

CS 439: Wireless Networking

MAC Layer – Bluetooth

Bluetooth

- ▶ Harald Blaatand
“Bluetooth” II
 - ▶ King of Denmark 940-981 AC
 - ▶ Runic stones in his capital city of Jelling
 - ▶ The stone’s inscription (“runes”) says:
 - ▶ Harald Christianized the Danes
 - ▶ Harald controlled the Danes
 - ▶ Harald believes that devices shall seamlessly communicate [wirelessly]



Classic Bluetooth

- ▶ **Cable replacement**

- ▶ 2.4 GHz

- ▶ FHSS over 79 channels (of 1MHz each), 1600hops/s

- ▶ 1Mbps

- ▶ Upgraded to 1 or 2 Mbps in 5.0

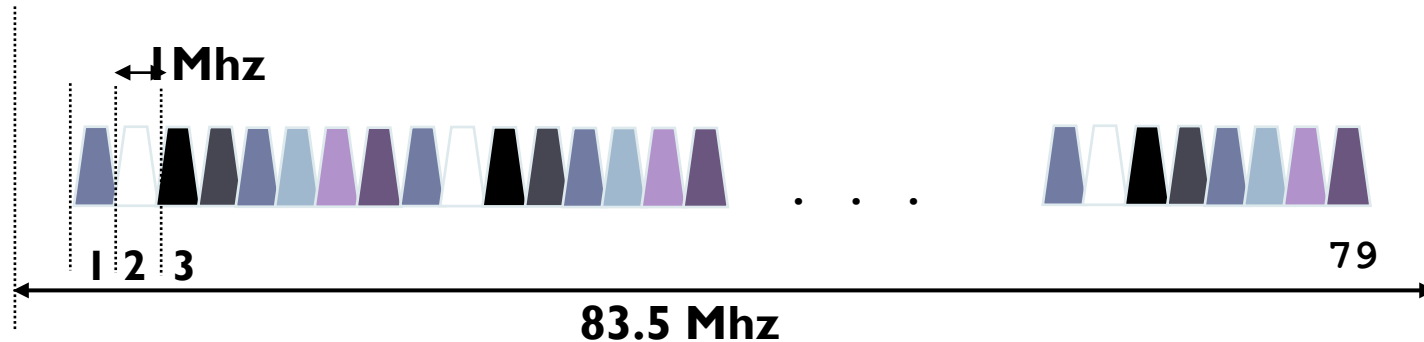
- ▶ Coexistence of multiple piconets

- ▶ 10 meters (extendible to 100 meters)

- ▶ Max Tx Power 10dB (extendible to 20dB in 5.0)



Bluetooth Radio



- ▶ MA scheme: Frequency hopping spread spectrum.
 - ▶ $2.402 \text{ GHz} + k \text{ MHz}$, $k=0, \dots, 78$
 - ▶ 1,600 hops per second.
 - ▶ 1 Mbps data rate.

- ▶ Upgraded to 2 Mbps in BT 5.0

Bluetooth Network Topology

▶ Radio designation

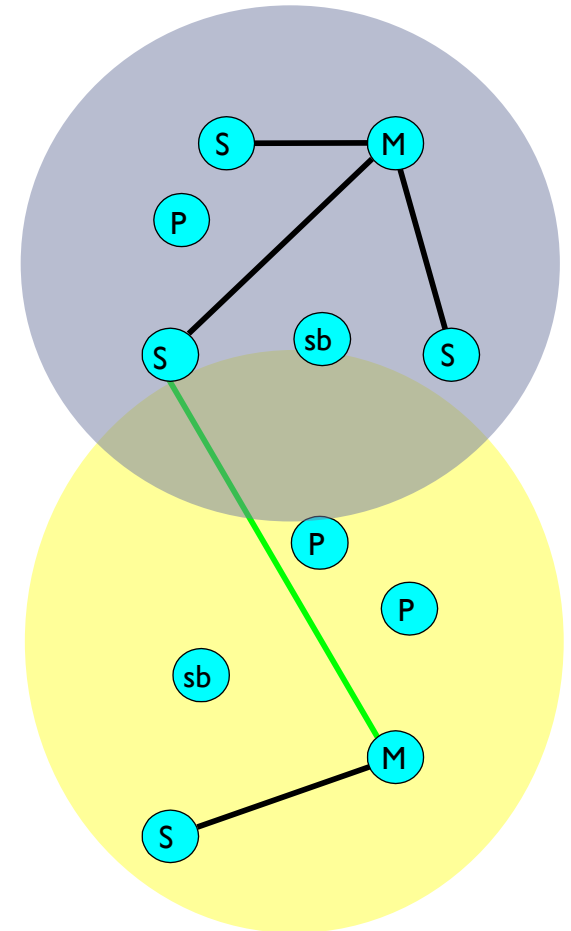
- ▶ Connected radios can be master or slave
- ▶ Radios are symmetric (same radio can be master or slave)

▶ Piconet

- ▶ Master can connect to 7 simultaneous or 200+ inactive (parked) slaves per piconet
- ▶ Each piconet has maximum capacity (1 Mbps)
- ▶ Unique hopping pattern/ID

▶ Scatternet

- ▶ High capacity system
- ▶ Minimal impact with up to 10 piconets within range
- ▶ Radios can share piconets!



Bluetooth – Contention-free MAC

- ▶ **Master performs medium access control**
 - ▶ Schedules traffic through polling.
- ▶ **Time slots alternate between master and slave transmission**
 - ▶ **Master-slave**
 - ▶ Master includes slave address.
 - ▶ **Slave-master**
 - ▶ Only slave chosen by master in previous master-slave slot allowed to transmit.
 - ▶ If master has data to send to a slave, slave polled implicitly; otherwise, explicit poll.



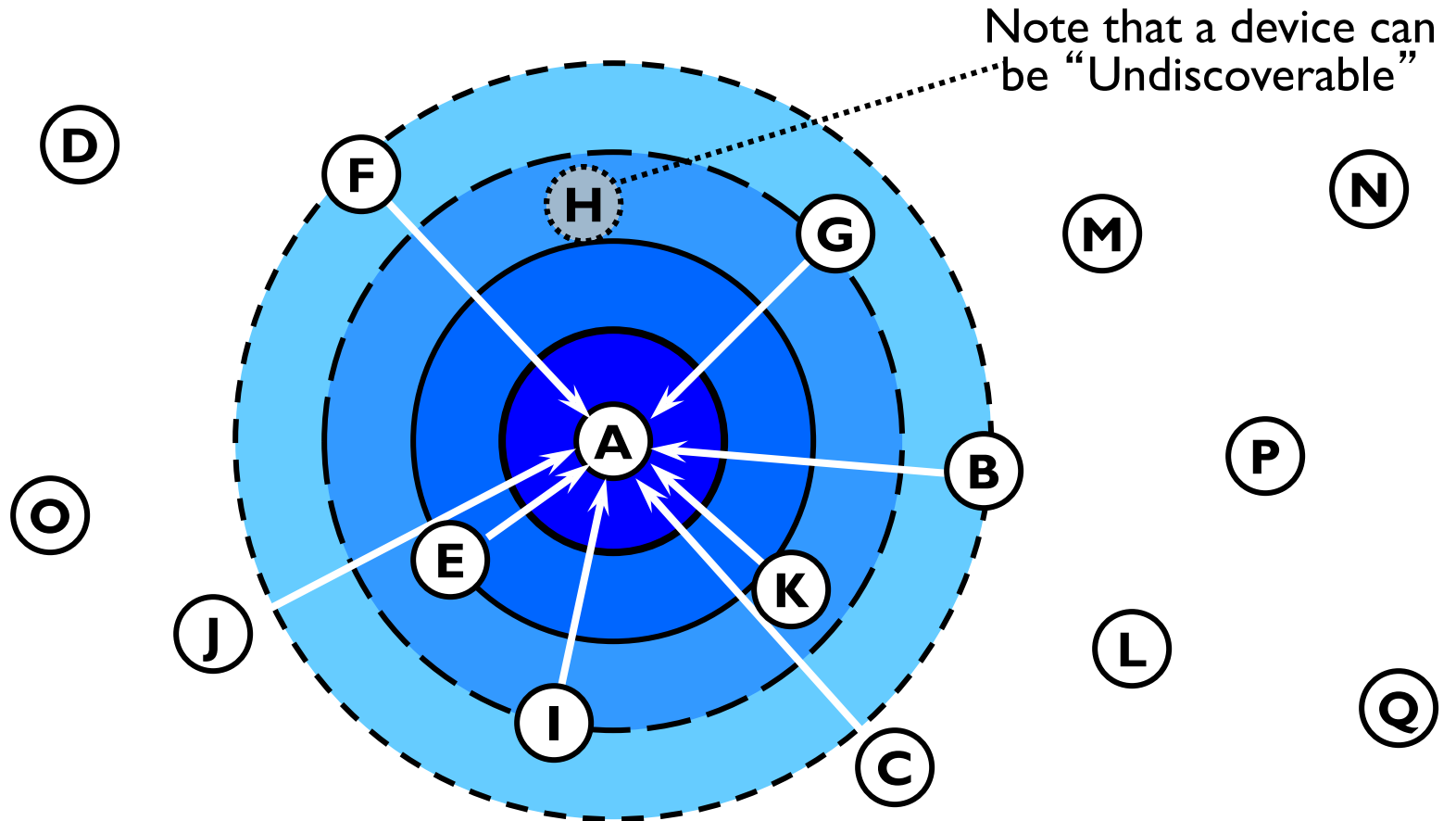
Bluetooth Device Discovery - Inquiry

▶ Device discovery

- ▶ Sends out an inquire, which is a request for nearby devices (within 10 meters)
- ▶ Devices that allow themselves to be discoverable issue an inquiry response
- ▶ Listeners respond with their address
- ▶ Can take up to 10.24 seconds, after which the inquiring device should know everyone within 10 meters of itself



Bluetooth Device Discovery - Inquiry



10 meters

After inquiry procedure, A knows about others within range

Bluetooth Inquiry

▶ Sender

- ▶ Inquiry sent on 16 different frequencies
- ▶ 16 channel train
 - ▶ about 1.28 seconds per channel
 - ▶ One full 16 channel train takes 10ms

▶ Receiver (device in standby mode)

- ▶ Scans long enough for an inquiring device to send the inquiry on 16 frequencies
- ▶ Scan must be frequent enough to guaranteed wake up during a 16 channel train
 - ▶ Enters inquiry scan state at least once every 1.28 seconds, and stays in that state for 10ms



Bluetooth Inquiry - Reliability

▶ Challenge

- ▶ Noisy channels
- ▶ Lost packets
 - ▶ Train scan is repeated up to 4 times for each train (10.24 seconds)
 - ▶ Designed to successfully communicate at least once with all devices within range



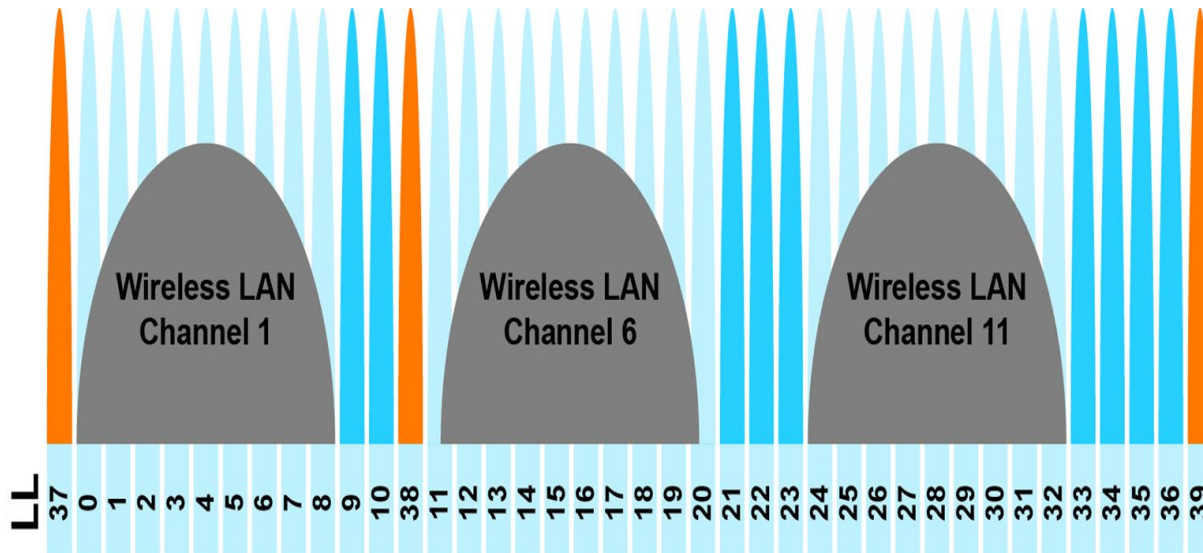
BLE Highlights

- ▶ Shared wireless channel
 - ▶ BLE operates in the 2.4 GHz ISM band with Wi-Fi and other technologies (phones, microwave ovens ...)
- ▶ BLE = Bluetooth Low Energy
 - ▶ Improved discovery
 - ▶ Key component: Beacons
 - ▶ Tags send out advertising beacons (typ. dist 30ft)
 - ▶ Phones scan for beacons



