Anonymizing Wireless Discovery

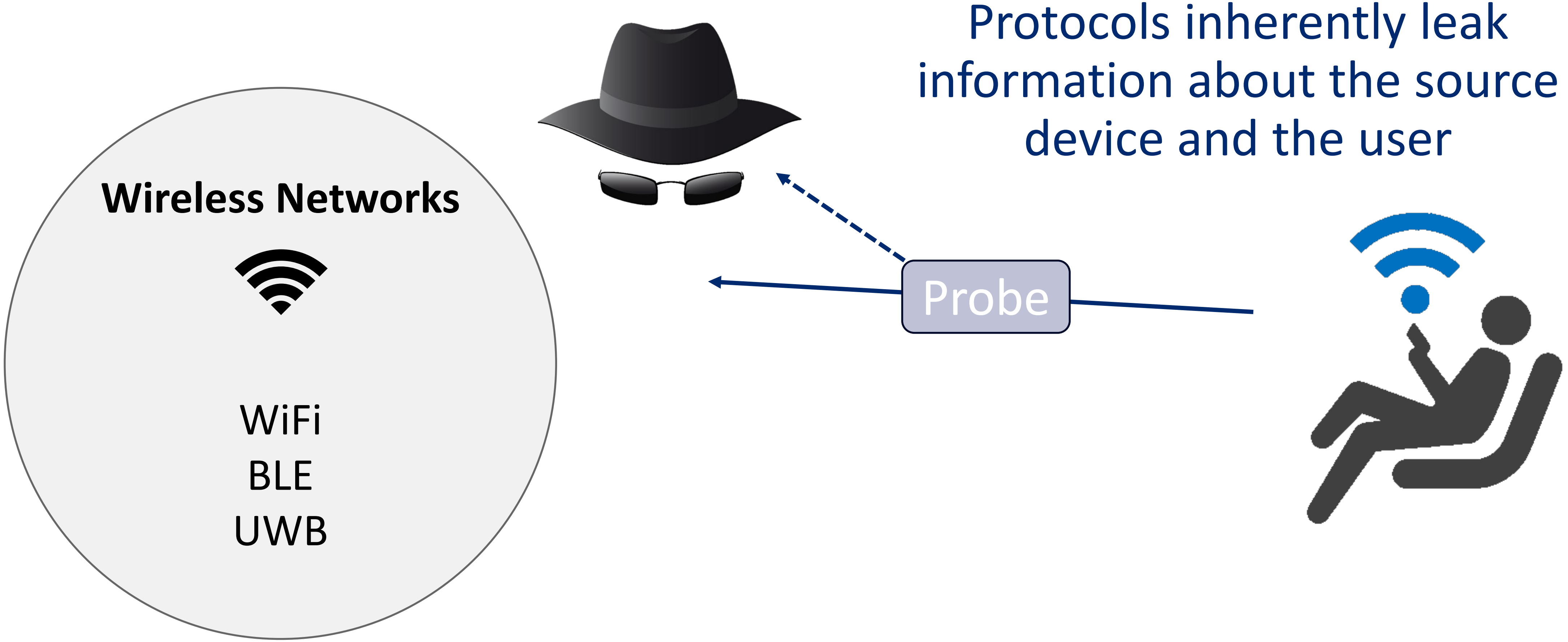
Fall 2024

Wireless is Pervasive

Wireless Networks

WiFi
BLE
UWB

Problem: Wireless is Invasive



Wireless Networks

WiFi
BLE
UWB

Probe

Protocols inherently leak information about the source device and the user

Problem: Wireless is Invasive

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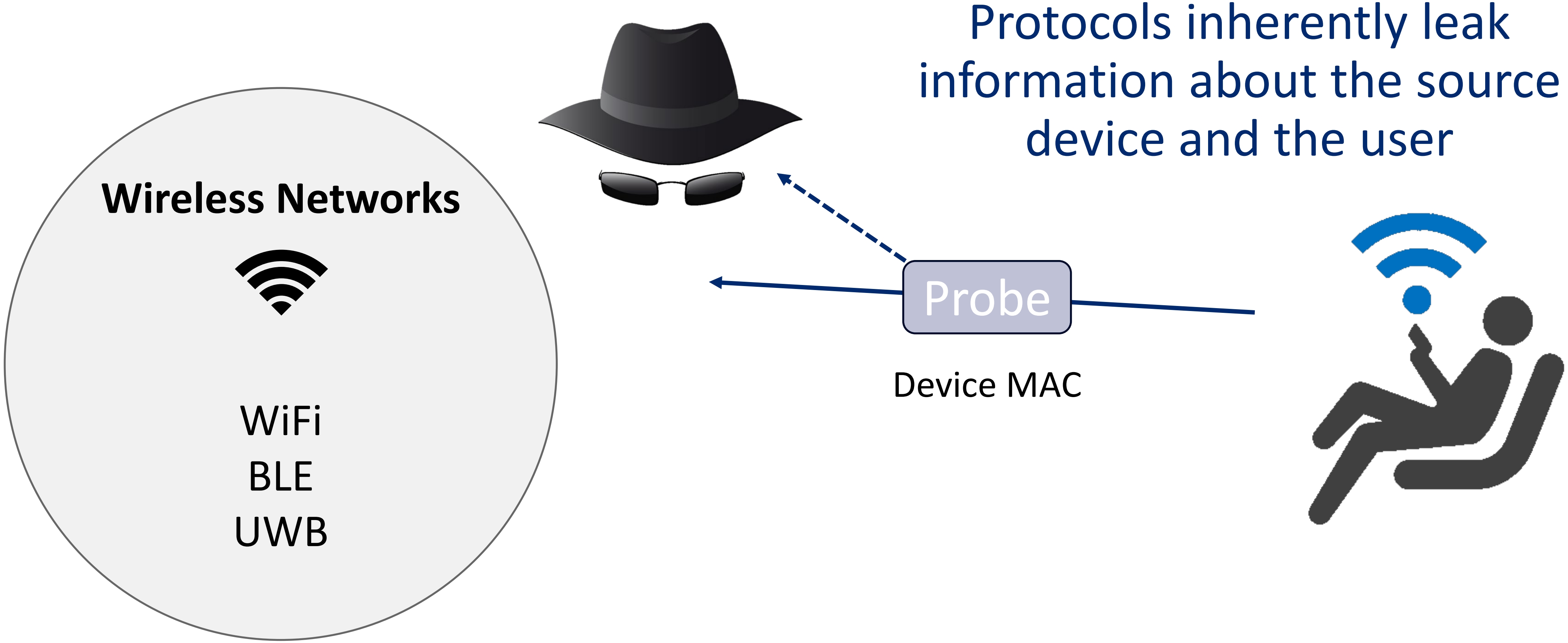

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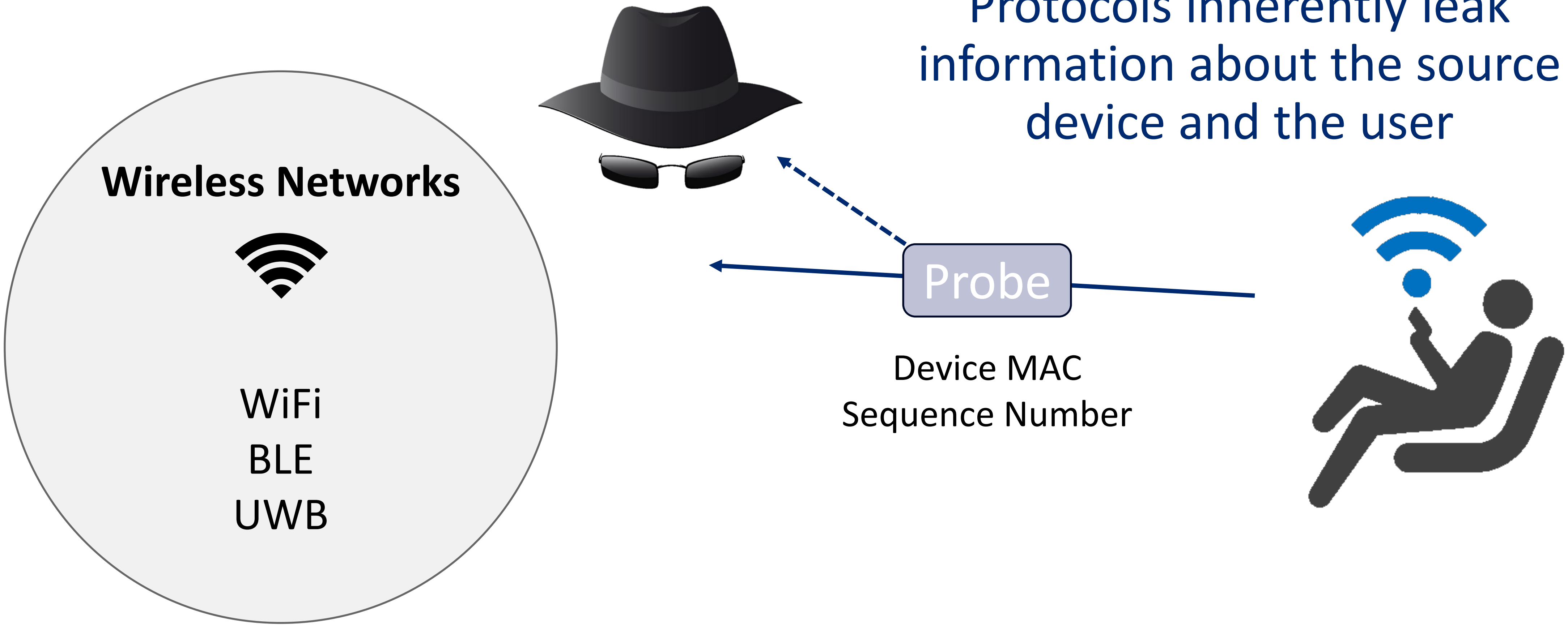
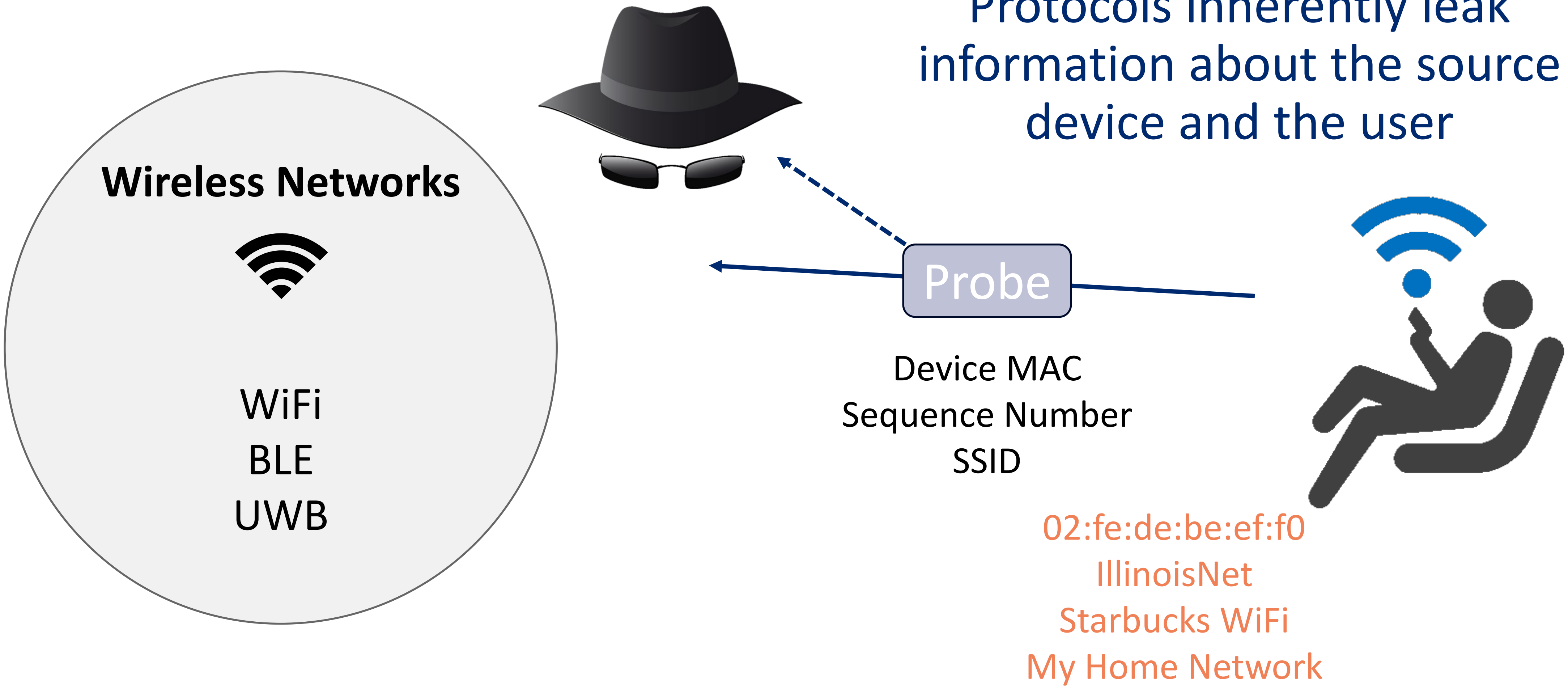


Wireless Networks

WiFi
BLE
UWB

Device MAC
Sequence Number

Problem: Wireless is Invasive



Protocols inherently leak information about the source device and the user

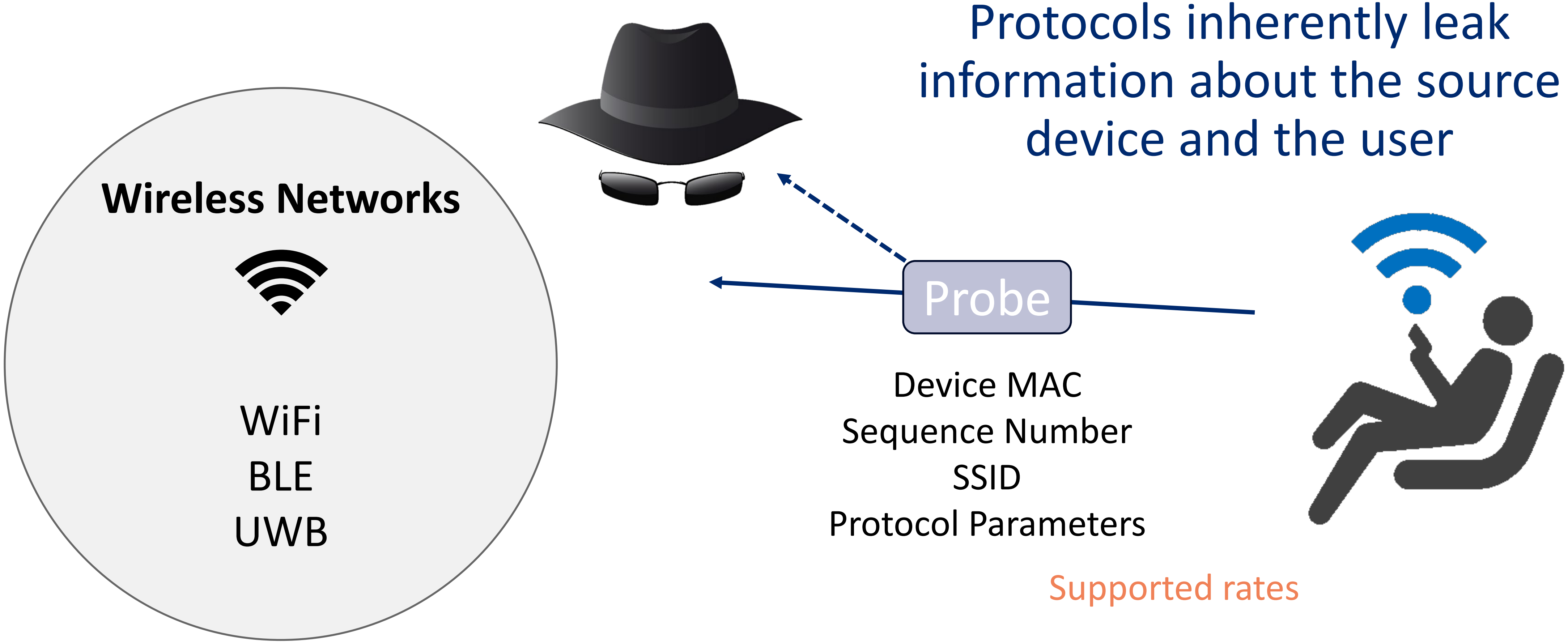
Wireless Networks

WiFi
BLE
UWB

Device MAC
Sequence Number
SSID

02:fe:de:be:ef:f0
IllinoisNet
Starbucks WiFi
My Home Network

Problem: Wireless is Invasive



Protocols inherently leak information about the source device and the user

Wireless Networks

WiFi
BLE
UWB

Probe

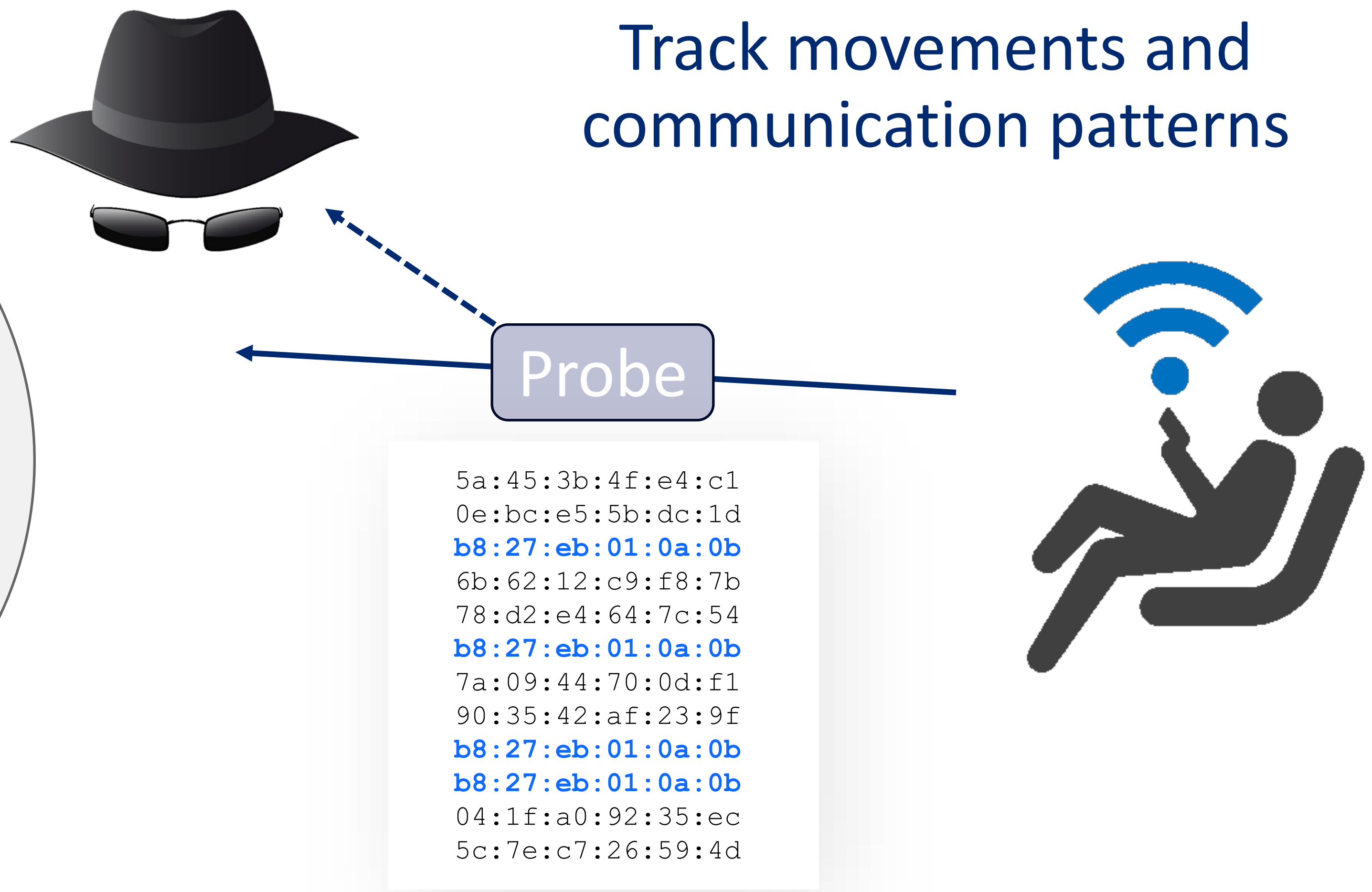
Device MAC
Sequence Number
SSID
Protocol Parameters

Supported rates

Problem: Wireless is Invasive

Wireless Networks

WiFi
BLE
UWB

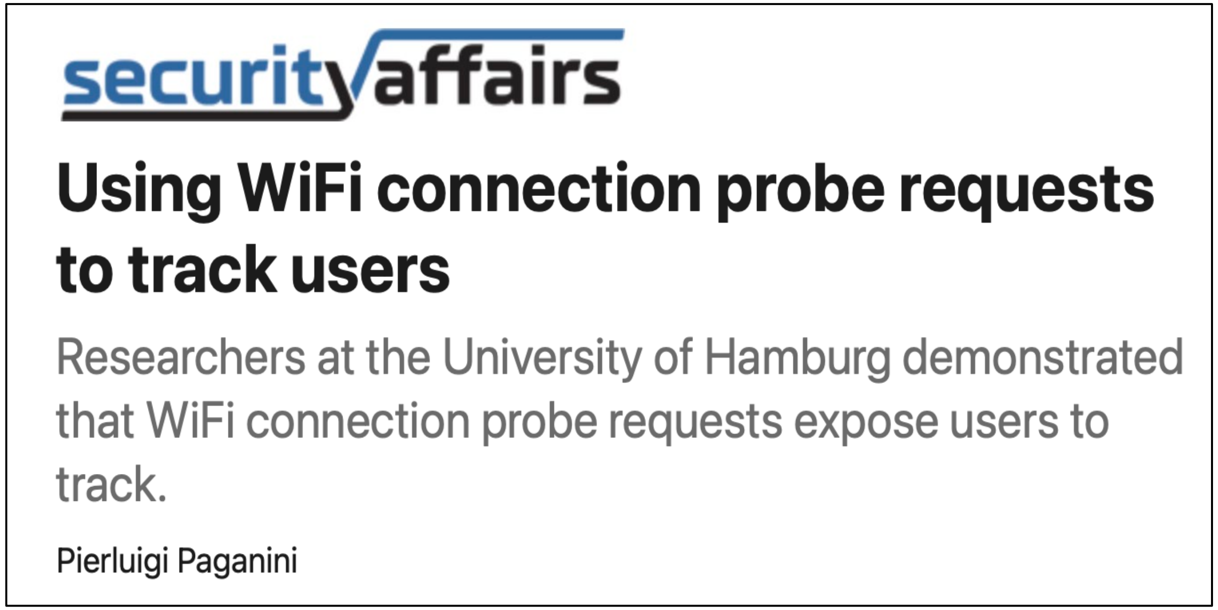


Track movements and communication patterns

```
5a:45:3b:4f:e4:c1
0e:bc:e5:5b:dc:1d
b8:27:eb:01:0a:0b
6b:62:12:c9:f8:7b
78:d2:e4:64:7c:54
b8:27:eb:01:0a:0b
7a:09:44:70:0d:f1
90:35:42:af:23:9f
b8:27:eb:01:0a:0b
b8:27:eb:01:0a:0b
04:1f:a0:92:35:ec
5c:7e:c7:26:59:4d
```

Add headline logos

Wireless is Invasive – But Who Cares?



securityaffairs

Using WiFi connection probe requests to track users

Researchers at the University of Hamburg demonstrated that WiFi connection probe requests expose users to track.

Pierluigi Paganini

Add headline logos

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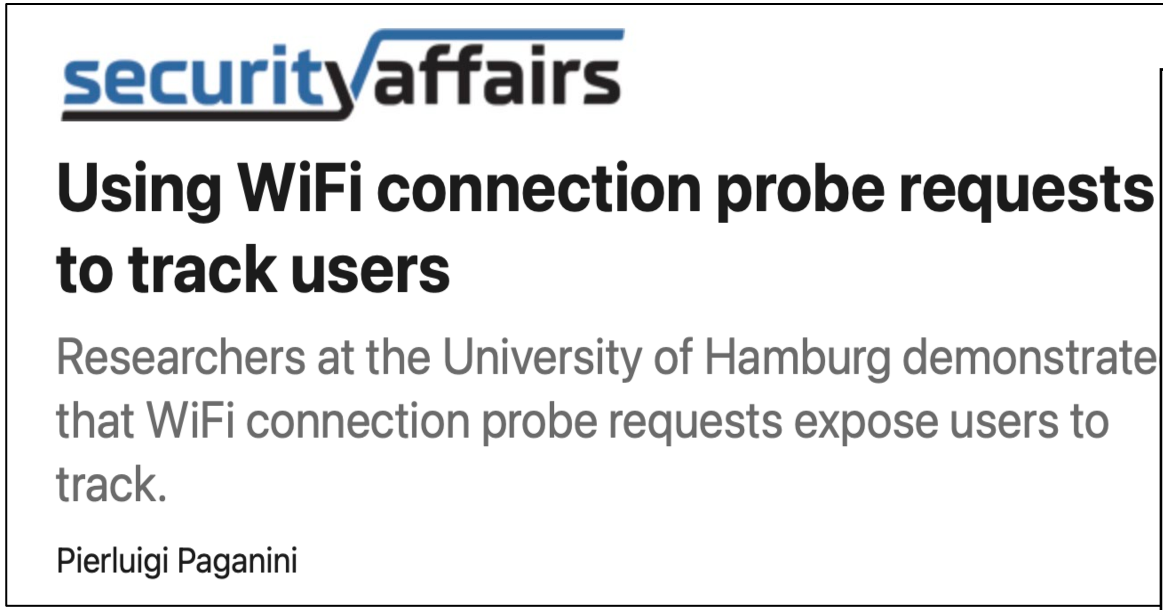

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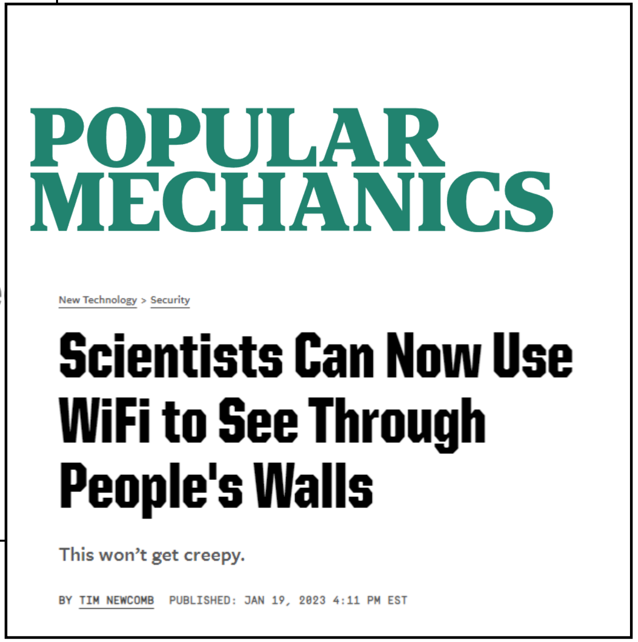

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New Technology > Security

Scientists Can Now Use WiFi to See Through People's Walls

This won't get creepy.

