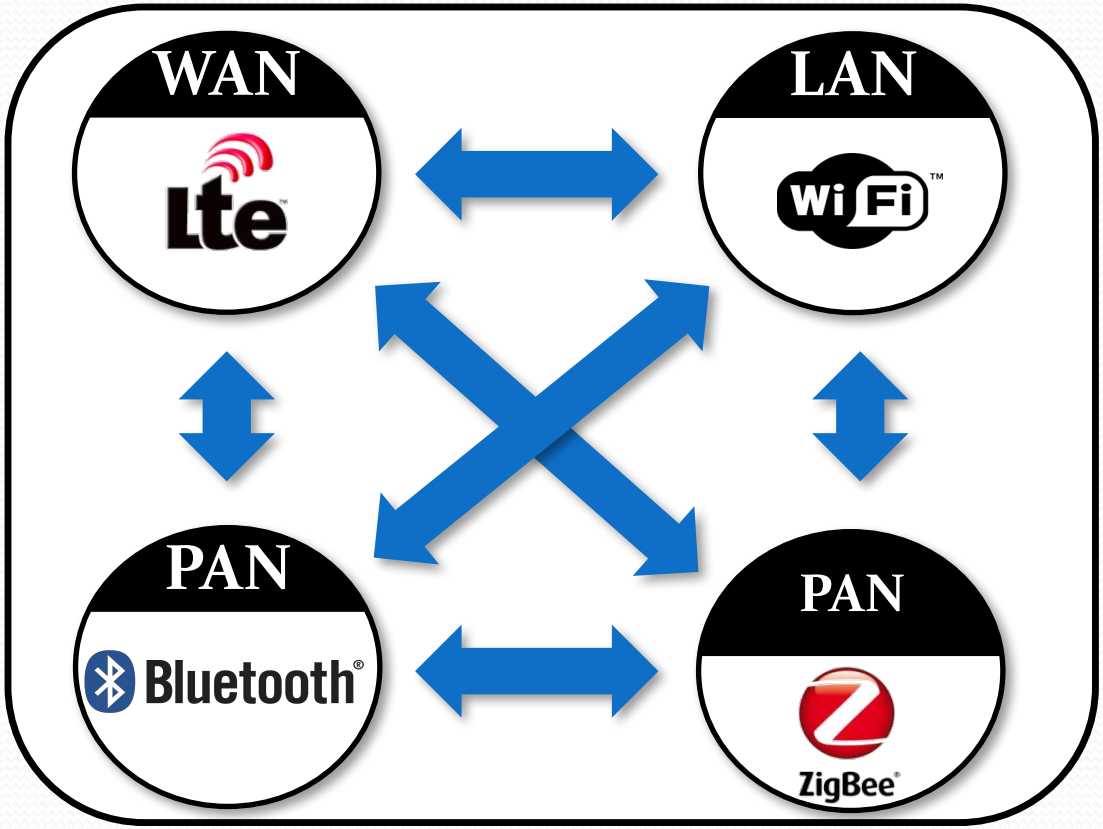
… also Diversifies Quickly

Coexist and Collaborate



Objective: Ubiquitous Connectivity

Q: How to Interconnect/bridge them?



Bridging Wireless Tech: Gateway

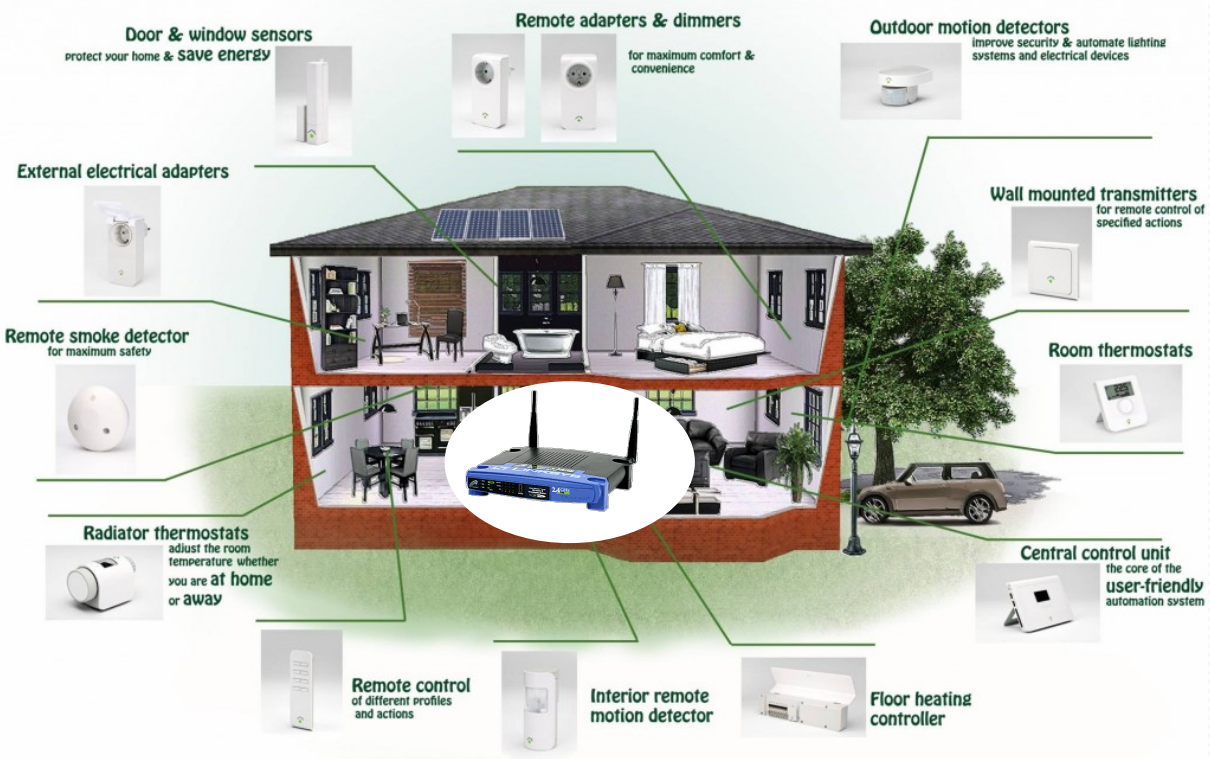
MutiRadio Gateway

- Extra HW/deployment **cost**
- Traffic **overhead** into/out of the gateway
- Pre-deployment, unsuitable for **ad hoc/mobile**

The New Paradigm: CTC

Cross-Technology Communication (CTC) enabling heterogeneous devices talks directly!

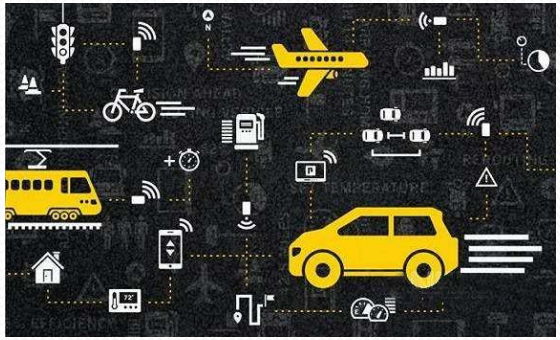
What CTC can Achieve: Low Cost



A WiFi AP controls all smart home ZigBee-enabled devices in one hop without gateway

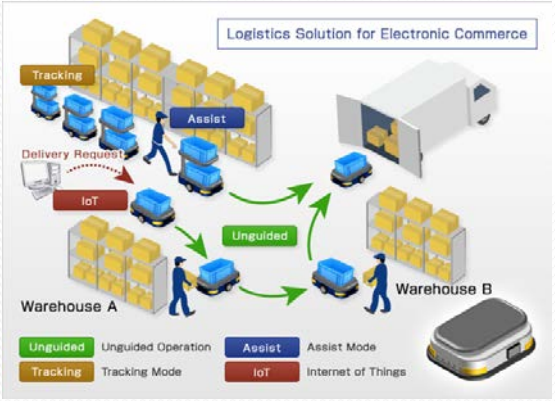
What CTC can Achieve: Mobility

VANET



Battle Field

Inventory Tracking

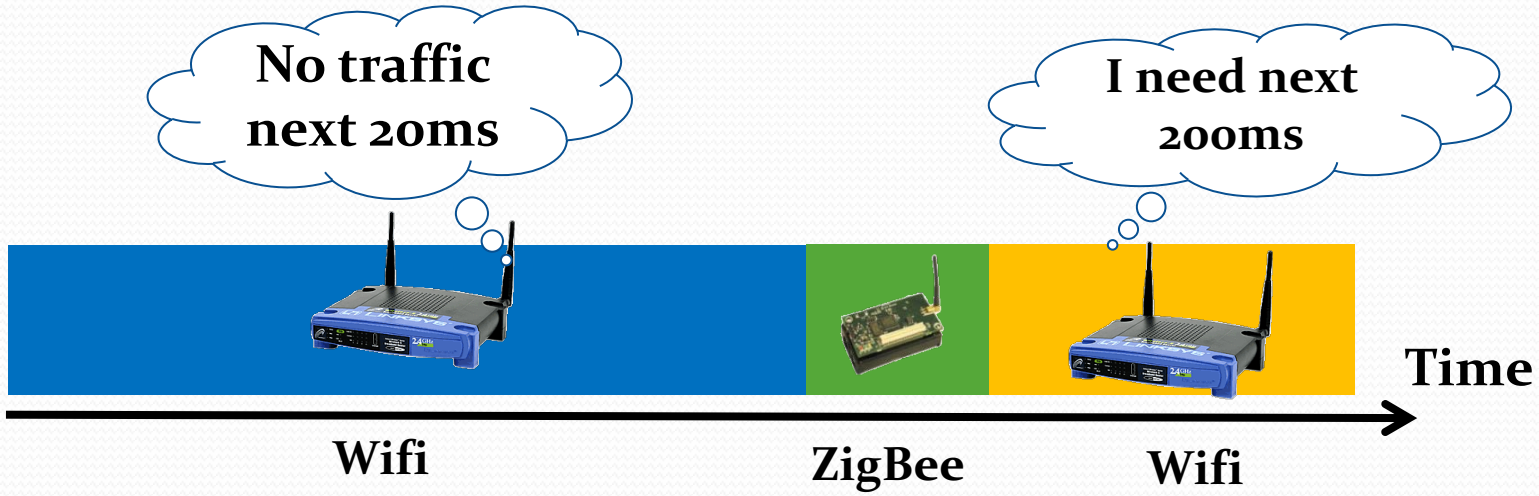


Wearables

Direct Communication among mobile IOT devices without pre-deployed gateways

What CTC can Achieve: Coordination

Support Explicit channel coordination



- Extends local mechanisms globally across wireless tech
  - Global RTS/CTS Reservation.
  - Global Time Division Multiple Access (TDMA)

Physical-Layer Cross-Technology Communication

WEBee: WiFi Emulated ZigBee

Outline

- The State of the Art
- The Design
- Implementation & Evaluation
- Extensions

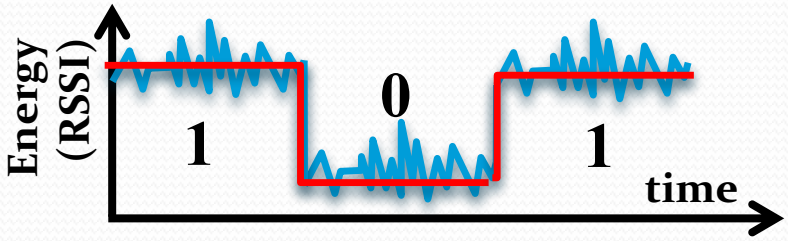
The State of the Art

A Brief History of CTC Research

Packet-level CTC

Using packet length, gap, or offset

A packet can only express a few bits



16,000X Faster!!!