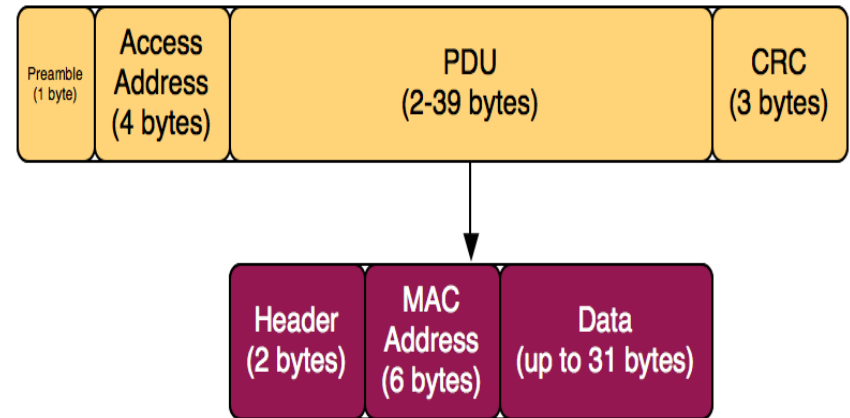
BLE Highlights: Channel Use and Coexistence with Wi-Fi

- ▶ **Separate advertising and connected channels**
 - ▶ Key: Three disjoint advertising channels (37, 38, 39)
 - ▶ Positioned between Wi-Fi channels (1, 6, 11)



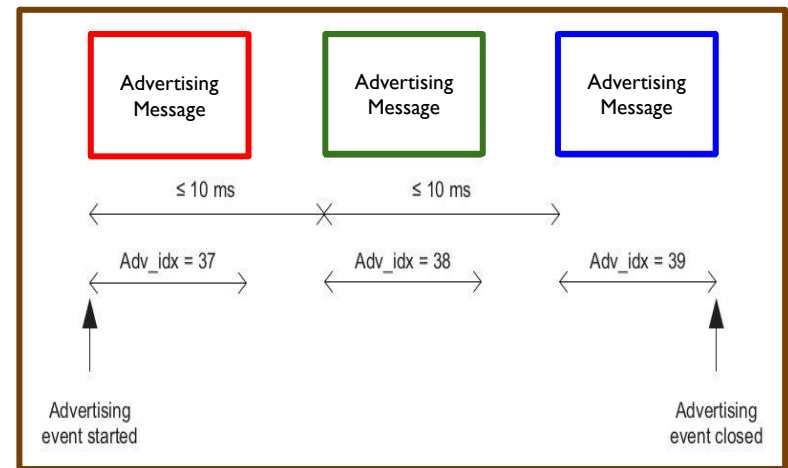
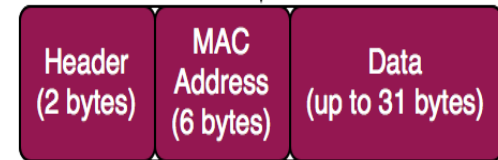
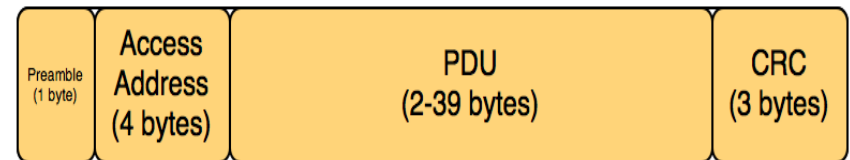
BLE Highlights: Advertising

- ▶ Advertising Tags
- ▶ Advertising Messages
 - ▶ Header + MAC Address + up to 31 Bytes of data
 - ▶ ~200 - 400 usec per packet
 - ▶ Two types: Non-scannable, Scannable



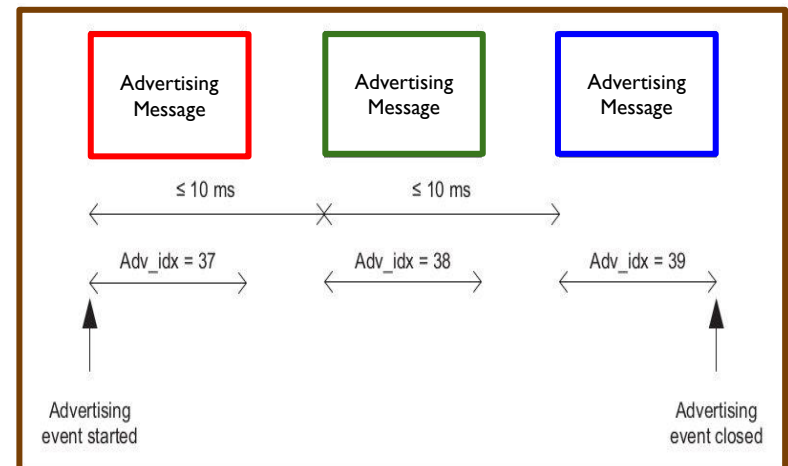
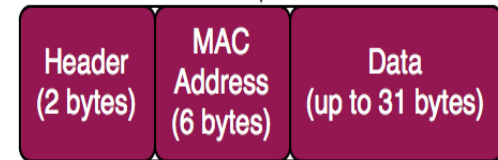
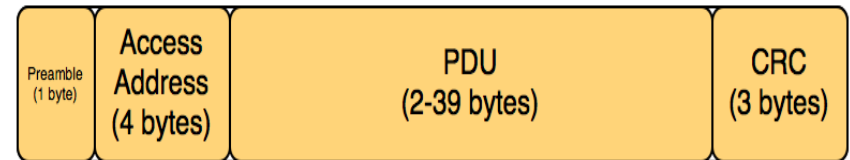
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- ▶ Advertising Event
 - ▶ One advertising message sent out on each advertising channel (37, 38, 39)

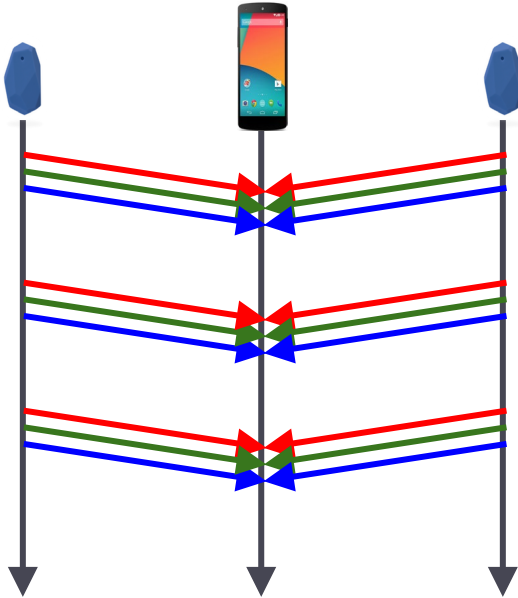


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 - ▶ Two types: Non-scannable, Scannable
- ▶ Advertising Event
 - ▶ One advertising message sent out on each advertising channel (37, 38, 39)
- ▶ Advertising Interval
 - ▶ One advertising event per advertising interval
 - ▶ e.g., every 1 sec or 100 msec

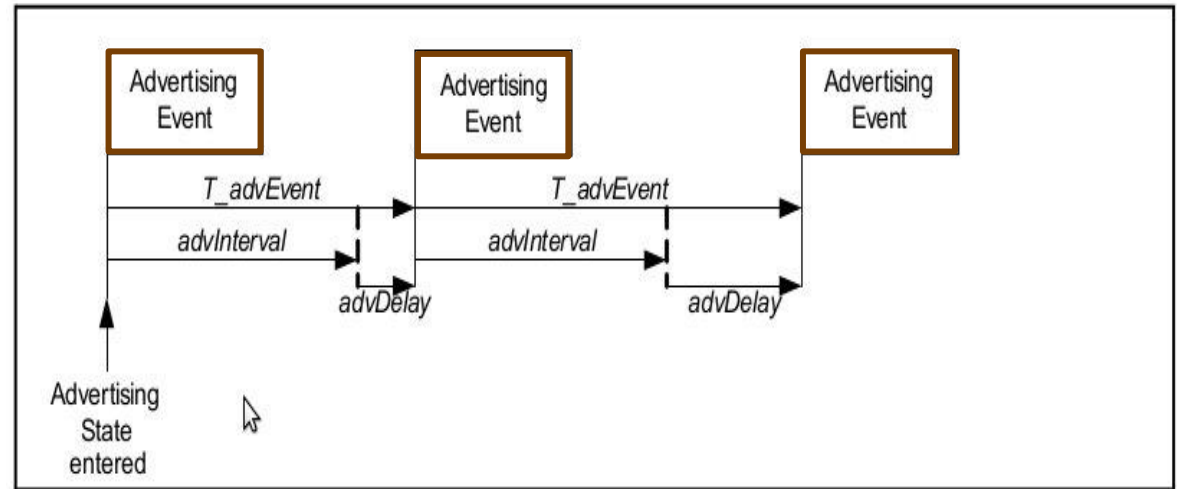
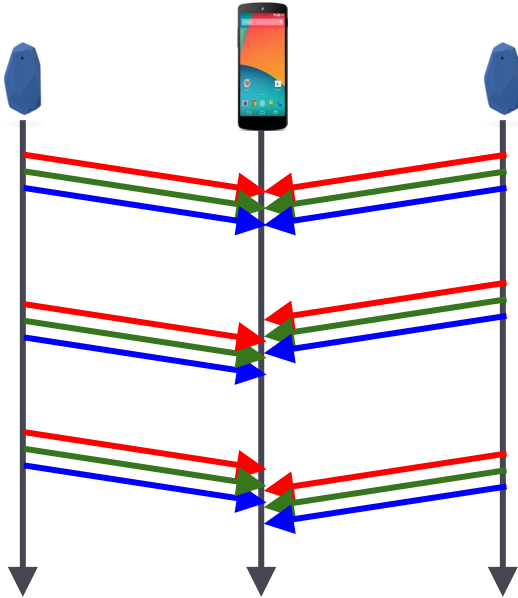


BLE Highlights: Advertising and Collisions



- ▶ If tags get synchronized, all advertising messages will collide

BLE Highlights: Advertising and Collisions

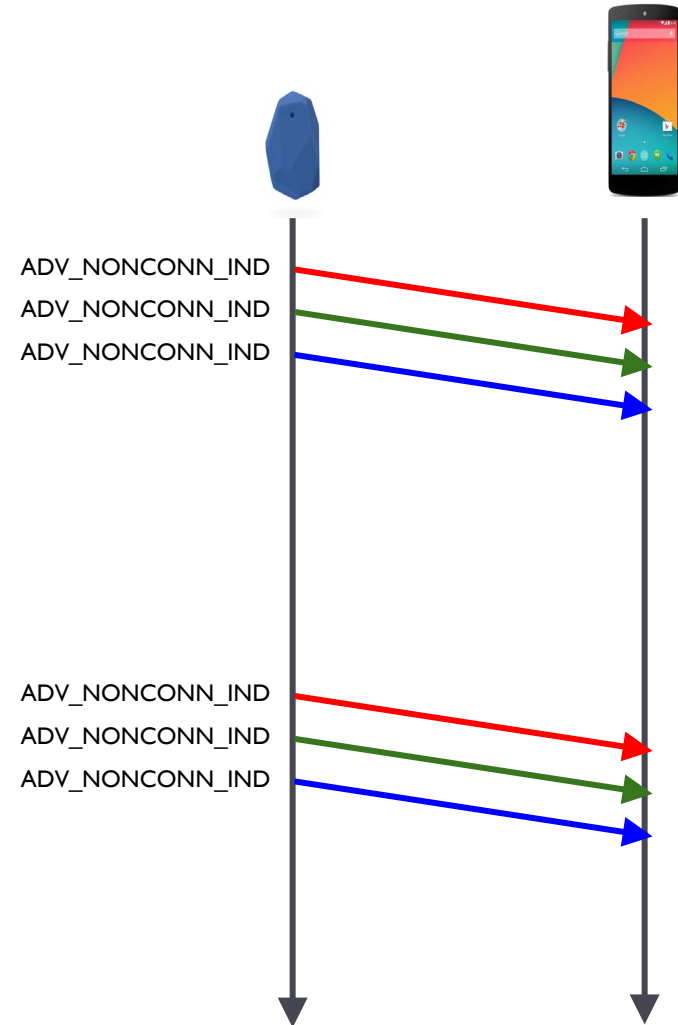
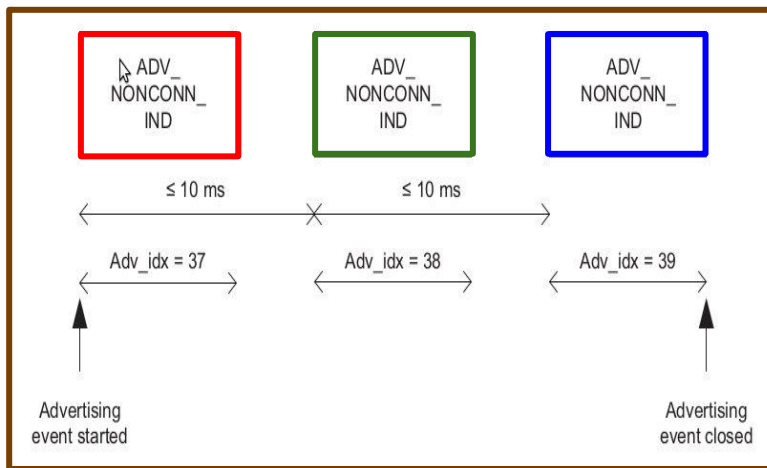