BY TIM NEWCOMB PUBLISHED: JAN 19, 2023 4:11 PM EST

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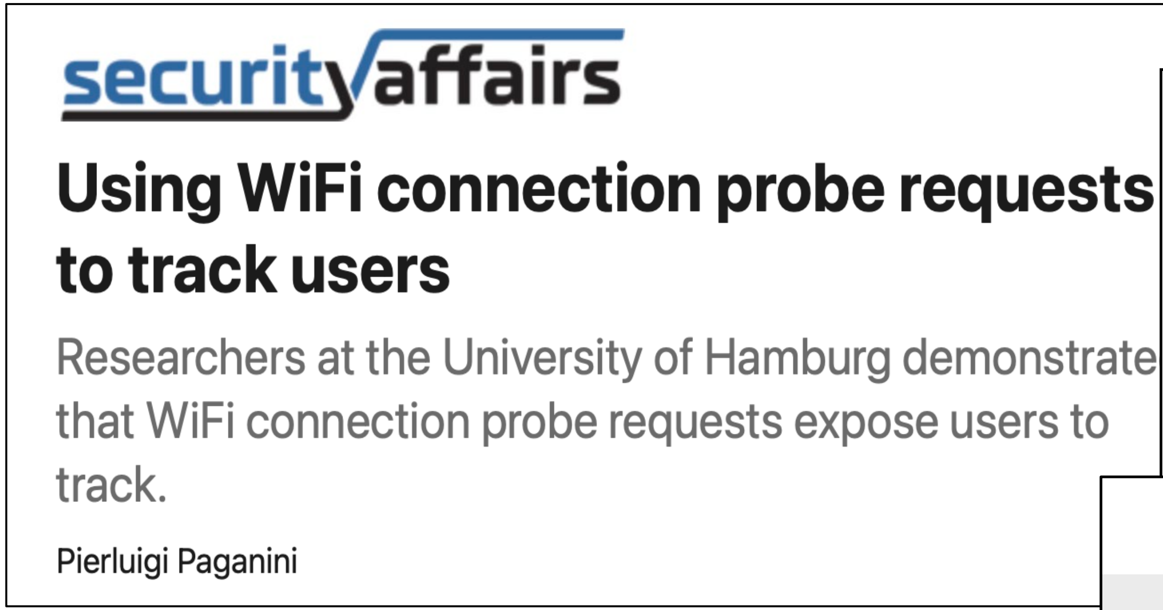
Wireless is Invasive – But Who Cares?



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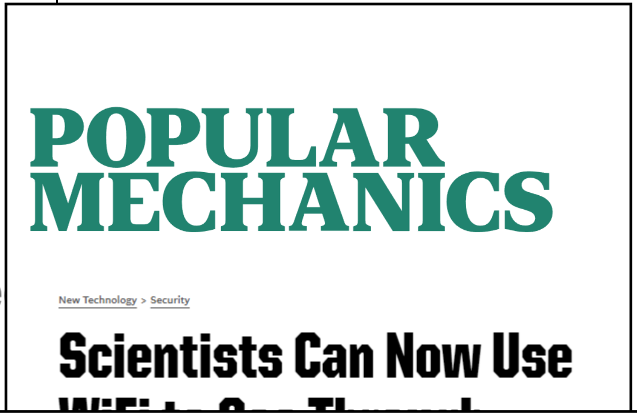

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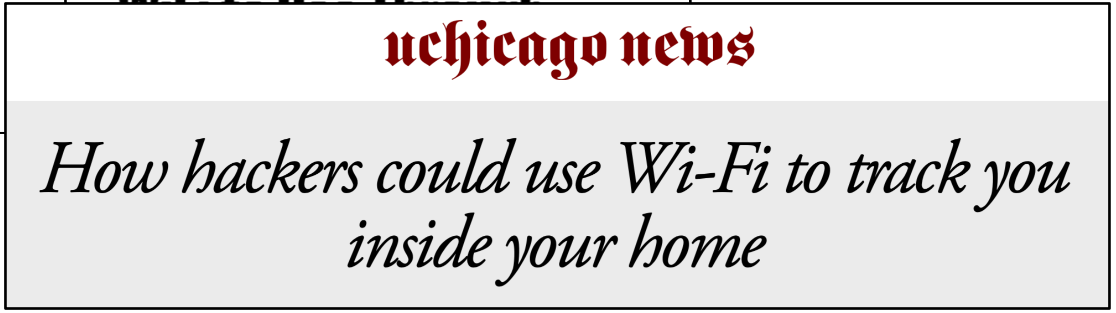
Scientists Can Now Use

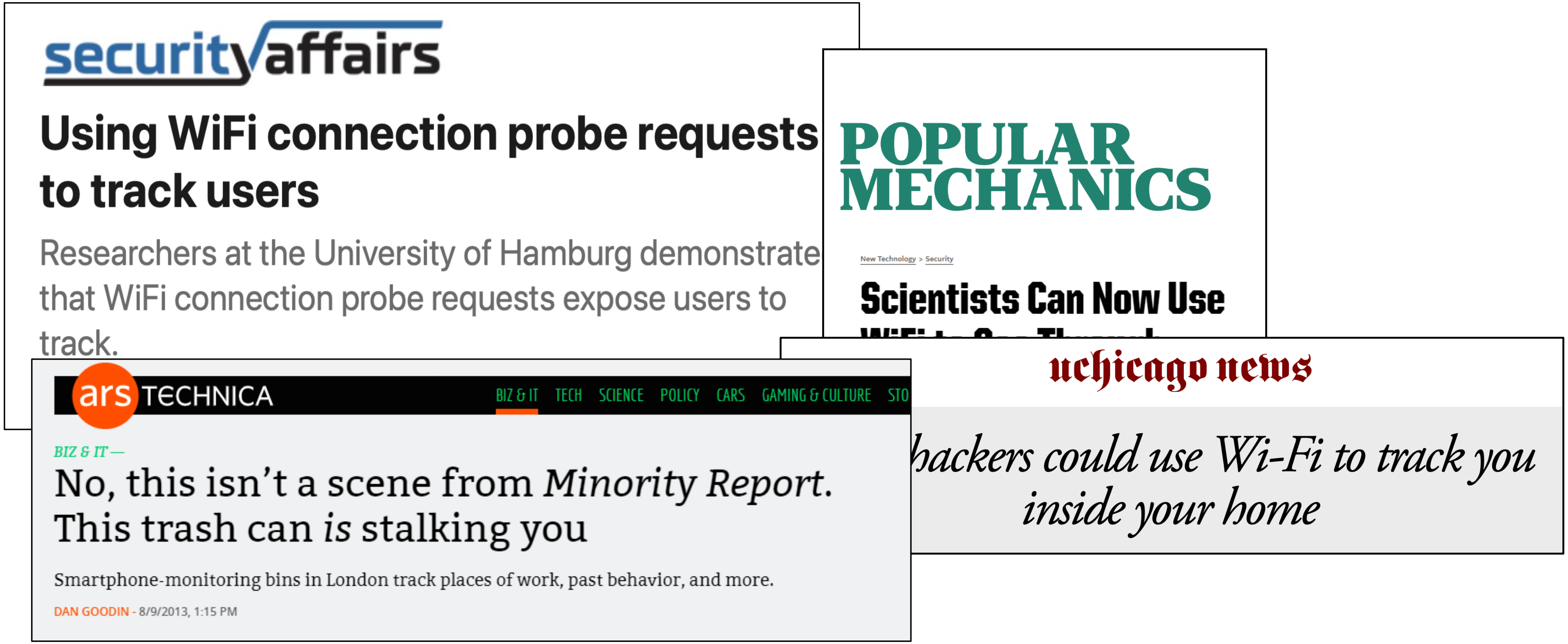


uchicago news

How hackers could use Wi-Fi to track you inside your home

Add headline logos

Wireless is Invasive – But Who Cares?



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ars TECHNICA

BIZ & IT —

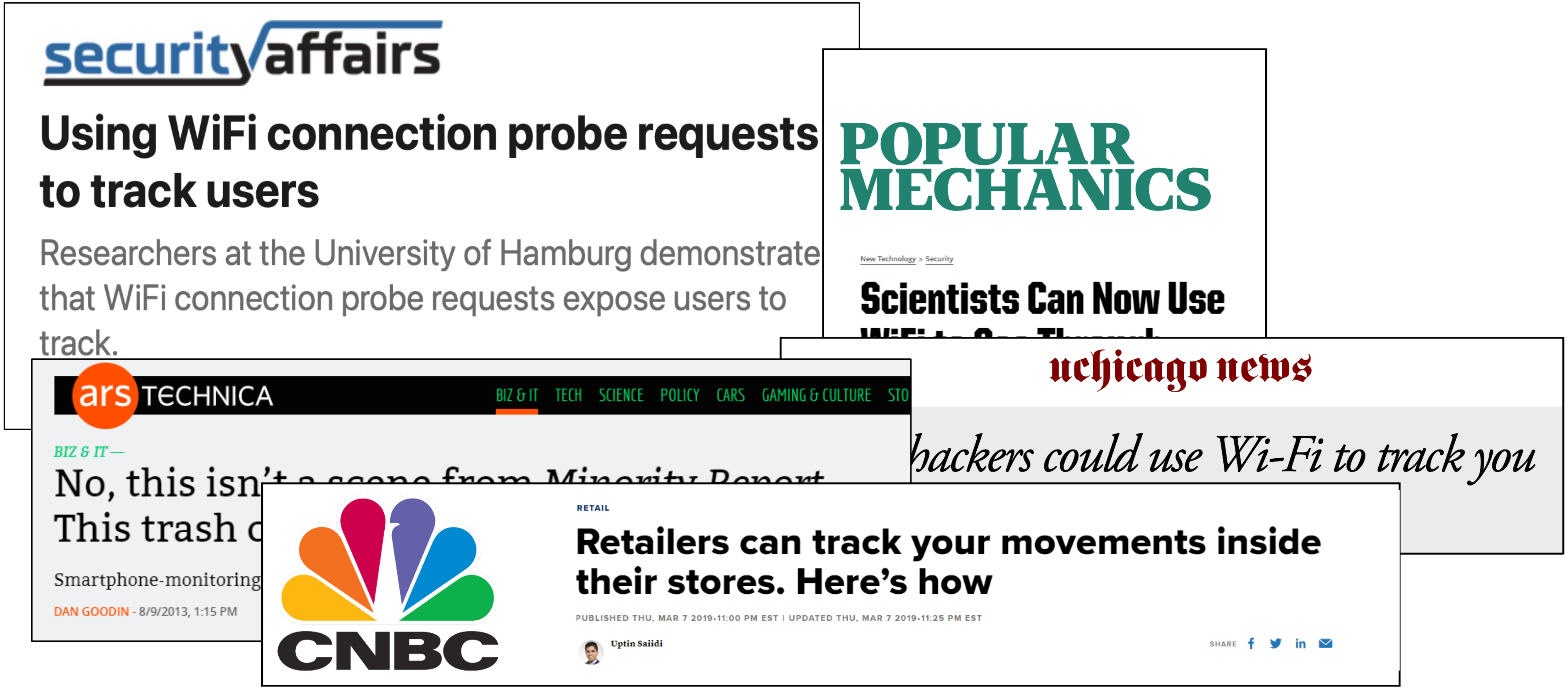
No, this isn't a scene from *Minority Report*. This trash can *is* stalking you

Smartphone-monitoring bins in London track places of work, past behavior, and more.

DAN GOODIN - 8/9/2013, 1:15 PM

Add headline logos

Wireless is Invasive – But Who Cares?



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Smartphone-monitoring

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CNBC

RETAIL

Retailers can track your movements inside their stores. Here's how

PUBLISHED THU, MAR 7 2019•11:00 PM EST | UPDATED THU, MAR 7 2019•11:25 PM EST

Uptin Saiidi

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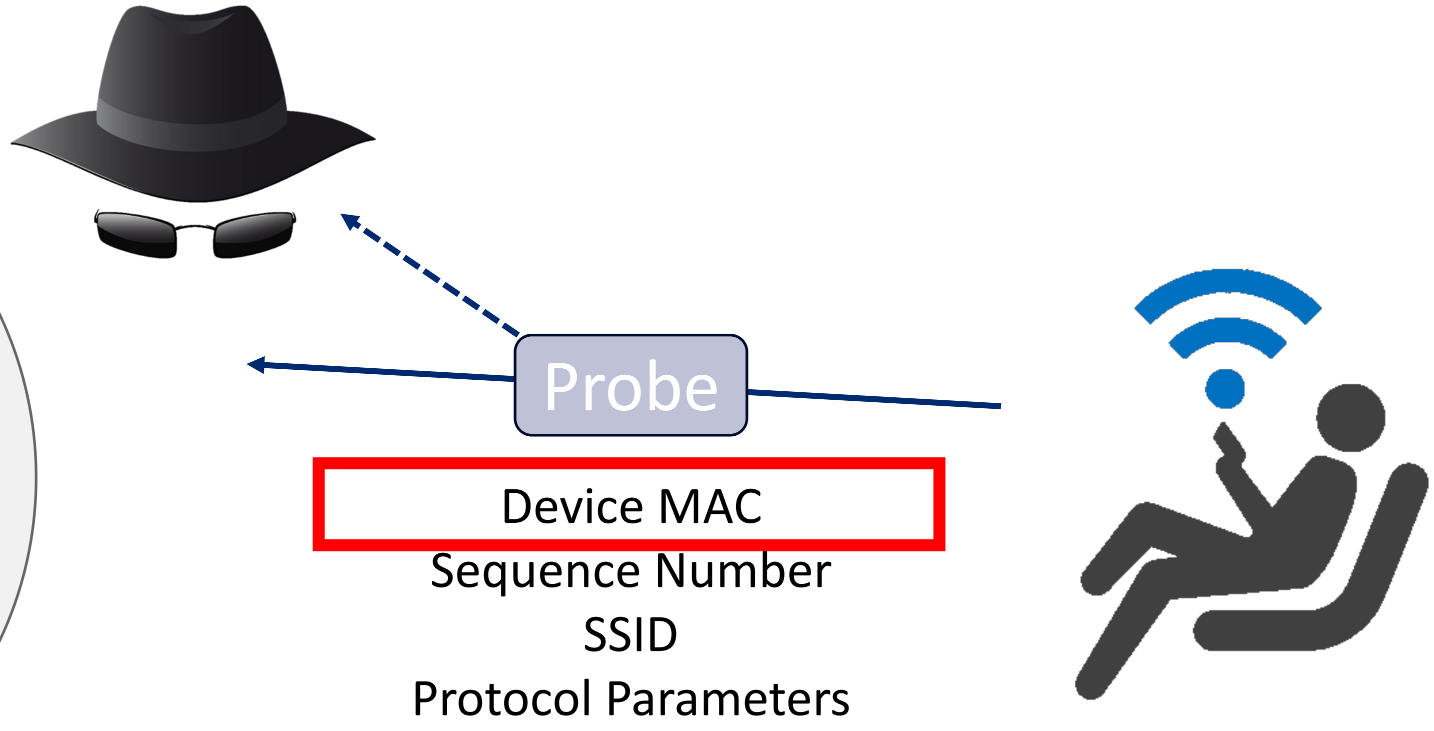


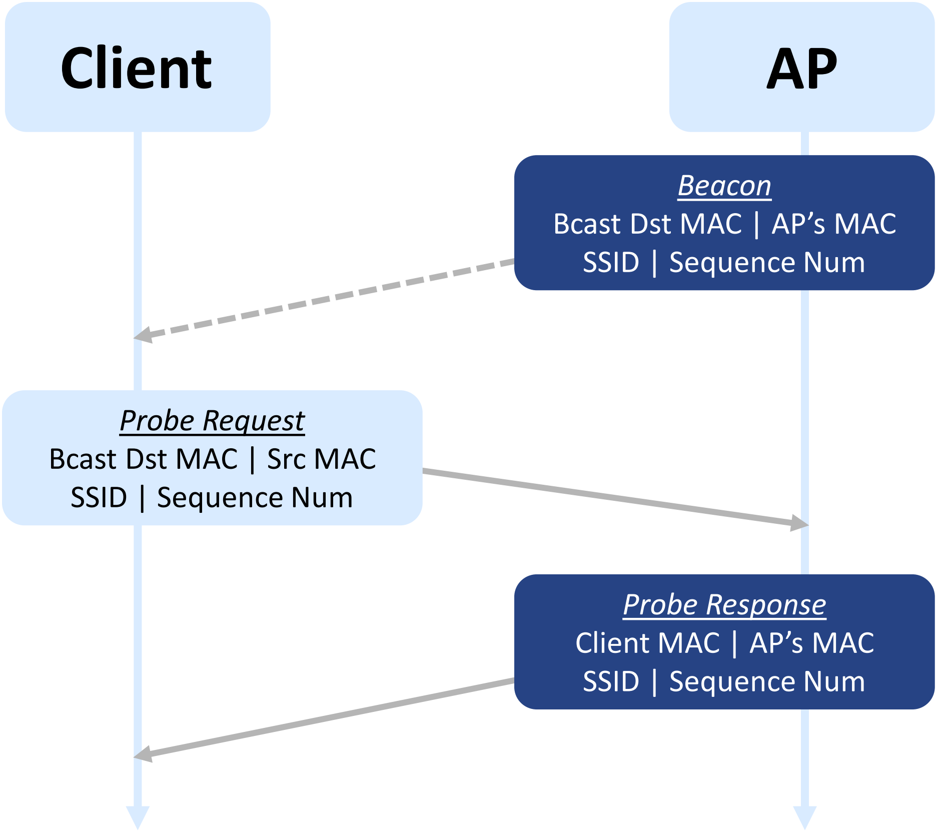
Probe

Device MAC
Sequence Number
SSID
Protocol Parameters

Anonymizing Discovery

- MAC Randomization
  - Change device MAC address from the factory-assigned address
    - WiFi: Discovery
    - BLE: Advertising
  - Enabled by default on most devices
    - Found in mobile OSes from Apple, Android, Windows, Samsung

Wi-Fi Discovery



```
5a:45:3b:4f:e4:c1
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6b:62:12:c9:f8:7b
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b8:27:eb:01:0a:0b
7a:09:44:70:0d:f1
90:35:42:af:23:9f
b8:27:eb:01:0a:0b
b8:27:eb:01:0a:0b
04:1f:a0:92:35:ec
5c:7e:c7:26:59:4d
```

✓

MAC address is kept the same in each probe event

Wi-Fi Discovery with MAC Randomization

✗

5a:45:3b:4f:e4:c1
0e:bc:e5:5b:dc:1d
5c:71:e9:7c:df:5d
6b:62:12:c9:f8:7b
78:d2:e4:64:7c:54
27:19:32:4a:da:e2
7a:09:44:70:0d:f1
90:35:42:af:23:9f
34:20:99:49:ad:8f
ed:4a:75:7d:21:1a
04:1f:a0:92:35:ec
5c:7e:c7:26:59:4d

5a:45:3b:4f:e4:c1
0e:bc:e5:5b:dc:1d
b8:27:eb:01:0a:0b
6b:62:12:c9:f8:7b
78:d2:e4:64:7c:54
b8:27:eb:01:0a:0b
7a:09:44:70:0d:f1
90:35:42:af:23:9f
b8:27:eb:01:0a:0b
b8:27:eb:01:0a:0b
04:1f:a0:92:35:ec
5c:7e:c7:26:59:4d

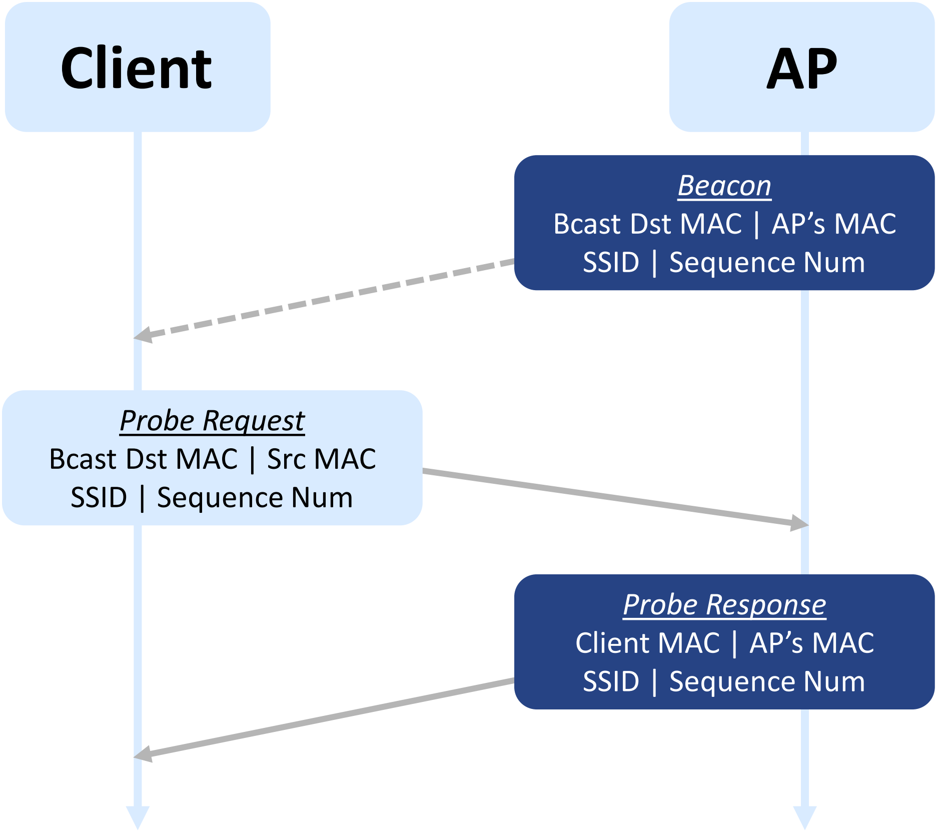
✓

MAC Randomization

- No standard for implementation
  - Address Randomization
    - Implemented by each vendor differently
  - Address Rotation
    - Persistent randomization: use a single random MAC address
    - Non-persistent randomization: use a random MAC address each session
    - Total randomization: use a random MAC address every packet

- Overhead
  - Random MAC address for every packet
    - 6.6% (4ms) overhead on a Raspberry Pi
    - Could be optimized, but is probably overkill

Attacking Wi-Fi Discovery



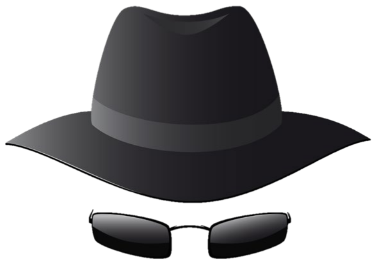
Client

AP

Beacon
Bcast Dst MAC | AP's MAC
SSID | Sequence Num

Probe Request
Bcast Dst MAC | Src MAC
SSID | Sequence Num

Probe Response
Client MAC | AP's MAC
SSID | Sequence Num



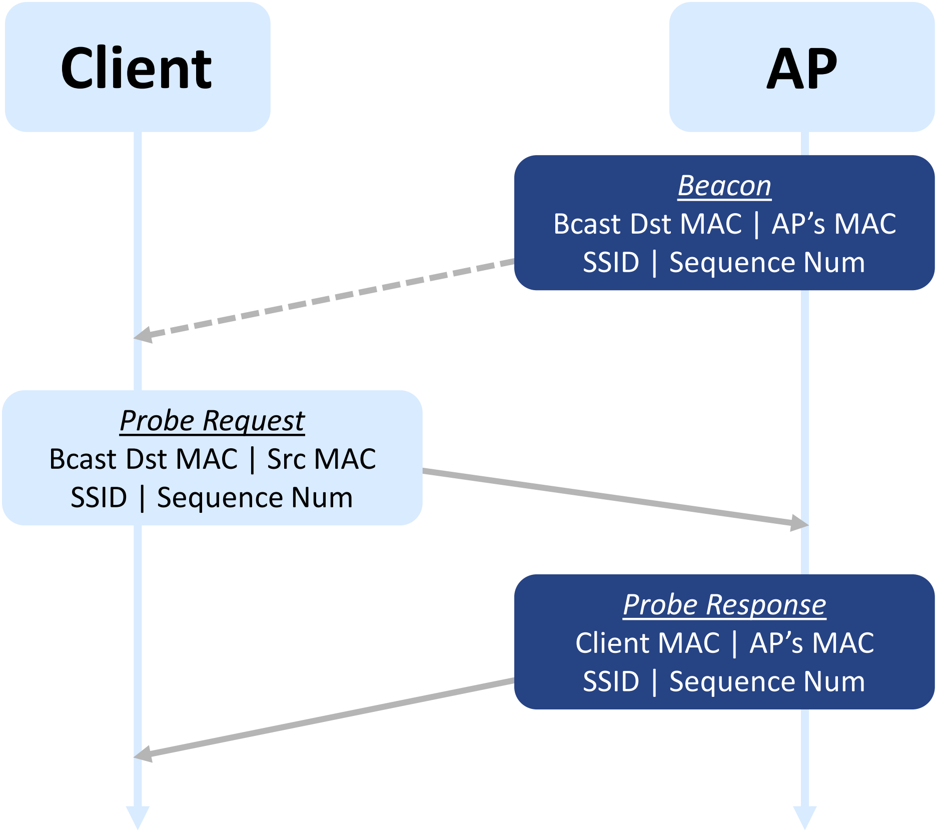
Attacks on Wi-Fi protocols

Control Frame Attack
[Martin et al. PETs '17]

Wi-Peep
[Abedi & Vasisht, MobiCom '22]

Grouping unique Information Elements
[Vanhoef et al. ASIA CCS '16]

Attacking Wi-Fi Discovery



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Beacon
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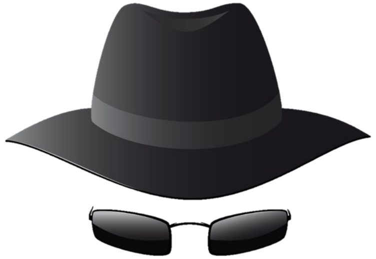

Exploiting leaked info from Wi-Fi

Location Histories
[Han et al. IEEE ICC ‘18]

Shopping Habits
[Barbera et al. IMC ‘13]

Users’ Workplaces
[Di Luzio et al. INFOCOM ‘16]

Is MAC Randomization Enough?

