

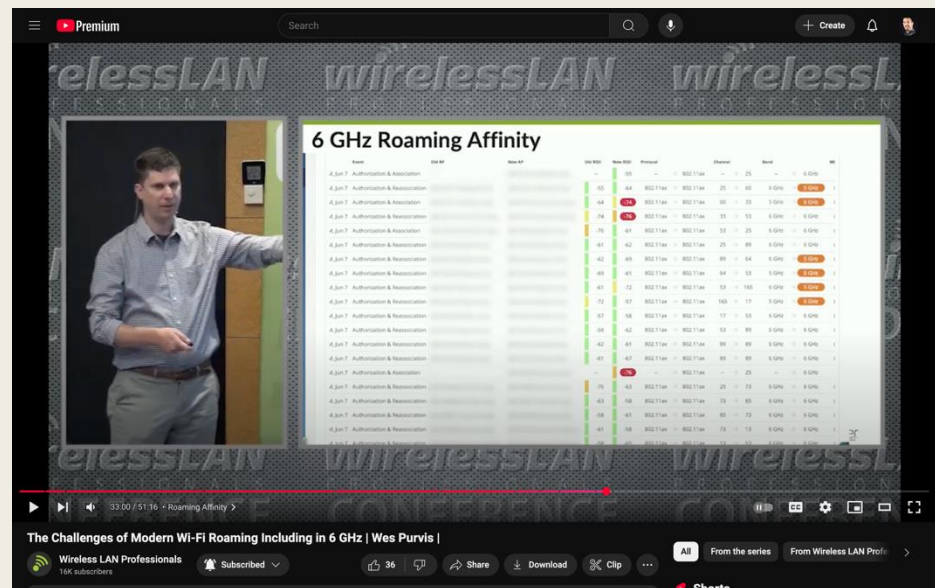
A thick black L-shaped frame is positioned on the left and right sides of the slide, framing the central text.

ROAMING WARS

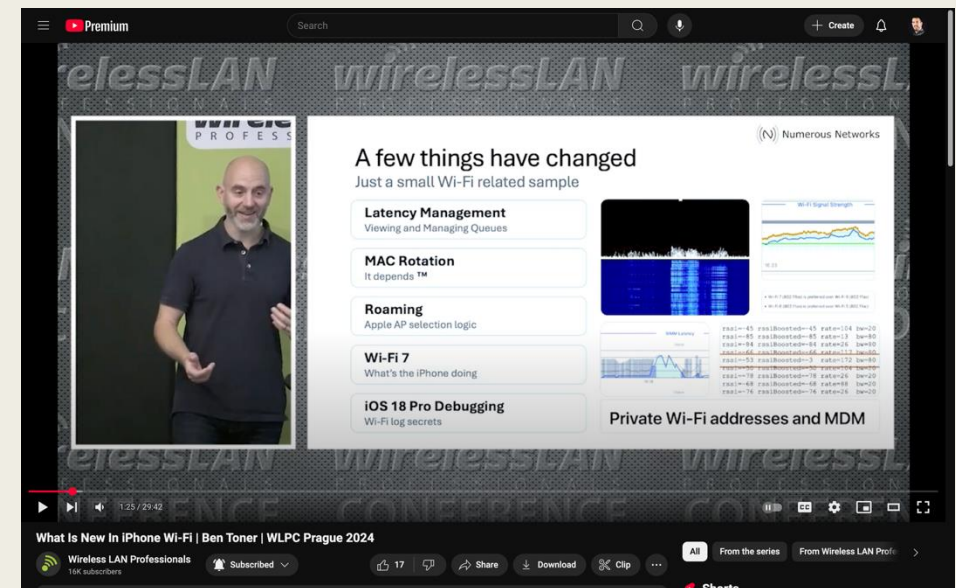
How Different Devices Roam

- Jerry Olla -

Previous related WLPC sessions



The Challenges of Modern Wi-Fi Roaming Including in 6 GHz | Wes Purvis



What Is New In iPhone Wi-Fi | Ben Toner



Devices Tested

- Apple M2 MacBook Pro (Wi-Fi 6E)
- Apple iPhone 15 Pro (Wi-Fi 6E)
- Windows 11 (24H2) Laptop
 - *Intel BE200 (Wi-Fi 7)*
 - *Intel AX210 (Wi-Fi 6E) – Failed*
 - *MediaTek MT7922 (Wi-Fi 6E)*
 - *MediaTek MT7902 (Wi-Fi 6E)*
 - *Qualcomm WCN7851 (Wi-Fi 7)*
- Android Pixel 8 (Wi-Fi 7)