▶ Collision avoidance

- ▶ Jitter advertising times
- ▶ $advDelay$ is added on to the end of each advertising event
- ▶ $advDelay = \text{rand}[0, 10\text{ms}]$

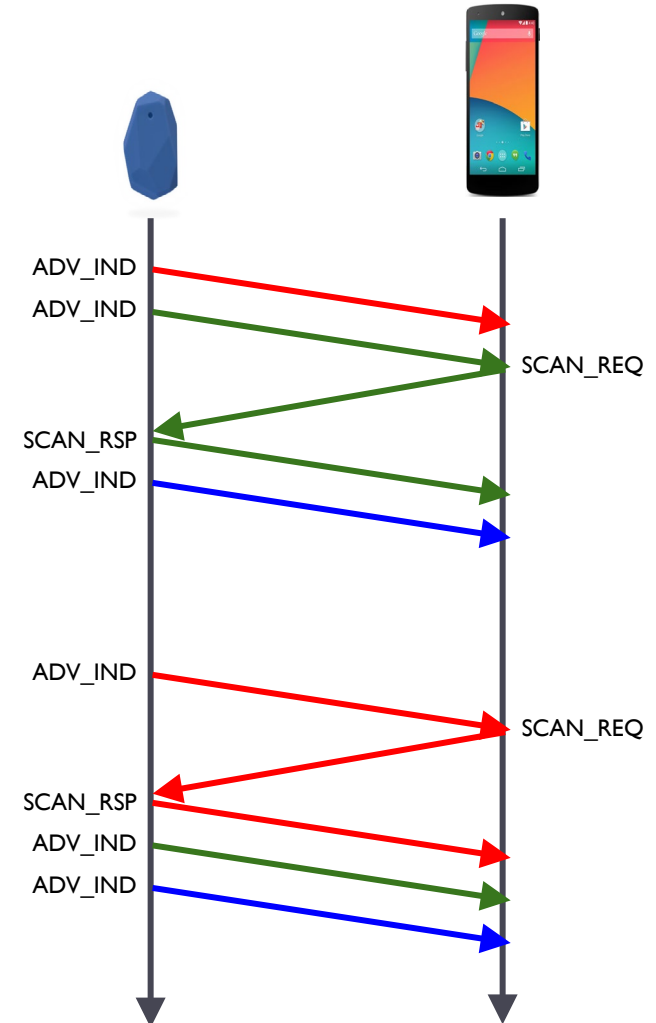
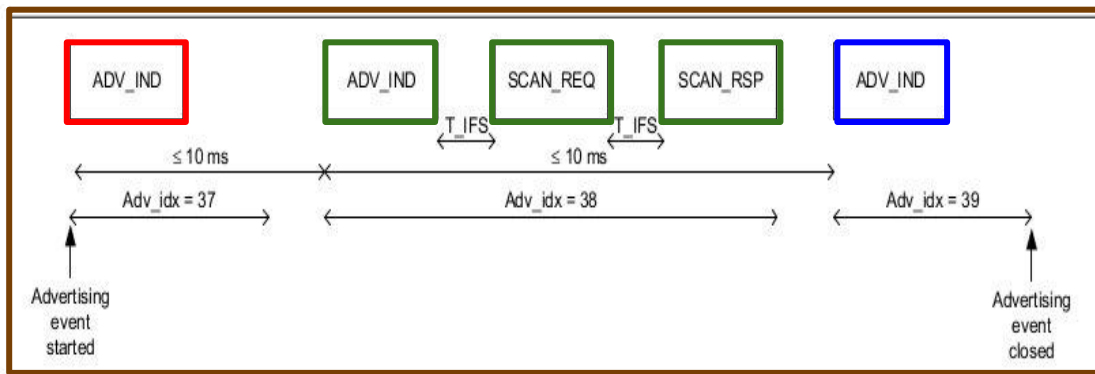
BLE Highlights: Tags Types - Non-Scannable

- ▶ Non-Scannable Tags
- ▶ Ex. gBeacon v3, iBeacon (?)
- ▶ Tags send `ADV_NONCONN_IND` messages
- ▶ Typically sent back-to-back
- ▶ Scanners listen, but do not respond



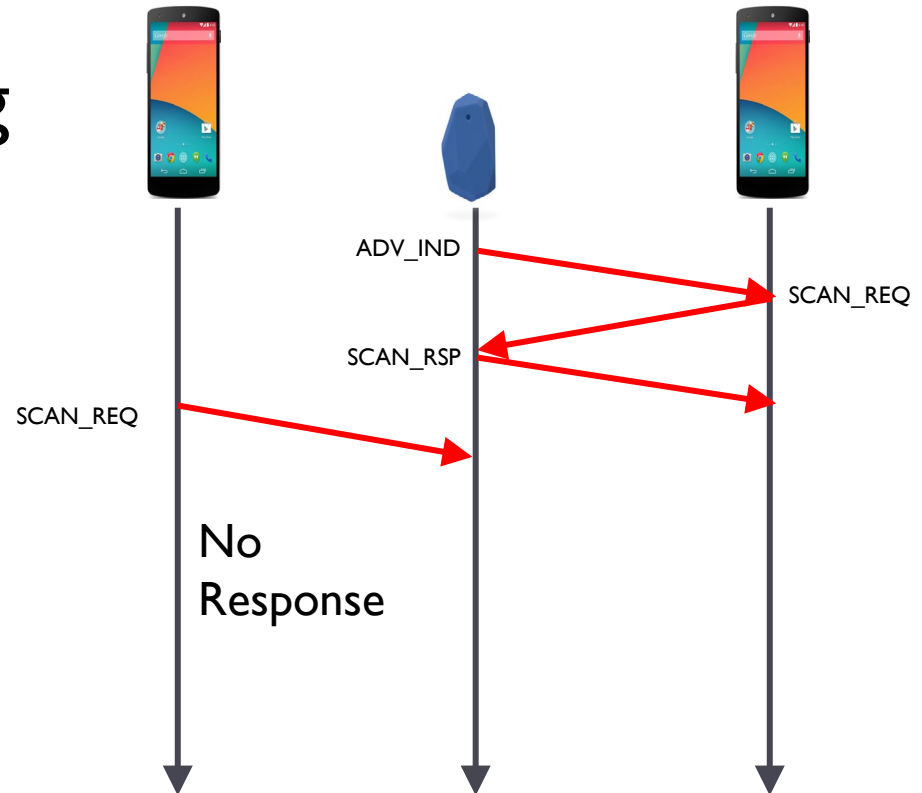
BLE Highlights: Tags Types - Scannable

- ▶ Scannable Tags
- ▶ Ex. gBeacon VI, Estimote
- ▶ Tags send ADV_IND messages
- ▶ Scanners respond with SCAN_REQ message
- ▶ Tags respond with SCAN_RSP message
- ▶ Up to 31 Bytes of extra data
- ▶ Tags wait ~150 usec for a request after beacon



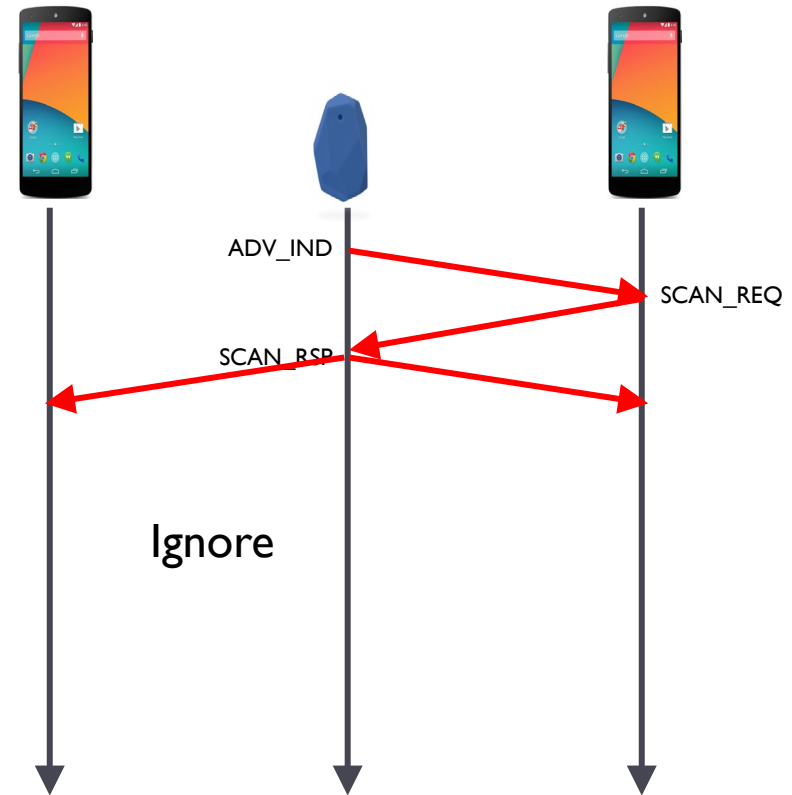
Scannable Tags

- ▶ One SCAN_RSP per channel per advertising event



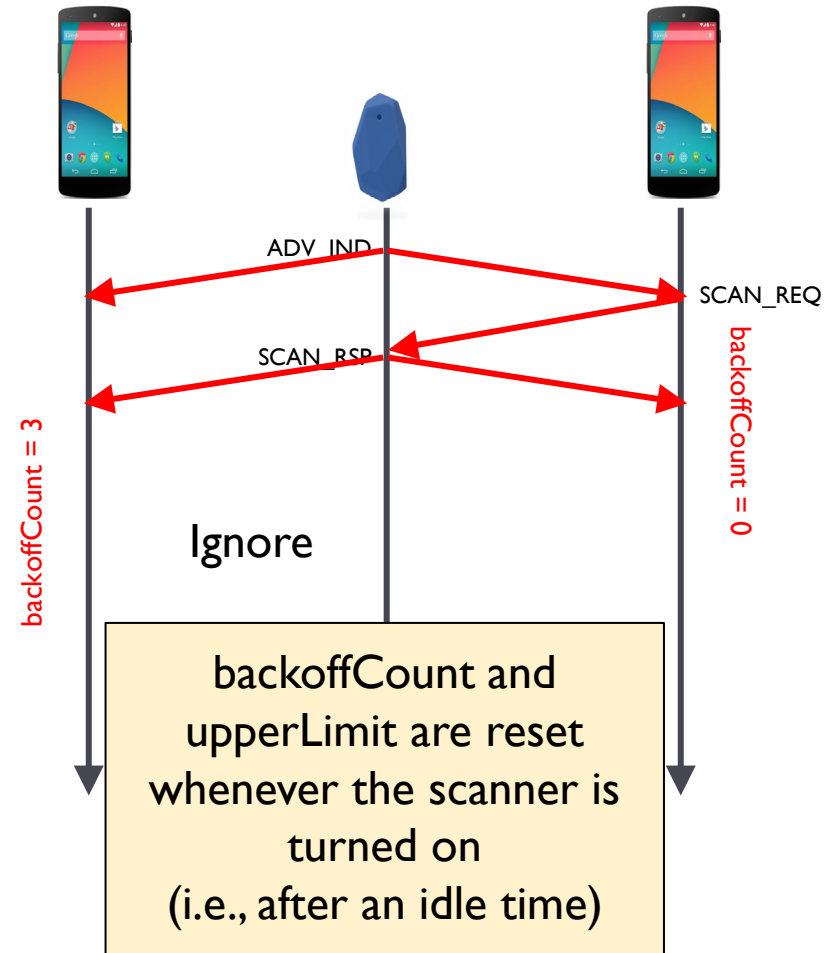
Scannable Tags

- ▶ **ONLY** accept SCAN_RSP if SCAN_REQ was sent to that tag on that channel during that advertising event
- ▶ **Some collision tolerance**
 - ▶ Any requesting scanner can receive a SCAN_RSP as long as one SCAN_REQ is received and the tag responds
 - ▶ **BUT, No SCAN_RSP** if all SCAN_REQs collide