Wi-Fi discovery is vulnerable even with MAC randomization

Packet Fields

- MAC Address
  [Martin et al. PETs ‘17]
- SSIDs
  [Han et al. IEEE ICC ‘18]
  [Barbera et al. IMC ‘13]
- Sequence Numbers
  [Fenske et al. PETs ‘21]
  [Freudiger, WiSec ‘15]

Signal Properties

- Angle of Arrival
  [Xiong & Jamieson, MobiCom ‘13]
- Signal strength
  [Bauer et al. PETs ‘09]
- Time of Flight
  [Abedi & Vasisht, MobiCom ‘22]

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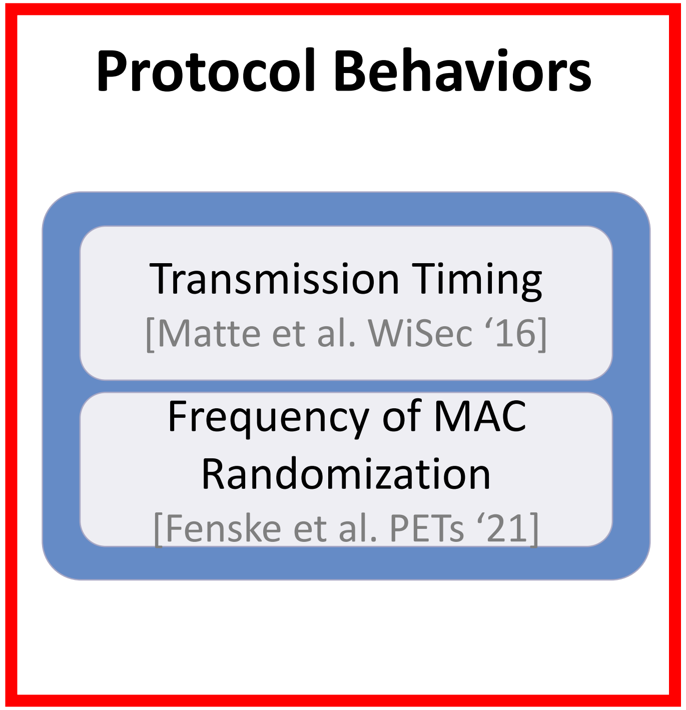
Protocol Behaviors

- Transmission Timing
  [Matte et al. WiSec ‘16]
- Frequency of MAC Randomization
  [Fenske et al. PETs ‘21]

Is MAC Randomization Enough?

Wi-Fi discovery is vulnerable even with MAC randomization

Timing attacks on network discovery

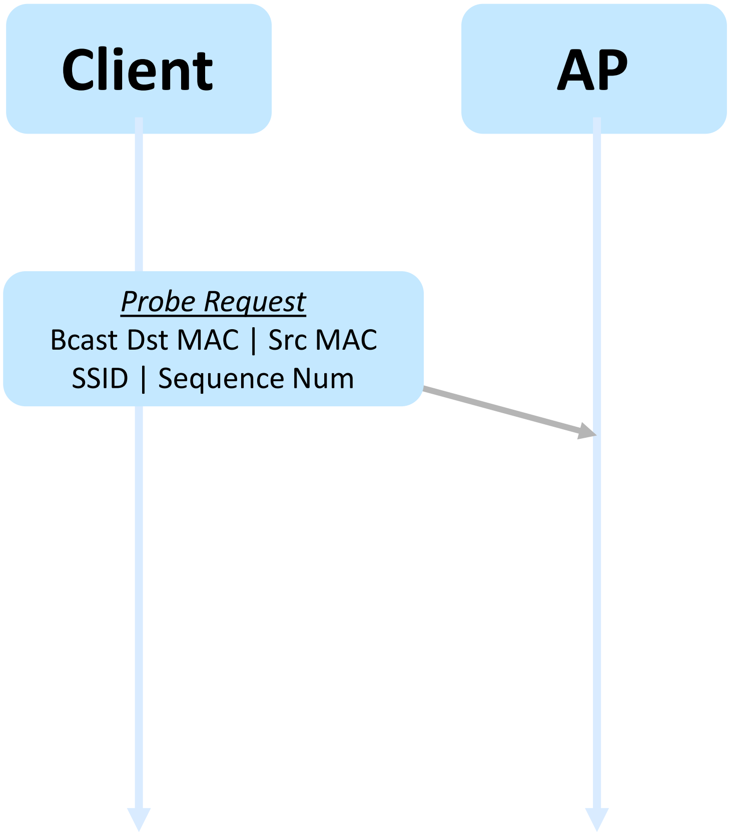


Protocol Behaviors

Transmission Timing
[Matte et al. WiSec ‘16]

Frequency of MAC Randomization
[Fenske et al. PETs ‘21]

Network Discovery: Probe Events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Probe Request
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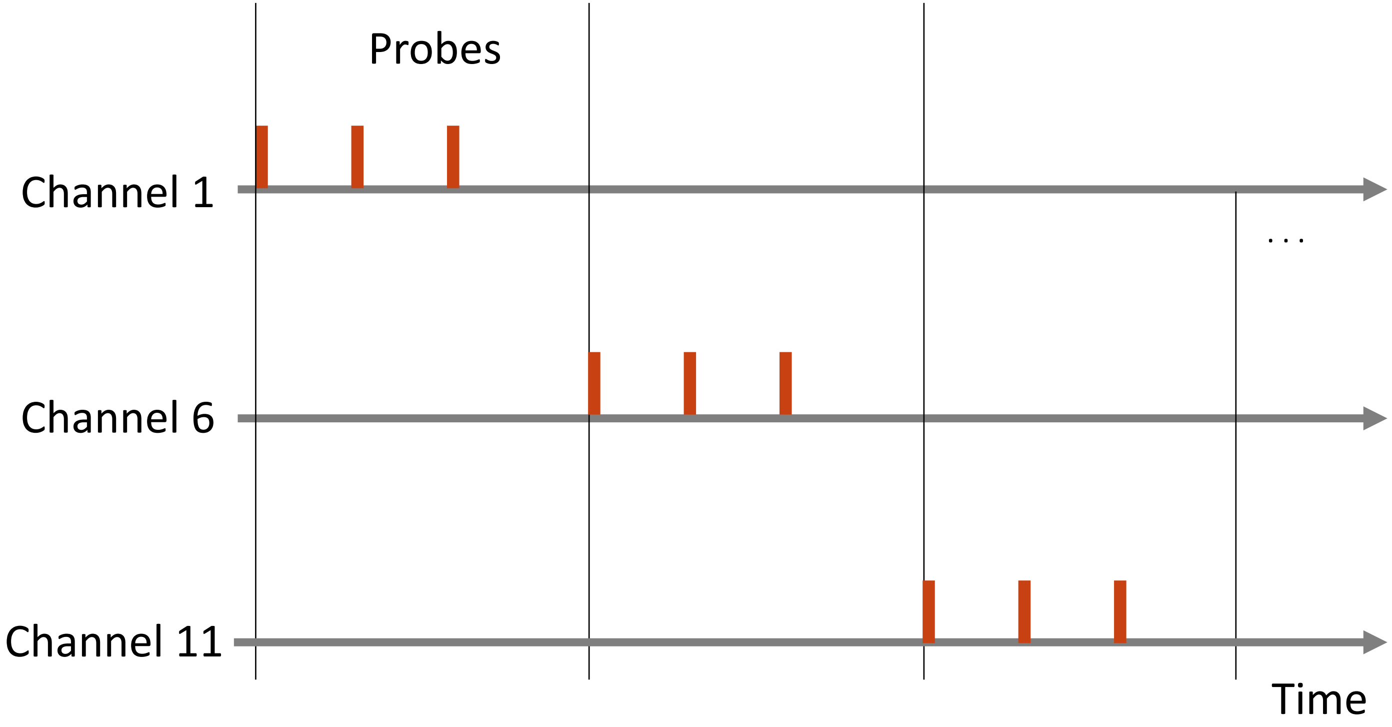

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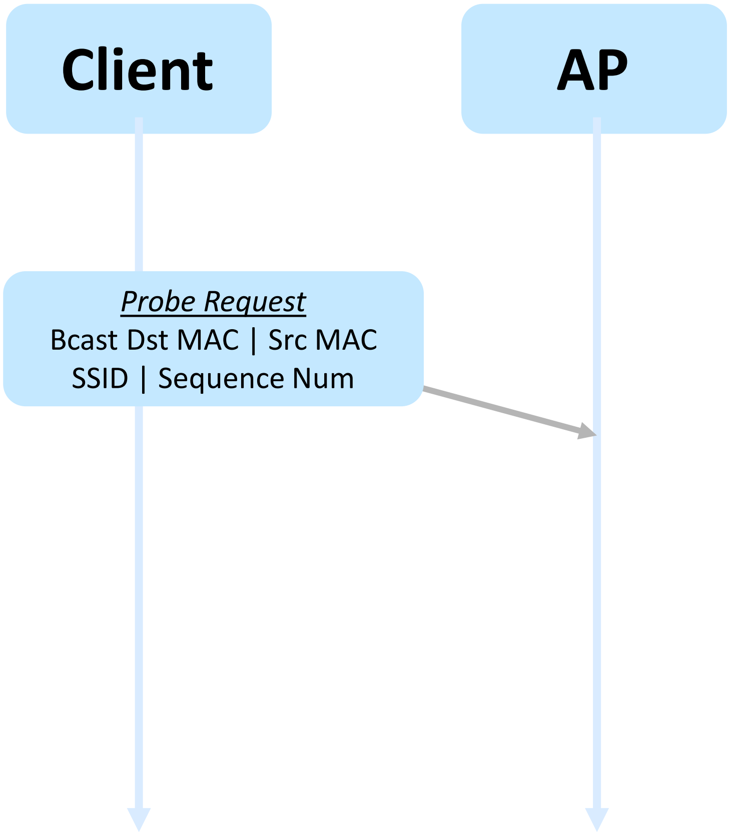

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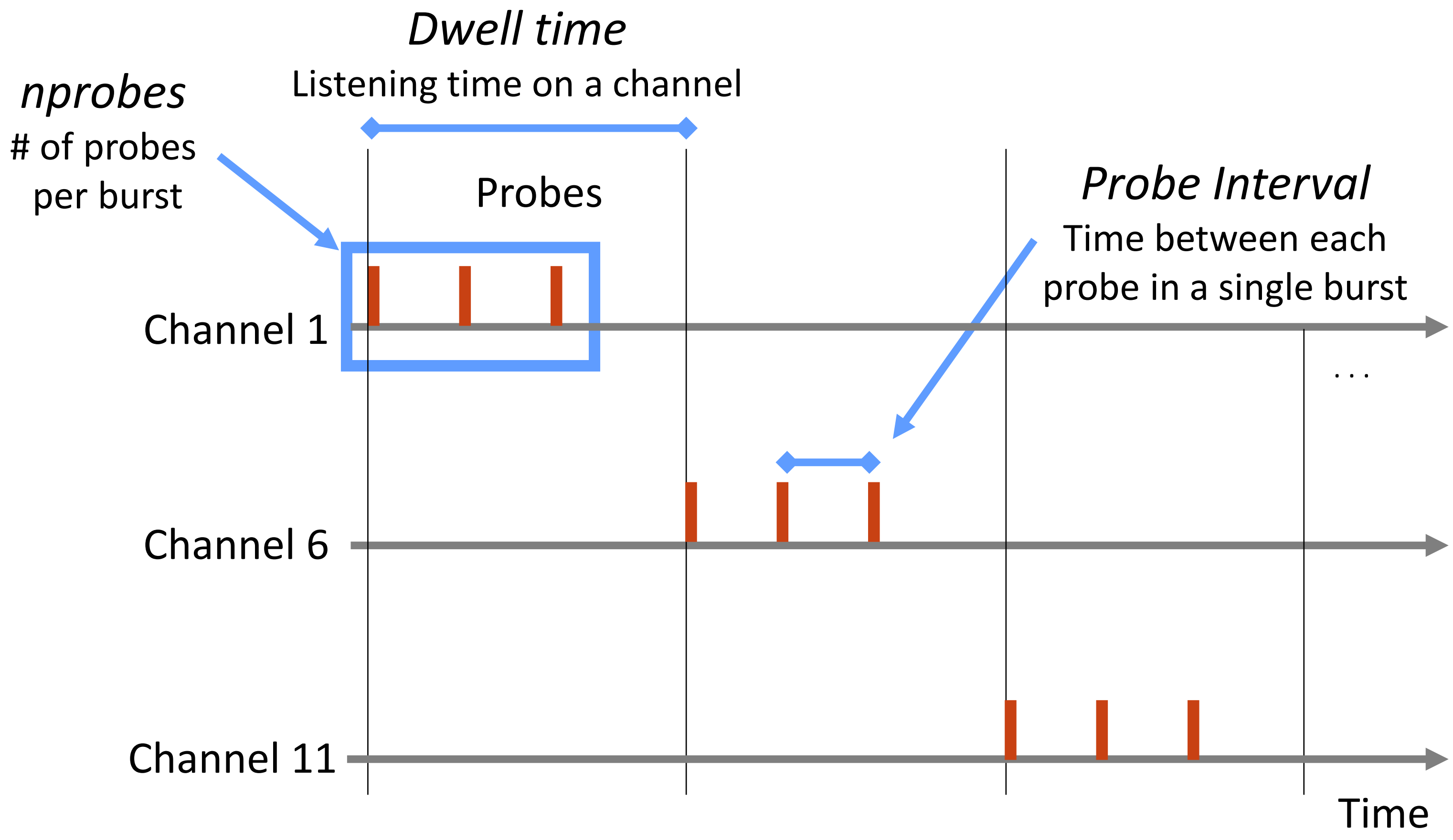


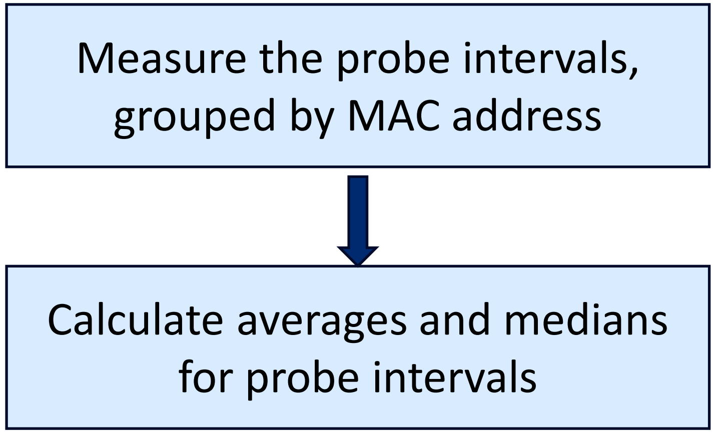
Computer Science

Observed Probe Intervals of Mobile Devices

Device Model	OS Version	Probe Interval
Apple iPhone 14 Pro Max	17.1	20.3ms ± 0.1ms
Apple iPhone 13	16.7.1	20.2ms
Apple iPhone 11	17.0.3	20.2ms ±0.1ms
Apple iPhone SE (2nd gen)	16.6.1	20.2ms± 0.1ms
Google Pixel 7 Pro	14	20ms ± 1ms
Google Pixel 6a	13	--
Samsung S22 Ultra	13	40ms
Samsung S21	13	40ms ± 2ms
Samsung S10e	12	11ms
Raspberry Pi 3B+	RPi OS 6.1	21ms
Raspberry Pi 4B	Kali 2023.2	20ms ± 1ms
Dell Inspiron 15R	Windows 10 22H2	11ms
Lenovo Yoga 710	Ubuntu 20.04	51ms

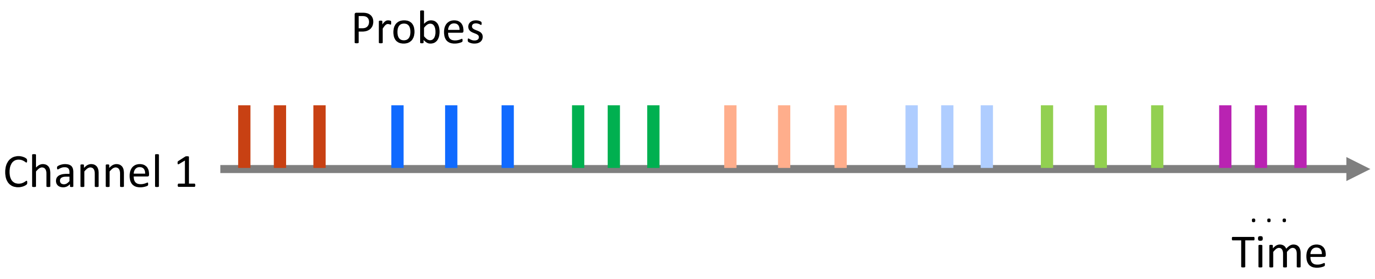
Make table consistent

Exploiting Probe Interval Patterns



Measure the probe intervals, grouped by MAC address

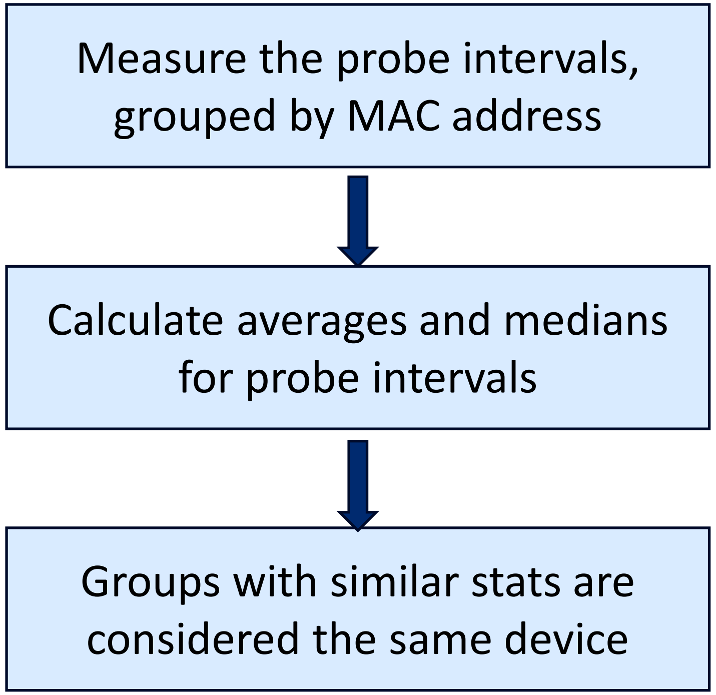
Calculate averages and medians for probe intervals



Transmission Timing
[Matte et al. WiSec '16]

Probe Interval Patterns
[Cifuentes-Urtubey et al. MobiSys '22]

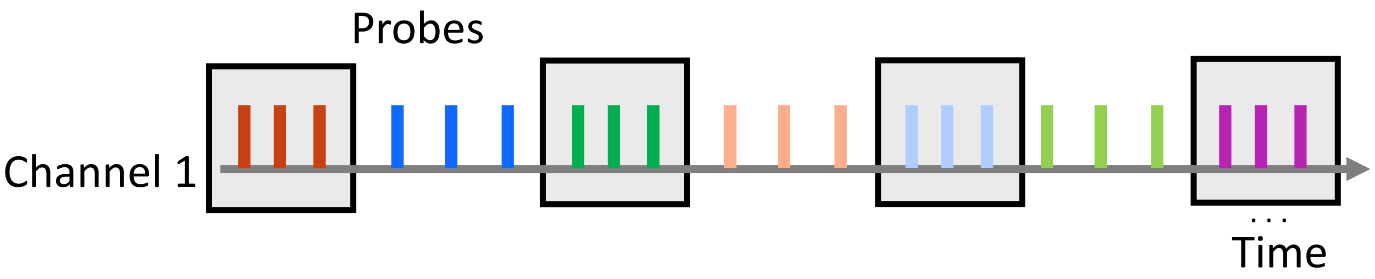
Exploiting Probe Interval Patterns



Measure the probe intervals, grouped by MAC address

Calculate averages and medians for probe intervals

Groups with similar stats are considered the same device



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[Matte et al. WiSec ‘16]

Probe Interval Patterns
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Exploiting Probe Interval Patterns

Measure the probe intervals,

All devices with the same probe interval will be grouped together

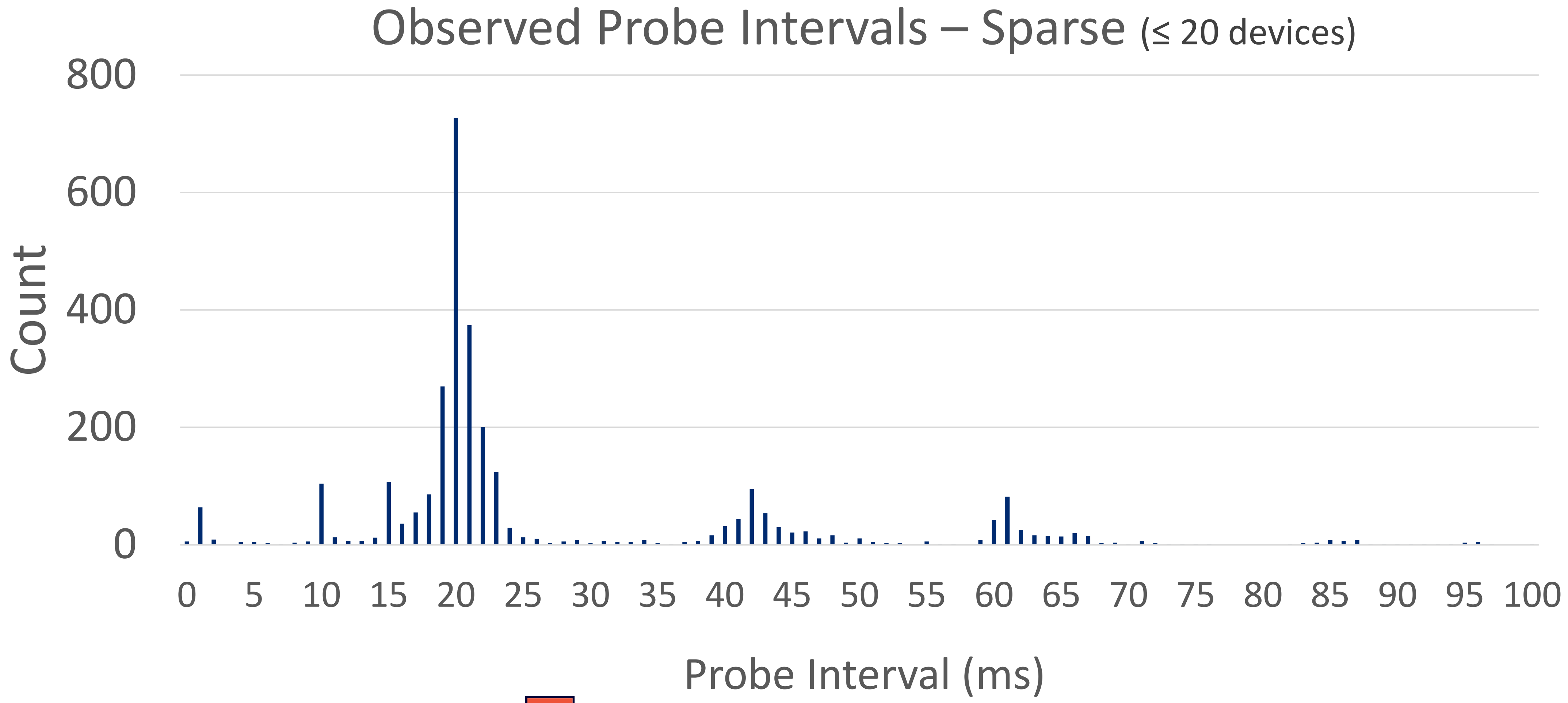
Calculate averages and medians for probe intervals

Groups with similar stats are considered the same device

Transmission Timing
[Matte et al. WiSec '16]

Probe Interval Patterns
[Cifuentes-Urtubey et al. MobiSys '22]