Drivers / OS

- Windows 11 24H2 26100.2894
 - *Intel Driver: 11/11/2024 23.100.0.4 (BE200)*
 - *MediaTek Driver: 6/11/2024 3.4.2.1046 (MT7902/MT7922)*
 - *Qualcomm Driver: 12/1/2023 3.0.0.1078 (WCN7851)*
- iPhone 15 Pro
 - *iOS 18.3*
- M2 MacBook Pro
 - *macOS 15.2 (Sequoia)*
- Google Pixel 8
 - *Android 15*

NOTE: All adapter/roaming options left at defaults

Roaming Test – Manual Method



Aruba AP-735
(Wi-Fi 7)



Aruba AP-735
(Wi-Fi 7)

Roaming Test - Automated Method

- *Automatically adjusted Tx power of each radio in +/- 1 dB increments every 3 seconds*
- *RSSI levels balanced across bands – 2.4 GHz clamped to 6 dB less than 5/6 GHz*
- *Devices in the same location and orientation for each test*
- *60 min / 20 “power” cycles - per test*
- *Captured 1000+ roaming events*

Access Point 735	Band	Bandwidth	Power Changes	Power (dBm)
● AP-735-01	2.4 GHz	20 MHz	18086	-3
● AP-735-01	5 GHz	20 MHz	22016	-2
● AP-735-01	6 GHz	20 MHz	22632	-3
● AP-735-02	2.4 GHz	20 MHz	16344	12
● AP-735-02	5 GHz	20 MHz	19816	14
● AP-735-02	6 GHz	20 MHz	20436	17

Roaming Test - Automated Method



DO TRI-BAND DEVICES
REALLY PREFER 6 GHZ?

Tri-Band 2.4/5/6 GHz - 20/20/20 MHz

Baseline – All things equal

Device	2.4GHz	5GHz	6GHz	Roams
Google Pixel 8 (Wi-Fi 7)	65%	9%	26%	34
Intel BE200 (Wi-Fi 7)	0%	0%	100%	15
iPhone 15 Pro (Wi-Fi 6E)	54%	15%	31%	13
M2 MacBook Pro (Wi-Fi 6E)	0%	0%	100%	19
MediaTek MT7902 (Wi-Fi 6E)	12%	71%	18%	17
MediaTek MT7922 (Wi-Fi 6E)	0%	71%	29%	19
Qualcomm WCN7851 (Wi-Fi 7)	0%	68%	32%	19

DO TRI-BAND DEVICES
PREFER WIDER CHANNELS?



Candidate scorers

Candidate scorers evaluate and provide a score for each candidate. The score for `ThroughputScorer` (the default scorer) is based on the following:

- A base score is computed based on RSSI where RSSI is capped at -73 dBm for the 2.4 GHz band or -70 dBm for the 5 GHz and 6 GHz bands (configured with the `config_wifi_framework_wifi_score_low_rssi_threshold_24GHz`, `config_wifi_framework_wifi_score_low_rssi_threshold_5GHz`, and `config_wifiFrameworkScoreLowRssiThreshold6ghz` overlays).
- A score boost is computed based on a throughput estimate derived from the technology, channel frequency, bandwidth, RSSI, channel conditions, the maximum number of spatial streams, and other parameters. The score boost is configurable using the `config_wifiFrameworkThroughputBonusNumerator` and

- A score boost is computed based on a throughput estimate derived from the technology, channel frequency, bandwidth, RSSI, channel conditions, the maximum number of spatial streams, and other parameters. The score boost is configurable using the `config_wifiFrameworkThroughputBonusNumerator` and `config_wifiFrameworkThroughputBonusDenominator` overlays, and is limited to a max value specified using the `config_wifiFrameworkThroughputBonusLimit` overlay.

`config_wifiFrameworkSecureNetworkBonus` overlay.

- An unmetered (free) network is scored higher than a metered (paid) network. The bonus is configured using the `config_wifiFrameworkUnmeteredNetworkBonus` overlay.
- A saved network is scored higher than a network suggested using the Suggestion API. The bonus is configured using the `config_wifiFrameworkSavedNetworkBonus` overlay.