WE ARE HERE

PHY CTC

100s Kbps

ESENSE
Packet Length
K. Chebrolu
bps
Mobicom
2009

GSense
Gap Length
X. Zhang

HoWiES
Comb. Packet Length
Y. Zhang
bps
INFOCOM
2013

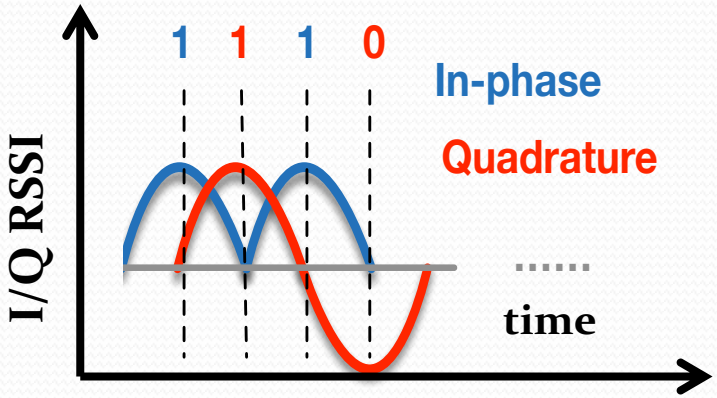
FreeBee
Beacon Interval
S. Kim
bps
MobiCom
2015

MobiCom
2017

A Brief History of CTC Research

Physical-Level CTC

By emulating receiver's RF waveform,
A packet achieves Rx's maximum rate



16,000X Faster!!!

WE ARE HERE

PHY CTC

100s Kbps

bps — Mobicom 2009

bps — INFOCOM 2013

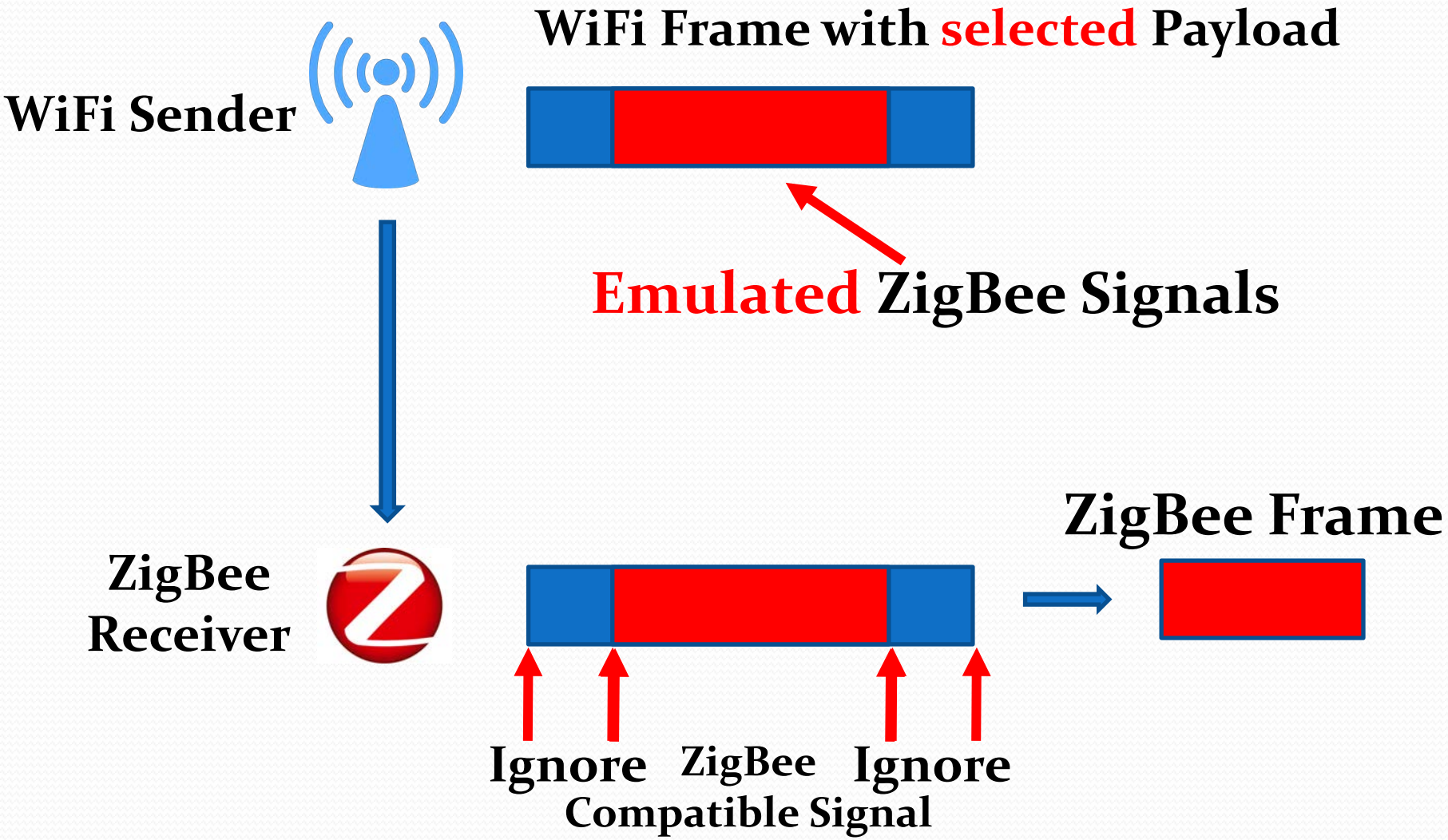
bps — MobiCom 2015

MobiCom 2017

The Design

ZigBee®

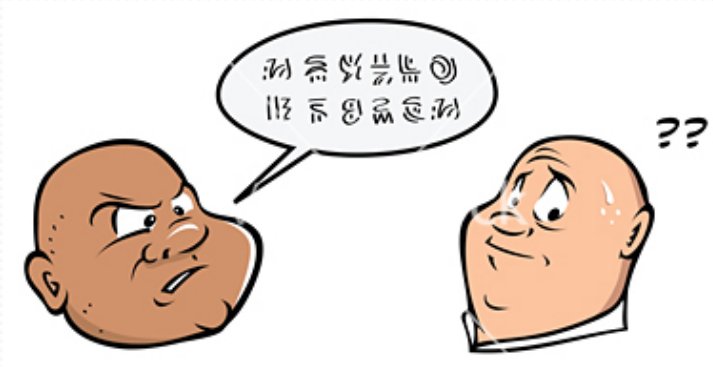
The Key Idea of WEBee



Challenges of Physical-Layer CTC

Modulation: QAM, OFDM
Rate: ~54Mbps (802.11g)
Distance : 300m
Tx : 26dBm
Sensitivity : -80dBm

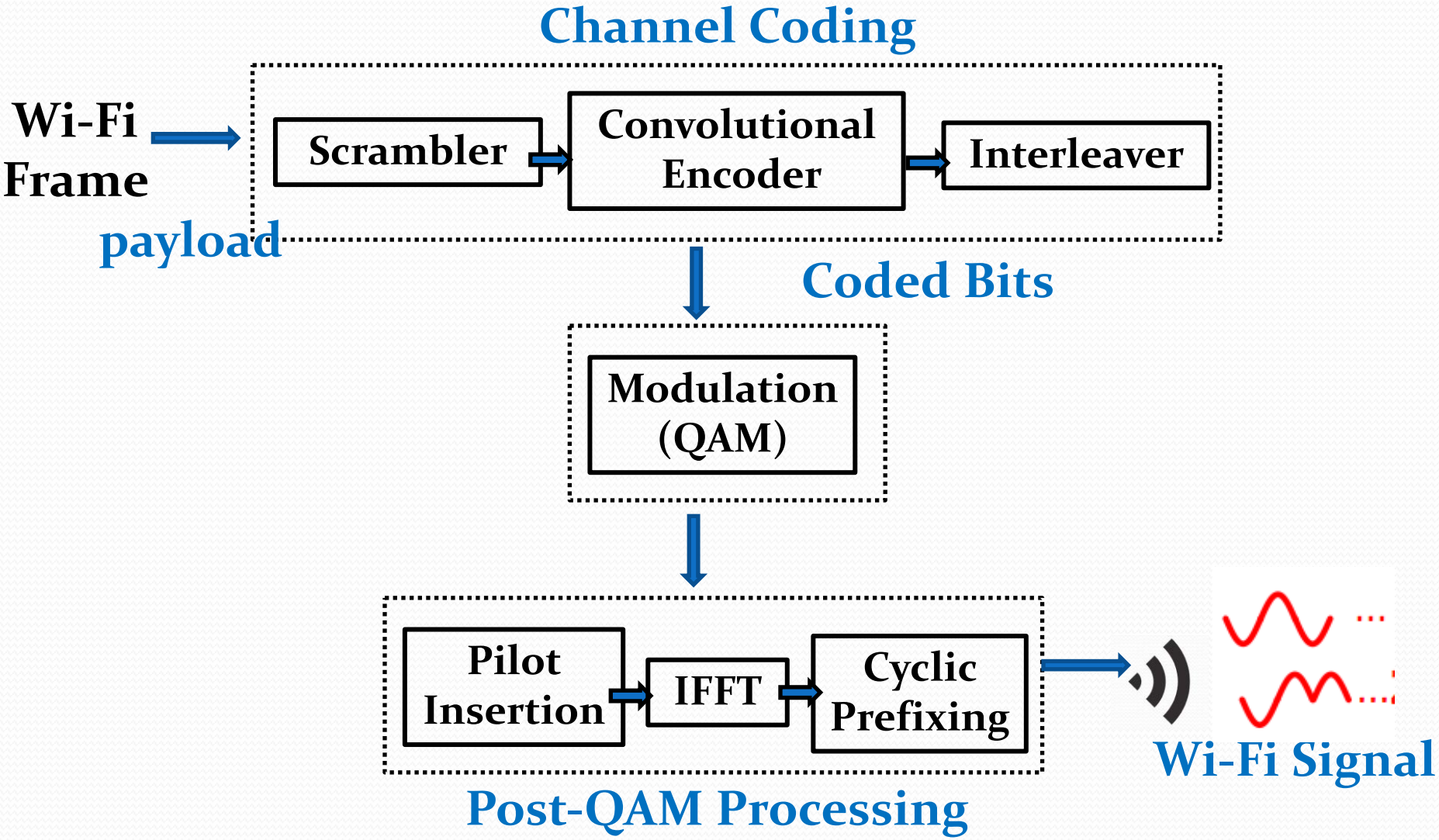
Key Innovation
Signal Emulation
@
Wi-Fi Sender