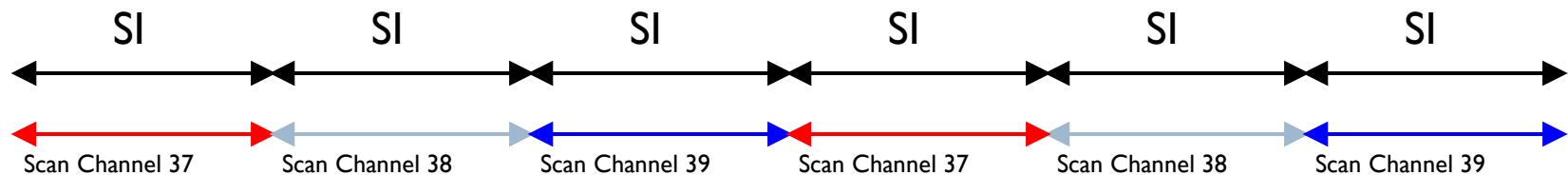
SCAN_REQ Collision Avoidance

- ▶ Scanner backoff procedure
 - ▶ Two parameters
 - ▶ backoffCount, upperLimit
 - ▶ On starting scan
 - ▶ upperLimit = 1, backoffCount = 1
 - ▶ Decrement backoffCount on receipt of ADV message
 - ▶ Only send SCAN_REQ if backoffCount == 0
 - ▶ Adapt upperLimit based on success or failure of receipt of SCAN_RSP
 - ▶ Reset backoffCount
 - ▶ backoffCount = rand (1, upperLimit)



BLE Highlights: Low-level Scanning

- ▶ Scanners
- ▶ Scan for tags on sequential channels (37, 38, 39)
- ▶ Scan Interval (SI)
 - ▶ Time spent on a channel



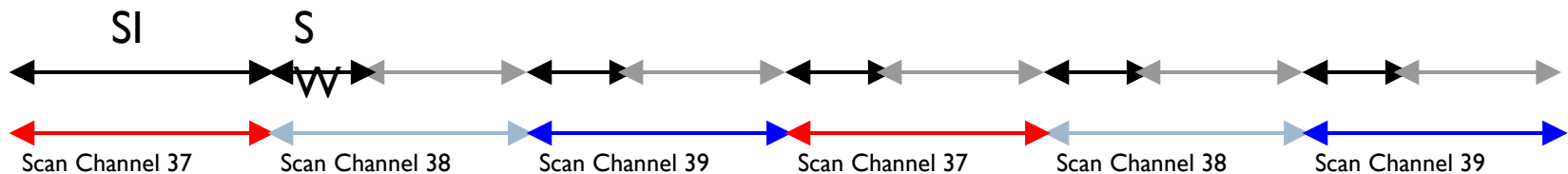
BLE Highlights: Low-level Scanning

▶ Scan Time

- ▶ Scan Int == Scan Window
⇒ Always on

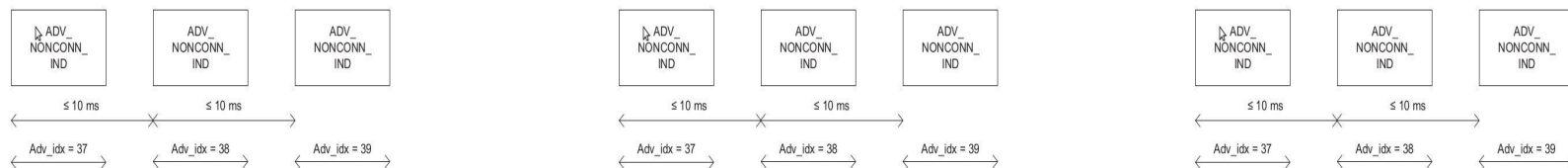
▶ Scanners

- ▶ Scan for tags on sequential channels (37, 38, 39)
- ▶ Scan Interval (SI)
 - ▶ Time spent on a channel
- ▶ Scan Window (SW)
 - ▶ Time spent scanning at beginning of Scan Interval



BLE Highlights: Application-level Scanning

- ▶ Scanners
- ▶ Application Scan Time
 - ▶ > Tag Advertising Interval



Application Scan Time



BLE Highlights: Application-level Scanning

▶ Scan Time

▶ 100% on Idle Time = 0

▶ (Continuous scanning)

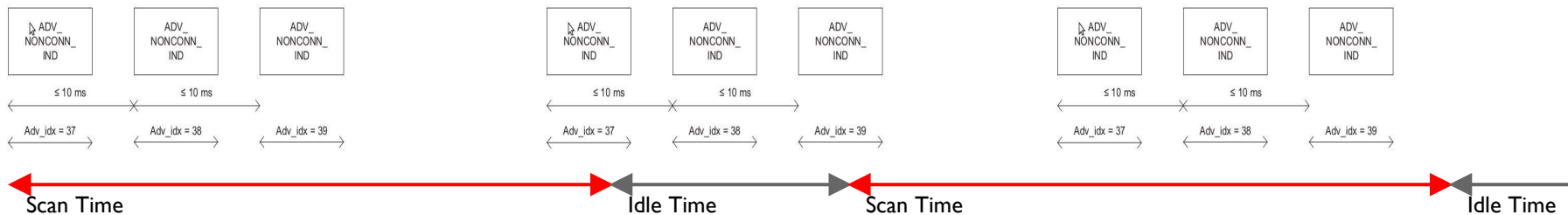
▶ 10% on Idle Time = $10 * \text{Scan Time}$

▶ Scanners

▶ Application Scan Time

▶ $>$ Tag Advertising Interval

▶ Application Idle Time



BLE Highlights: MAC Behavior

- ▶ **No Carrier Sense**
 - ▶ Tag does not listen for a clear channel before sending any message
- ▶ **Minimal Contention Avoidance**
 - ▶ Jitter length of advertising interval + rand [0, 10 ms]
 - ▶ Backoff for sending SCAN_REQ
- ▶ **Other parameters**
 - ▶ Inter-frame spacing 150us (from spec)
 - ▶ Channel switching delay 274us (from Nordic)
 - ▶ Scan Interval 11.25ms (from spec/Nexus 5)
 - ▶ Scan Window scanning) 11.25ms (continuous)

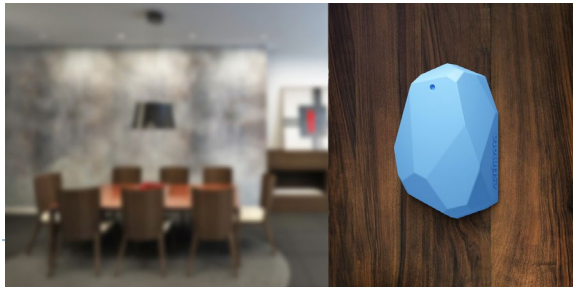


BLE in the Real World

- ▶ BLE beacons (or tags)
 - ▶ Location-specific information
 - ▶ Deployed in public places
 - ▶ Stores, airports, museums
 - ▶ Accessed via phones with BLE



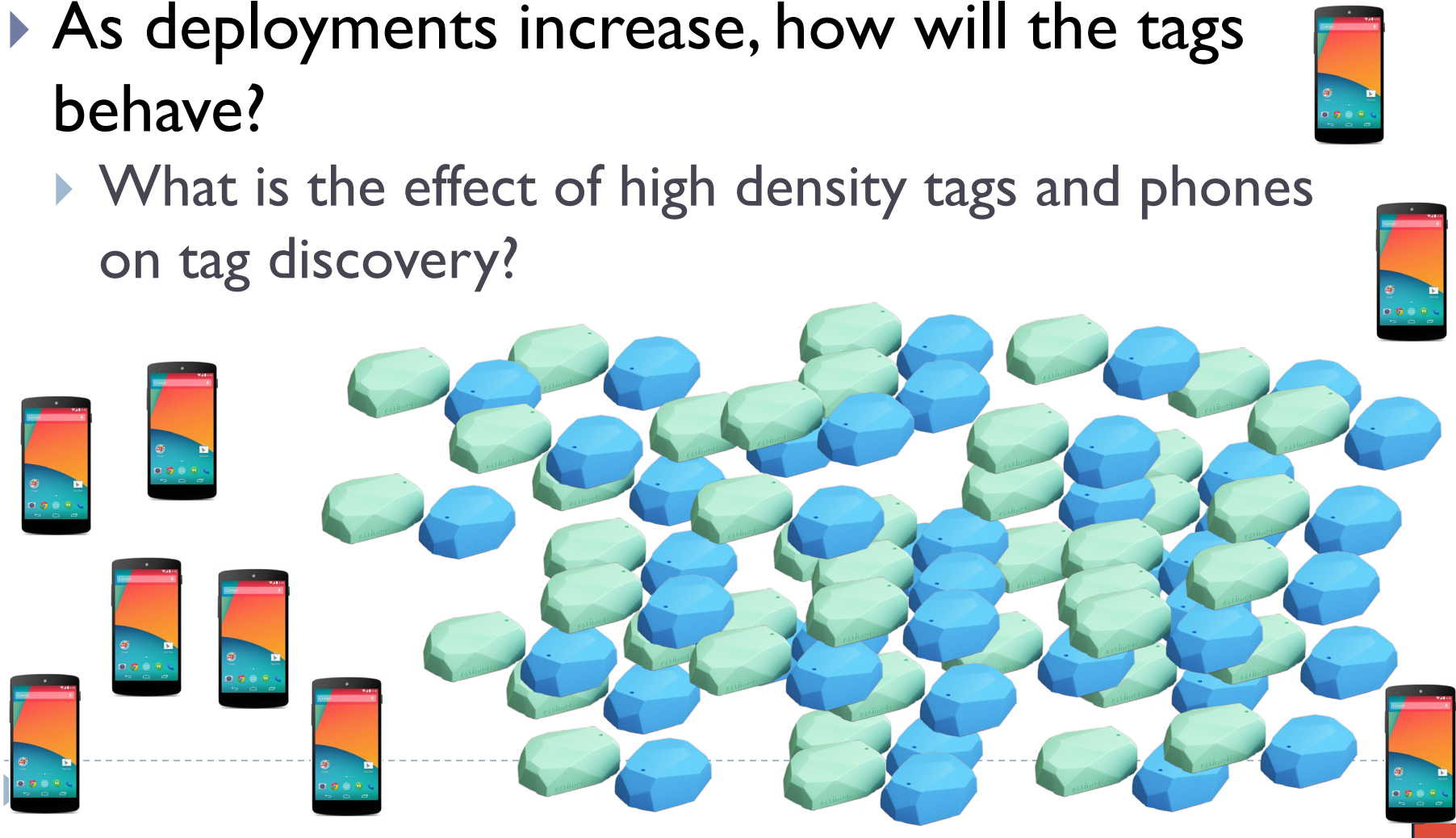
- Performance questions
 - How long does it take to detect a nearby tag?
 - Can we detect a tag within 5 sec with 95% success?



BLE in the Real World - Density

▶ As deployments increase, how will the tags behave?

▶ What is the effect of high density tags and phones on tag discovery?



Evaluating Tag Behavior

▶ Environmental Impact

- ▶ At what density of tags or phones does the system break down?