Selection criteria for band, network, and roam candidates

Beyond reaching the roam trigger threshold, the candidate basic service set (or access point) must have a signal that's better than the current one. For macOS, the candidate BSS must have an RSSI that's 12 dB stronger than the current BSS, whether the Mac is idle or transmitting data. For iOS, iPadOS, and visionOS, the candidate BSS must have an RSSI that's 8 dB stronger if the iPhone, iPad, or

- Wi-Fi 7 (802.11be) is preferred over Wi-Fi 6 (802.11ax)
- Wi-Fi 6 (802.11ax) is preferred over Wi-Fi 5 (802.11ac)
- Wi-Fi 5 (802.11ac) is preferred over Wi-Fi 4 (802.11n) or 802.11a
- Wi-Fi 4 (802.11n) is preferred over 802.11a
- 160 MHz channel width is preferred over 80 MHz, 40 MHz, or 20 MHz
- 80 MHz channel width is preferred over 40 MHz or 20 MHz
- 40 MHz channel width is preferred over 20 MHz
- Wi-Fi 4 (802.11n) is preferred over 802.11a
- 160 MHz channel width is preferred over 80 MHz, 40 MHz, or 20 MHz
- 80 MHz channel width is preferred over 40 MHz or 20 MHz
- 40 MHz channel width is preferred over 20 MHz

Tri-band 2.4/5/6 – 20/20/80 MHz

Increase Ch. Width on 6 GHz to 80 MHz

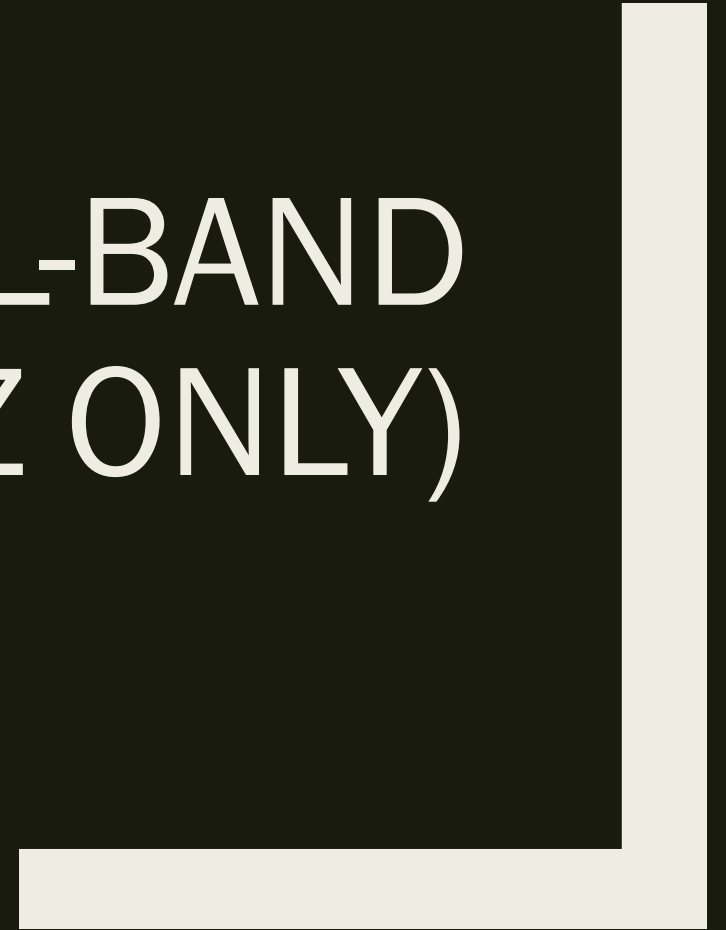
Device	2.4GHz	5GHz	6GHz	Roams
Google Pixel 8 (Wi-Fi 7)	10%	5%	85%	20
Intel BE200 (Wi-Fi 7)	0%	0%	100%	20
iPhone 15 Pro (Wi-Fi 6E)	12%	0%	88%	16
M2 MacBook Pro (Wi-Fi 6E)	6%	0%	94%	18
MediaTek MT7902 (Wi-Fi 6E)	0%	0%	100%	7
MediaTek MT7922 (Wi-Fi 6E)	0%	5%	95%	20
Qualcomm WCN7851 (Wi-Fi 7)	5%	30%	65%	20

Tri-Band 2.4/5/6 – 20/40/80 MHz

Mixed Channel Widths

Device	2.4GHz	5GHz	6GHz	Roams
Google Pixel 8 (Wi-Fi 7)	0%	0%	100%	24
Intel BE200 (Wi-Fi 7)	0%	0%	100%	19
iPhone 15 Pro (Wi-Fi 6E)	46%	15%	38%	13
M2 MacBook Pro (Wi-Fi 6E)	0%	0%	100%	19
MediaTek MT7902 (Wi-Fi 6E)	29%	0%	71%	7
MediaTek MT7922 (Wi-Fi 6E)	0%	0%	100%	20
Qualcomm WCN7851 (Wi-Fi 7)	14%	5%	81%	21