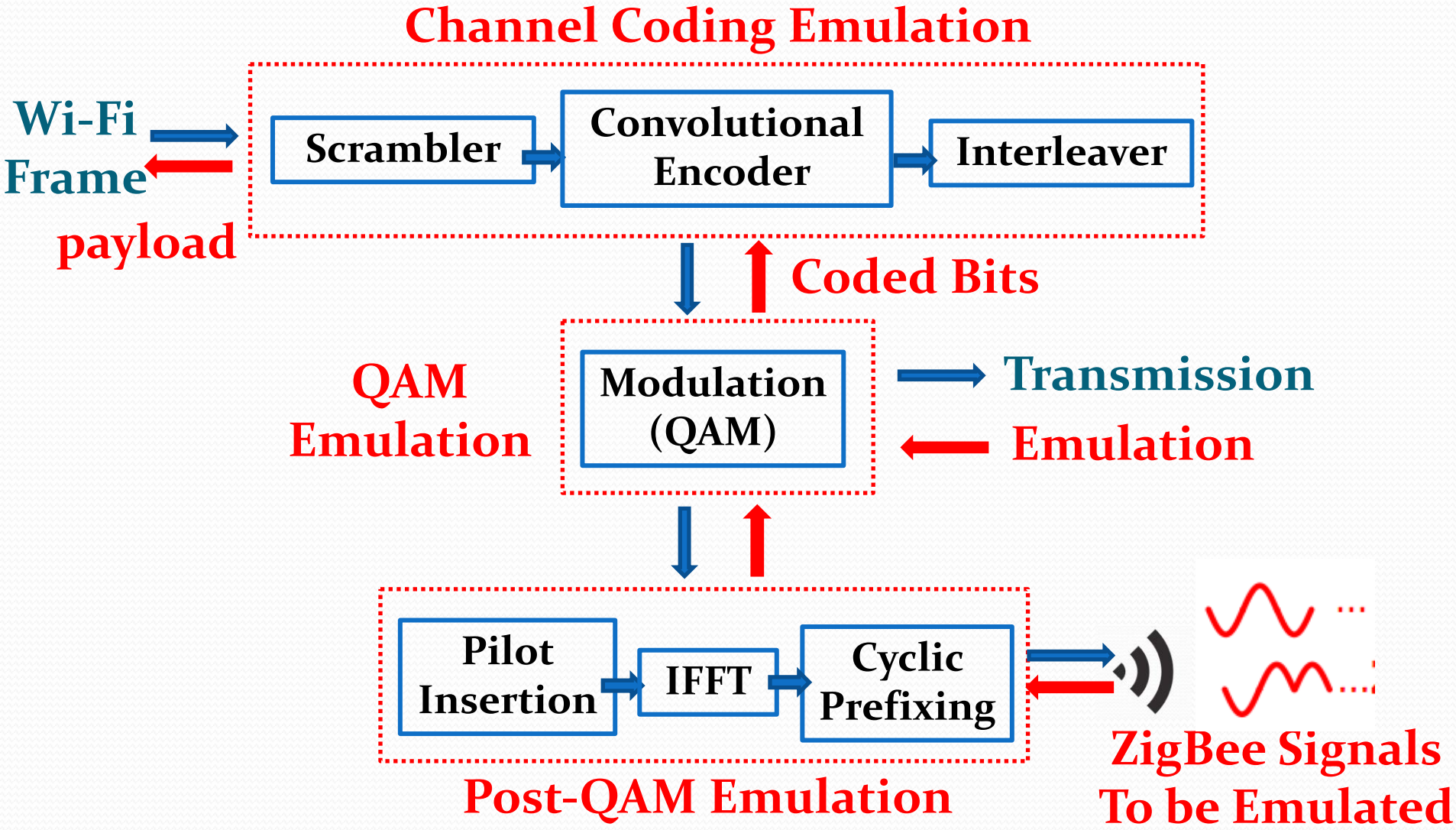
Without translator

Modulation : OQPSK, DSSS
Rate: ~250Kbps
Distance : 100m
Tx : 0dBm
Sensitivity : -97dBm

How Wi-Fi Transmits

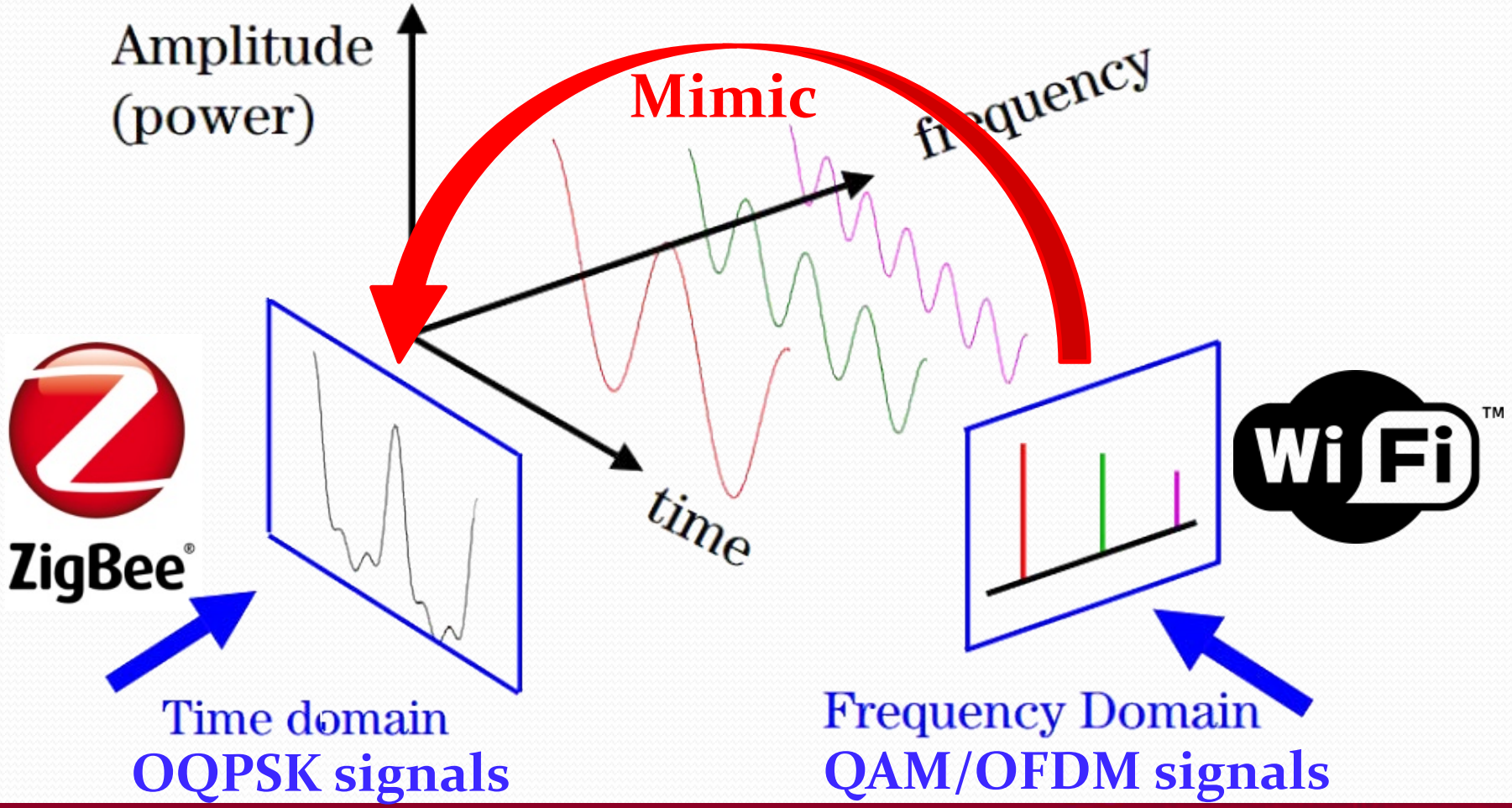


Emulation via a Reverse Path



QAM Emulation

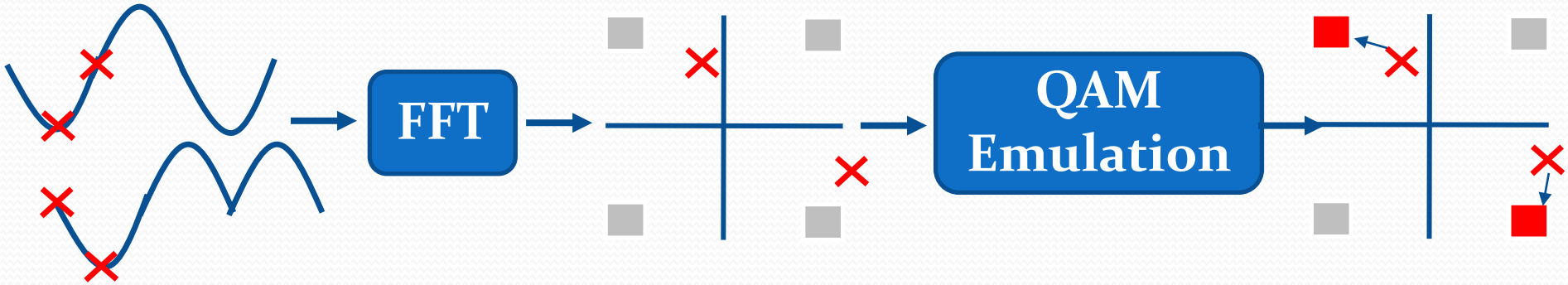
RF Signal Spectrogram in the Air



Minimizing Emulation Distortion

- Minimizing emulation distortion in the time-domain is equivalent to minimizing the total deviation of frequency components (based on Parseval's theorem)