▶ Metric

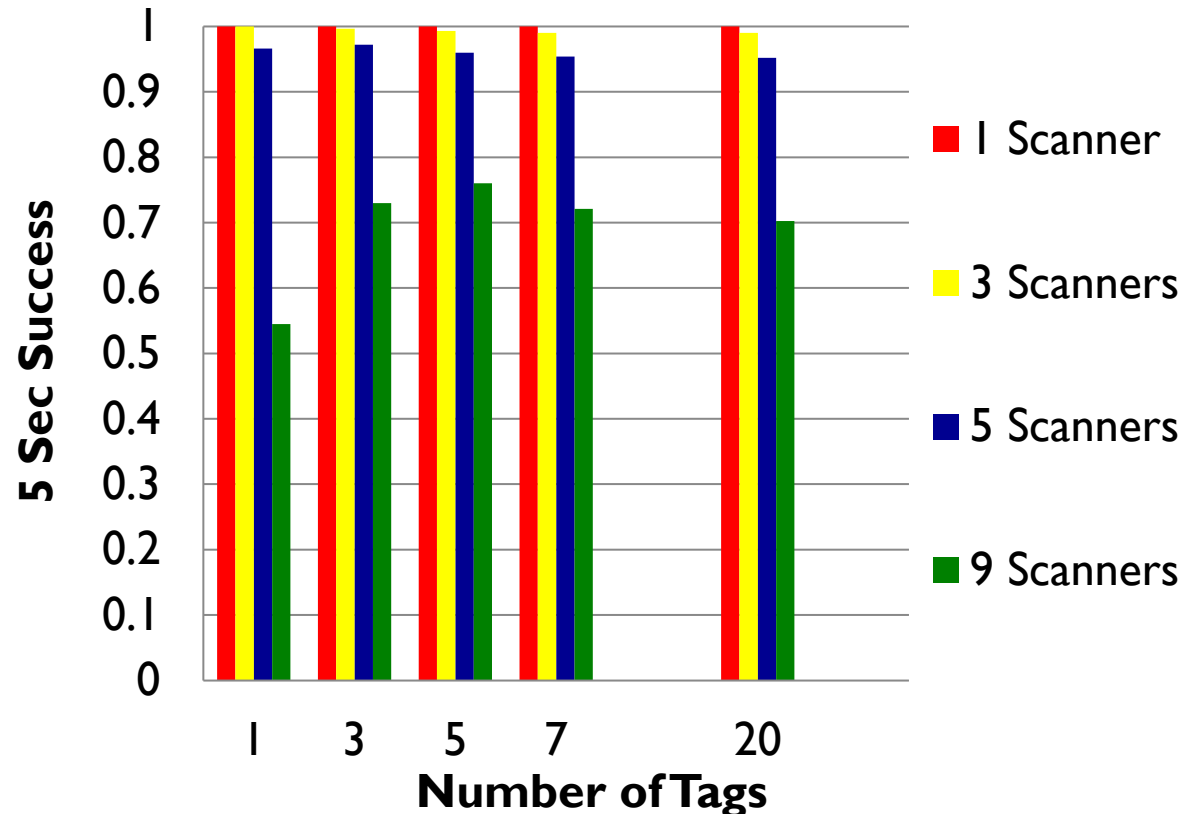
- ▶ 5 Sec Success
 - ▶ Could the tag be found in 5 sec?
 - ▶ Checked every 1 sec over the whole run



Evaluation: BLE Scan/Response

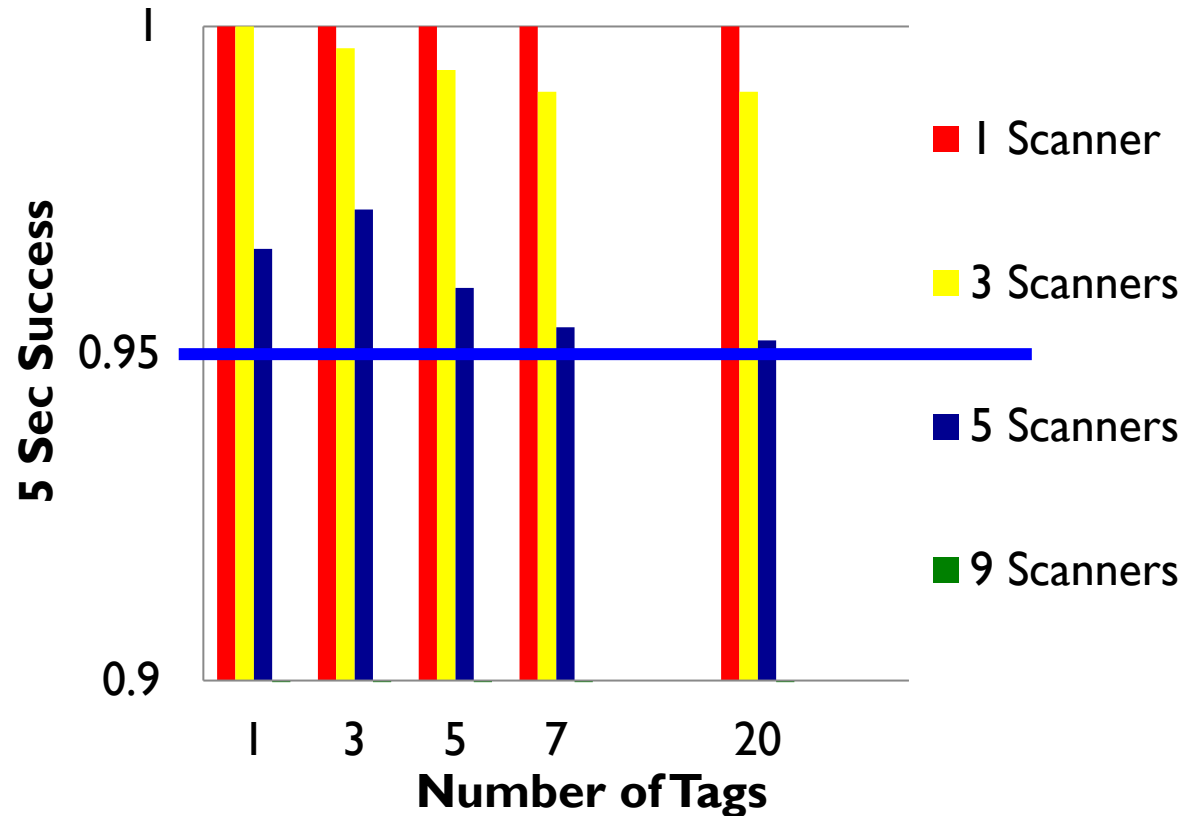
▶ 5 second success

- ▶ Multiple chances to find the tag
- ▶ Success decreases significantly as more phones are added
- ▶ Number of phones is more important than number of tags



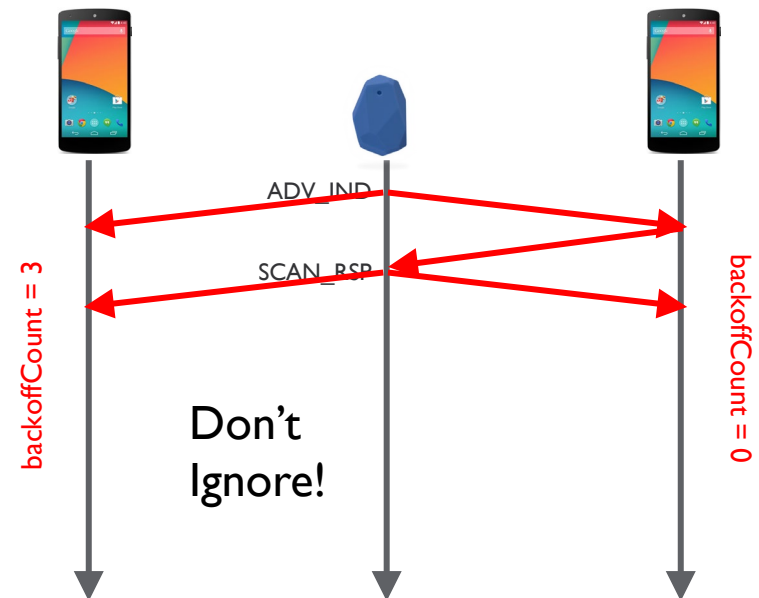
Evaluation: BLE Scan/Response

- 5 second success
 - Below target threshold for more than 5 phones



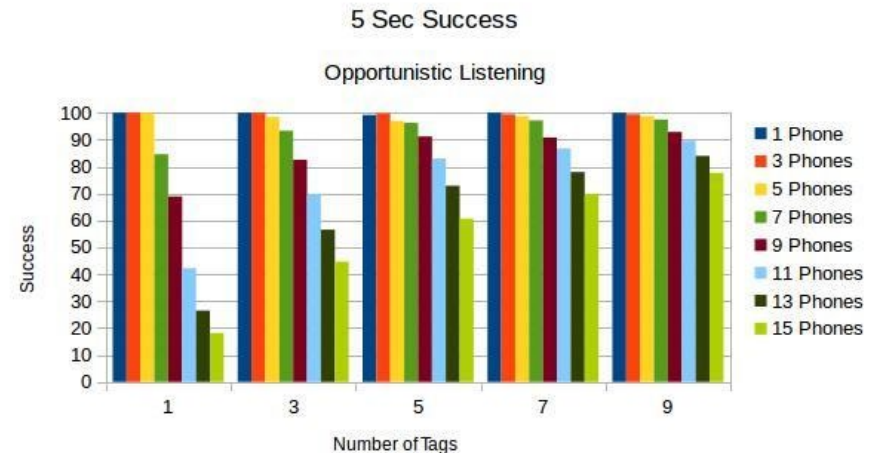
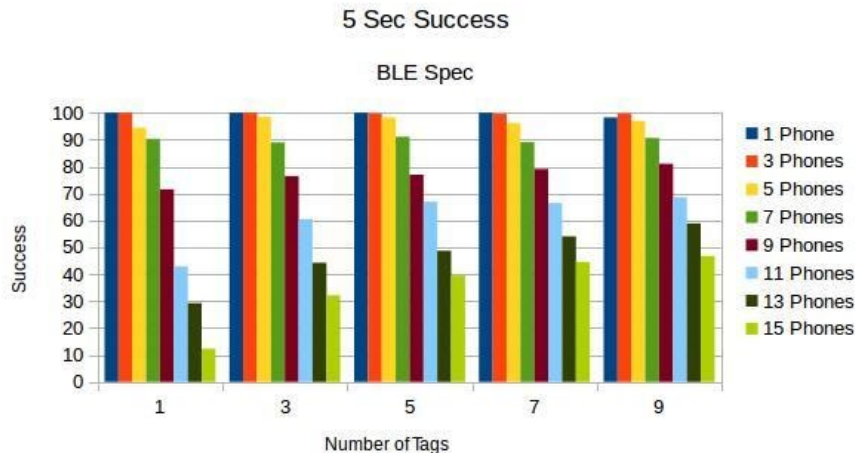
SCAN_REQ: Opportunistic Listening

- Accept a SCAN_RSP on a channel if a SCAN_REQ would have been sent, but the backoff procedure indicated not to send it
 - Any requesting or **backing off** scanner can receive a SCAN_RSP as long as one SCAN_REQ is received and the tag responds
 - Still, No SCAN_RSP if all SCAN_REQs collide



Opportunistic Listening: Simulation Comparison

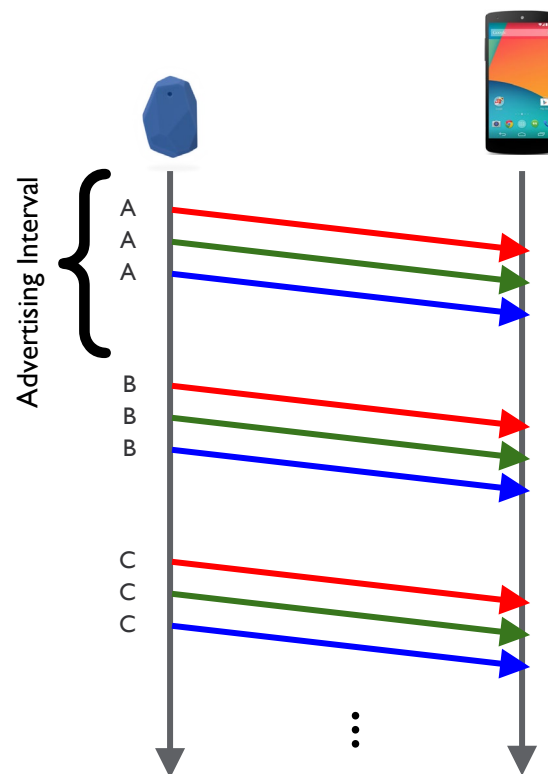
- Significant increase in success rate as number of phones increases
- Cannot prevent SCAN_REQ collisions



Beacon Trains

▶ Approach

- ▶ Advertising data is broken in n beacons
 - ▶ For n = 5: A, B, C, D, E
 - ▶ Max 31 bytes
- ▶ Alternate sending data in non-scannable beacons
 - ▶ Send A in 1st advertising interval, Send B in 2nd advertising interval, etc
 - ▶ Must receive all n to get complete advertising data



Beacon Trains

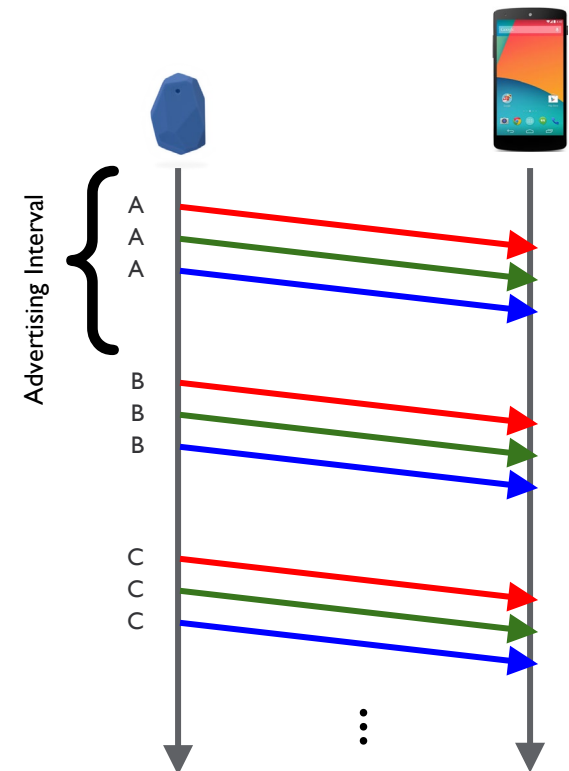
▶ Approach

▶ Pro

- ▶ Advertising data = $n * 3I$

▶ Con

- ▶ Delay to receive all n packets in a train



Evaluation

▶ Goal

- ▶ Evaluate effect of higher tag density on tag discovery for beacon trains

▶ Parameters

- ▶ Number of tags: 25-200
- ▶ Beacon interval: 1s, 500ms, 250ms, 100ms

▶ Metric

- ▶ t Sec Success: are all packets from the train received in t sec?