DUAL-BAND
(5 & 6 GHZ ONLY)

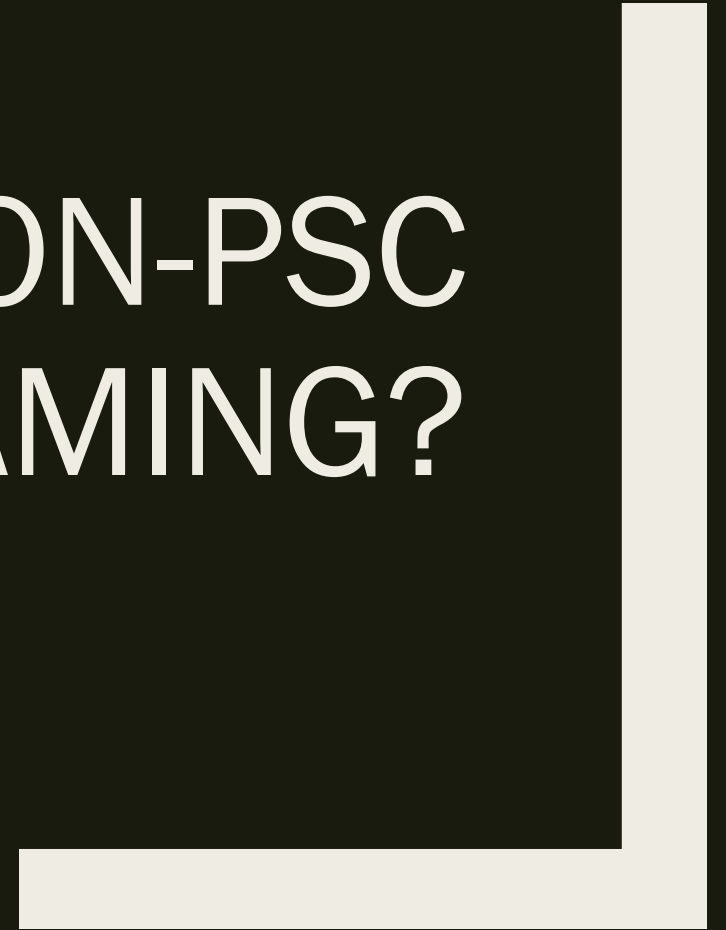


Dual-Band 5/6 GHz - 40/80 MHz

5 + 6 GHz Only Test

Device	2.4GHz	5GHz	6GHz	Roams
Google Pixel 8 (Wi-Fi 7)	0%	3%	97%	31
Intel BE200 (Wi-Fi 7)	0%	0%	100%	13
iPhone 15 Pro (Wi-Fi 6E)	0%	50%	50%	18
M2 MacBook Pro (Wi-Fi 6E)	0%	0%	100%	20
MediaTek MT7902 (Wi-Fi 6E)	0%	20%	80%	10
MediaTek MT7922 (Wi-Fi 6E)	0%	8%	92%	13
Qualcomm WCN7851 (Wi-Fi 7)	0%	61%	39%	18

DOES USING NON-PSC
IMPACT ROAMING?