$$\int_{t=-T/2}^{T/2} |u(t) - v(t)|^2 dt = T \sum_k |U[k] - V[k]|^2$$



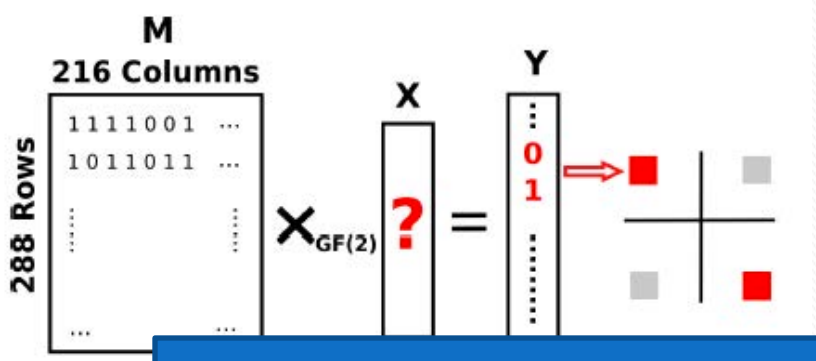
Desired Time-domain ZigBee Signals

Corresponding Frequency-domain Components

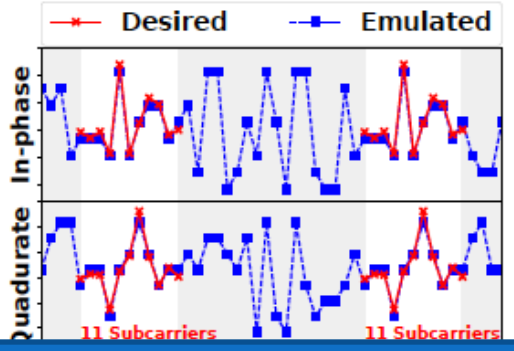
The Closest Wi-Fi QAM Points

Other Technical Challenges

Reverse channel coding

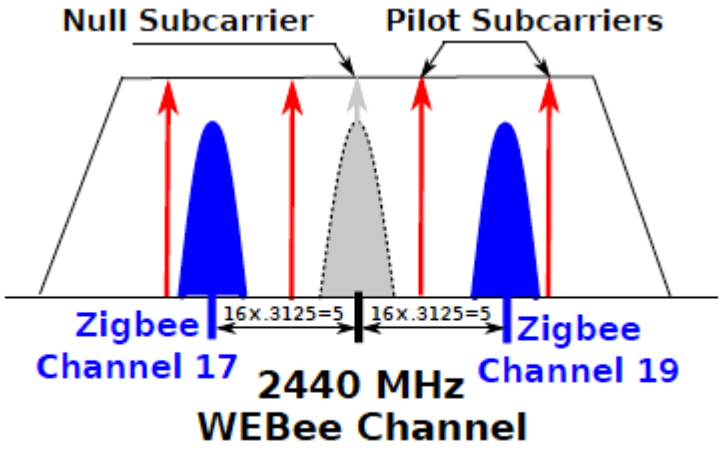


Parallel CTC

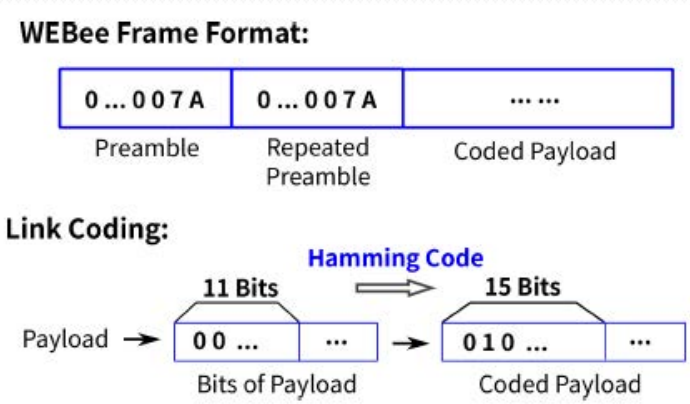


For details, refer to the paper

Pilot/Null avoidance



Link-level reliability



Innovative Features of WEBee

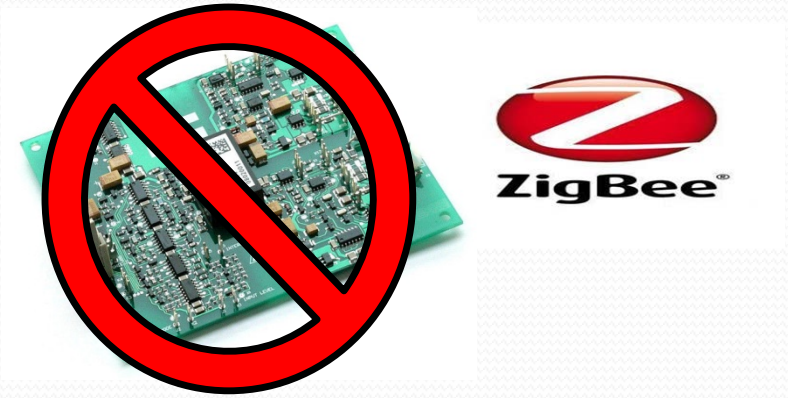
Dual-Standard Compliance

A part of WiFi frame is a Zigbee frame

No change in Sender's Hardware/Firmware

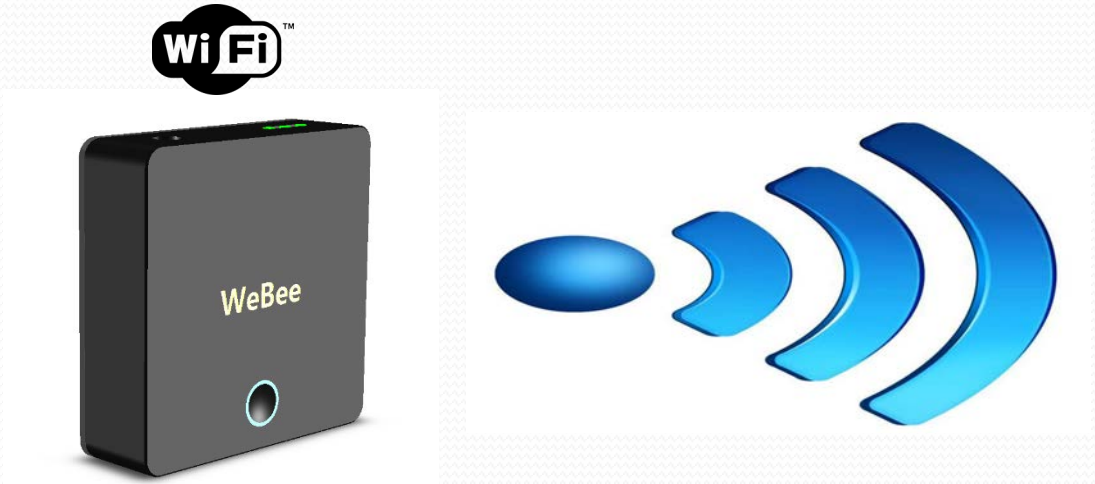
*Send a normal **WiFi** Frame*

No change in receiver's Hardware/firmware



*Receive a normal **ZigBee** Frame*

Combine the advantages of two technologies.



Tx : 26dbm
Sensitivity : -65dbm

Big Mouth

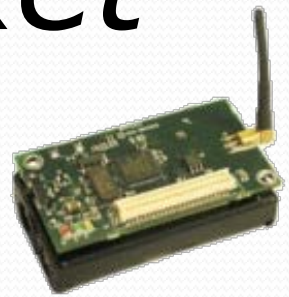
Rx : 0dbm
Sensitivity : -97dbm

Good Ear

WEBee has a longer range than Wi-Fi!

Support parallel CTC in one WIFI Packet

20MHZ

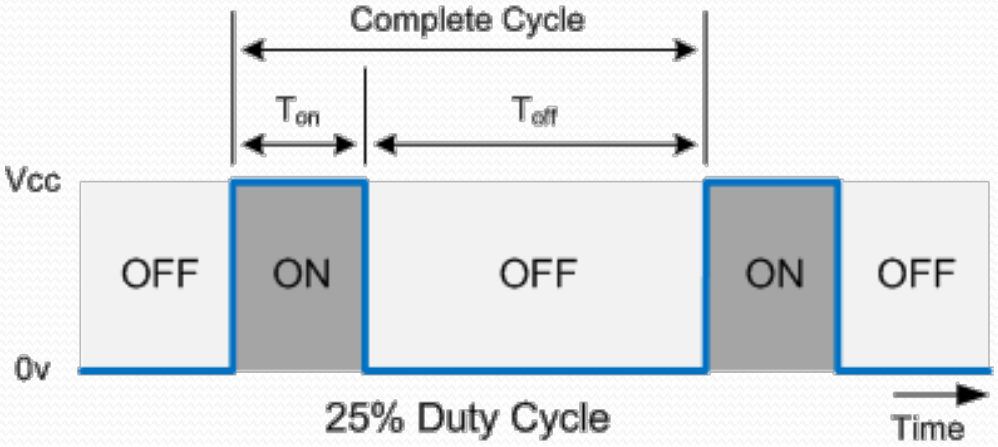


2MHZ

2MHZ

Simultaneous Unicast

Support high mobility and duty cycled operations



Longer Range, better mobility

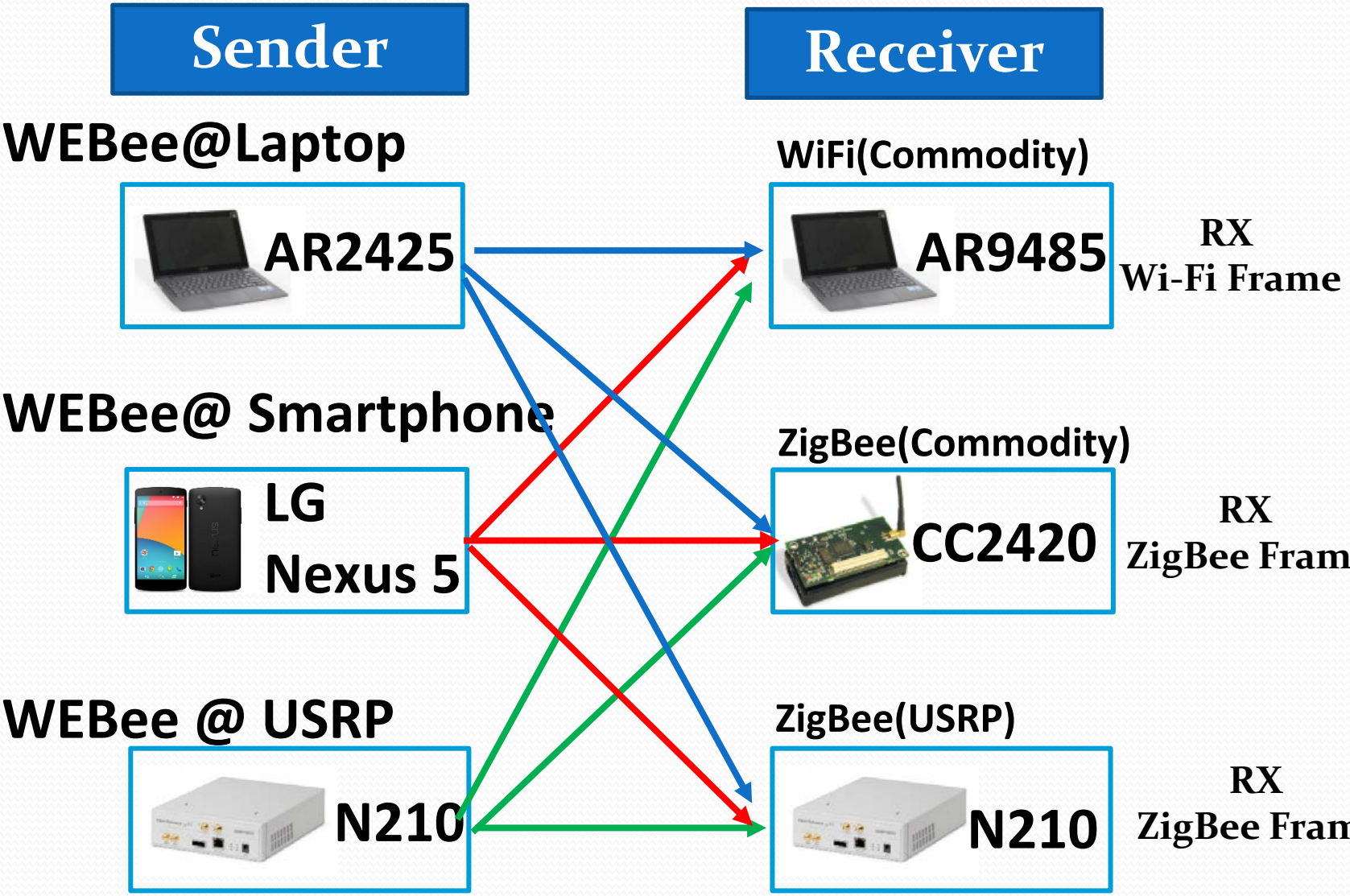
Low Power Listening

An 16,000x faster CTC with 99.9% reliability

For details referring to our mobicom 2017 paper

Implementation & Evaluation

System Implementation



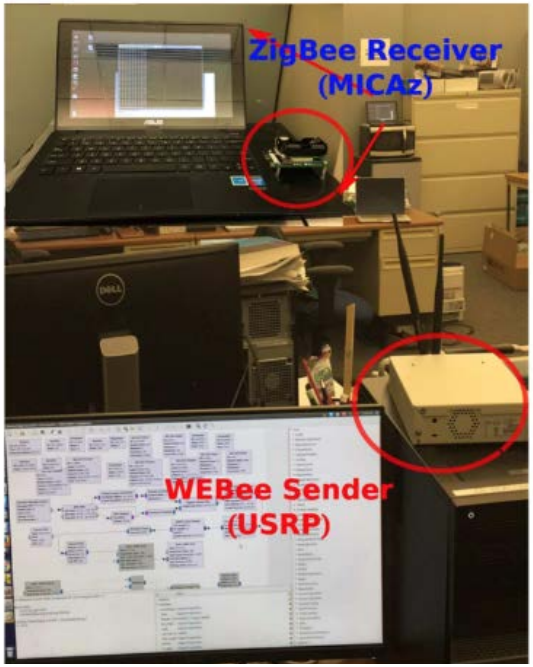
Experimental Setting

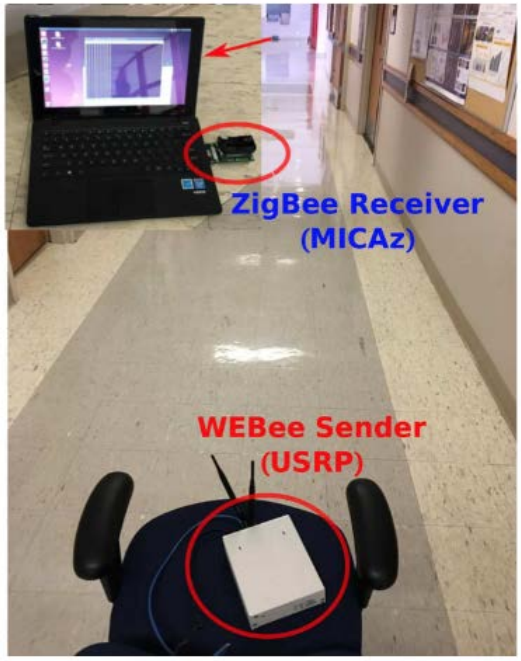
- Lab
- Hallway
- Outdoor

Experiment setting

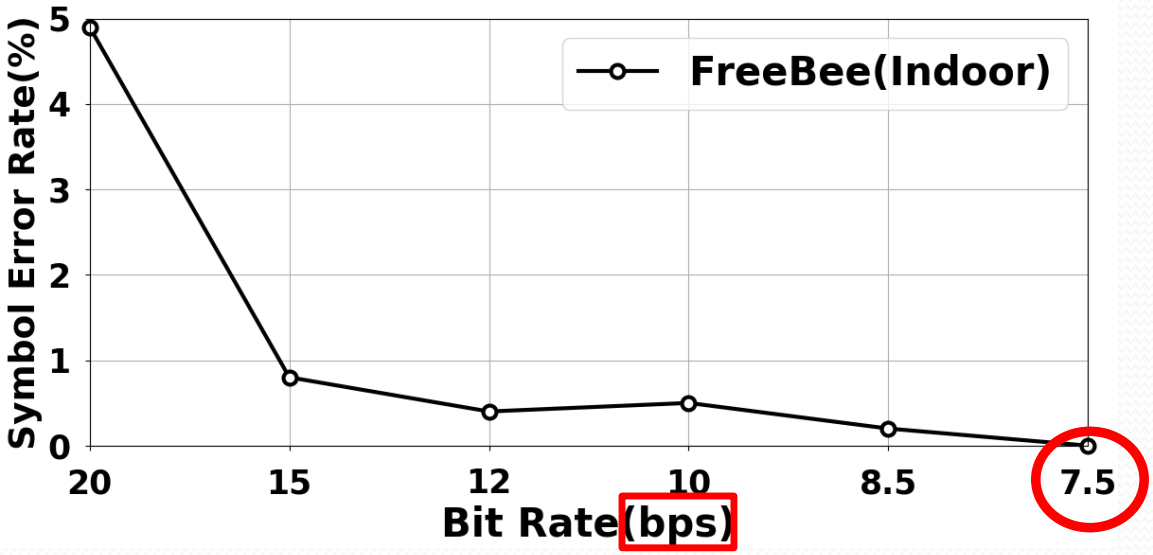
10,000 runs each trial

- Varying distances
- Varying Tx Power
- Varying packet length
- Varying content
- Varying duty-cycle
- Varying Mobility