Limitation: Probe Interval Patterns



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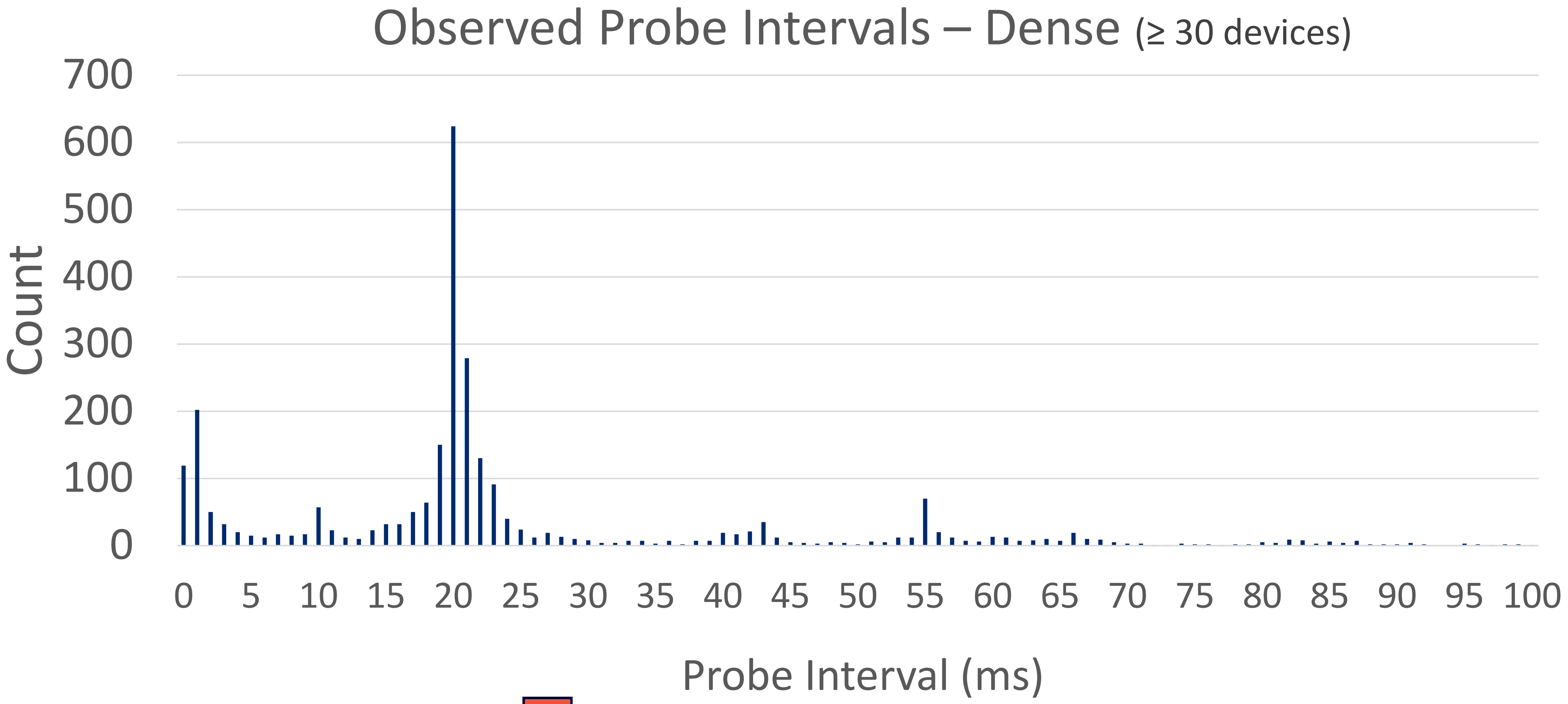

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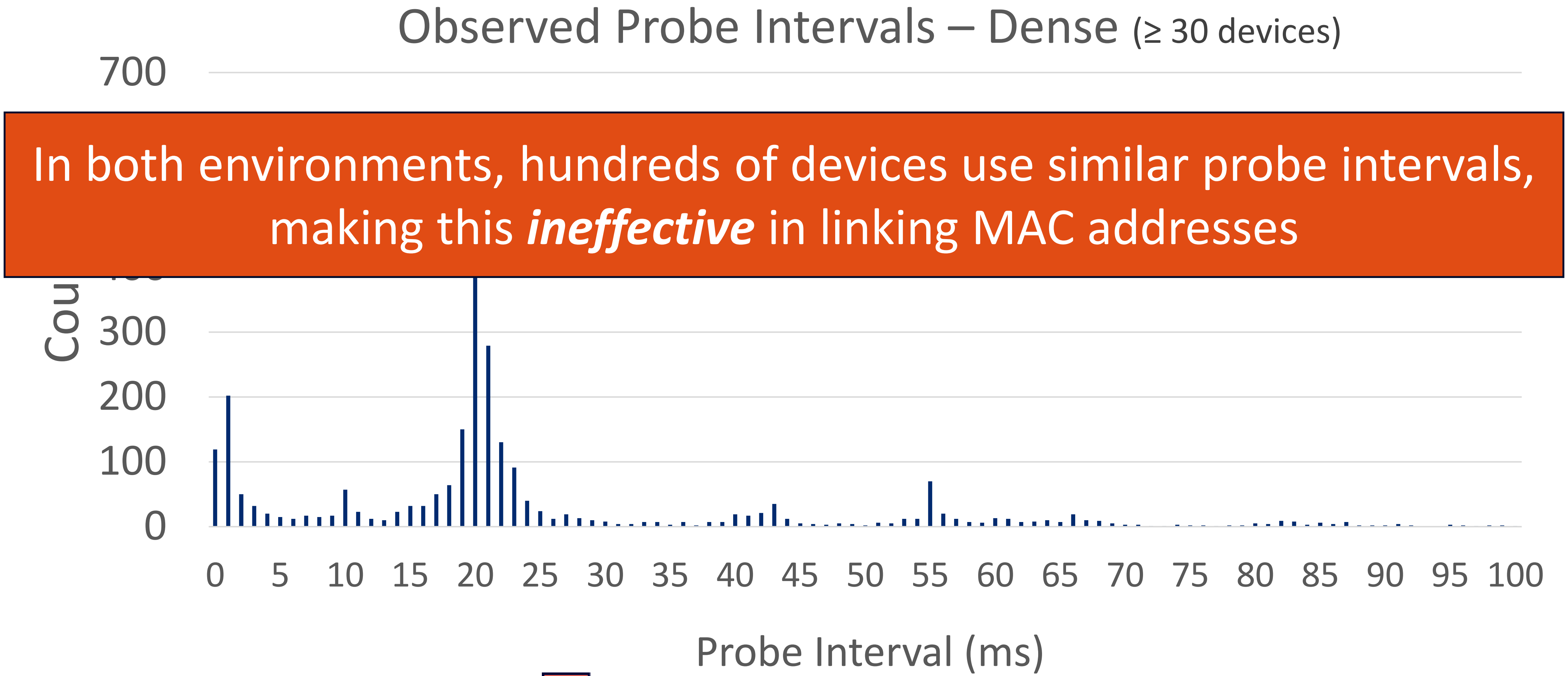
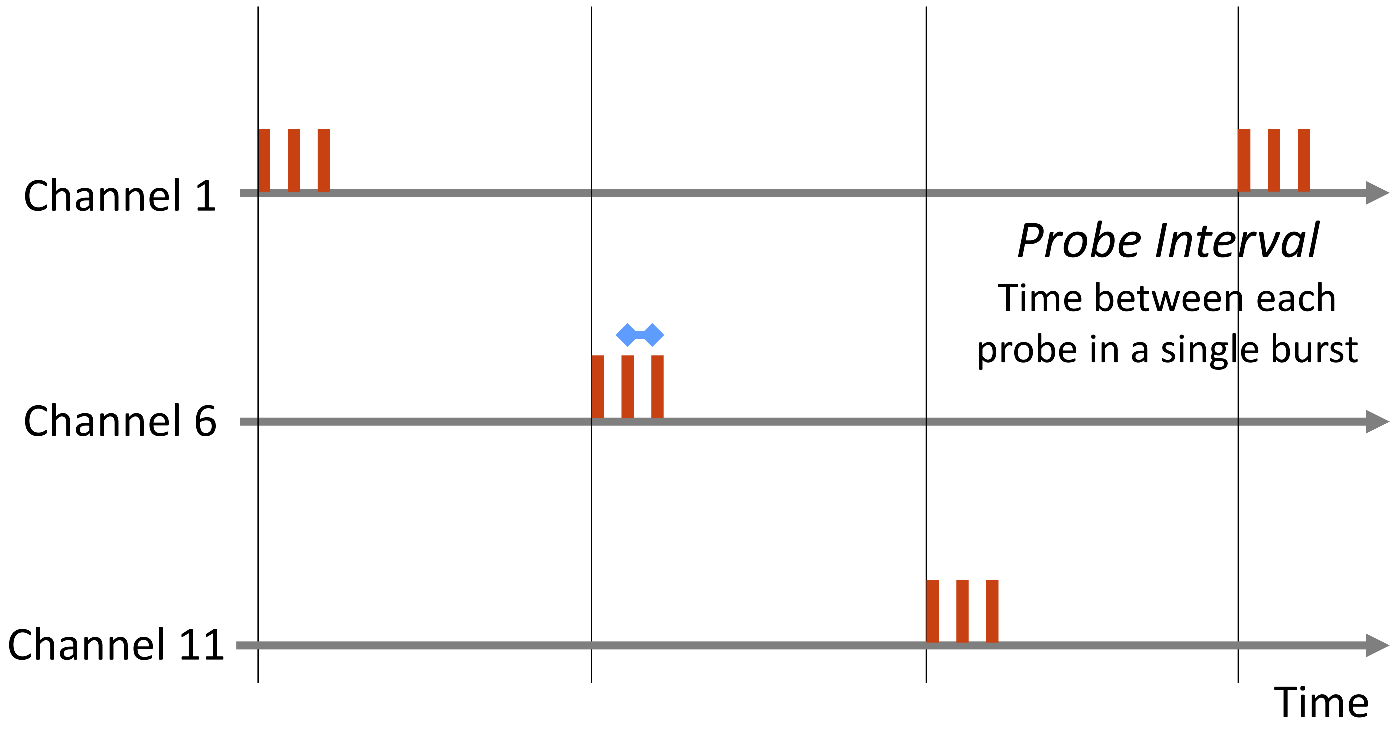


In both environments, hundreds of devices use similar probe intervals, making this ***ineffective*** in linking MAC addresses

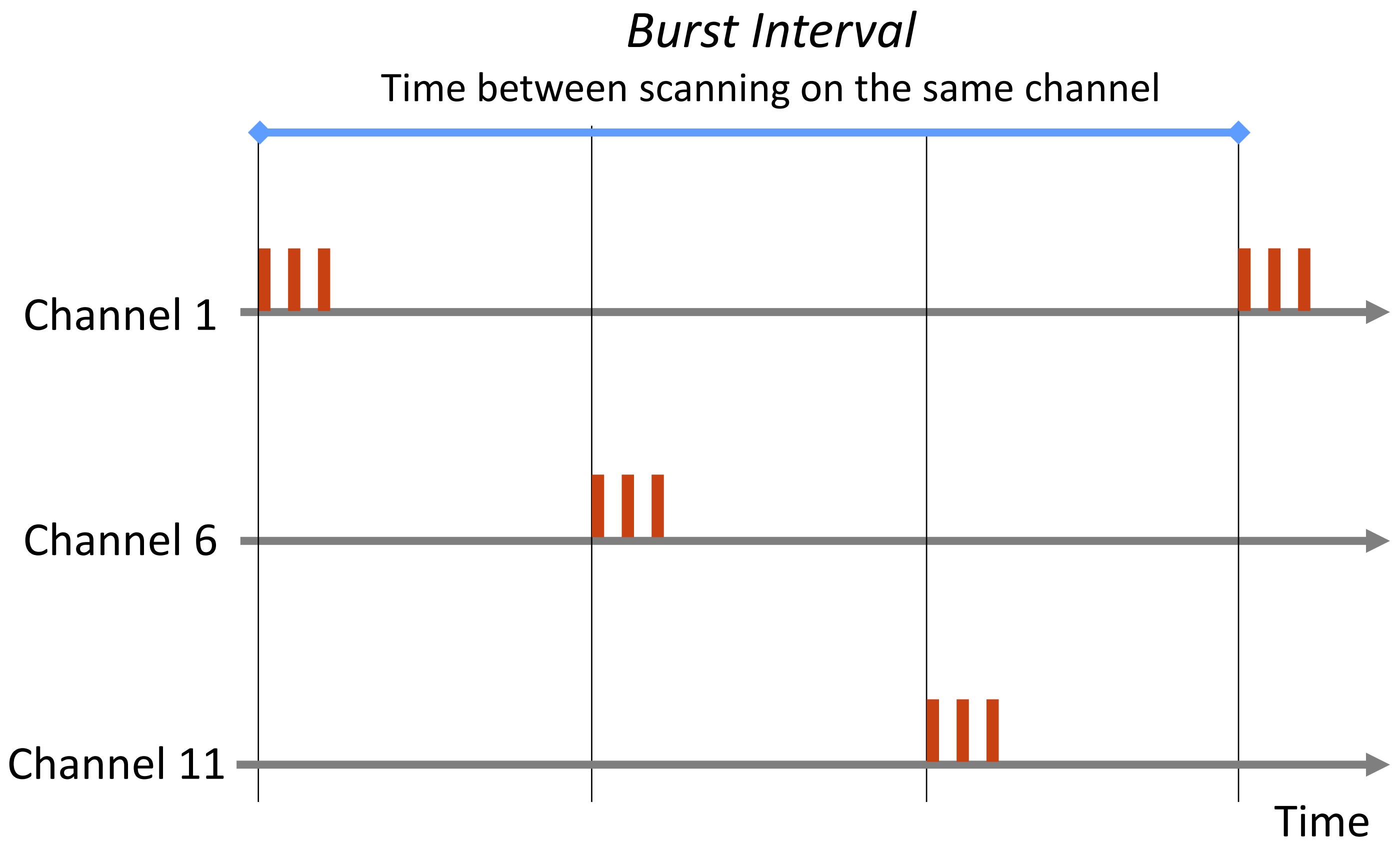
Time Scale is the Key

- Prior work focused solely on probe intervals



Time Scale is the Key

- Prior work focused solely on probe intervals
- New approach: Analyze timing patterns **across bursts**

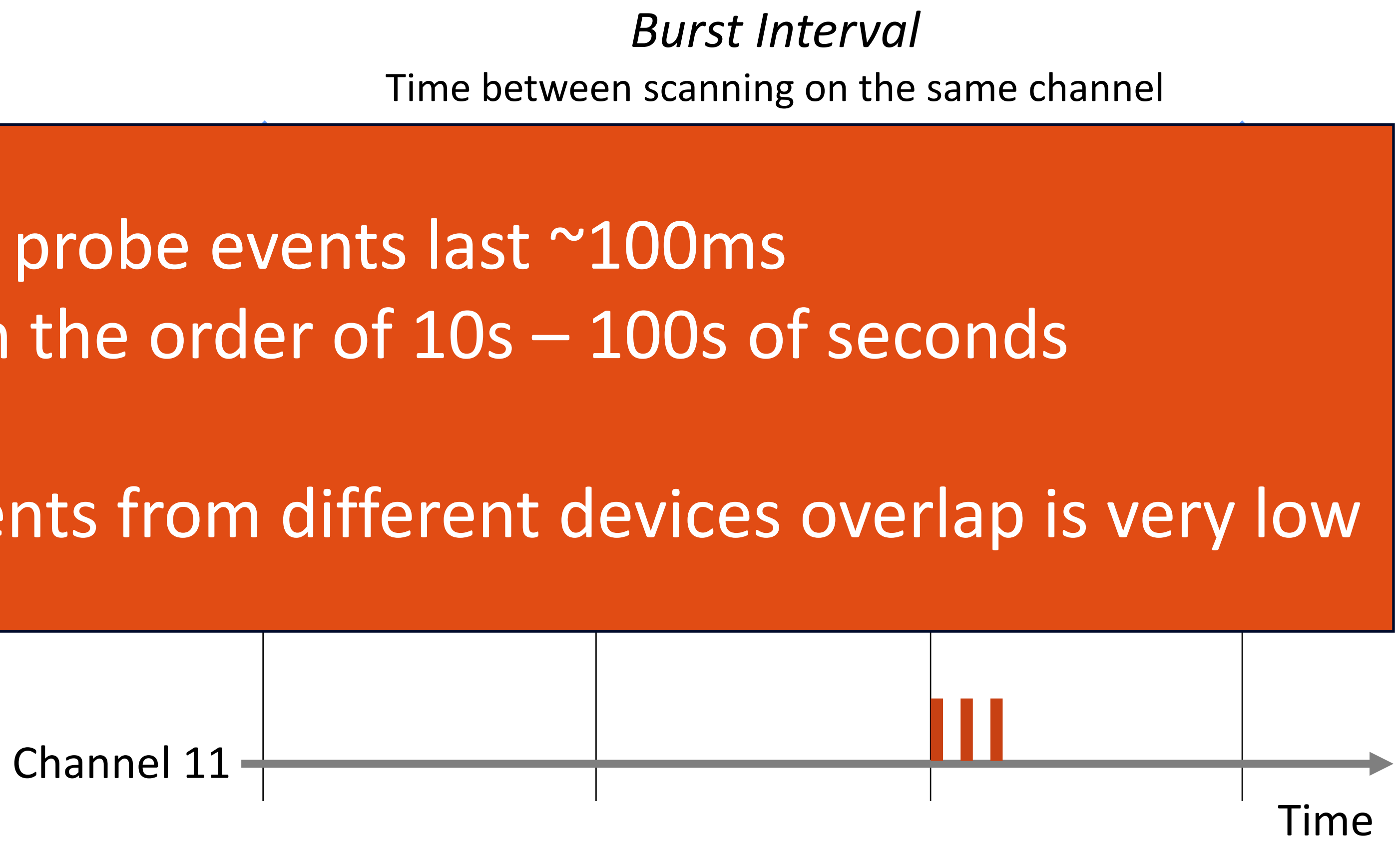


Time Scale is the Key

- Prior work focused

Device probe events last ~100ms
Devices burst on the order of 10s – 100s of seconds

Probability that probe events from different devices overlap is very low



Observed Burst Intervals

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Apple iPhone 11	17.0.3	20.2ms ±0.1ms	--
Apple iPhone SE (2nd gen)	16.6.1	20.2ms± 0.1ms	--
Google Pixel 7 Pro	14	20ms ± 1ms	160 sec
Google Pixel 6a	13	--	160 sec
Samsung S22 Ultra	13	40ms	40 sec
Samsung S21	13	40ms ± 2ms	13 sec
Samsung S10e	12	11ms	40 sec
Raspberry Pi 3B+	RPi OS 6.1	21ms	60sec ± 25ms
Raspberry Pi 4B	Kali 2023.2	20ms ± 1ms	60 sec
Dell Inspiron 15R	Windows 10 22H2	11ms	59.7sec ± 20ms
Lenovo Yoga 710	Ubuntu 20.04	51ms	63.0sec ±30ms

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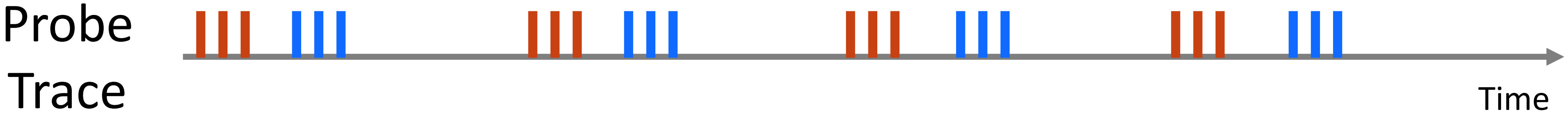
Google Pixel 7 Pro			160 sec
Google Pixel 6a			160 sec
Samsung S22 Ultra			40 sec
Samsung S21			13 sec
Samsung S10e			40 sec
Raspberry Pi 3B+			60sec ± 25ms
Raspberry Pi 4B			60 sec
Dell Inspiron 15R	Windows 10 22H2	11ms	59.7sec ± 20ms
Lenovo Yoga 710	Ubuntu 20.04	51ms	63.0sec ±30ms

Knowing the target burst interval enables tracking the device

Exploiting Burst Interval Patterns



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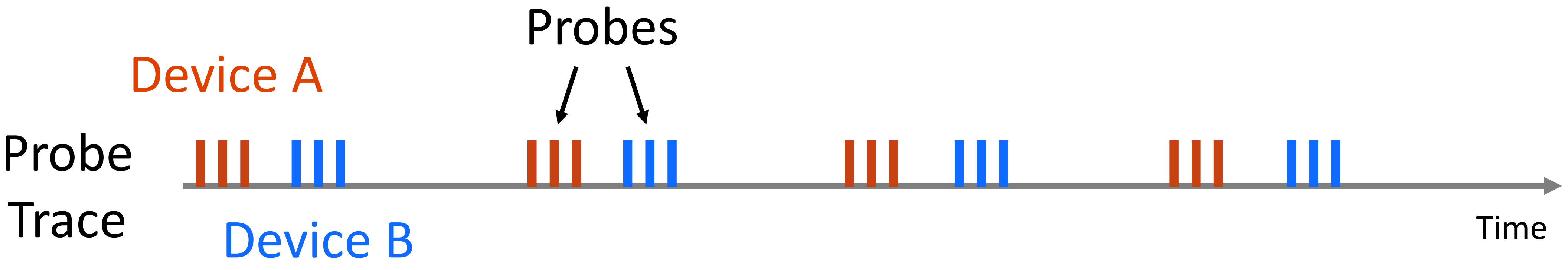

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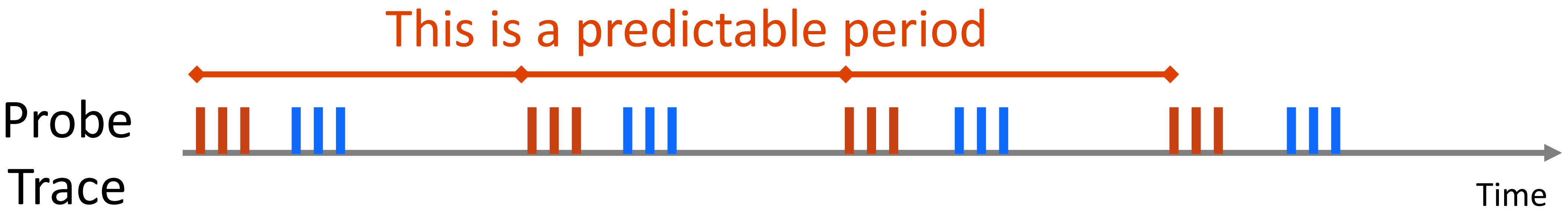
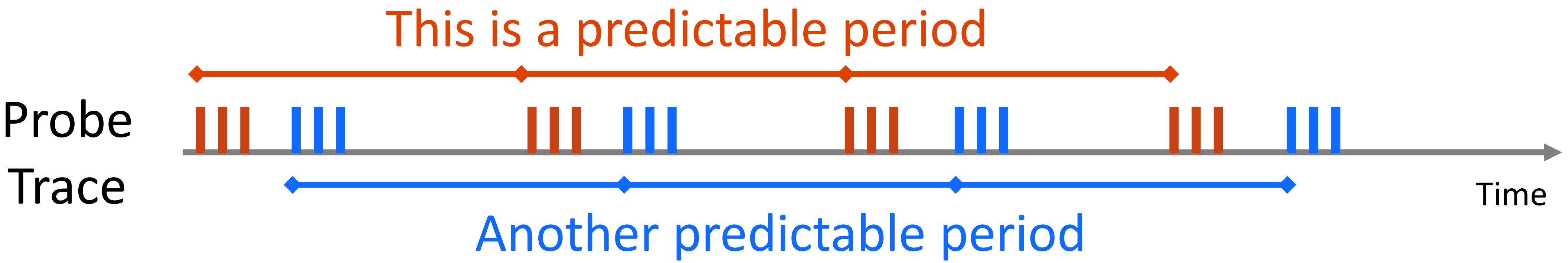


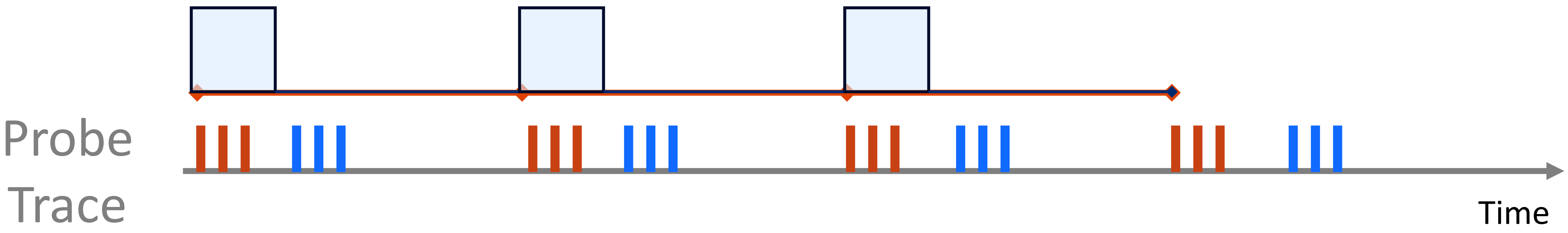
Exploiting Burst Interval Patterns



How do we extract the MAC addresses?