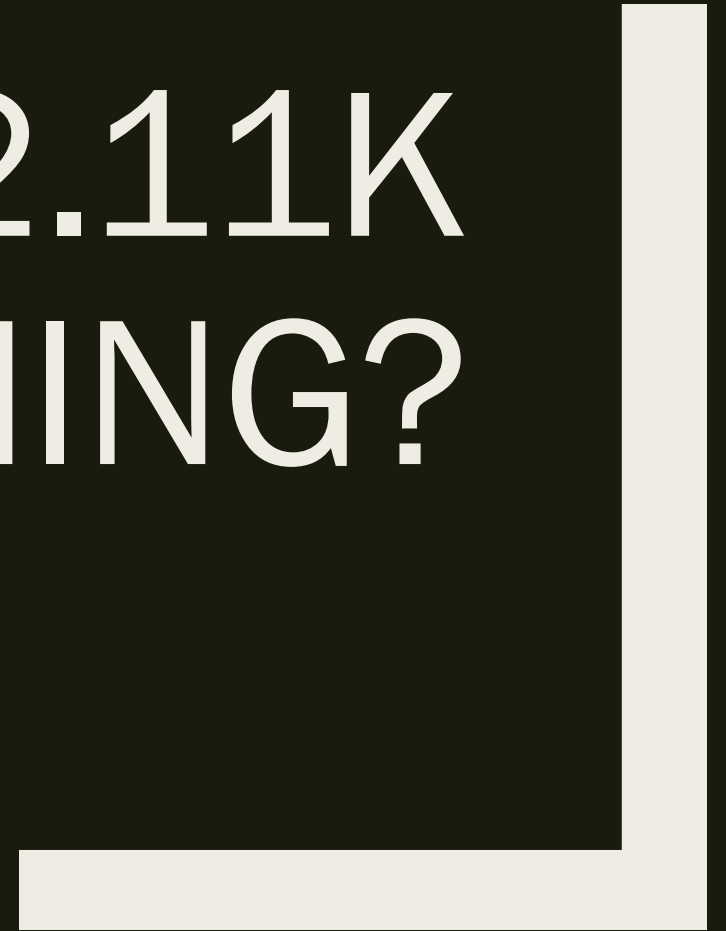


Tri-band 2.4/5/6 – 20/40/40 MHz

Non-PSC Test

Device	2.4GHz	5GHz	6GHz	Roams
Google Pixel 8 (Wi-Fi 7)	21%	4%	75%	24
Intel BE200 (Wi-Fi 7)	0%	0%	100%	12
iPhone 15 Pro (Wi-Fi 6E)	50%	9%	41%	22
M2 MacBook Pro (Wi-Fi 6E)	0%	0%	100%	19
MediaTek MT7902 (Wi-Fi 6E)	0%	90%	10%	10
MediaTek MT7922 (Wi-Fi 6E)	0%	62%	38%	21
Qualcomm WCN7851 (Wi-Fi 7)	0%	36%	64%	22

DOES 802.11K
IMPACT ROAMING?



iOS & 802.11k

A roam scan is the process used by a device to check for access points that support the currently associated ESSID. The device checks all available channels in the 2.4 GHz, 5 GHz, and primary scanning channels in 6 GHz. In addition, 6 GHz networks are discovered out-of-band by listening for the Reduced Neighbor Report information element of beacons in the 2.4 GHz and 5 GHz bands.

The roam scan runs more quickly if 802.11k is enabled on the network. This helps because supported Apple devices and operating systems use the first six entries in the Neighbor Report to prioritize the channels to be scanned. If the 802.11k Neighbor Report isn't enabled, those devices must scan more methodically.

For example, a user who is on a call might walk to the other side of the building. When the iPhone crosses the -70 dBm threshold, it scans for roam targets. If it uses the Neighbor Report that 802.11k provides, it finds APs that support the current ESSID on three channels. It immediately scans those channels, finds that the AP on a channel has the appropriate signal strength, and roams. If 802.11k isn't enabled on the network, the client has to scan every channel on each band to find a roam target. This can add several seconds to the process.

<https://support.apple.com/guide/deployment/wi-fi-roaming-support-dep98f116c0f/web>

Tri-Band 2.4/5/6 – 20/40/80 MHz

802.11k enabled

Device	2.4GHz	5GHz	6GHz	Roams
Google Pixel 8 (Wi-Fi 7)	4%	0%	96%	27
Intel BE200 (Wi-Fi 7)	0%	0%	100%	20
iPhone 15 Pro (Wi-Fi 6E)	31%	3%	66%	29
M2 MacBook Pro (Wi-Fi 6E)	0%	0%	100%	19
Mediatek MT7902 (Wi-Fi 6E)	0%	14%	86%	7
Mediatek MT7922 (Wi-Fi 6E)	0%	10%	90%	20
Qualcomm WCN7851 (Wi-Fi 7)	10%	25%	65%	20