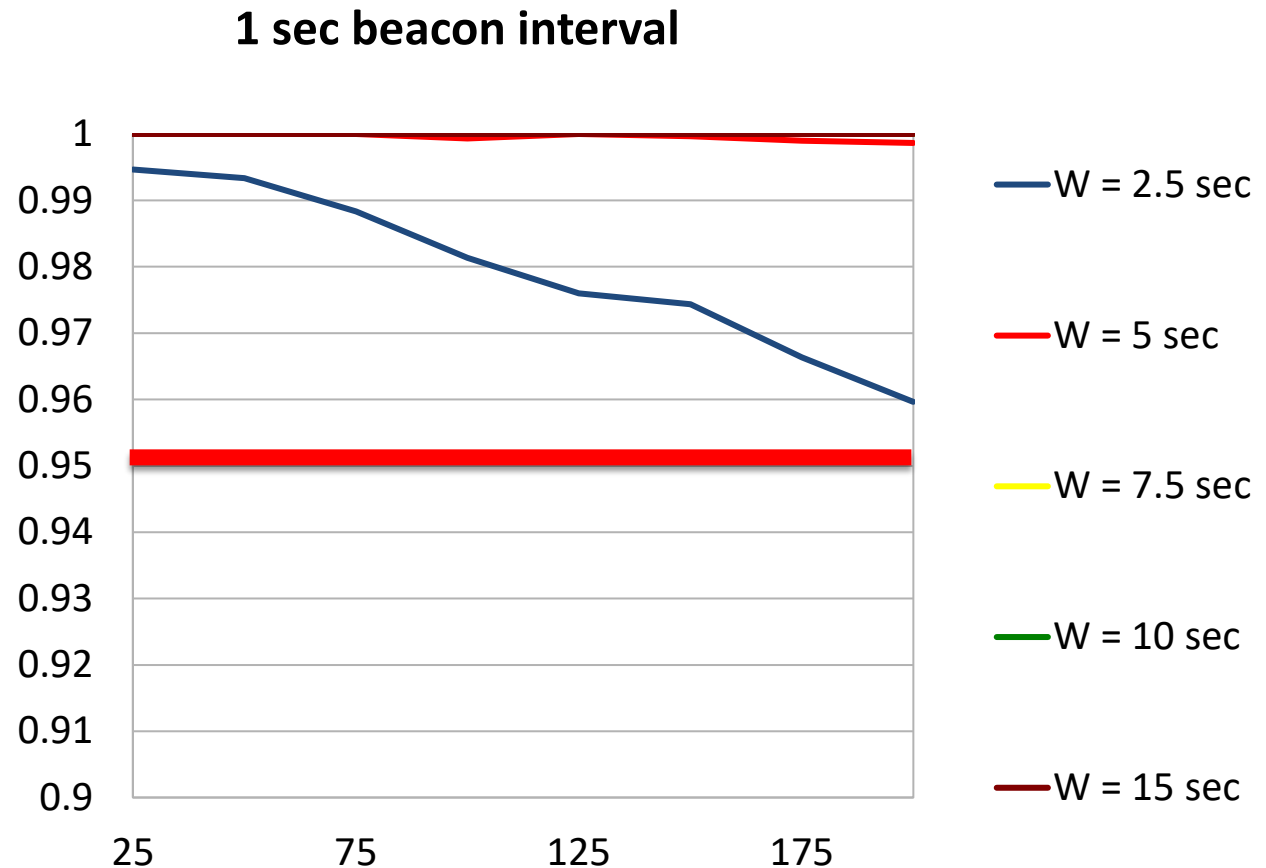
▶ Discrete Event Simulator

- ▶ ns-3: No true BLE
- ▶ Based on Zigbee PHY layer adapted to 1Mbps channel



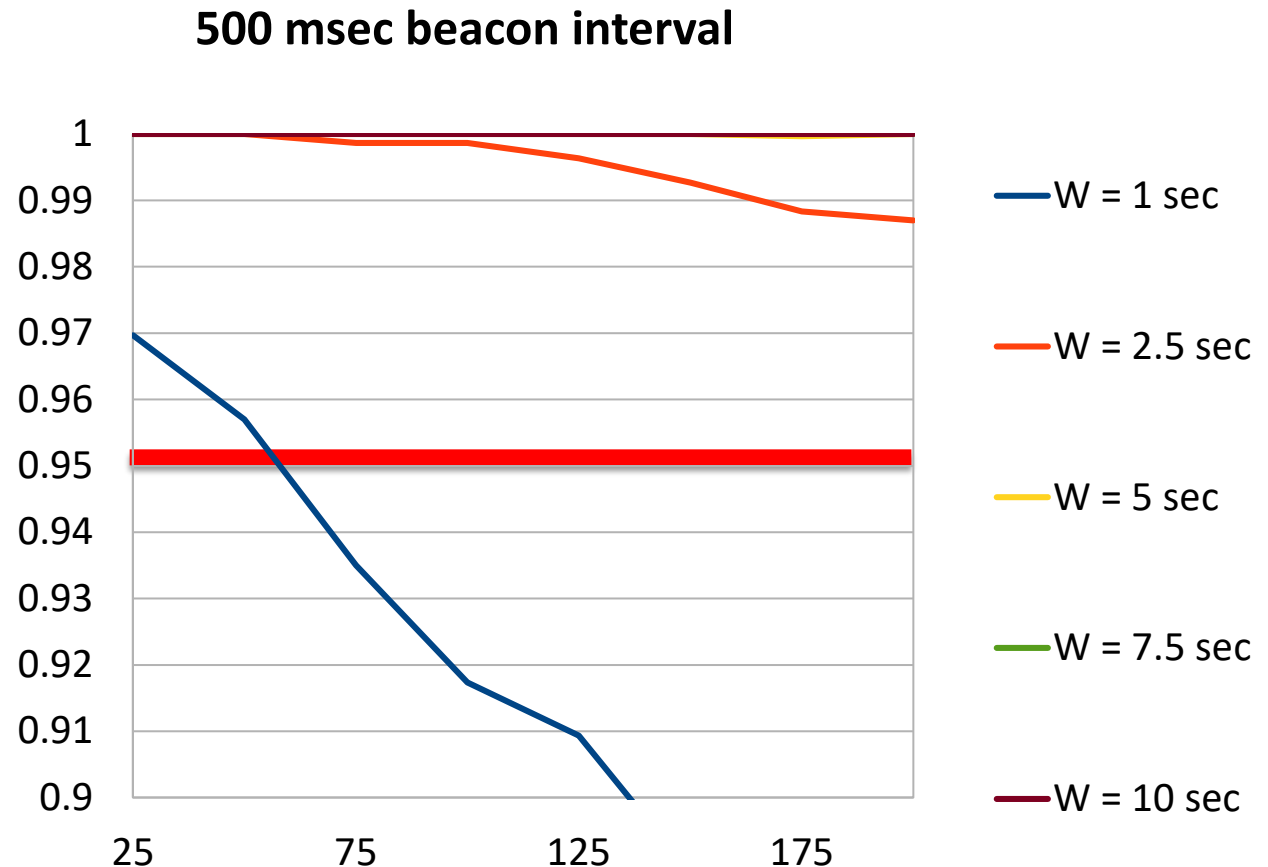
Passive Beacons: Success

- Density has little effect above a 5 sec wait time
- Success is still over 95% with a 2.5 sec wait time
- Wait $\sim 2.5x$ AdvInt



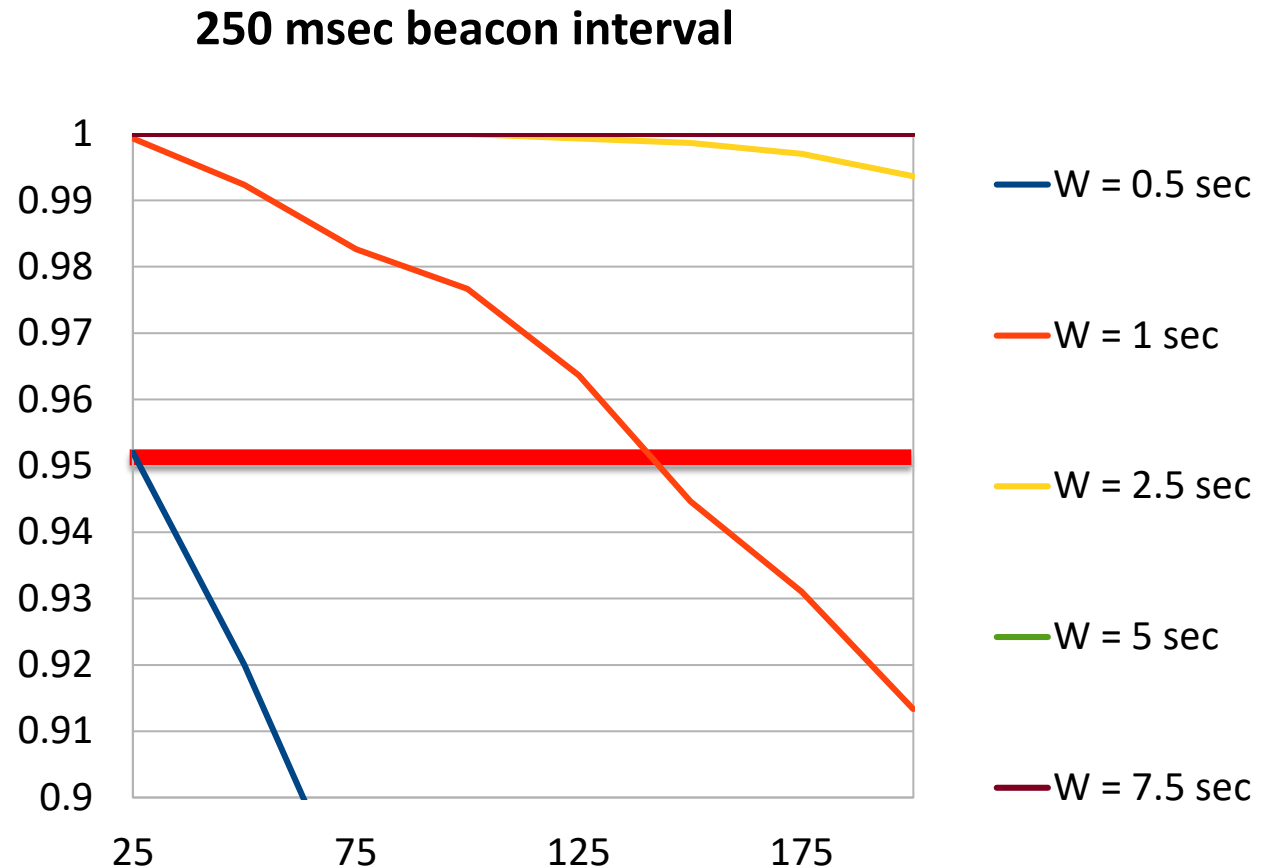
Passive Beacons: Success

- Density has little above a 2.5 sec wait time
- Success quickly drops below 95% with a 1 sec wait time
- Wait $\sim 5x$