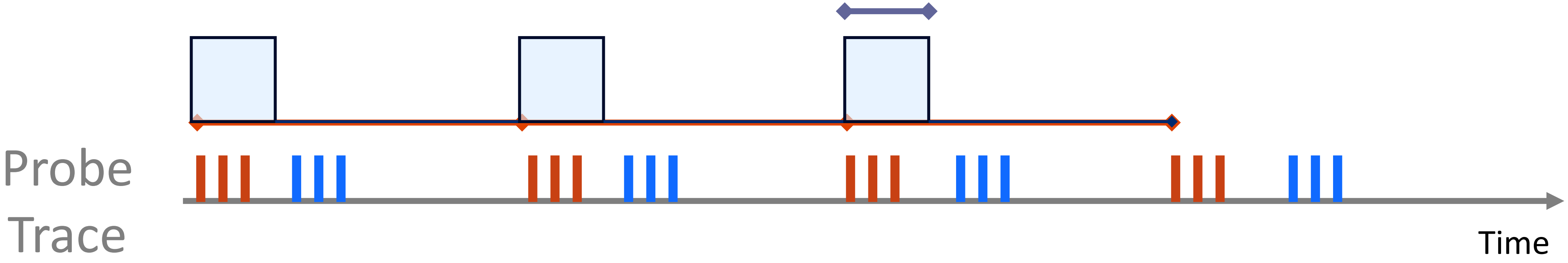
Exploiting Burst Interval Patterns

Create a template (base) pattern of where the probes will be



Exploiting Burst Interval Patterns

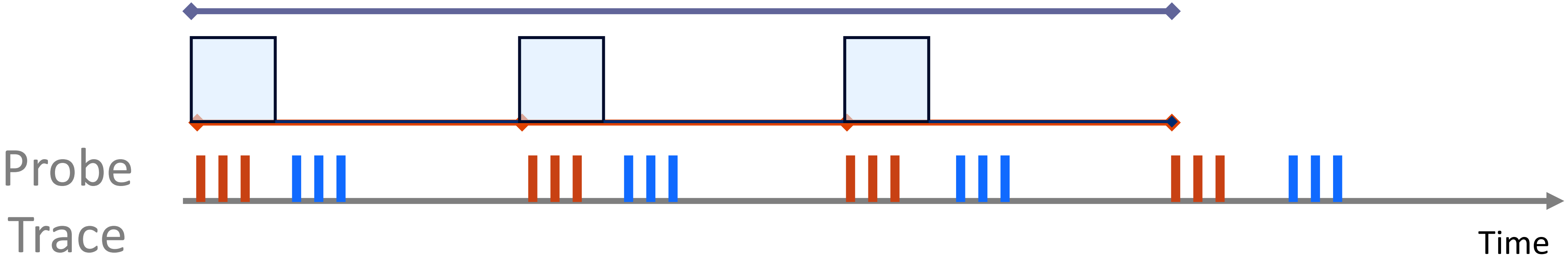
Create a template (base) pattern of where the probes will be



This *window size* is determined by the number of probes and their probe interval within a burst

Exploiting Burst Interval Patterns

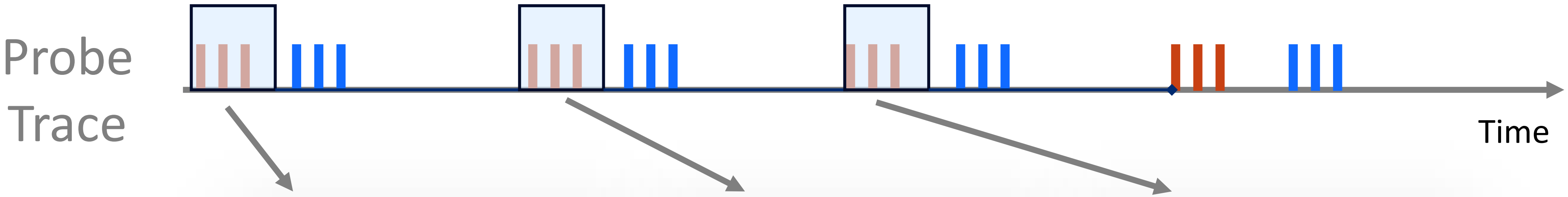
Create a template (base) pattern of where the probes will be



This *pattern length* is time in minutes to search a pattern for

Exploiting Burst Interval Patterns

Output the MAC addresses of probes matching this pattern



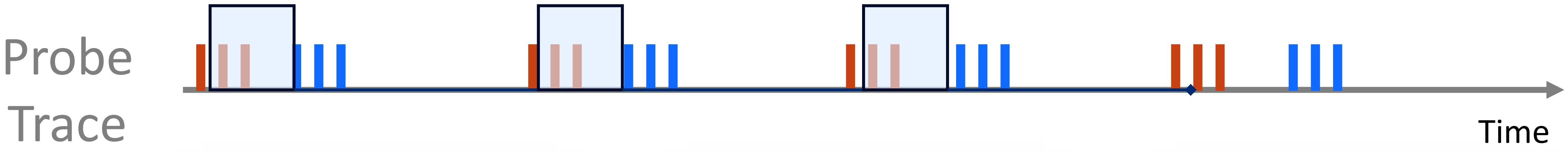
```
8a:46:2b:f2:db:8d
8a:46:2b:f2:db:8d
8a:46:2b:f2:db:8d
```

```
b6:1a:e9:06:f1:c4
b6:1a:e9:06:f1:c4
b6:1a:e9:06:f1:c4
```

```
2a:a0:d5:3b:53:72
2a:a0:d5:3b:53:72
2a:a0:d5:3b:53:72
```

Exploiting Burst Interval Patterns

Time-shifted copies find the best match by amount of probes present



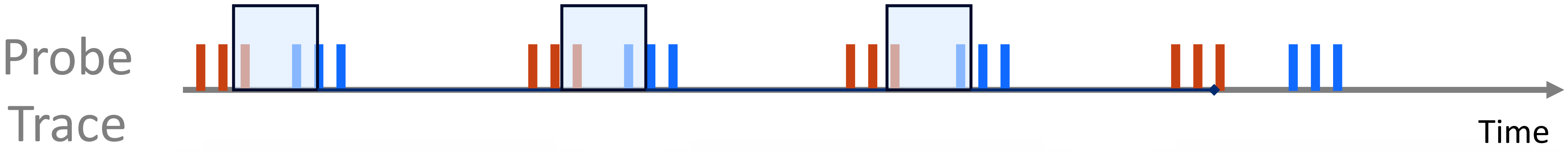
8a:46:2b:f2:db:8d
8a:46:2b:f2:db:8d

b6:1a:e9:06:f1:c4
b6:1a:e9:06:f1:c4

2a:a0:d5:3b:53:72
2a:a0:d5:3b:53:72

Exploiting Burst Interval Patterns

Time-shifted copies find the best match by amount of probes present



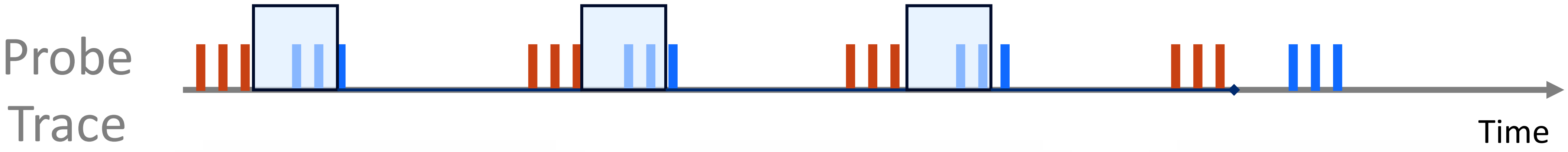
8a:46:2b:f2:db:8d
16:67:c1:04:39:bf

b6:1a:e9:06:f1:c4
54:8a:53:be:1d:df

2a:a0:d5:3b:53:72
9c:99:c4:cb:84:ea

Exploiting Burst Interval Patterns

Time-shifted copies find the best match by amount of probes present



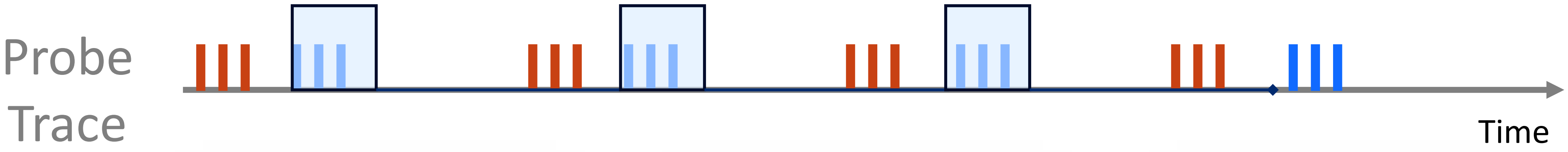
16:67:c1:04:39:bf
16:67:c1:04:39:bf

54:8a:53:be:1d:df
54:8a:53:be:1d:df

9c:99:c4:cb:84:ea
9c:99:c4:cb:84:ea

Exploiting Burst Interval Patterns

Time-shifted copies find the best match by amount of probes present



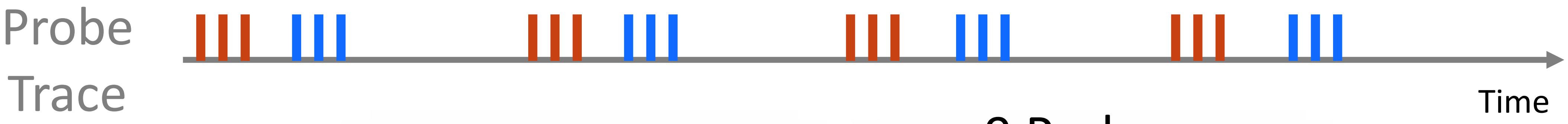
```
16:67:c1:04:39:bf
16:67:c1:04:39:bf
16:67:c1:04:39:bf
```

```
54:8a:53:be:1d:df
54:8a:53:be:1d:df
54:8a:53:be:1d:df
```

```
9c:99:c4:cb:84:ea
9c:99:c4:cb:84:ea
9c:99:c4:cb:84:ea
```

Exploiting Burst Interval Patterns

Find the **best** match by **# of probes**



9 Probes

```
8a:46:2b:f2:db:8d (3x)
b6:1a:e9:06:f1:c4 (3x)
2a:a0:d5:3b:53:72 (3x)
```

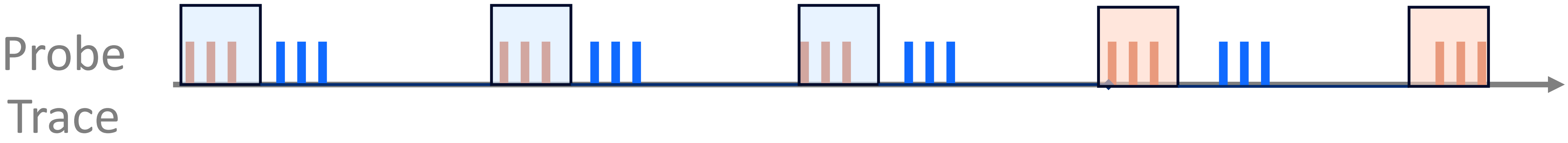
9 Probes

```
16:67:c1:04:39:bf (3x)
54:8a:53:be:1d:df (3x)
9c:99:c4:cb:84:ea (3x)
```

Highest ranking sets

Exploiting Burst Interval Patterns

Problem:
The pattern only finds probes within the length of the base pattern



Exploiting Burst Interval Patterns

Solution:

To extract longer sets, *iteratively chain* through them starting from the largest set to find probes belonging to the same device

```
8a:46:2b:f2:db:8d
b6:1a:e9:06:f1:c4
2a:a0:d5:3b:53:72
```

```
16:67:c1:04:39:bf
54:8a:53:be:1d:df
9c:99:c4:cb:84:ea
```

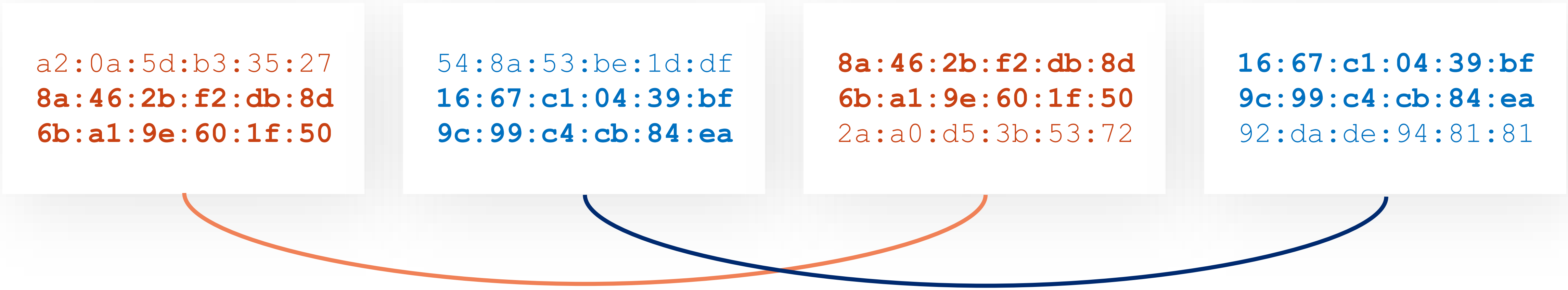
```
a2:0a:5d:b3:35:27
8a:46:2b:f2:db:8d
6b:a1:9e:60:1f:50
```

```
16:67:c1:04:39:bf
6a:54:9f:23:41:0a
92:da:de:94:81:81
```

Exploiting Burst Interval Patterns

Solution:

To extract longer sets, *iteratively chain* through them starting from the largest set to find probes belonging to the same device



a2:0a:5d:b3:35:27
8a:46:2b:f2:db:8d
6b:a1:9e:60:1f:50

54:8a:53:be:1d:df
16:67:c1:04:39:bf
9c:99:c4:cb:84:ea

8a:46:2b:f2:db:8d
6b:a1:9e:60:1f:50
2a:a0:d5:3b:53:72

16:67:c1:04:39:bf
9c:99:c4:cb:84:ea
92:da:de:94:81:81

If there are intersecting MAC addresses, take the union to form a chain

Exploiting Burst Interval Patterns

Solution:

To extract longer sets, *iteratively chain* through them starting from the largest set to find probes belonging to the same device

a2:0a:5d:b3:35:27
8a:46:2b:f2:db:8d
6b:a1:9e:60:1f:50
2a:a0:d5:3b:53:72

54:8a:53:be:1d:df
16:67:c1:04:39:bf
9c:99:c4:cb:84:ea
92:da:de:94:81:81

Result: Sets containing common probes across the packet trace

Metrics for Evaluation

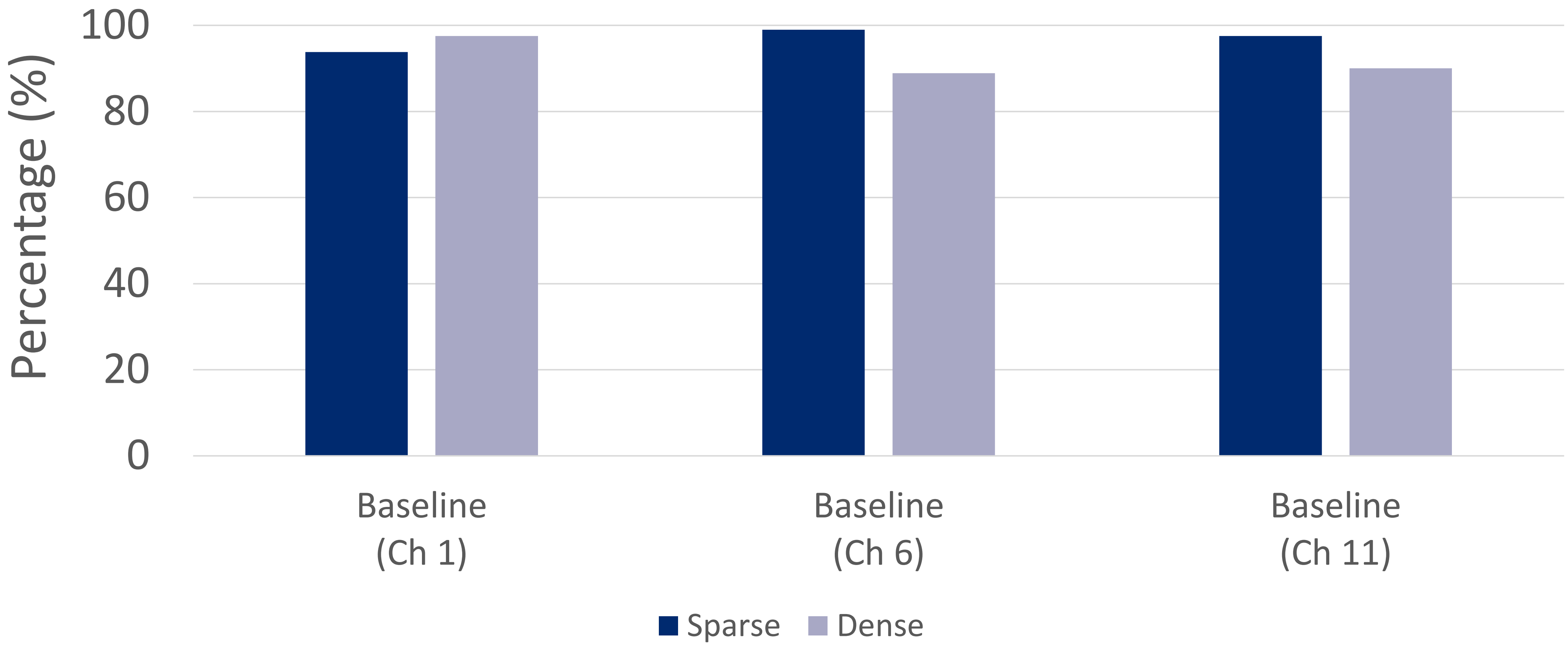
Accuracy

$$\frac{\text{Correct matches}}{\text{Number of probes identified}}$$

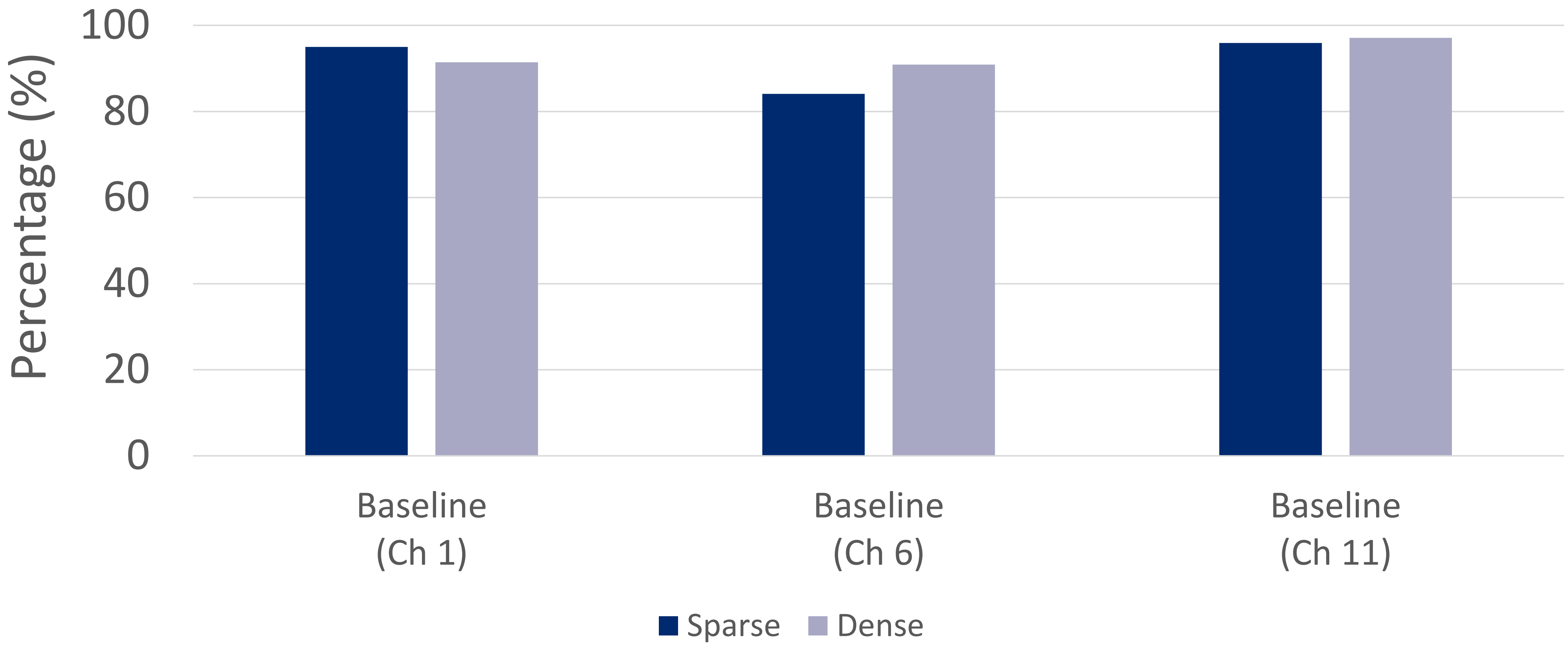
Precision

$$\frac{\text{Correct matches}}{\begin{array}{c}\text{Total number of probes}\\ \text{from the device in the trace}\end{array}}$$

Accuracy – Burst Interval Attack



Precision – Burst Interval Attack

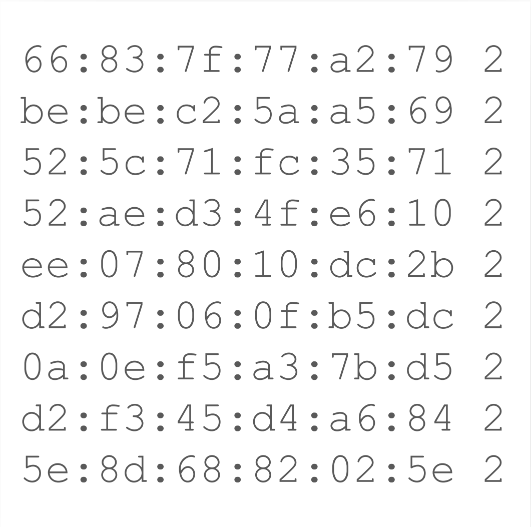


Example: Finding a Phone

Packet trace from
Pixel 7 Pro
160sec Burst Interval

Burst Interval
Attack

Top set of MAC addresses



```
66:83:7f:77:a2:79 2
be:be:c2:5a:a5:69 2
52:5c:71:fc:35:71 2
52:ae:d3:4f:e6:10 2
ee:07:80:10:dc:2b 2
d2:97:06:0f:b5:dc 2
0a:0e:f5:a3:7b:d5 2
d2:f3:45:d4:a6:84 2
5e:8d:68:82:02:5e 2
```

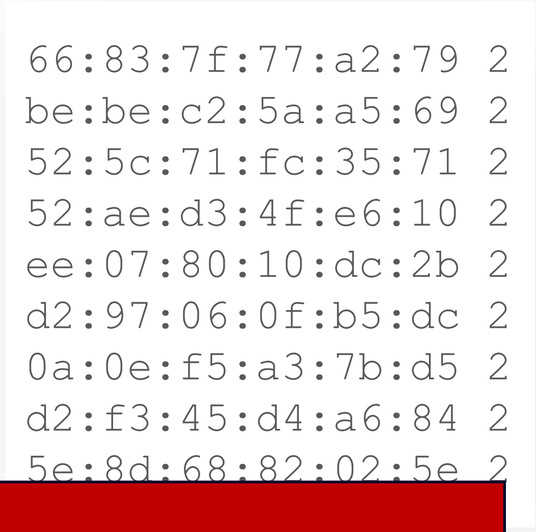
18/20 identified
2 missed from the end
from timing drift

Example: Finding a Phone

Packet trace from
Pixel 7 Pro
160sec Burst Interval

Burst Interval Attack

Top set of MAC addresses



```
66:83:7f:77:a2:79 2
be:be:c2:5a:a5:69 2
52:5c:71:fc:35:71 2
52:ae:d3:4f:e6:10 2
ee:07:80:10:dc:2b 2
d2:97:06:0f:b5:dc 2
0a:0e:f5:a3:7b:d5 2
d2:f3:45:d4:a6:84 2
5e:8d:68:82:02:5e 2
```

Timing attacks are effective even with MAC randomization

nd
from timing drift

Jittery: a set of Wi-Fi privacy defense mechanisms

- Recovers MAC randomization privacy benefits
  - Break timing patterns in network discovery
- Randomize built-in parameters of 802.11
  - MAC Randomization on all 6 bytes of the source address
  - Number of probes per burst (nprobes)
  - Random dwell time (1-100ms)
  - Shuffled channel ordering
  - Dynamic burst intervals

- No changes to infrastructure
- Potential for standardization in MAC randomization

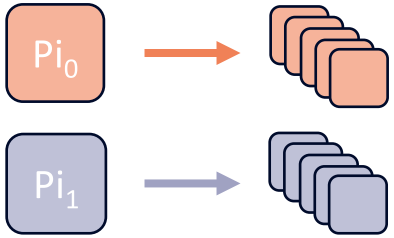
Driver-level Implementation

- Modified *brcmfmac* driver deployed on Raspberry Pi 3B+ devices
- Burst interval modifications tested with Netlink

Dataset

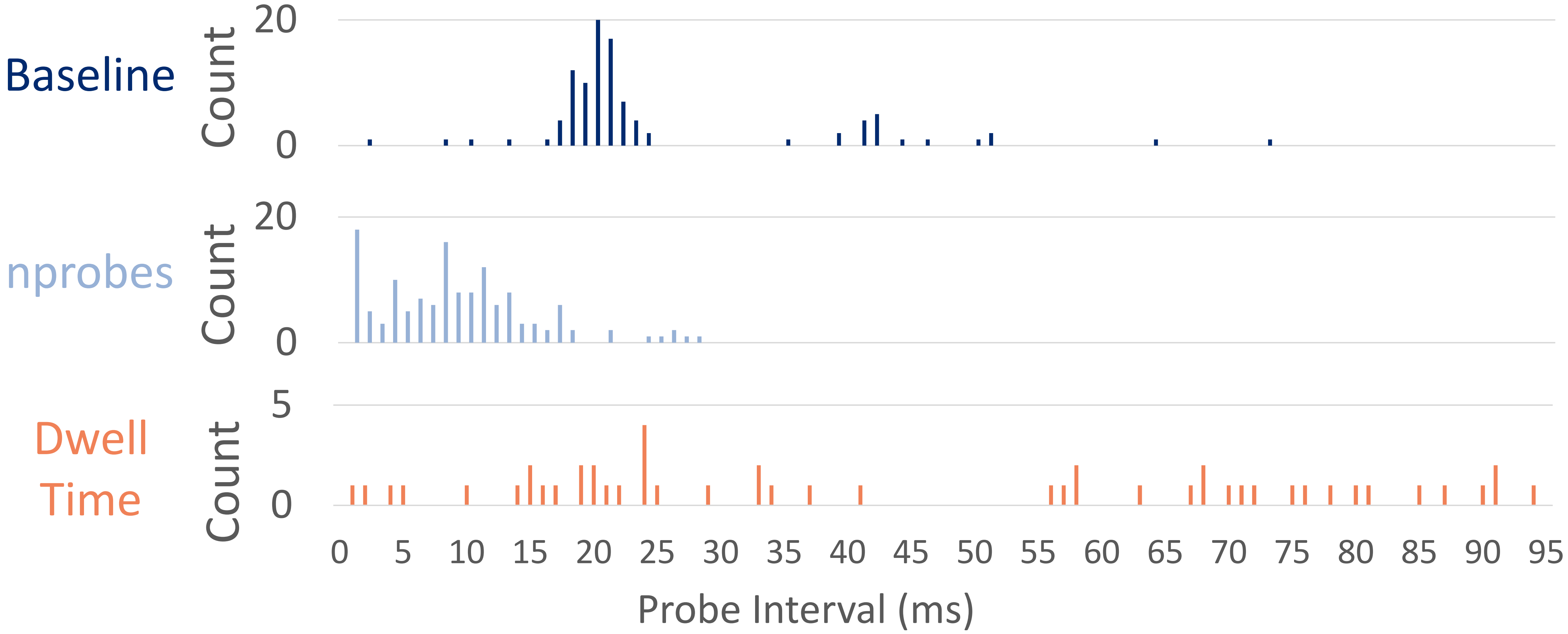
Packet captures from sparse and dense environments