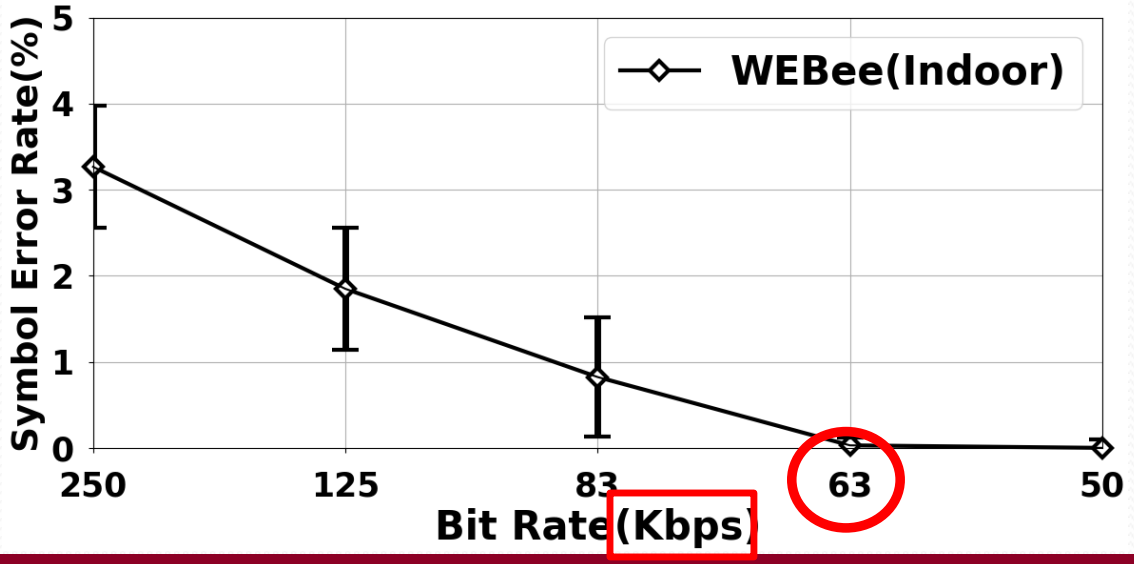


Symbol Error Ratio vs Data Rate



FreeBee [Mobicom '15]

7.5bps @ 99%



WEBee [Mobicom '17]