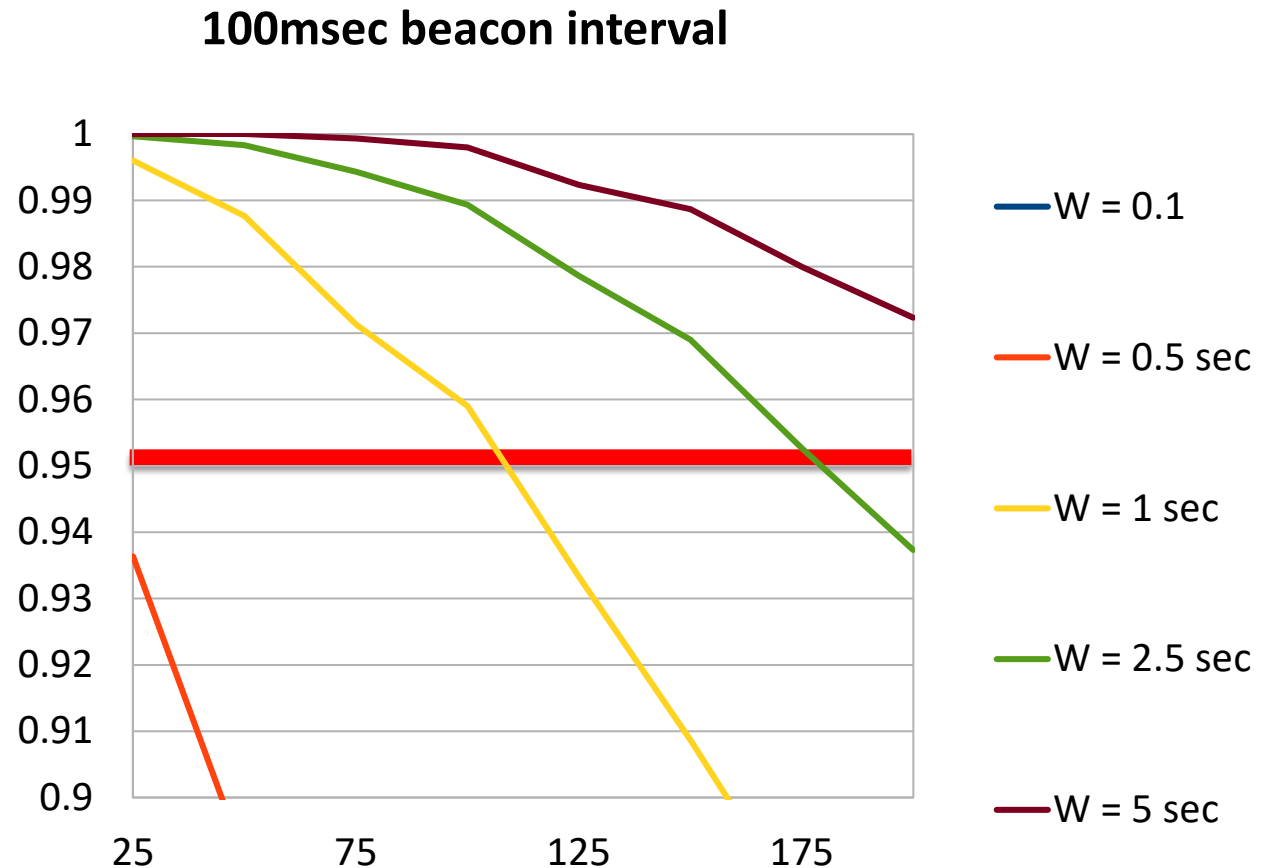
Passive Beacons: Success

- Density has more effect, reducing the success of 1 sec wait time
- Success is almost always below 95% with a 0.5 sec wait time
- Wait $\sim 4x$ AdvInt



Passive Beacons: Success

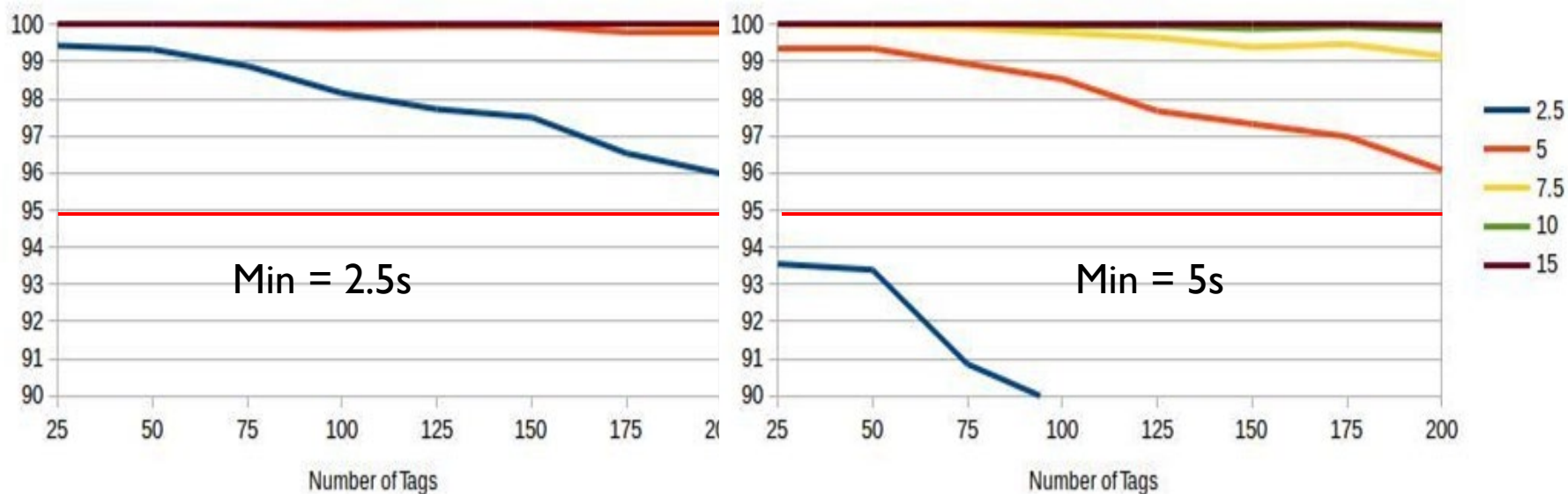
- ▶ Density has the worst effect
- ▶ Only 5 sec wait time has effective success
- ▶ Even 2.5 sec wait time drops below 95%
- ▶ Wait > 10x AdvInt



Beacon Train Success - 1 sec BI

N = 1

N = 2



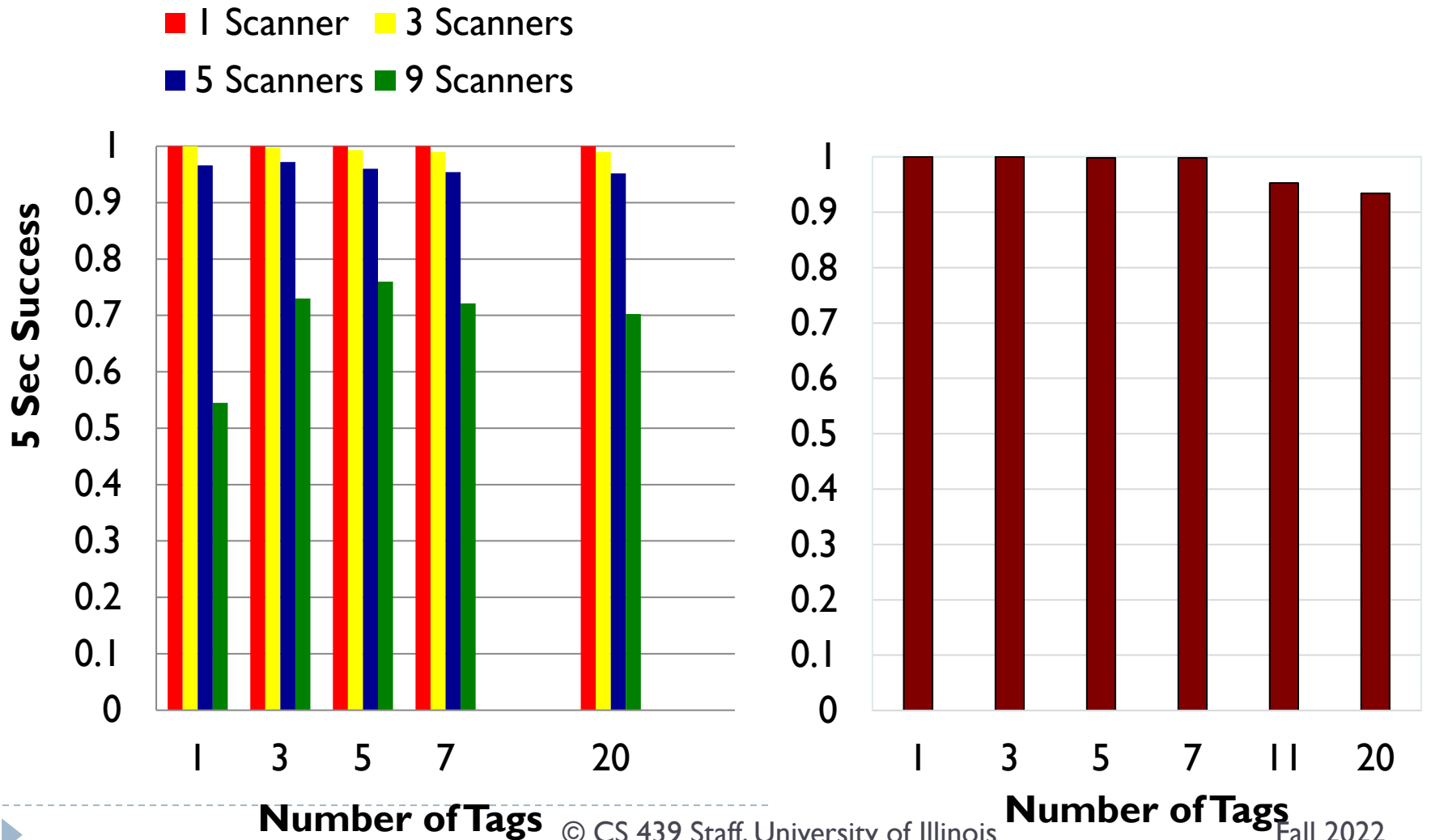
Success = all packets in train

1 sec advertising interval

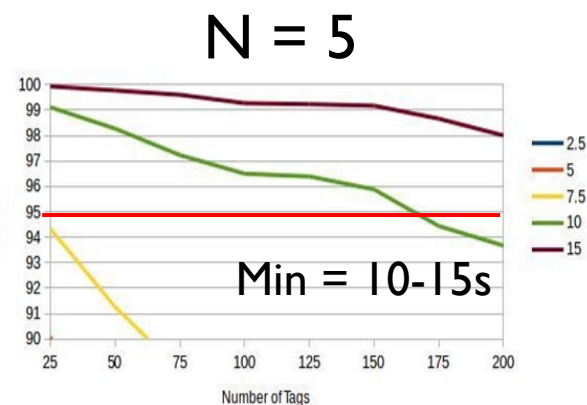
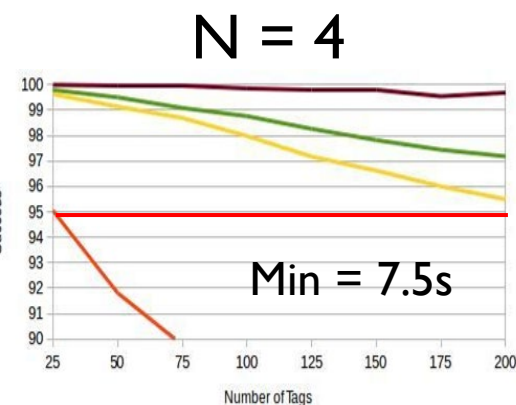
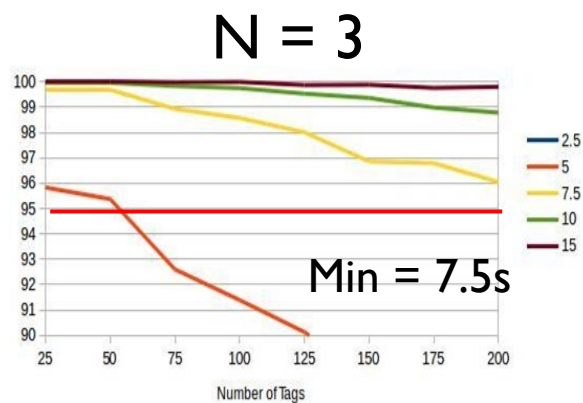
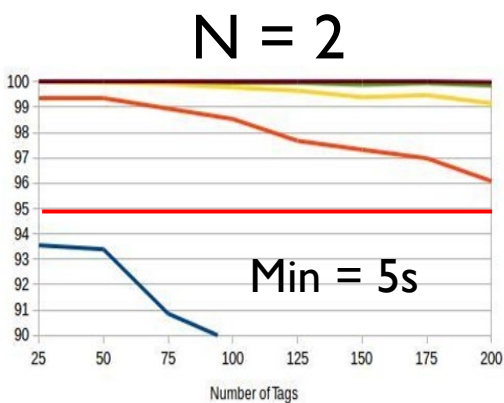
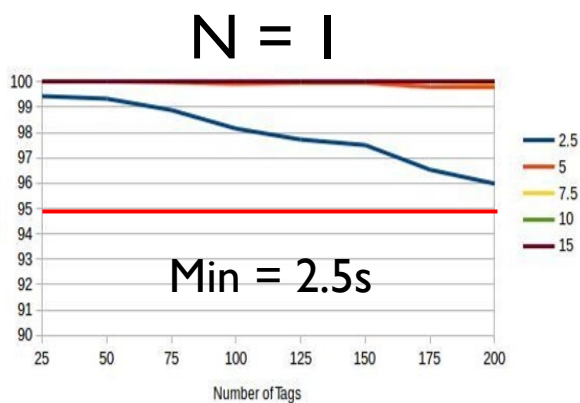
$\tau = 2.5, 5, 7.5, 10, 15$