Traffic collected from Channels 1, 6, and 11



Random MAC addresses stored for ground truth

Probe Interval Distribution: Sparse



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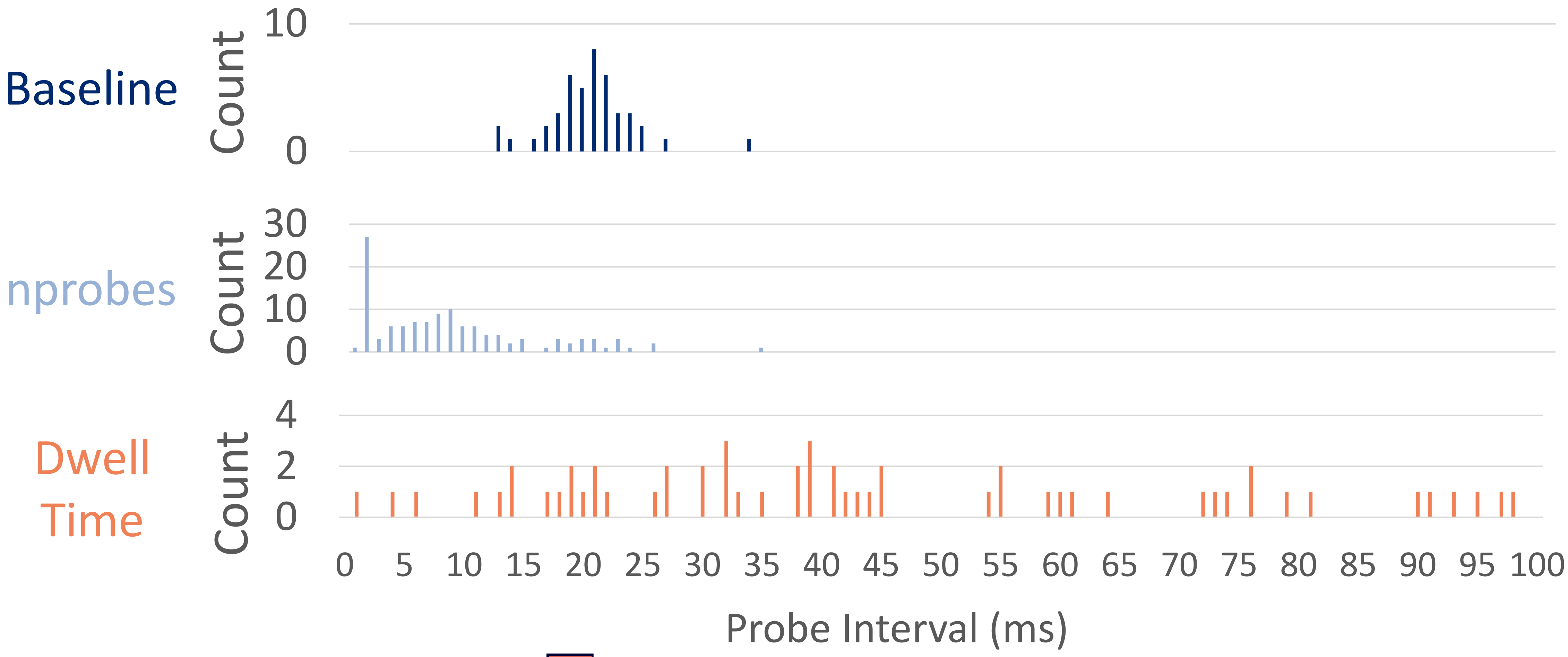
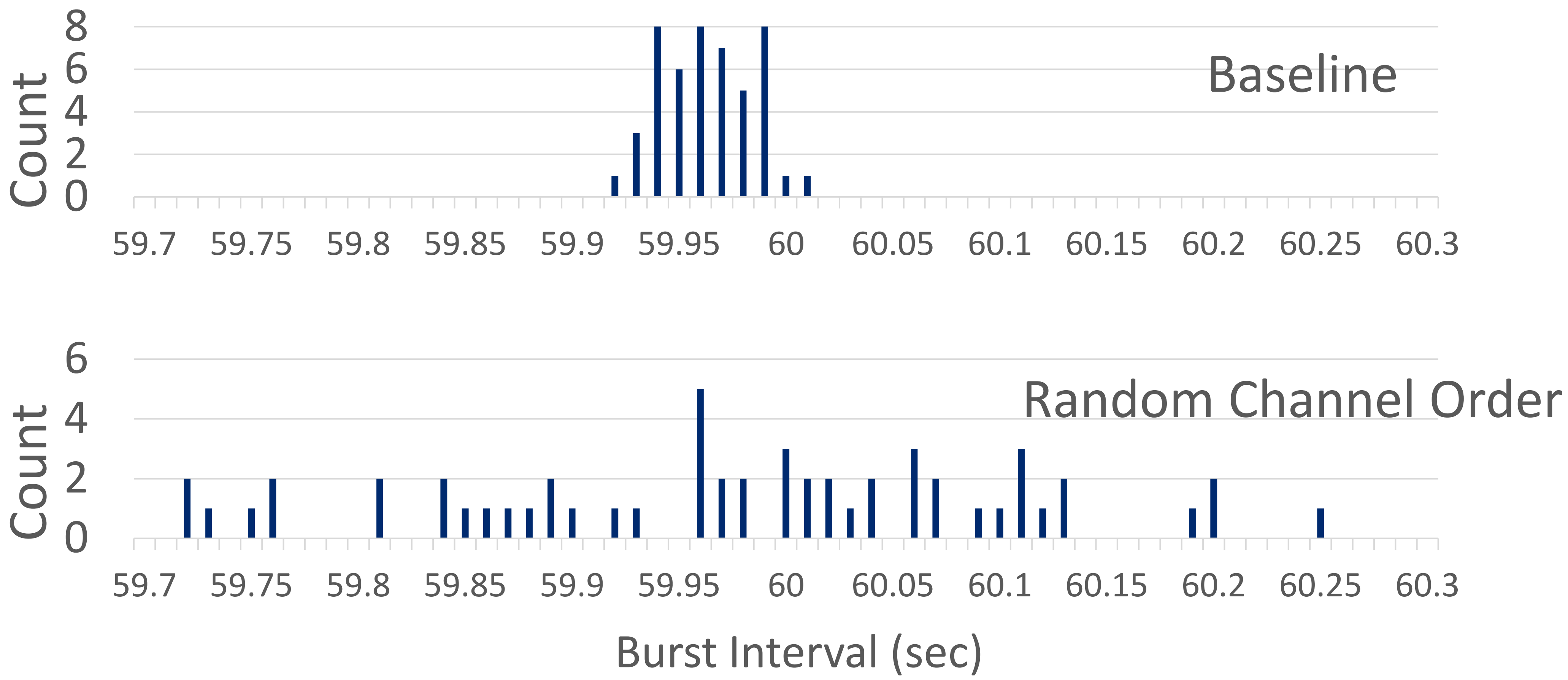
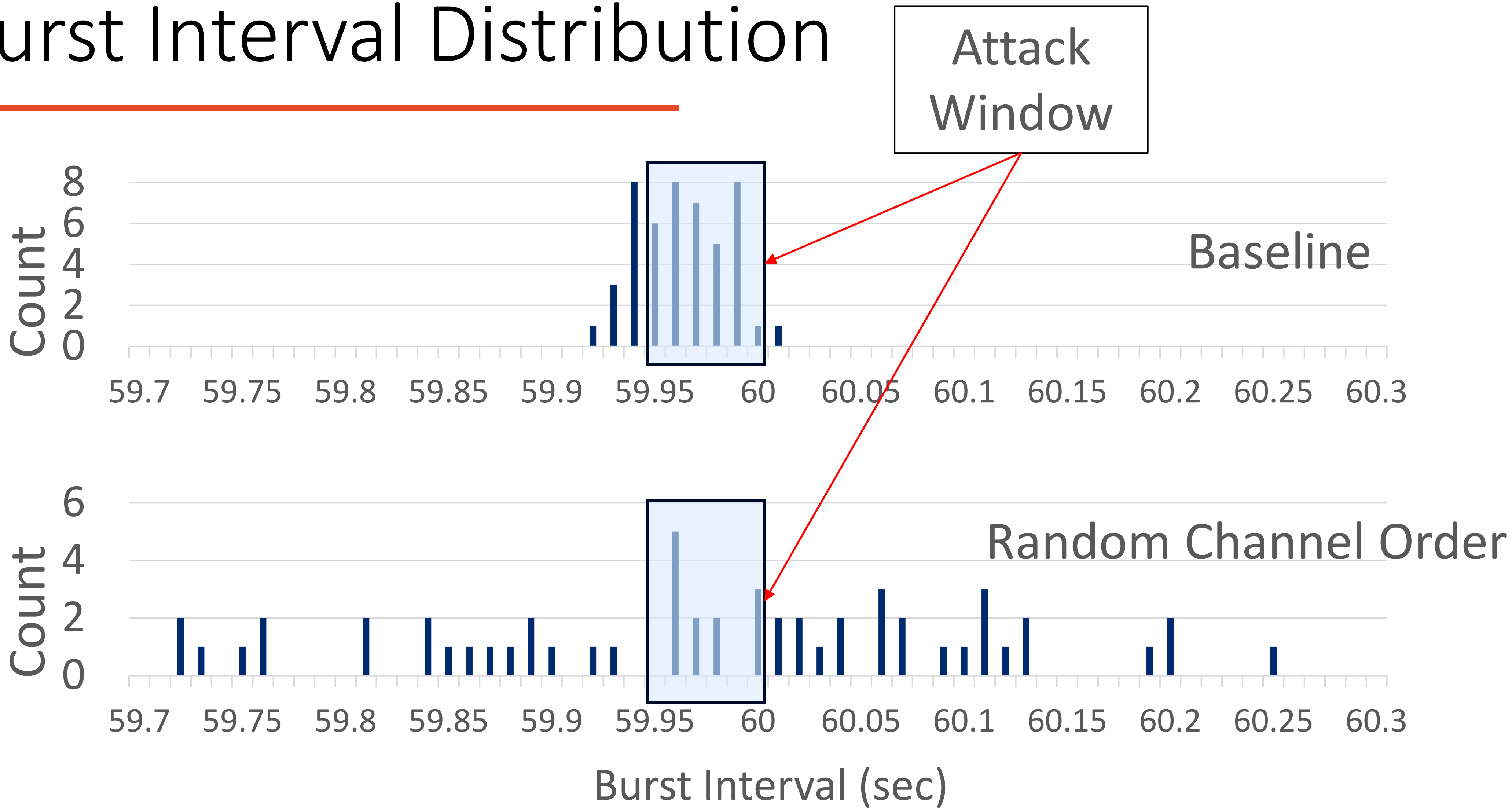
Probe Interval Distribution: Dense



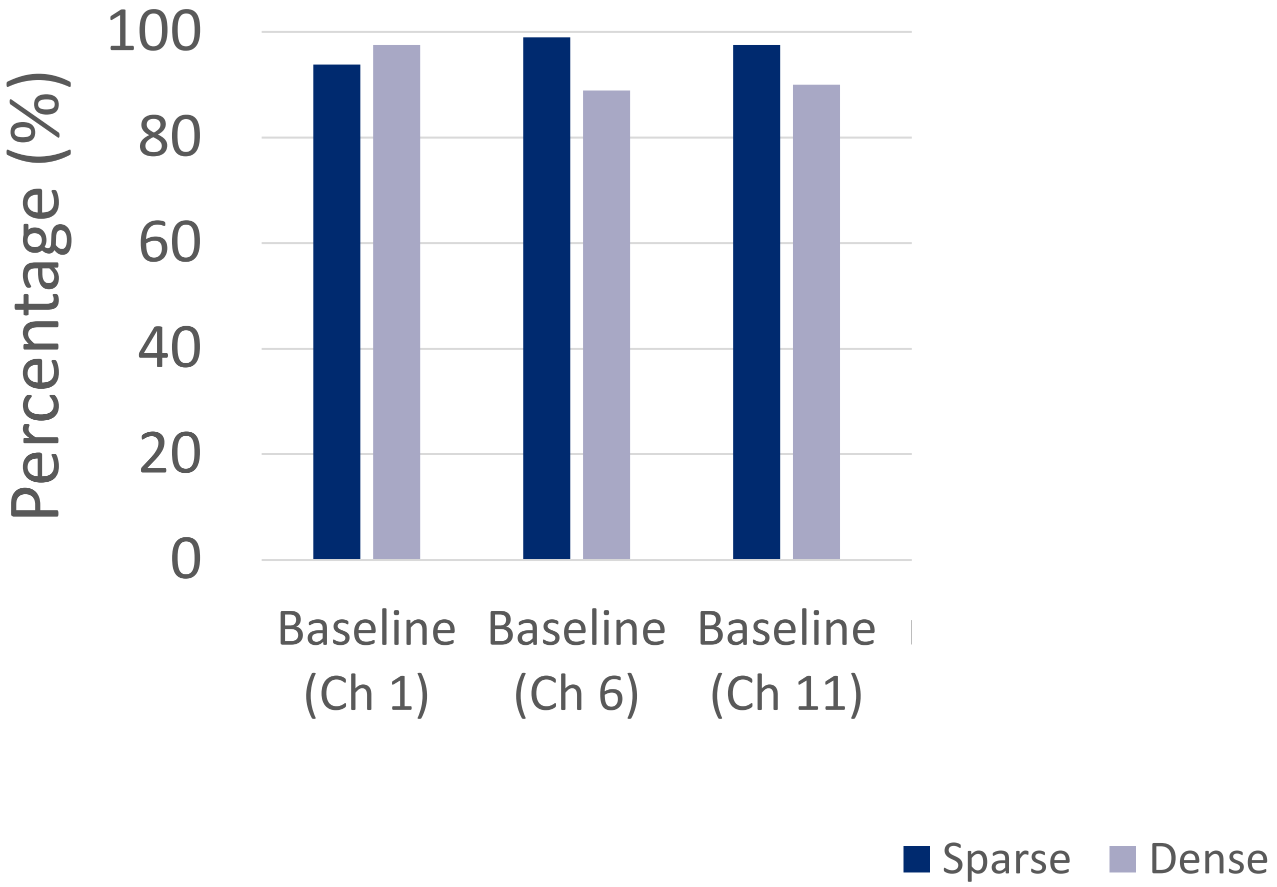
Burst Interval Distribution



Burst Interval Distribution

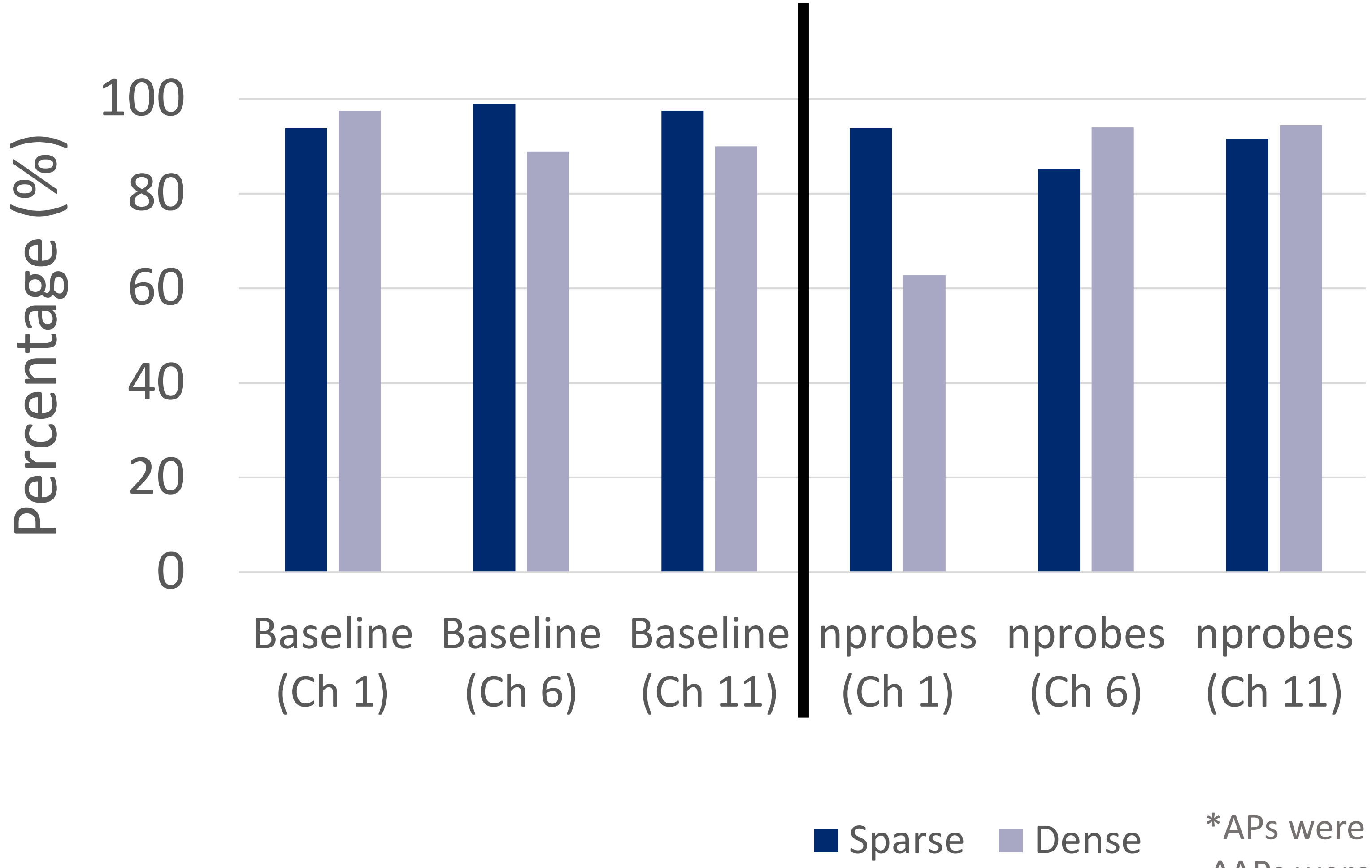


Burst Interval Attack: Accuracy



*APs were not operating in the sparse environment
^APs were not operating in the dense environment

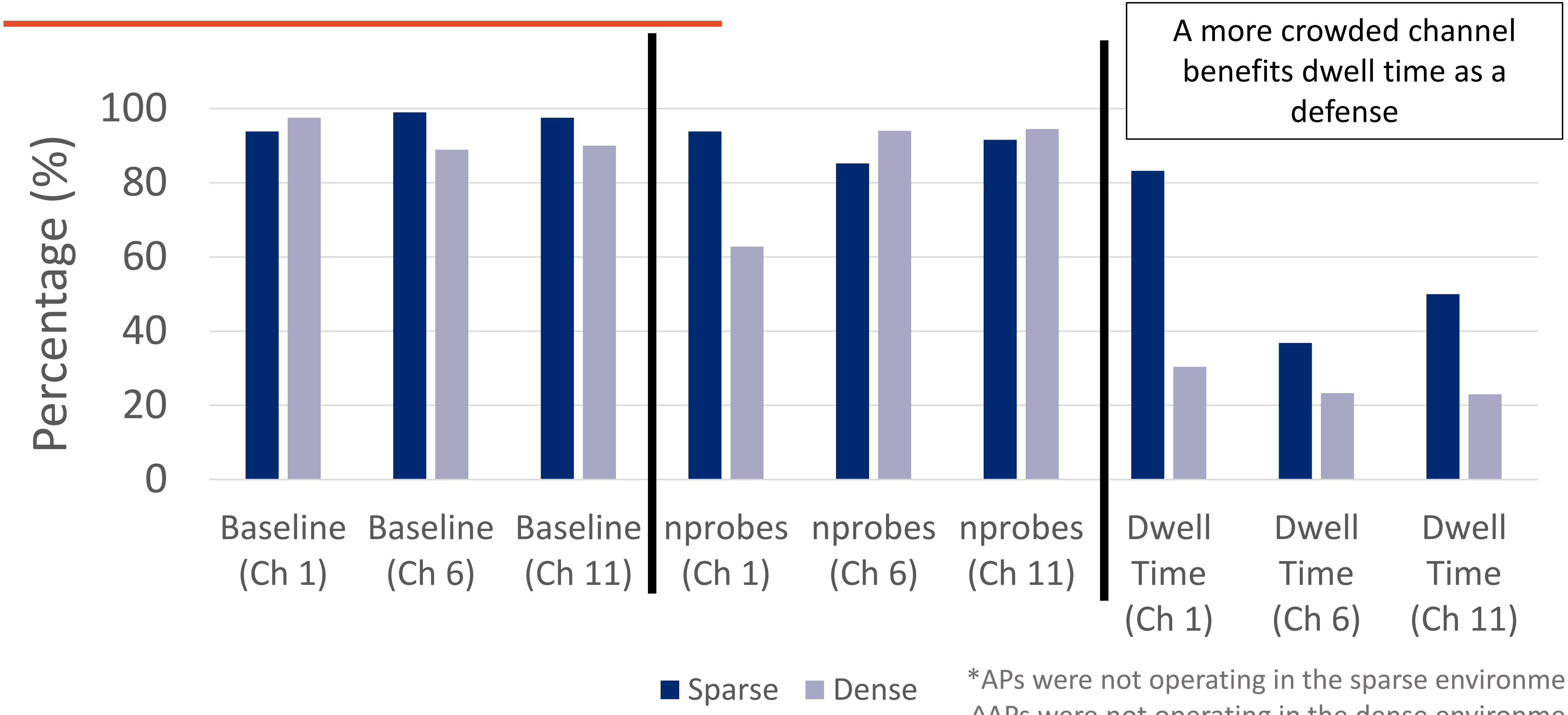
Burst Interval Attack: Accuracy



More probes on Channel 1 results in higher false pos

*APs were not operating in the sparse environment
^APs were not operating in the dense environment