No 11k vs 11k enabled

Device	2.4GHz	5GHz	6GHz	Roams	Test
Google Pixel 8 (Wi-Fi 7)	0%	0%	100%	24	Tri-Band 20-40-80 MHz
Google Pixel 8 (Wi-Fi 7)	4%	0%	96%	27	Tri-Band 20-40-80 MHz + 11k
Intel BE200 (Wi-Fi 7)	0%	0%	100%	19	Tri-Band 20-40-80 MHz
Intel BE200 (Wi-Fi 7)	0%	0%	100%	20	Tri-Band 20-40-80 MHz + 11k
iPhone 15 Pro (Wi-Fi 6E)	46%	15%	38%	13	Tri-Band 20-40-80 MHz
iPhone 15 Pro (Wi-Fi 6E)	31%	3%	66%	29	Tri-Band 20-40-80 MHz + 11k
M2 MacBook Pro (Wi-Fi 6E)	0%	0%	100%	19	Tri-Band 20-40-80 MHz
M2 MacBook Pro (Wi-Fi 6E)	0%	0%	100%	19	Tri-Band 20-40-80 MHz + 11k
MediaTek MT7902 (Wi-Fi 6E)	29%	0%	71%	7	Tri-Band 20-40-80 MHz
MediaTek MT7902 (Wi-Fi 6E)	0%	14%	86%	7	Tri-Band 20-40-80 MHz + 11k
MediaTek MT7922 (Wi-Fi 6E)	0%	0%	100%	20	Tri-Band 20-40-80 MHz
MediaTek MT7922 (Wi-Fi 6E)	0%	10%	90%	20	Tri-Band 20-40-80 MHz + 11k
Qualcomm WCN7851 (Wi-Fi 7)	14%	5%	81%	21	Tri-Band 20-40-80 MHz
Qualcomm WCN7851 (Wi-Fi 7)	10%	25%	65%	20	Tri-Band 20-40-80 MHz + 11k

MLO AND ROAMING



MLO Compatibility

Windows

> **Wi-Fi** > **triband+mlo**

Manufacturer:
Intel Corporation

Description:
Intel(R) Wi-Fi 7 BE200 320MHz

Driver version:
23.100.0.4

Network band (channel):
2.4 GHz (6), 6 GHz (37)

Aggregated link speed (Receive/
Transmit):
960/960 (Mbps)

Android

2:59 31 □ ▶

← Internet ↻

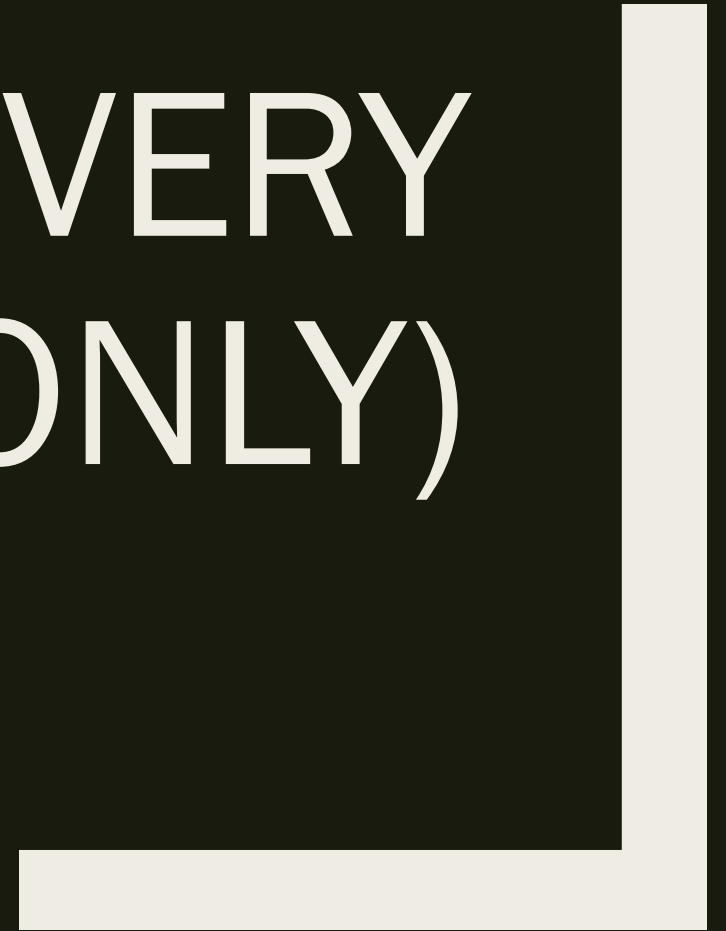
triband+mlo

Connected / f = 6615
98:8f:00:ee:0f:c3 standard =
Wi-Fi 7 rssi = -77 score = 60
tx=0.9, 1.4, 0.0 rx=0.9 mldMac =
98:8f:00:ee:0f:c3 linkId = 0 affLinks
= [MloLink{6GHz, channel: 133, id:
0, state: MLO_LINK_STATE_ACTIVE,
RSSI: -77, Rx Link speed: 97Mbps,
Tx Link speed: 154Mbps, AP MAC
Address: 98:8f:00:ee:0f:c3, STA
MAC Address: 3e:2a:be:0d:33:c2},
MloLink{2.4GHz, channel: 1, id: 2,
state: MLO_LINK_STATE_ACTIVE,
RSSI: -83, Rx Link speed: 8Mbps,
Tx Link speed: 229Mbps, AP MAC
Address: 98:8f:00:ee:0f:b3, STA