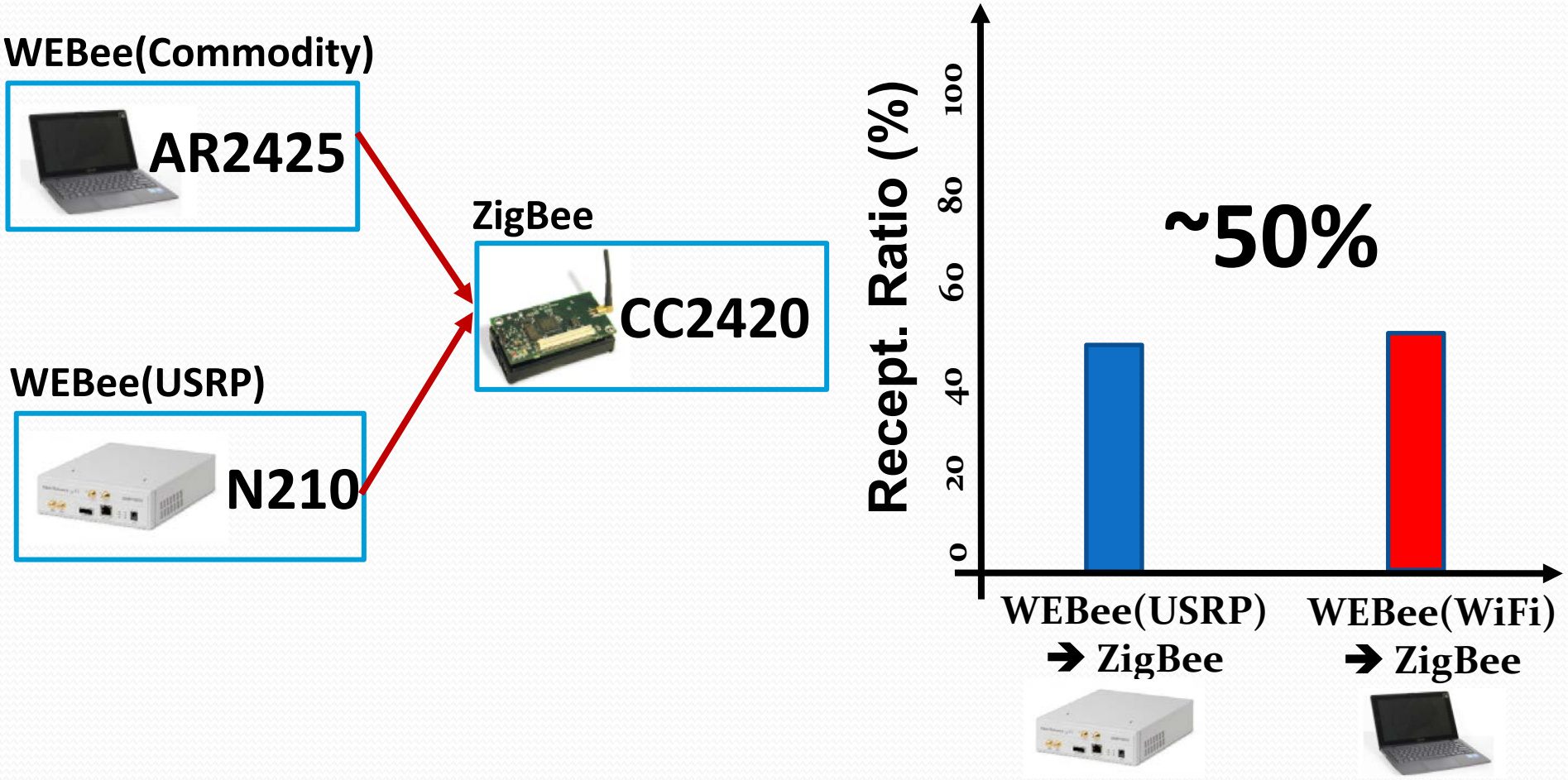
63,000bps @ 99%

~8,000x Speed up

*250kbps theoretically

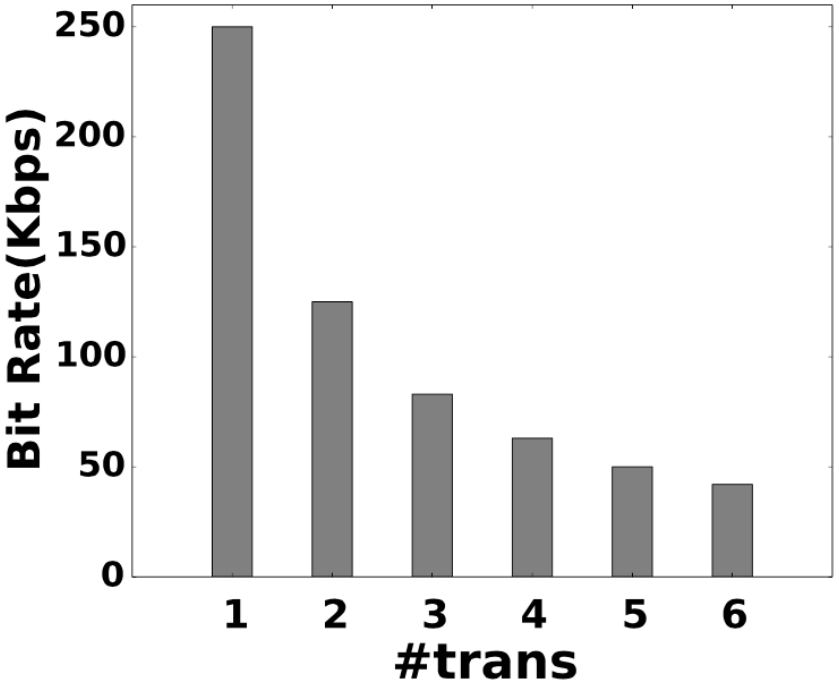
Frame Reception Ratio

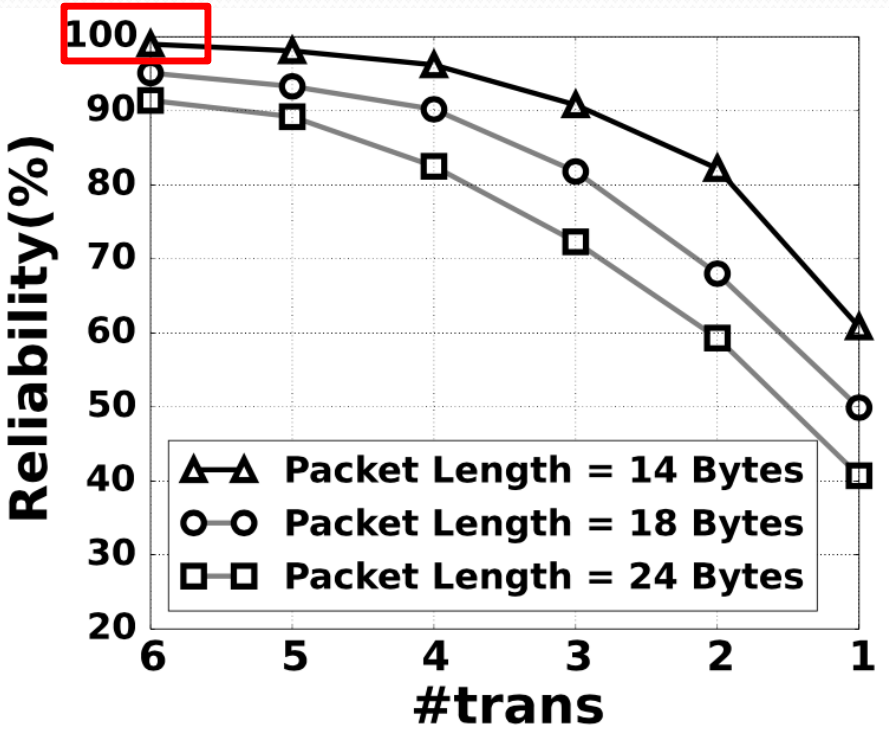
A frame fails with one symbol error



Reliability after Retransmission

99% after 6 retransmissions

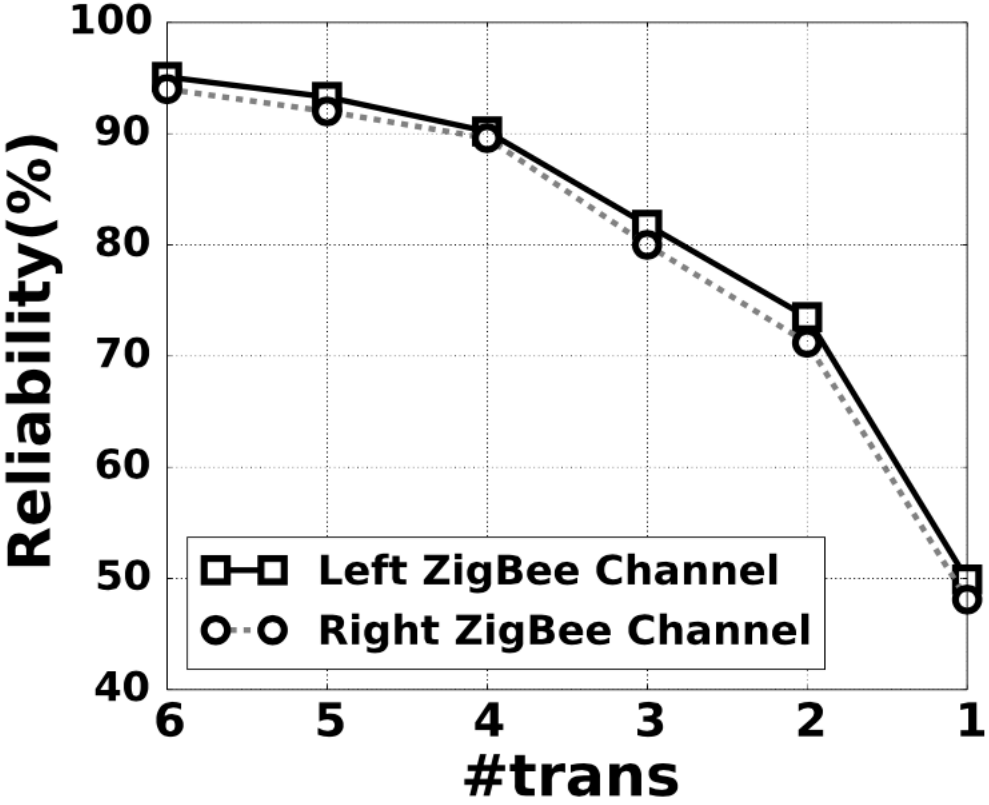


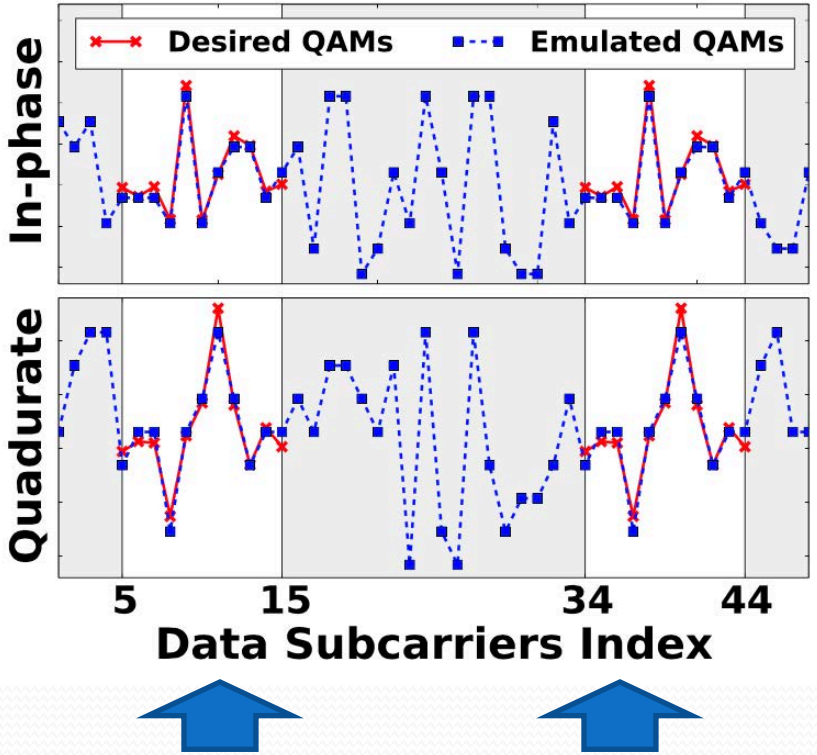


Less re-TX with Repeated preamble and coding

Parallel CTC

With two channels, WEBee vs. FreeBee = ~16,000x

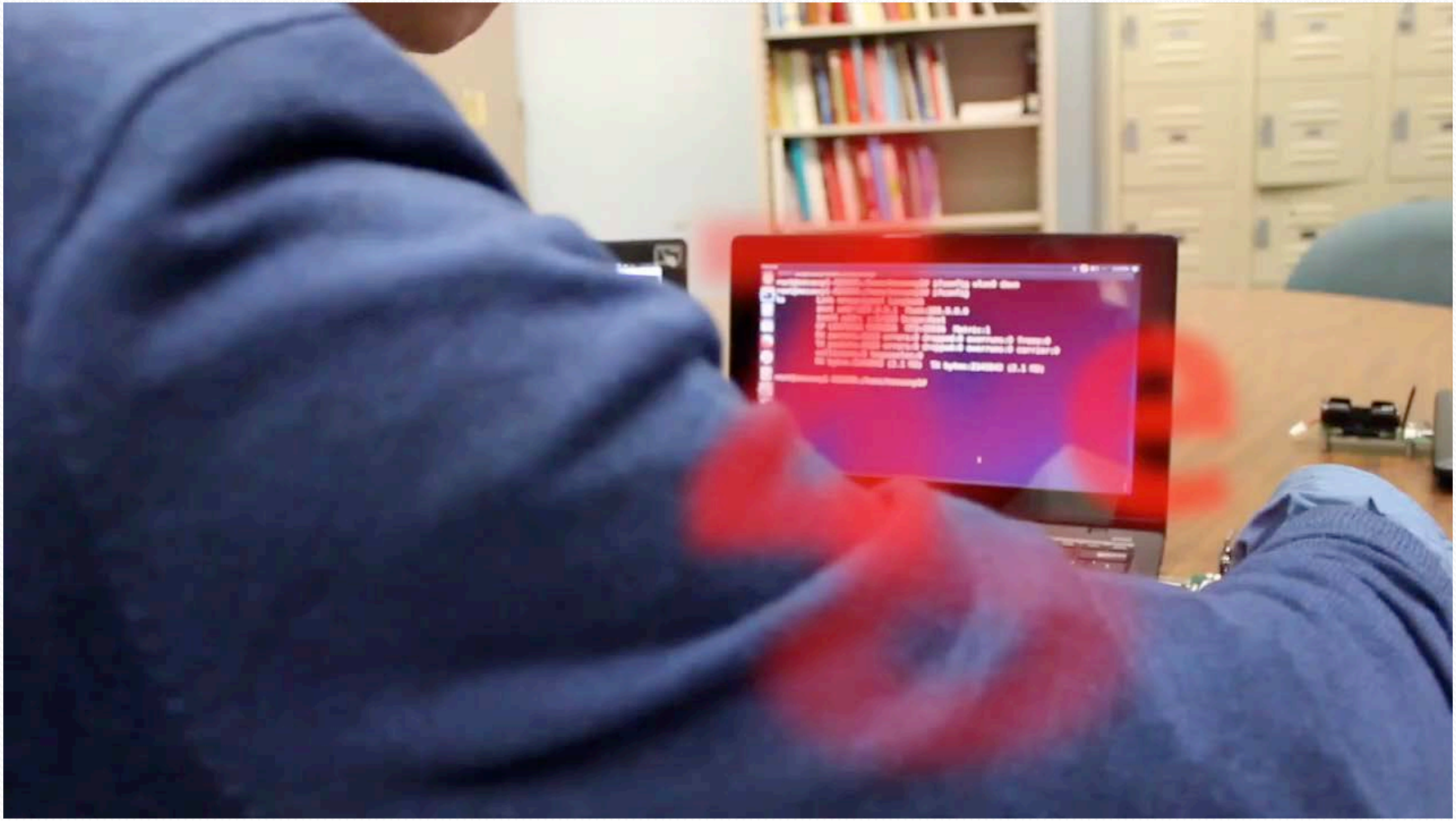




Channel I **Channel II**

WEBee in Action

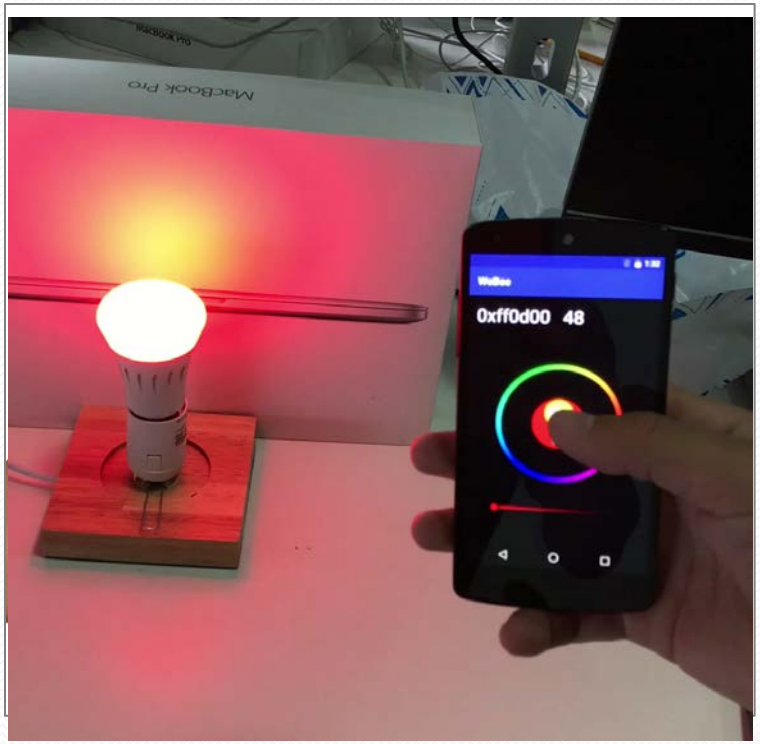
WEBee Demo



Application: Smart Light Control

- You can control ZigBee Smart Bulb with WEBee

Vs.



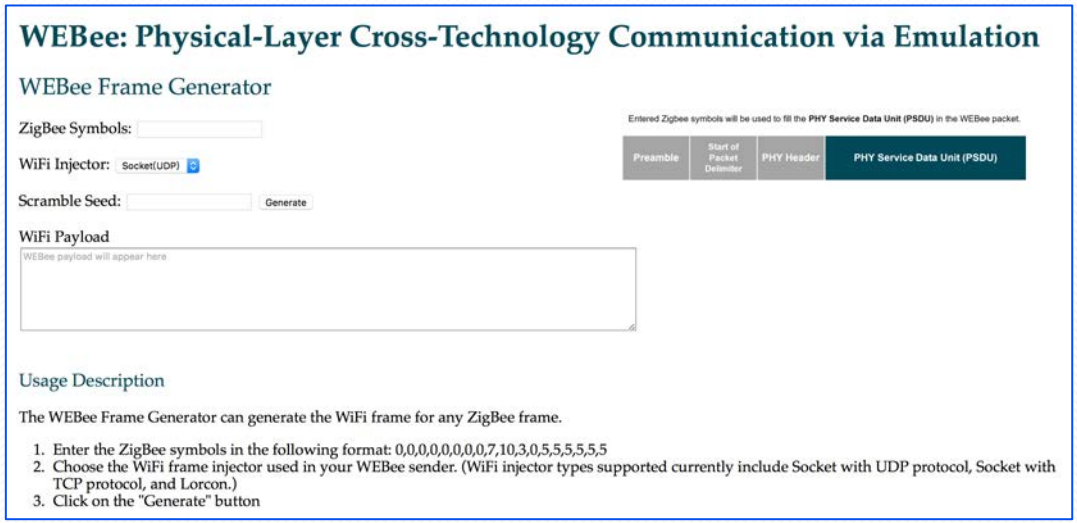
GE Gateway Solution

WeBee Solution

Release: WEBee Payload Generator V1.0

You can conduct cross-technology research using WEBee Generator!