Burst Interval Attack: Accuracy

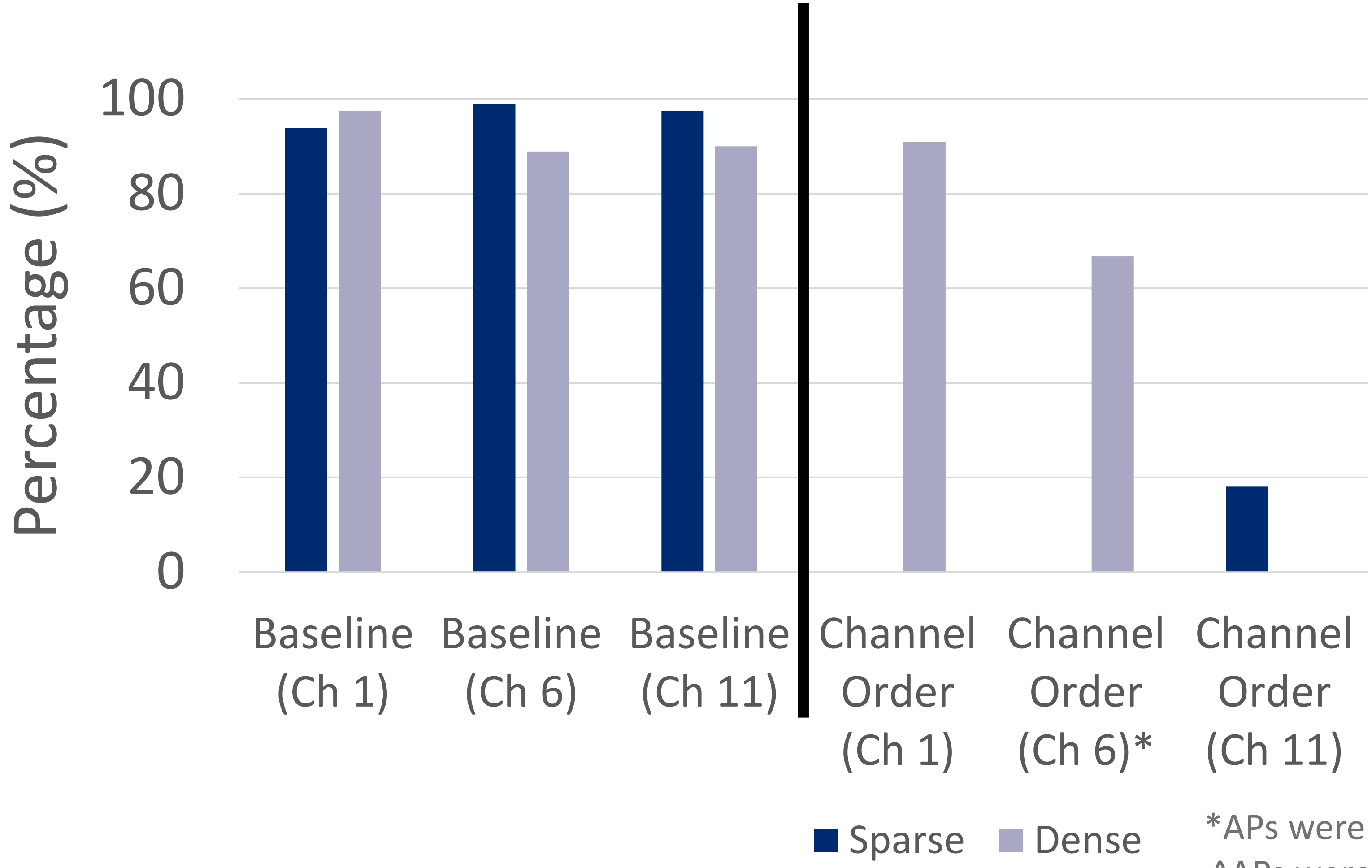


A more crowded channel benefits dwell time as a defense

*APs were not operating in the sparse environment

^APs were not operating in the dense environment

Burst Interval Attack: Accuracy



Random channel order greatly benefits sparse networks

*APs were not operating in the sparse environment

^APs were not operating in the dense environment

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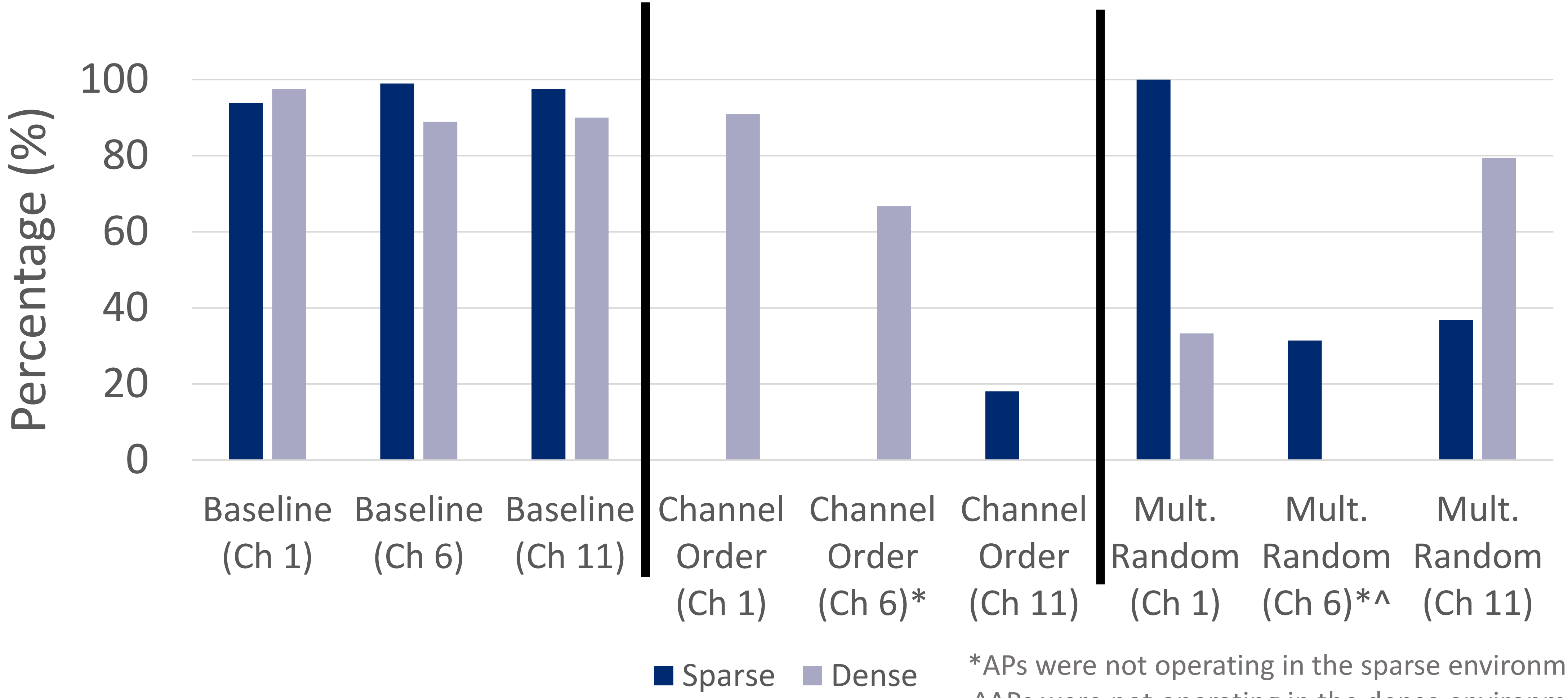
Burst Interval Attack: Accuracy



*APs were not operating in the sparse environment
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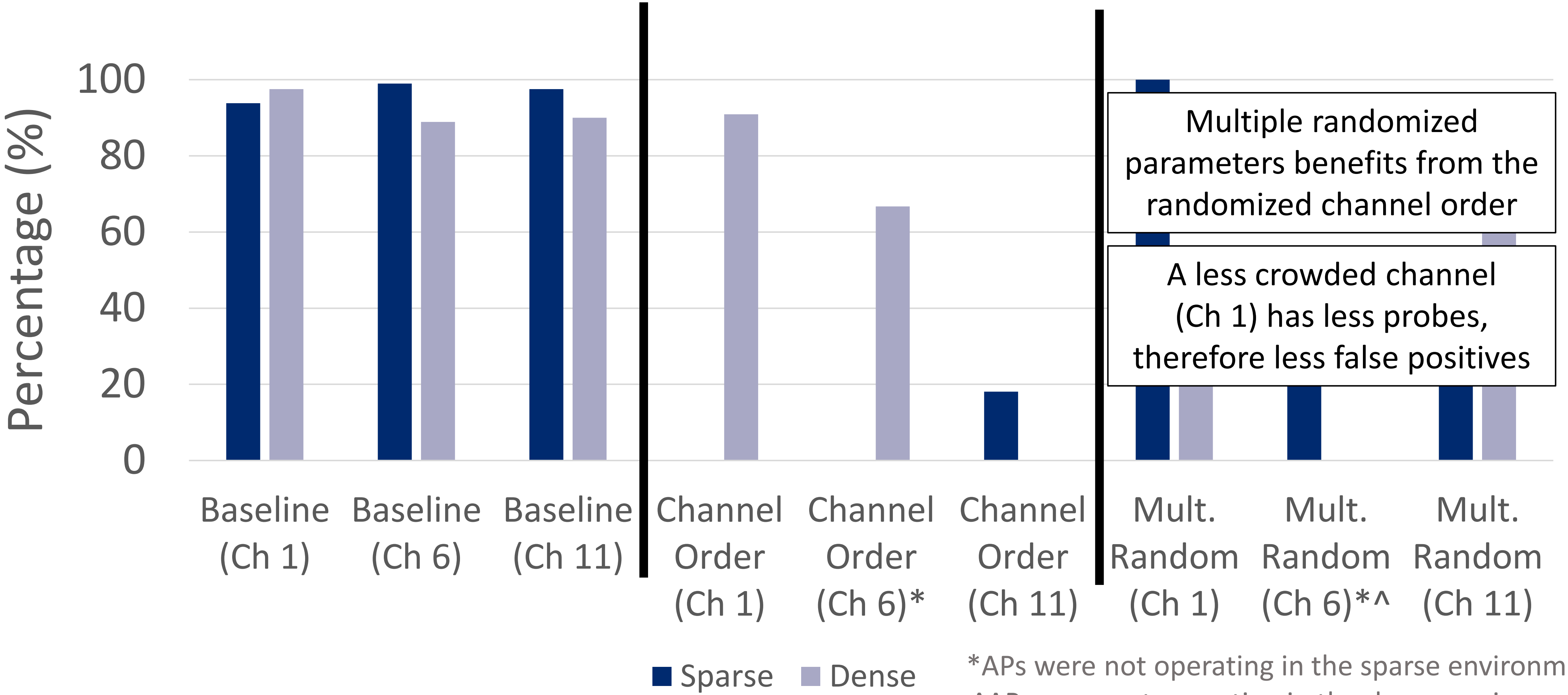
Burst Interval Attack: Accuracy



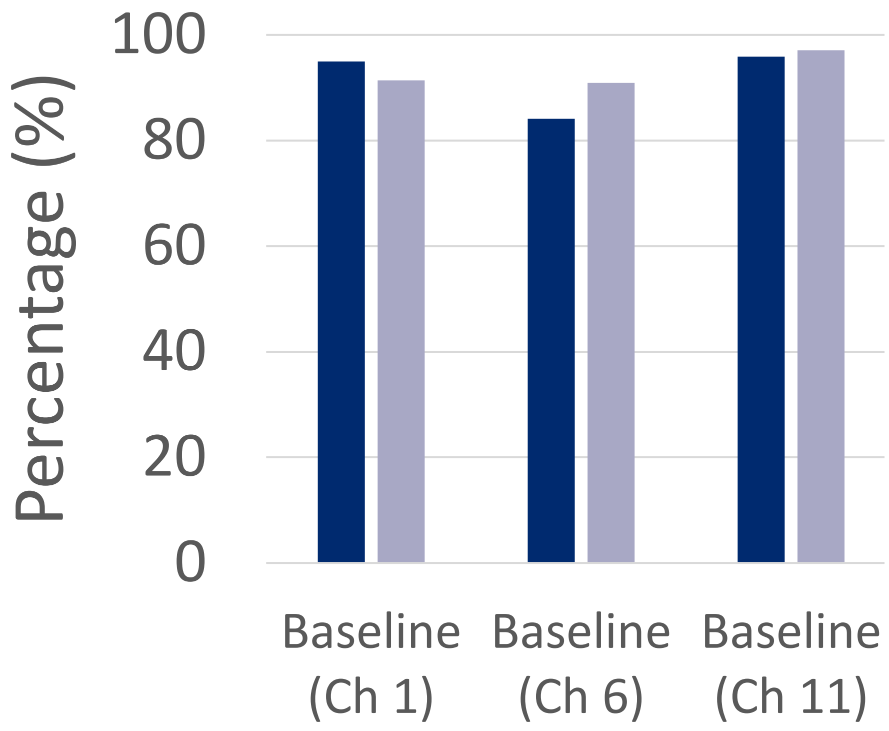
Multiple randomized parameters benefits from the randomized channel order

A less crowded channel (Ch 1) has less probes, therefore less false positives

*APs were not operating in the sparse environment

^APs were not operating in the dense environment

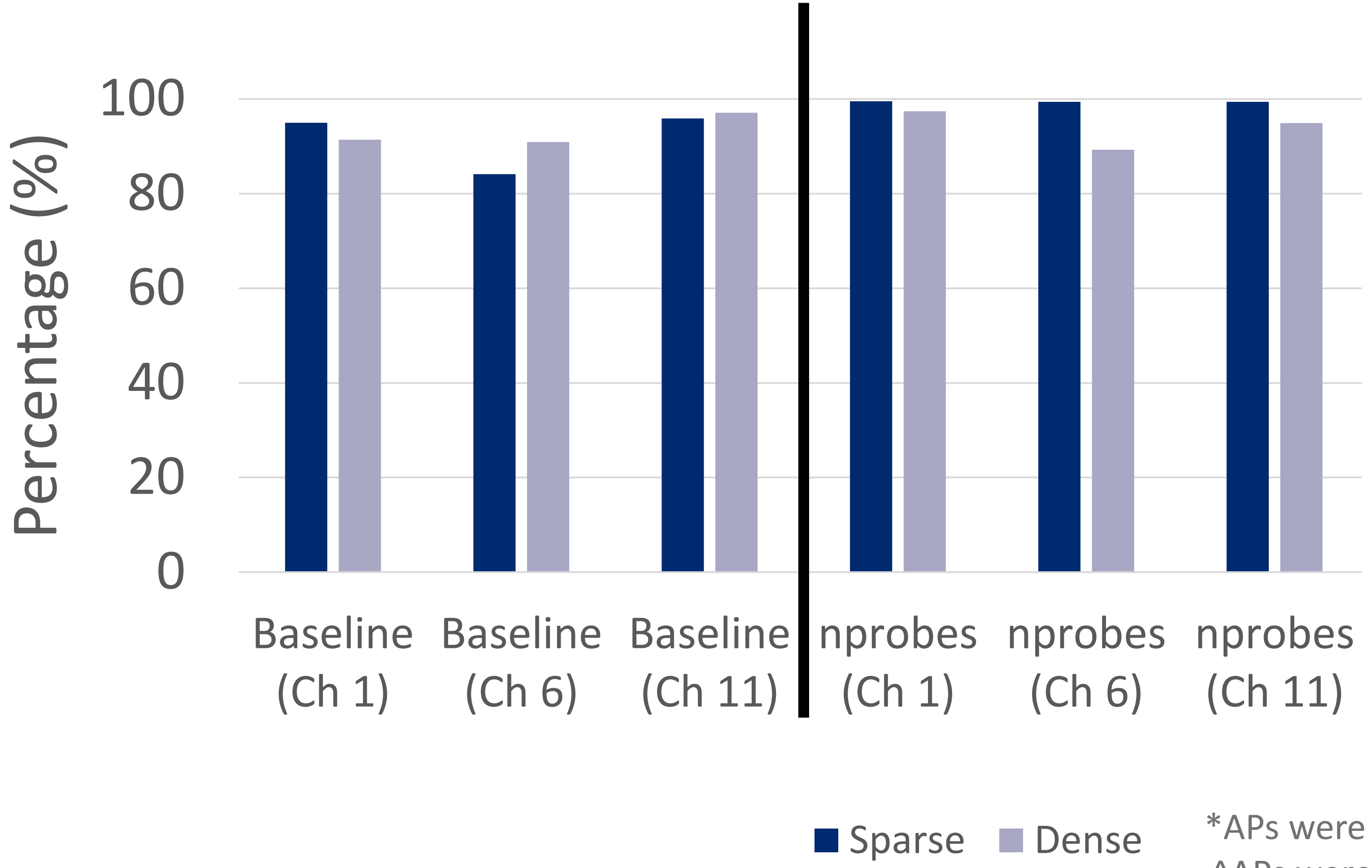
Burst Interval Attack: Precision



■ Sparse ■ Dense

*APs were not operating in the sparse environment
^APs were not operating in the dense environment

Burst Interval Attack: Precision

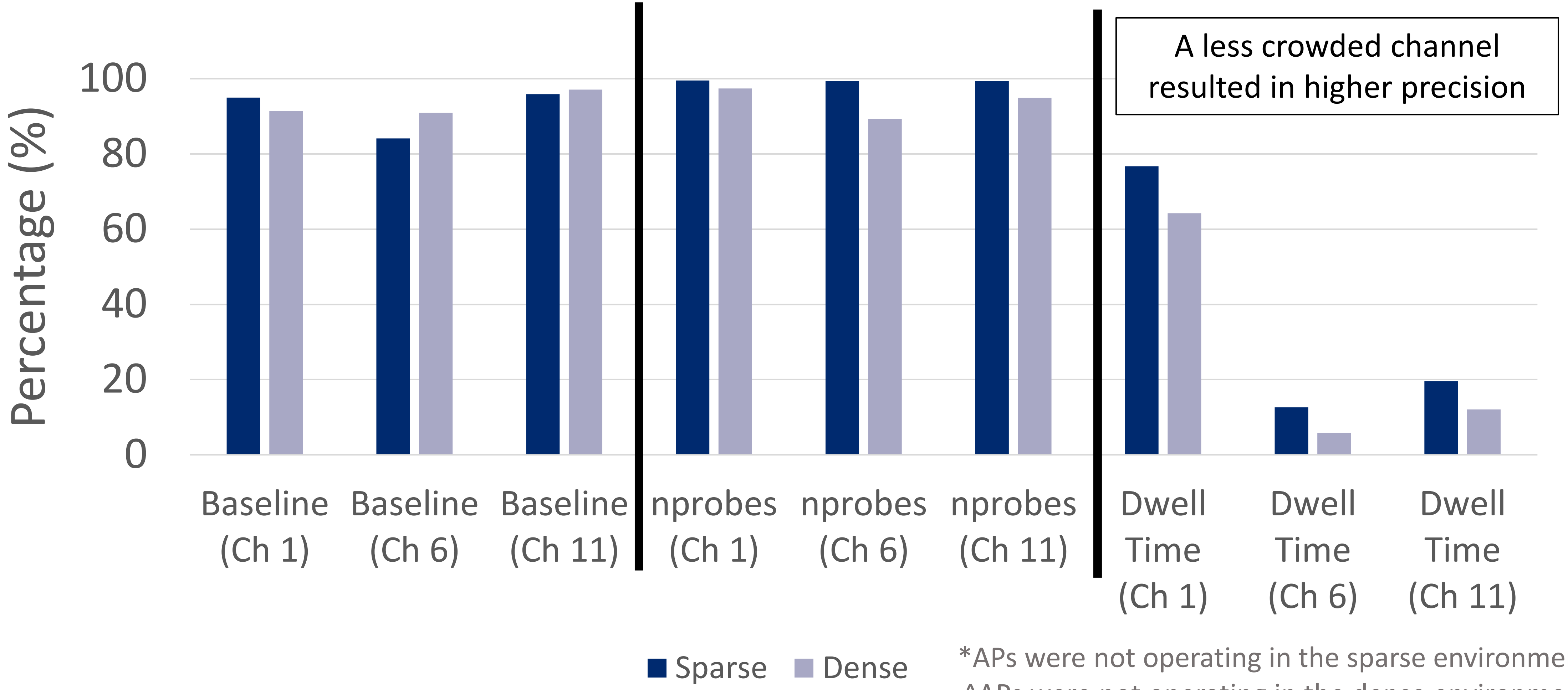


Random nprobes is not enough to be hidden

*APs were not operating in the sparse environment

^APs were not operating in the dense environment

Burst Interval Attack: Precision

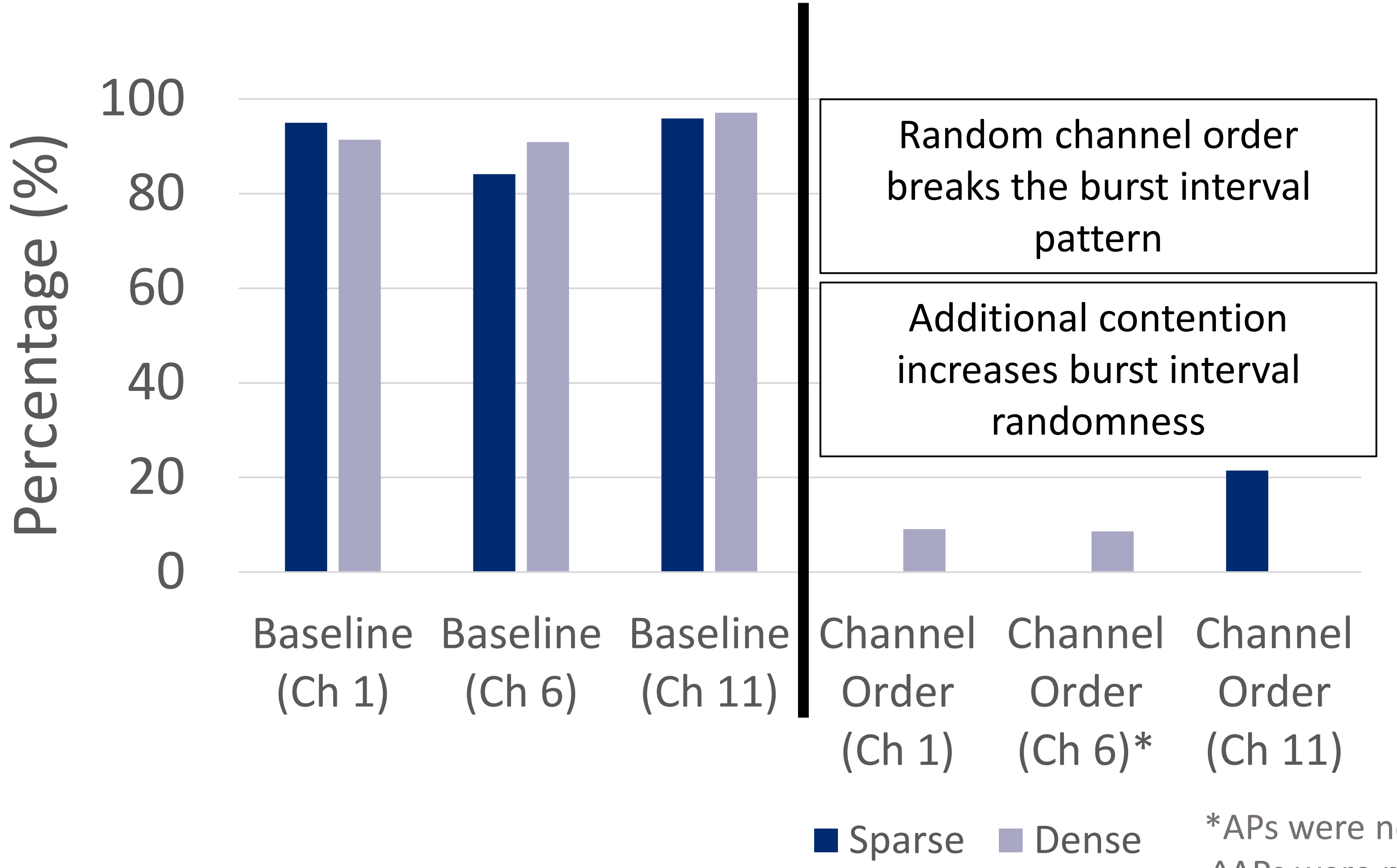


A less crowded channel resulted in higher precision

*APs were not operating in the sparse environment

^APs were not operating in the dense environment

Burst Interval Attack: Precision

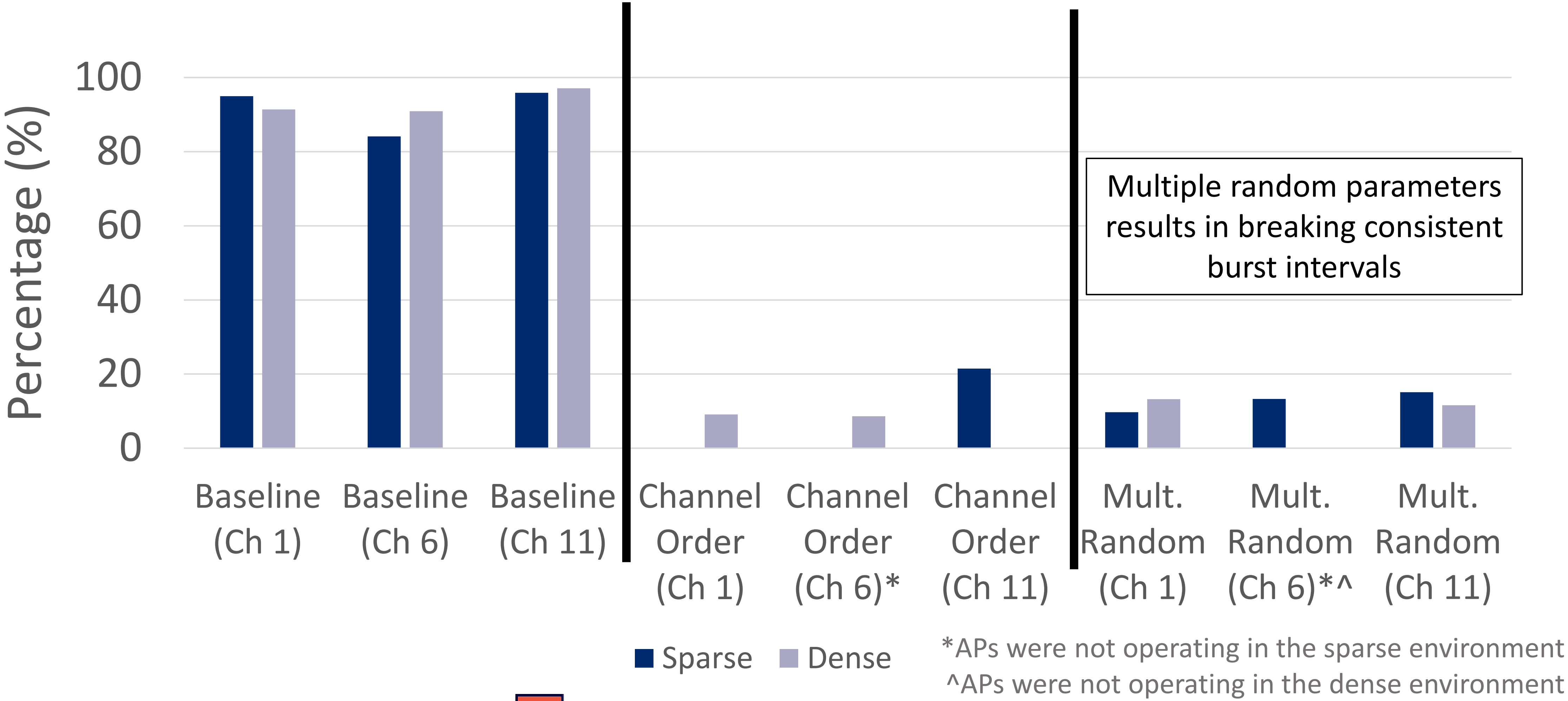


Random channel order breaks the burst interval pattern

Additional contention increases burst interval randomness

*APs were not operating in the sparse environment
^APs were not operating in the dense environment