Compare: No MLO vs MLO Enabled

Device	2.4GHz	5GHz	6GHz	Roams	
Google Pixel 8 (Wi-Fi 7)	0%	0%	100%	24	
Google Pixel 8 (Wi-Fi 7)	19%	38%	44%	16	w/ MLO
Intel BE200 (Wi-Fi 7)	0%	0%	100%	19	
Intel BE200 (Wi-Fi 7)	0%	0%	100%	14	w/ MLO
Qualcomm WCN7851 (Wi-Fi 7)	14%	5%	81%	21	
Qualcomm WCN7851 (Wi-Fi 7)	14%	14%	71%	14	w/ MLO

FILS DISCOVERY
(6 GHZ ONLY)



6 GHz Only

FILS Discovery Method

Device	2.4GHz	5GHz	6GHz	Roams
Google Pixel 8 (Wi-Fi 7)	0%	0%	100%	2
Intel BE200 (Wi-Fi 7)	0%	0%	100%	8
iPhone 15 Pro (Wi-Fi 6E)	0%	0%	100%	7
M2 MacBook Pro (Wi-Fi 6E)	0%	0%	100%	18
Mediatek MT7902 (Wi-Fi 6E)	0%	0%	100%	4
Mediatek MT7922 (Wi-Fi 6E)	0%	0%	100%	19
Qualcomm WCN7851 (Wi-Fi 7)	0%	0%	100%	20

6 GHz Design Considerations

- Optimize Tx power for 6 GHz
- Design for secondary coverage
- Use a wider channel on 6 GHz – Typically 80 MHz, if channel reuse allows
- Use PSC channels when possible
- Some AP vendors may not support using 40 MHz channels on PSC's

6 GHz Design Considerations (Cont.)

- Avoid mixing channel widths within the same band
- Consider disabling some or all 2.4 GHz radios
- Enable 802.11k, especially if supporting iOS devices
- Some devices prefer 6 GHz more than others (Ex. MacBook & Intel BE200)
- Avoid using 6 GHz only (FILS Discovery), use RNR by also enabling 5 GHz (or 2.4 GHz)

TOOLS USED TO CAPTURE ROAMING DATA



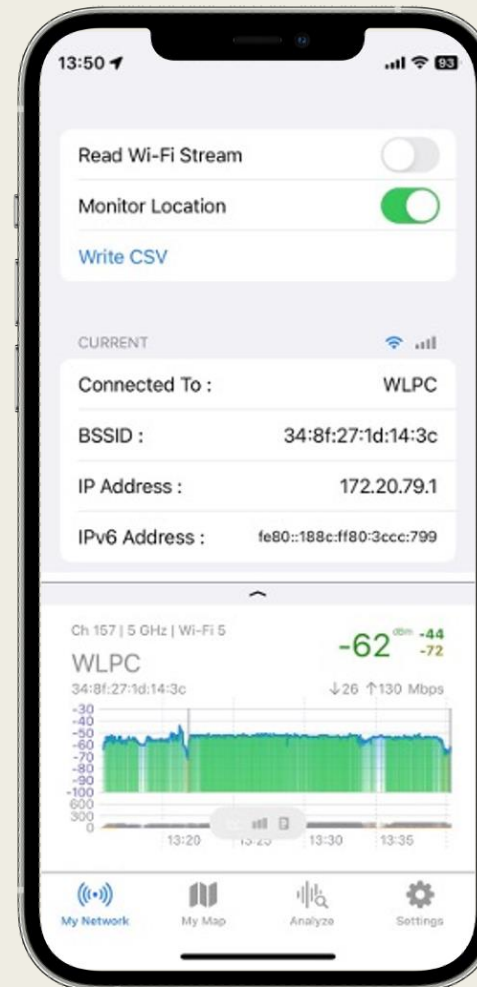
iPhone/iPad



nOversight WiFi Analyzer

- iOS app, available in app store
- Live Wi-Fi analysis
- Export roaming events to CSV file