Available at: http://tianhe.cs.umn.edu/CTC



Possible New Topics:

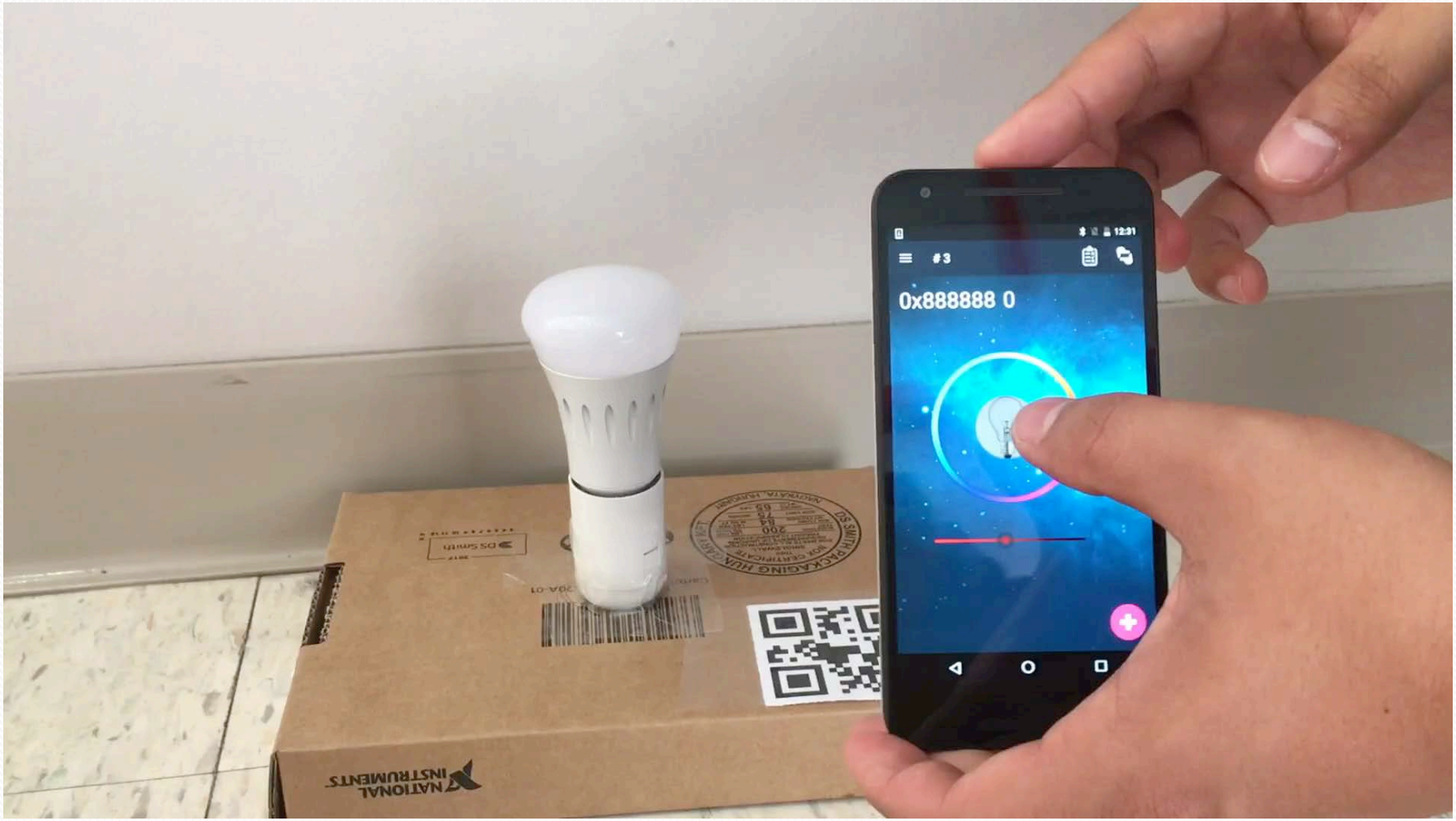
- **Channel Access Control**
- **Coordination**
- **Neighbor Discovery**
- **Multi-Technology Routing**
- **CTC Time Synch.**
- **CTC Localization**
- **.....**

Extension

Question:

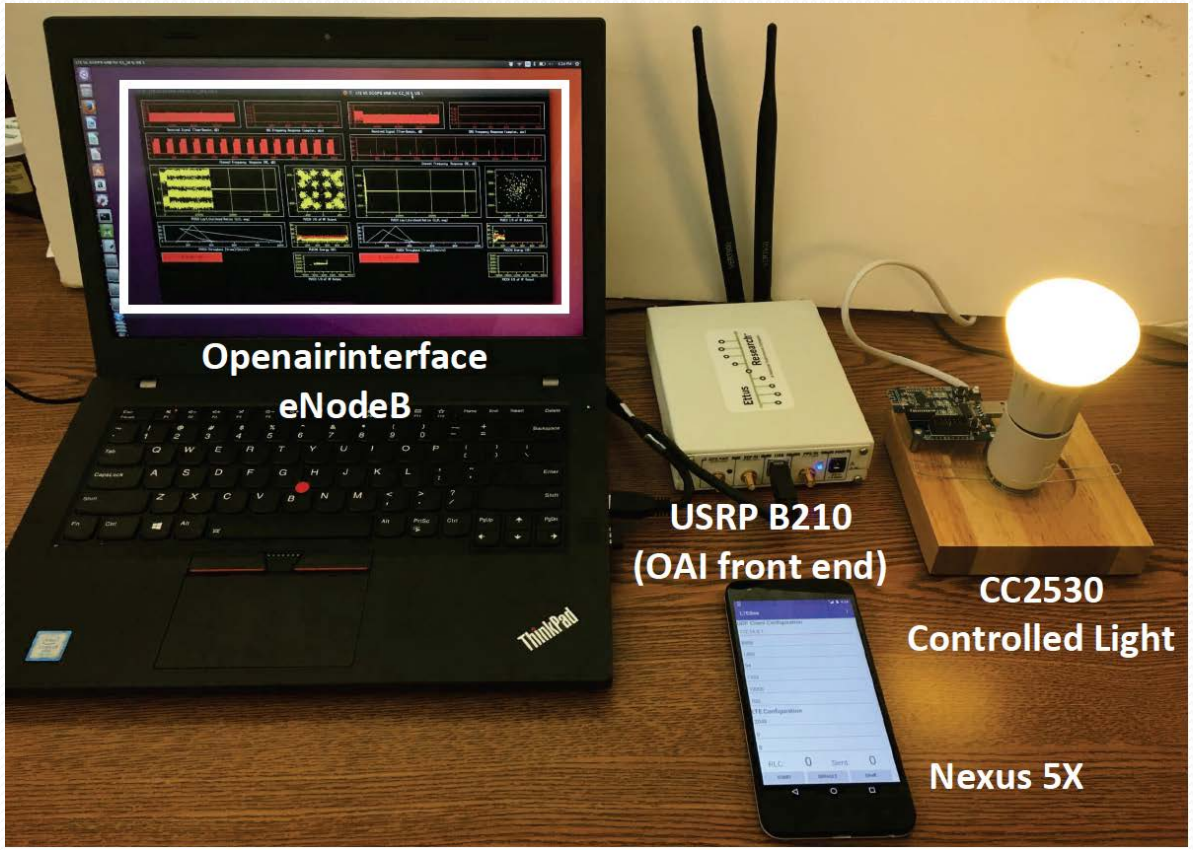
Whether Signal Emulation is a generic technology?

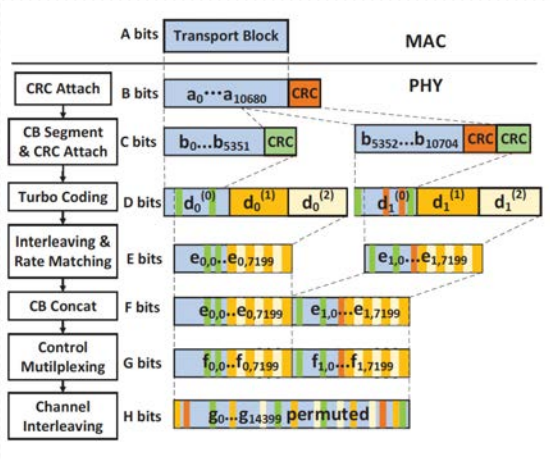
BlueBee: BlueTooth to ZigBee [SenSys '17]

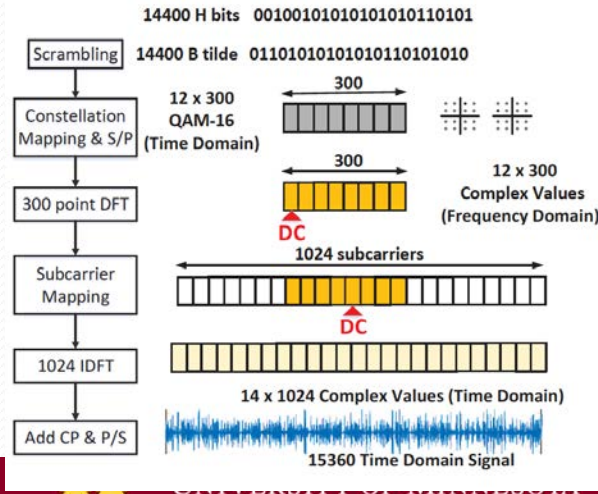


LTEBee: LTE (band 7) to ZigBee

- LTE smartphone controls a CC2530 ZigBee Blub directly after 7-layers channel coding and 6-step modulation.







Conclusion

- WEBee is the first physical-layer CTC design, a paradigm shift with a significantly higher throughput, while requiring no change of HW.
- Our work indicates Signal Emulation is a generic technology to build light-weight SDR, striking a delicate balance between flexibility and cost.
- Our work brings a surge of opportunities to expand many local wireless mechanisms globally (e.g., coordination, discovery, etc.) across technologies.

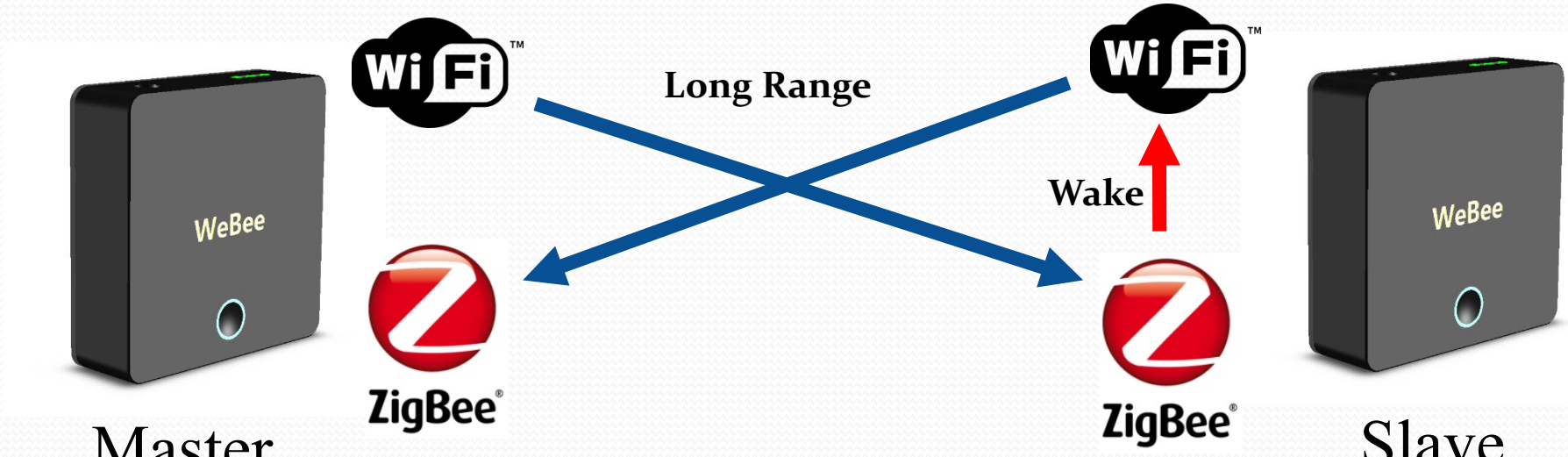
Thank you!!

Questions?