Burst Interval Attack: Precision



Multiple random parameters results in breaking consistent burst intervals

*APs were not operating in the sparse environment

^APs were not operating in the dense environment

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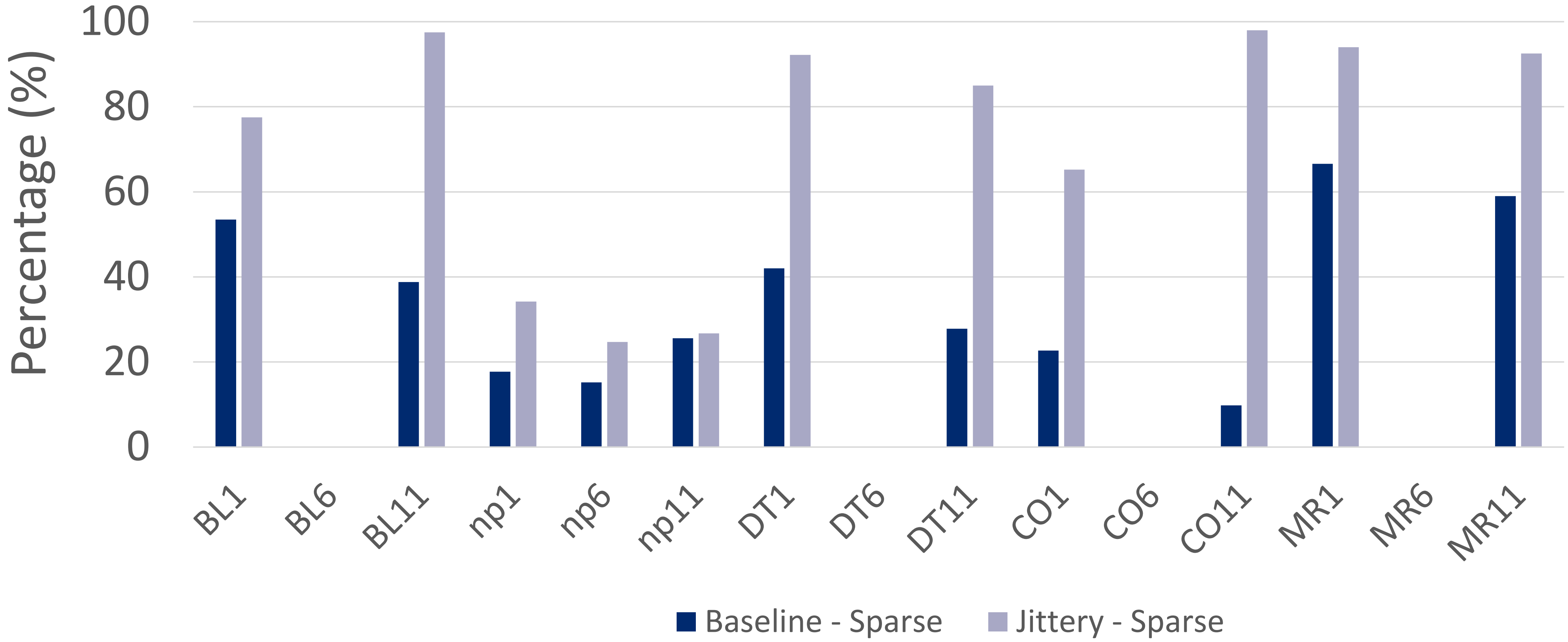
AP Discovery Rates - Sparse



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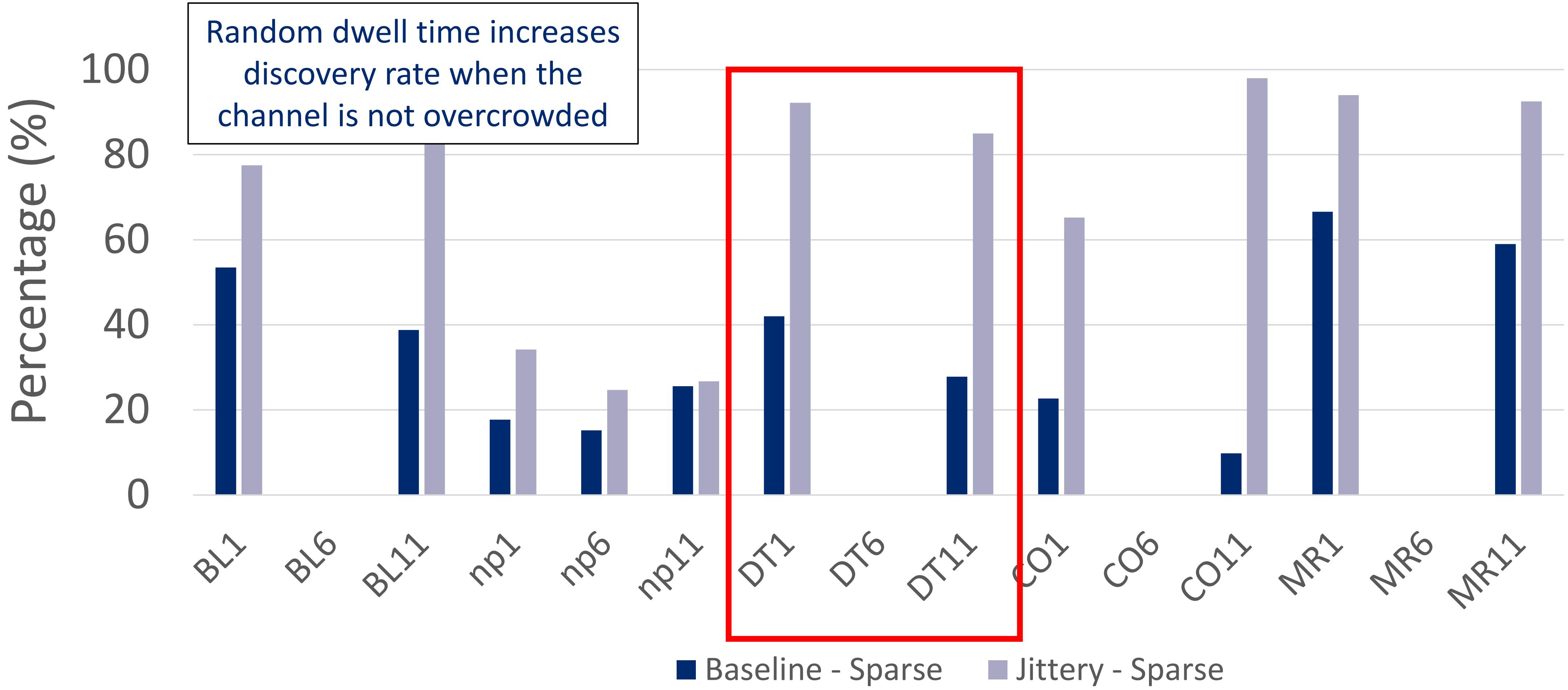
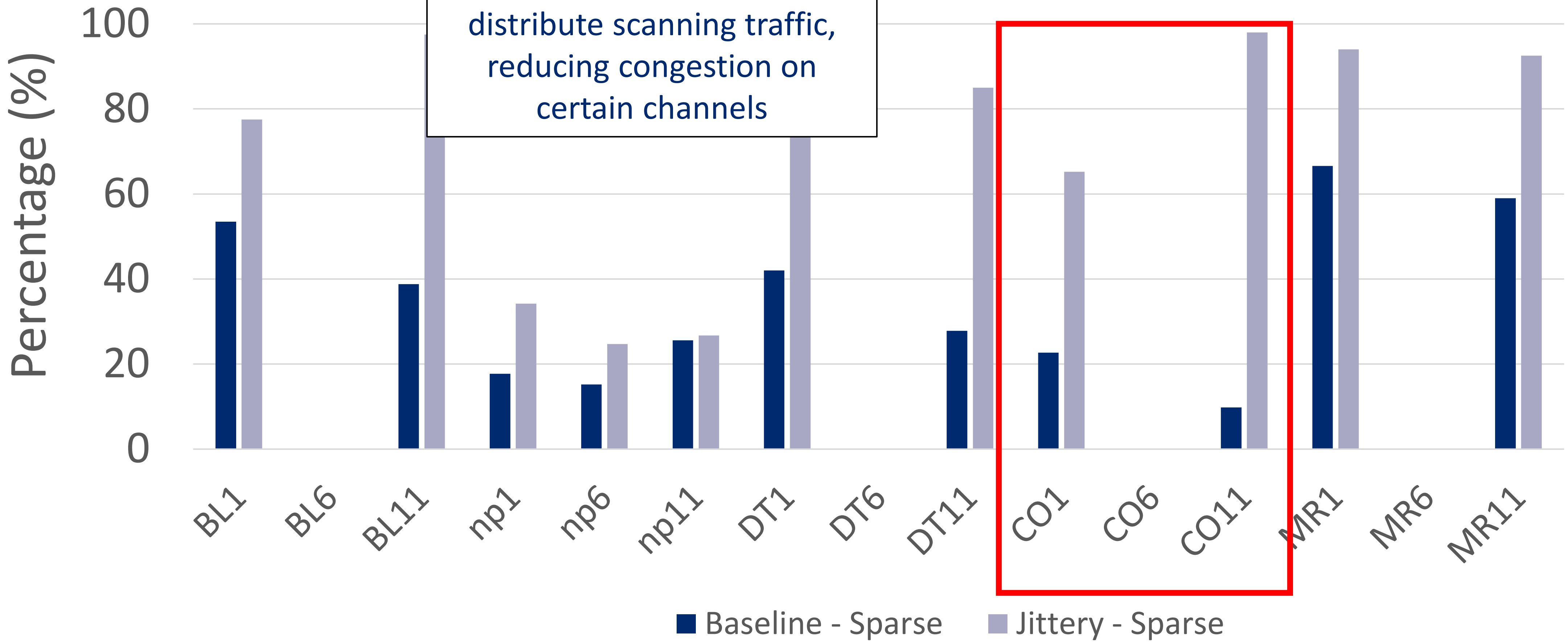
AP Discovery Rates - Sparse

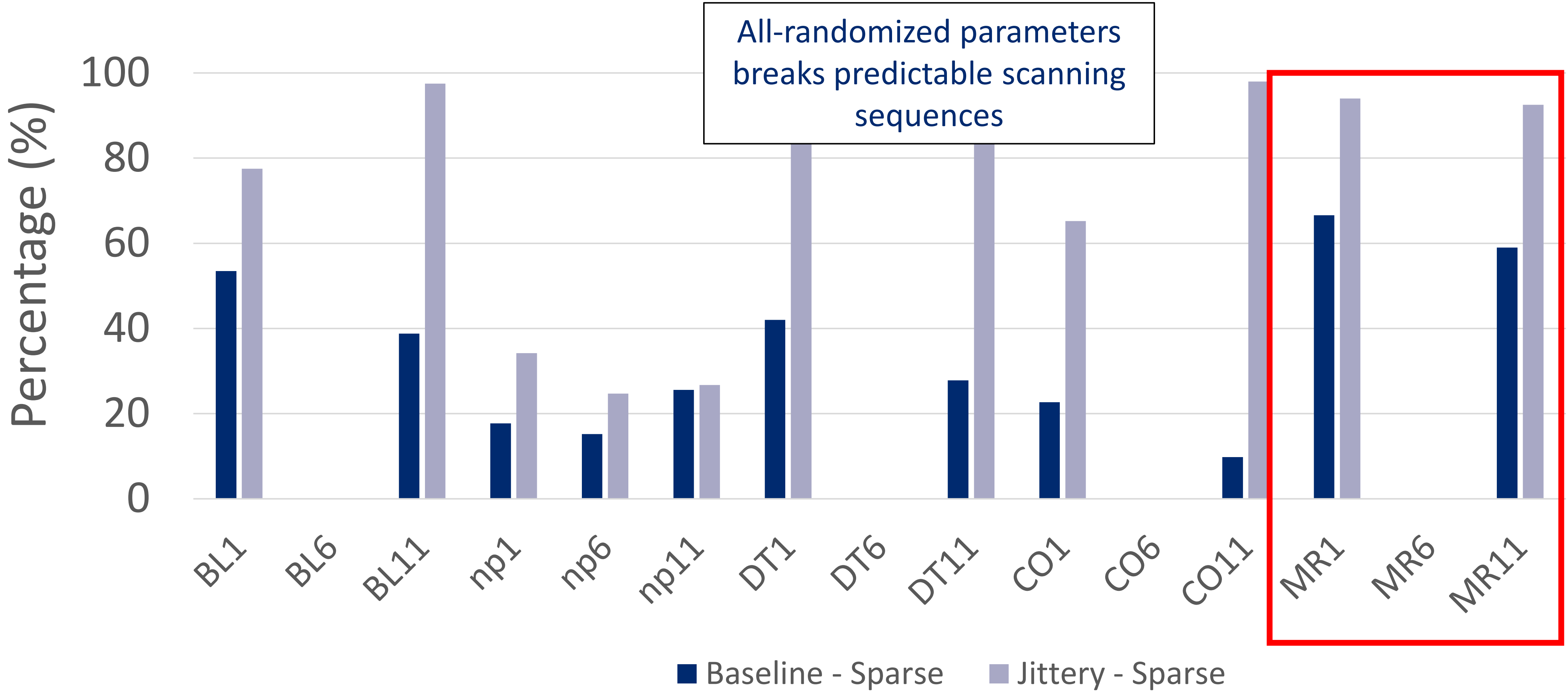

Random dwell time increases discovery rate when the channel is not overcrowded

AP Discovery Rates - Sparse



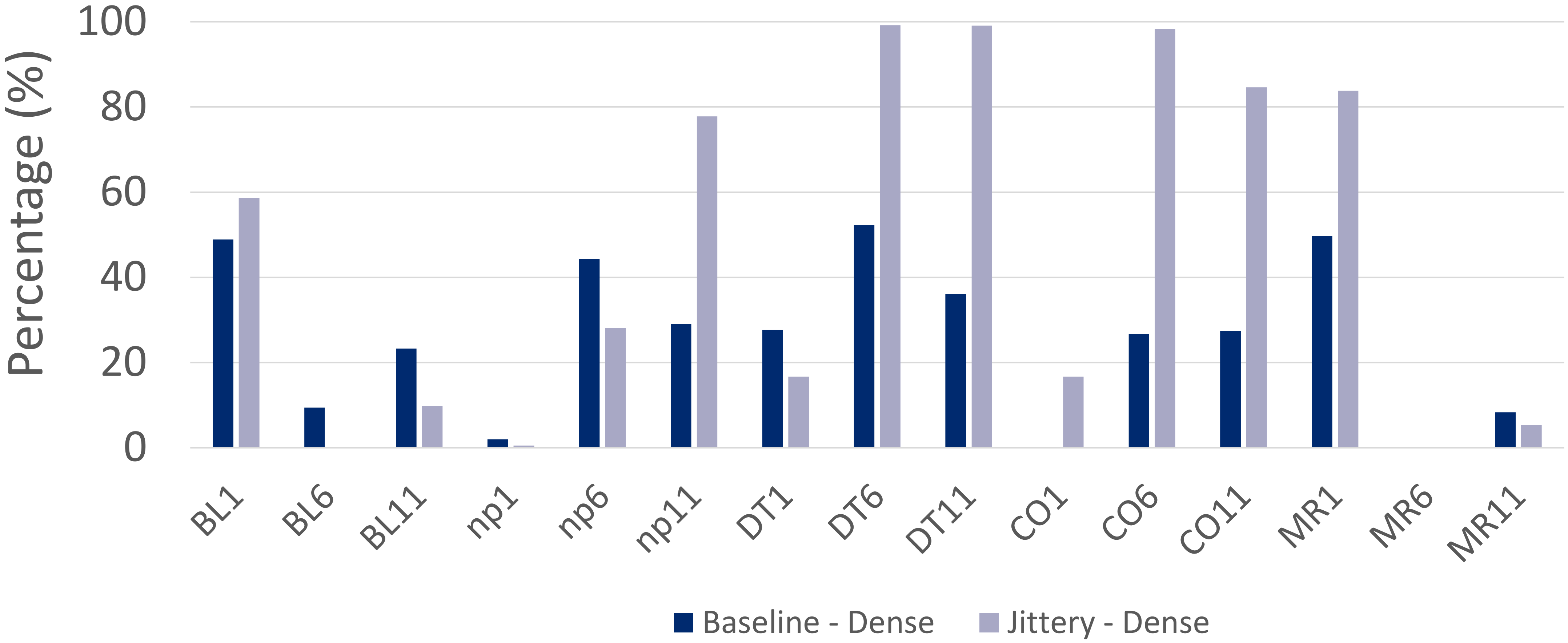
Shuffled channel order may distribute scanning traffic, reducing congestion on certain channels

AP Discovery Rates - Sparse



All-randomized parameters breaks predictable scanning sequences

AP Discovery Rates - Dense



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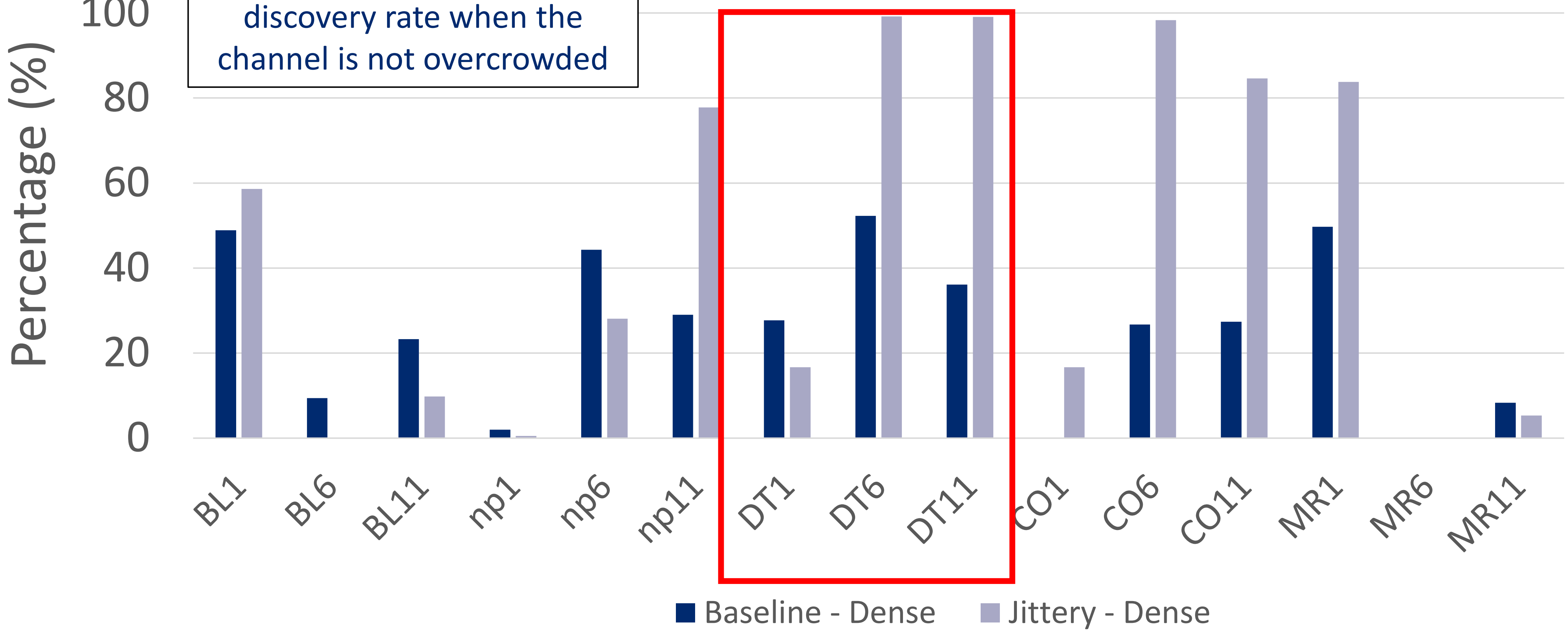
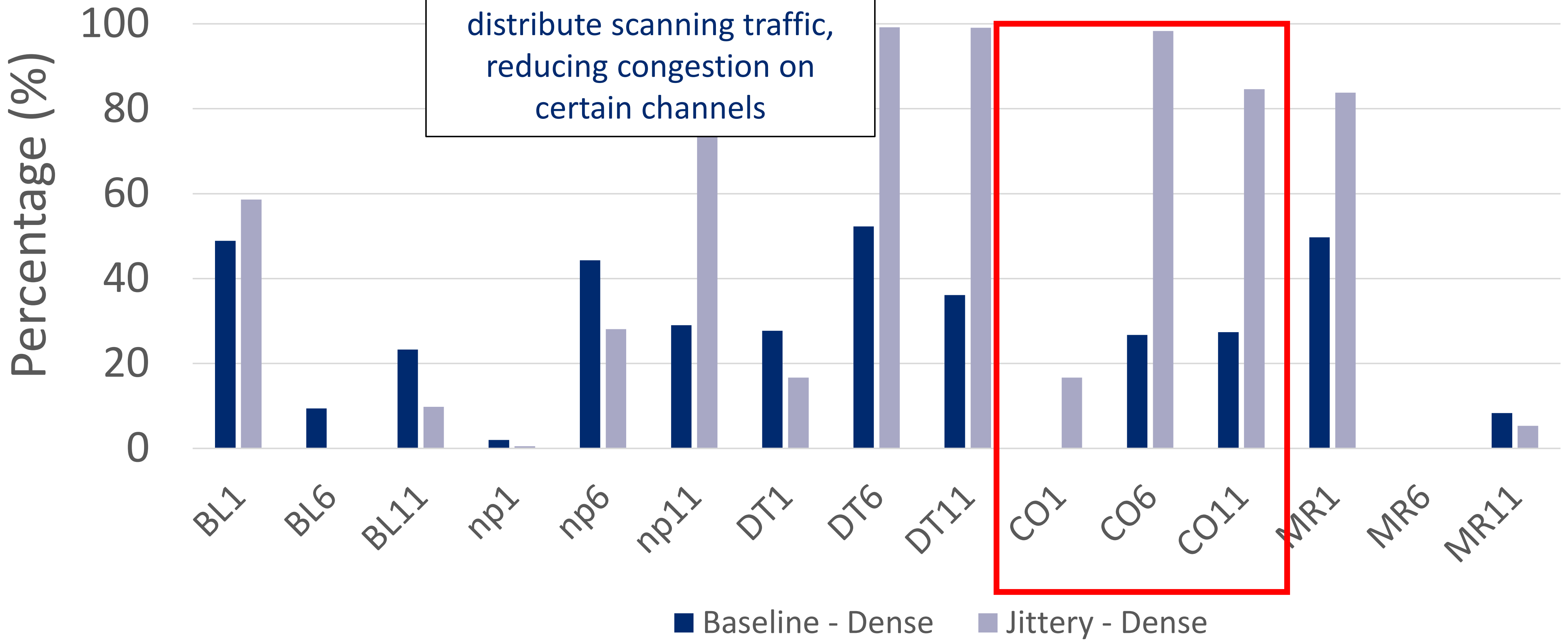
AP Discovery Rates - Dense



Random dwell time increases discovery rate when the channel is not overcrowded

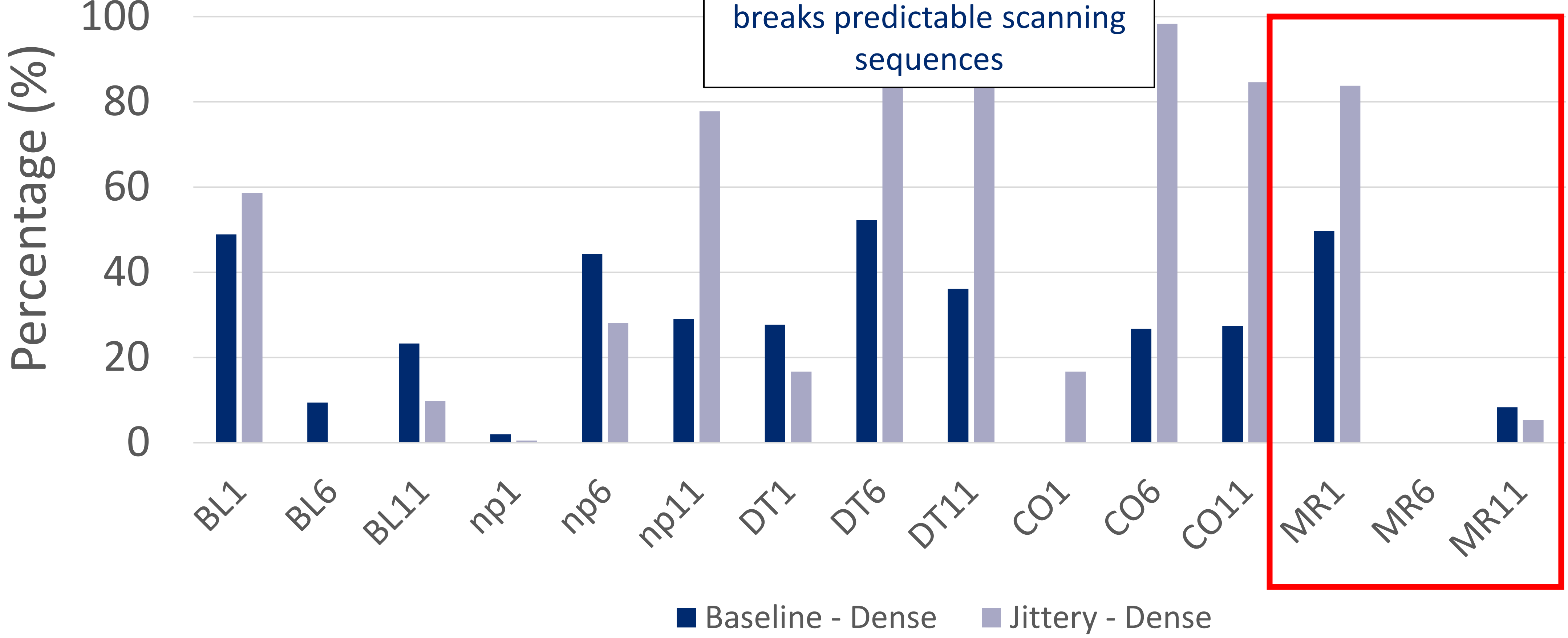
AP Discovery Rates - Dense



Shuffled channel order may distribute scanning traffic, reducing congestion on certain channels

Computer Science

AP Discovery Rates - Dense



All-randomized parameters breaks predictable scanning sequences

Computer Science

Future Directions

- Identifying devices from the same vendor with higher accuracy may require additional metrics that are not timing-based
  - We constrain the attack to solely use timing metrics
  - Future approaches may expand this by using other data fields *with* timing

- Signal strength of the probe responses is a factor in calculating successful AP discovery rate
  - Reported results could be lower than actual due to monitor devices not receiving probe responses

Recommendations for Standardization

- Configure network discovery with
  - Random sequence numbers
  - Changing number of probes each burst
  - Variable dwell time per burst
  - Variable burst intervals
- Randomize the full length of the MAC address (48 bits)
- Change the MAC address each burst in network discovery
- Eliminate using directed probes
- Offload features from IEs to the Association phase