Active Scanning vs. N=2 Beacon Trains (experimental results)



Beacon Train Success - 1 sec BI



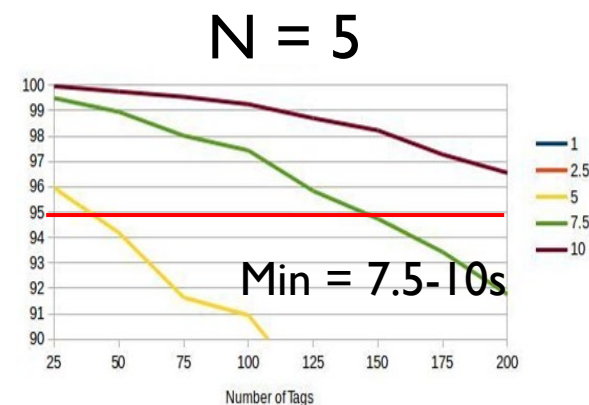
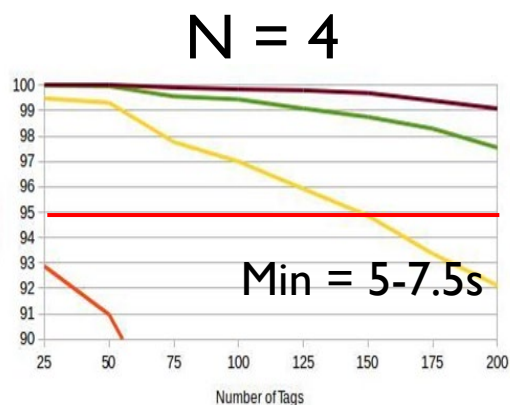
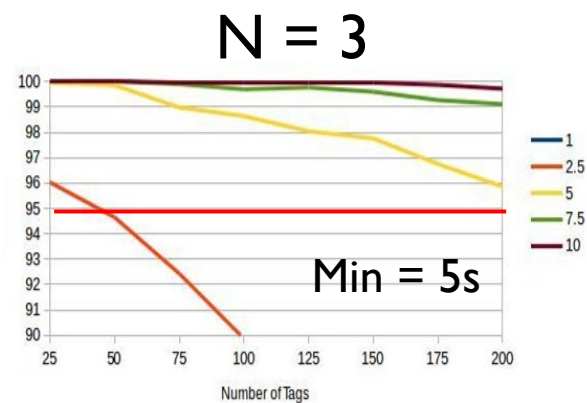
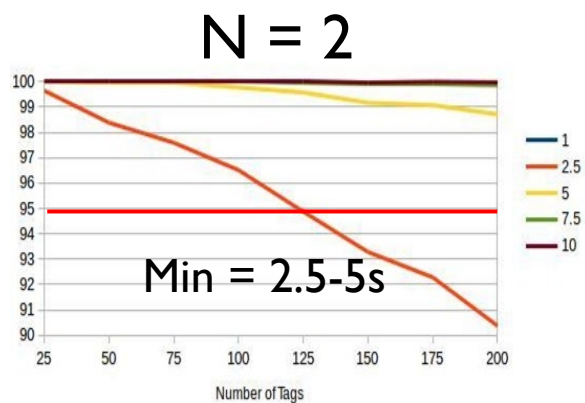
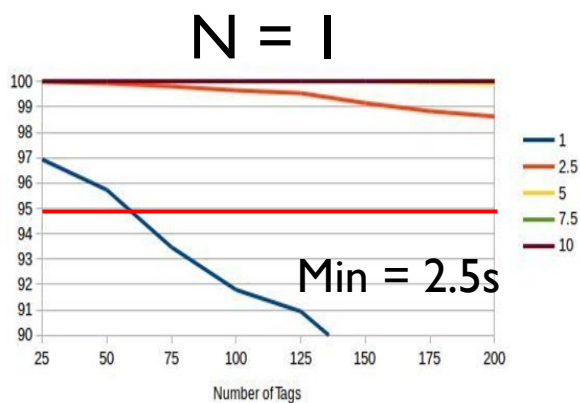
Success = all packets in train

1 sec advertising interval

$t = 2.5, 5, 7.5, 10, 15$



Beacon Train Success - 500 msec BI



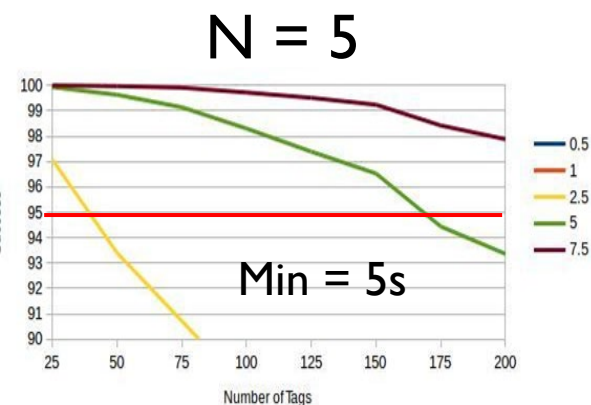
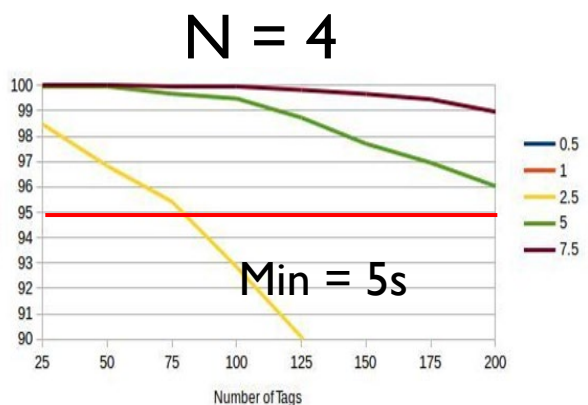
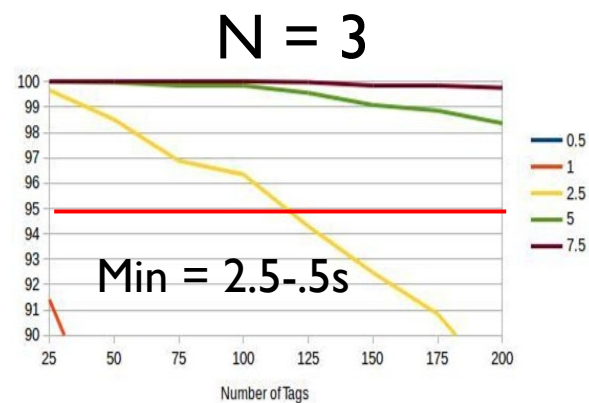
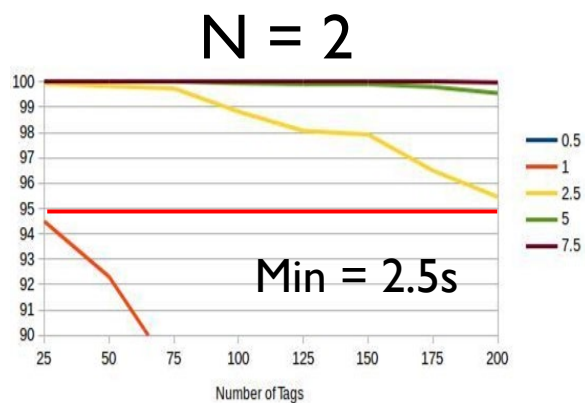
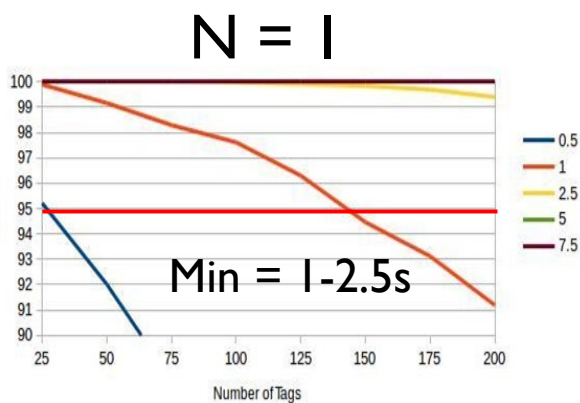
Success = all packets in train

500 msec advertising interval

$\tau = 1, 2.5, 5, 7.5, 10$



Beacon Train Success - 250 msec BI



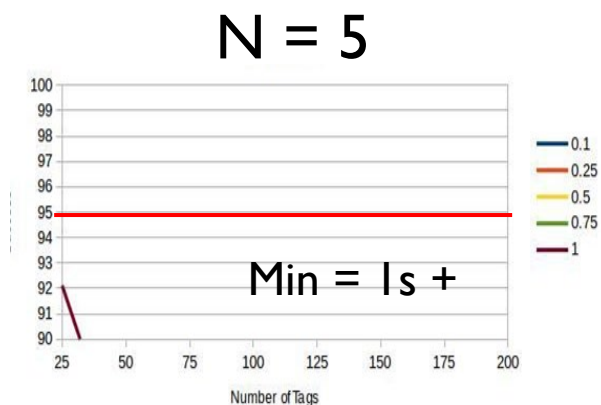
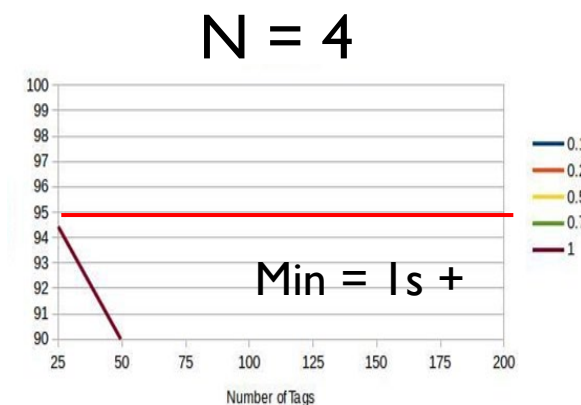
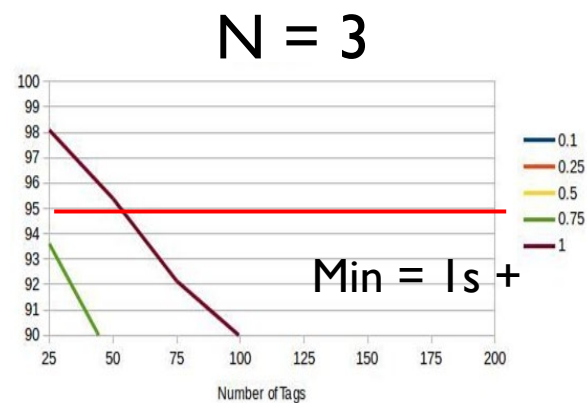
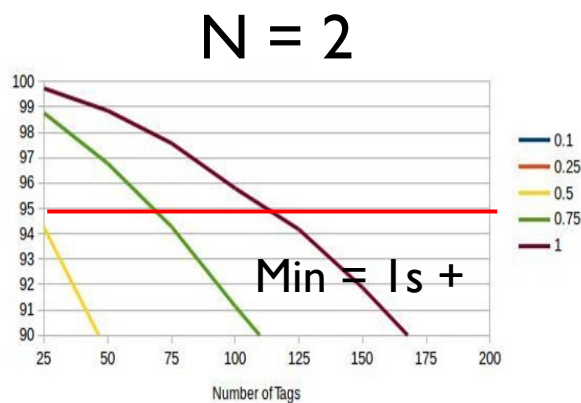
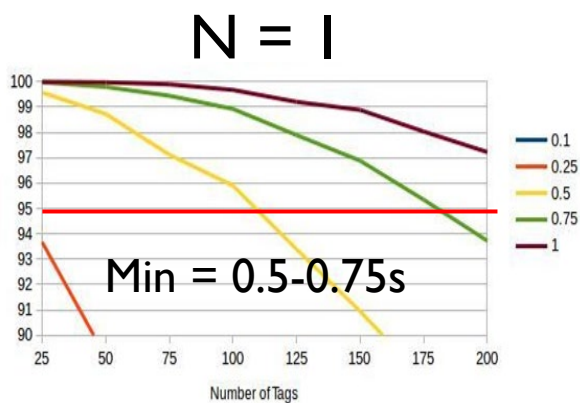
Success = all packets in train

250 msec advertising interval

$\tau = 0.5, 1, 2.5, 5, 7.5$



Beacon Train Success - 100 msec BI



Success = all packets in train

100 msec advertising interval

$\tau = 0.1, 0.5, 1, 2.5, 5$