CTC Technical Support is available at

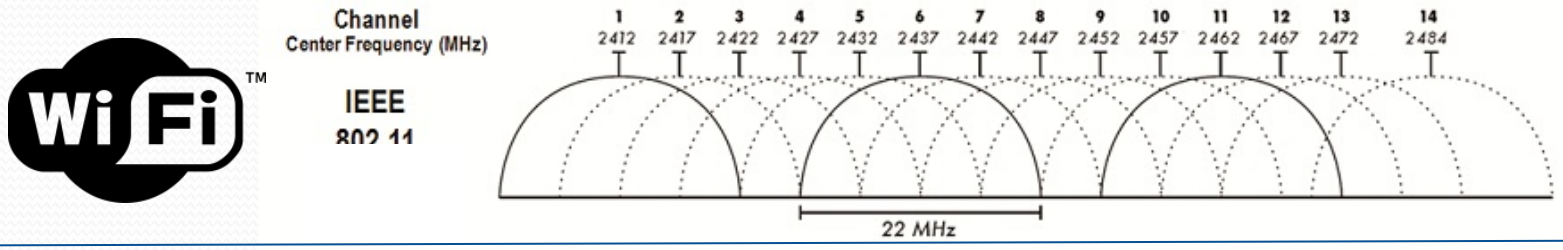
http://tianhe.cs.umn.edu/CTC

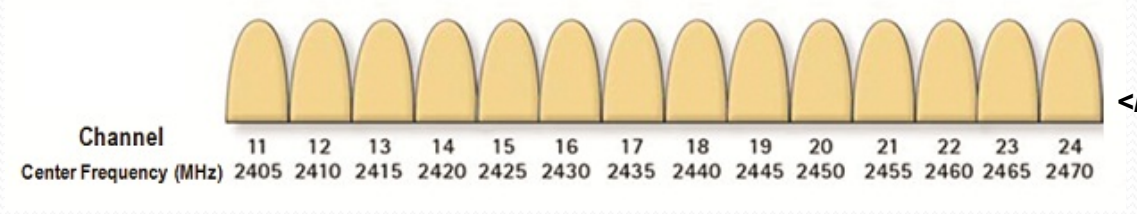
Can support two-way



Opportunity for Cross-Tech.-Comm.

- Wireless technologies share unlicensed ISM bands, offering opportunity for cross-tech. communication





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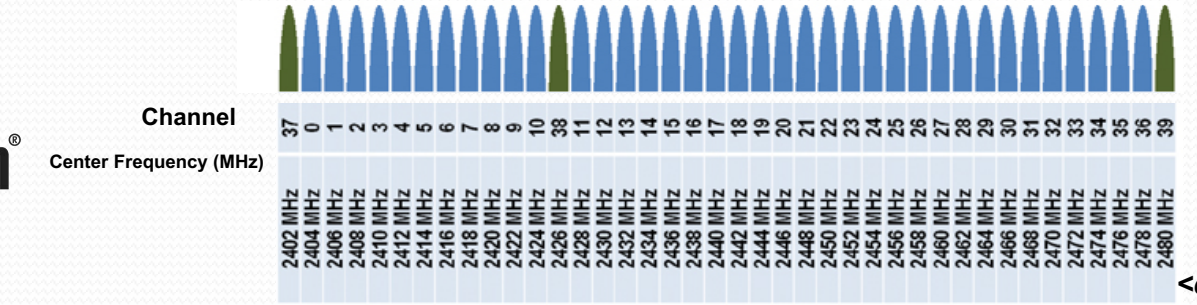

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2.4G ISM

Channel Mapping

- OFDM Has 64 subcarrier, 48 data, 12 null and 4 pilot

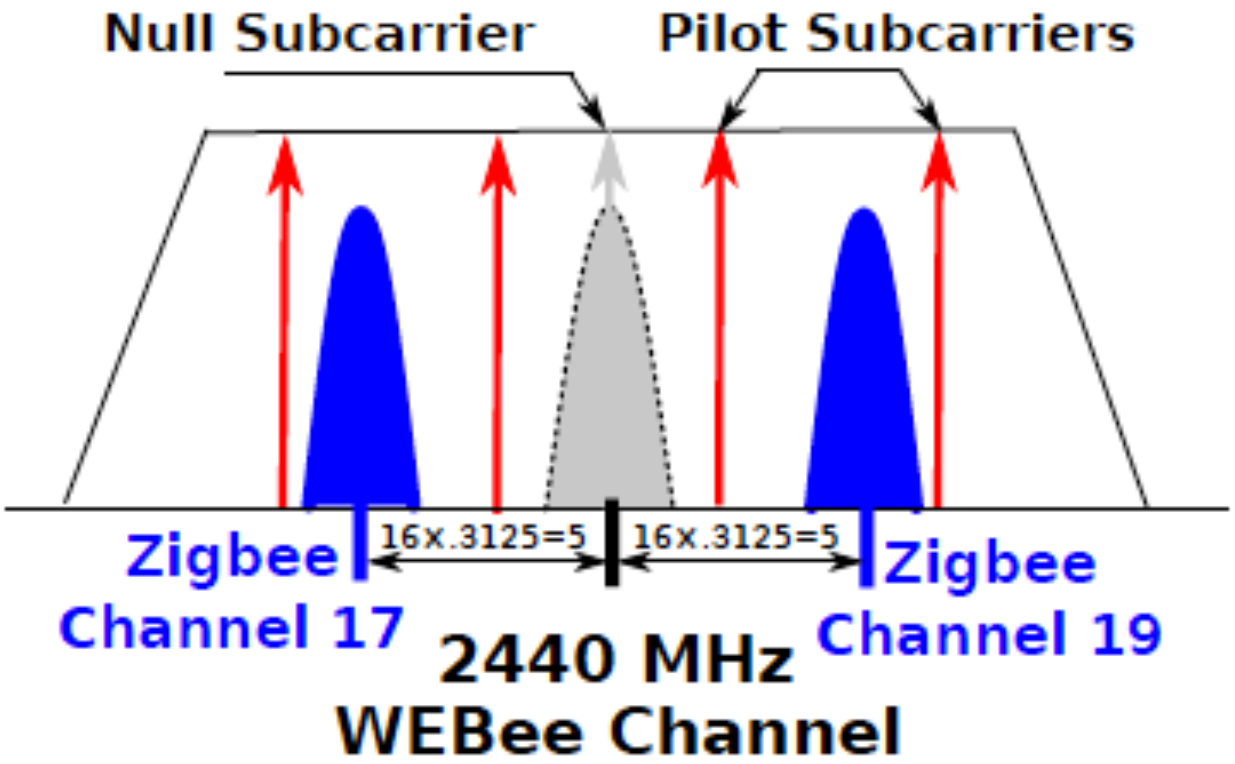

Figure 9: Channels Mapping for Pilot Avoidance

Four-to-one emulation

- Four Wi-Fi symbols are used to emulate one ZigBee symbol

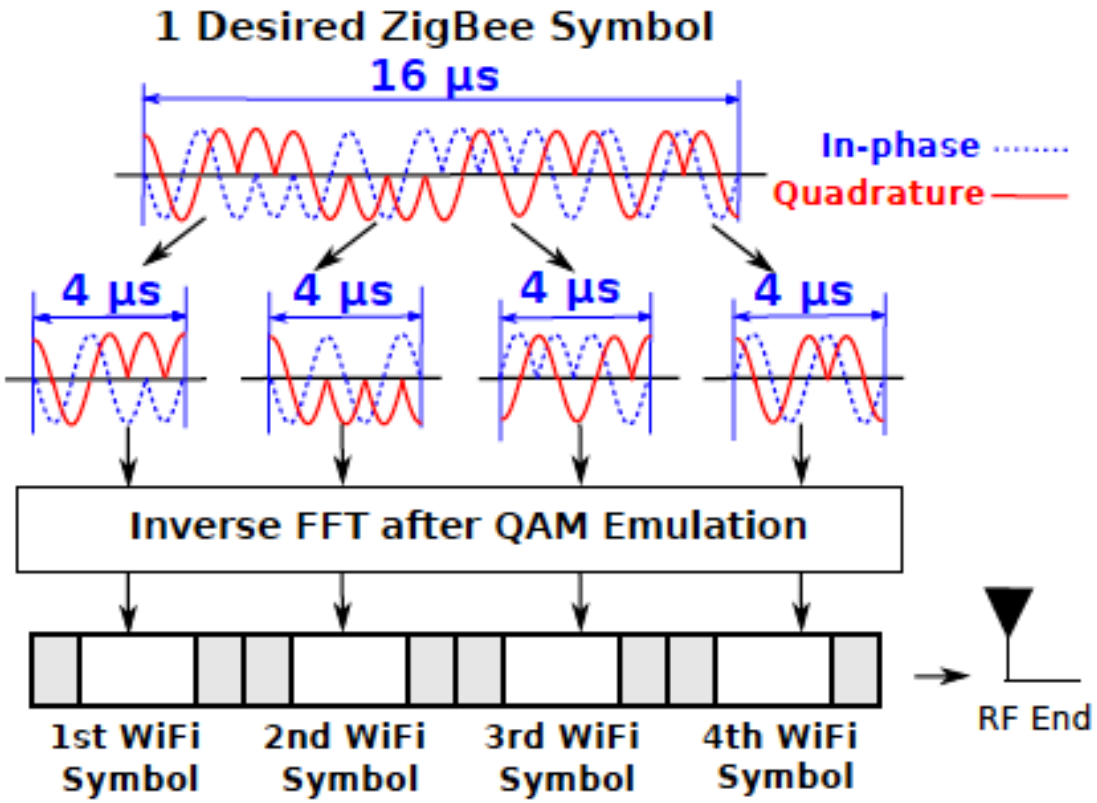

Figure 10: Emulate OQPSK with WiFi QAM.

Link Layer Reliability

- Repeated preamble and hamming coding

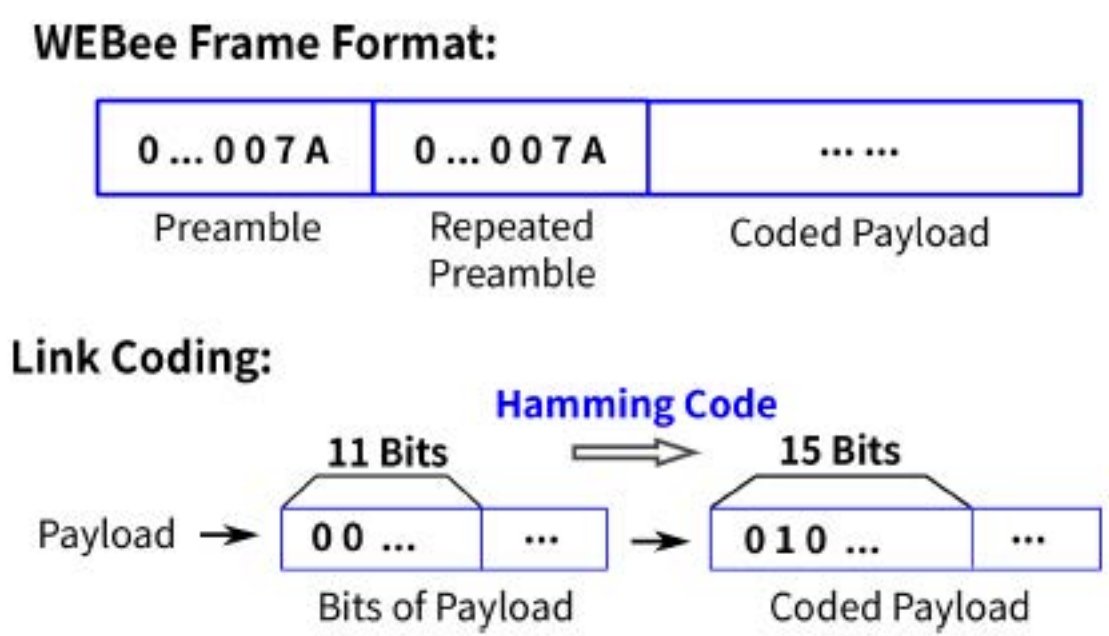

Figure 14: Reliable CTC with Link Coding