<https://www.numerousnetworks.co.uk>



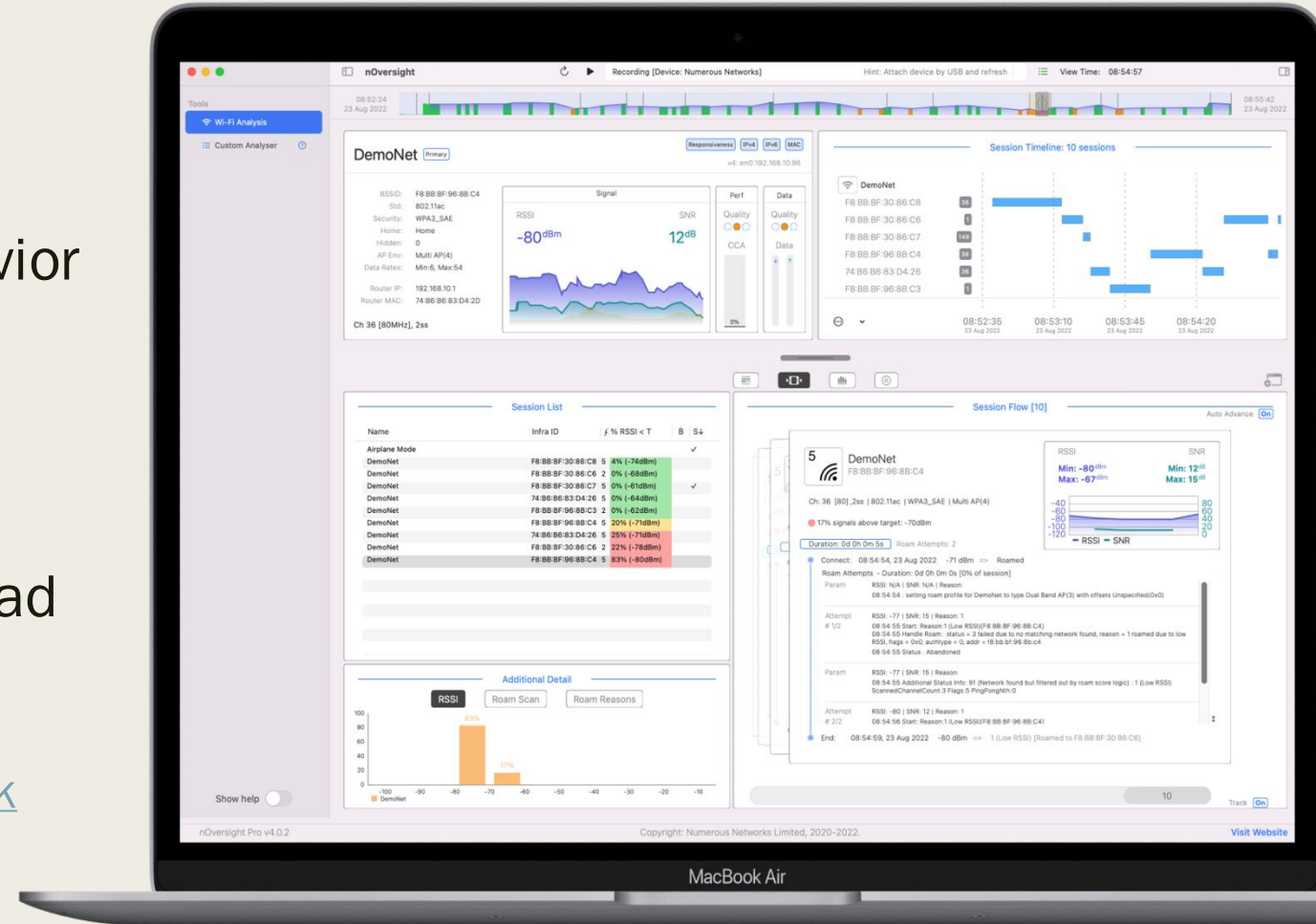
macOS



nOversight Pro

- Analyze Mac Roaming Behavior in detail
- Record, Save, and Playback sessions
- Analyze logs from iPhone/iPad

<https://www.numerousnetworks.co.uk>



Windows



```
freq: (6.135), ssid: (triband+mlo), rssi: (-70), event: (roaming_end)
freq: (6.135), ssid: (triband+mlo), rssi: (-68), event: (signal_quality_change)
freq: (6.135), ssid: (triband+mlo), rssi: (-64), event: (signal_quality_change)
freq: (6.135), ssid: (triband+mlo), rssi: (-62), event: (signal_quality_change)
freq: (6.135), ssid: (triband+mlo), rssi: (-57), event: (signal_quality_change)
freq: (6.135), ssid: (triband+mlo), rssi: (-57), event: (scan_complete), scan: (16 BSSIDs found)
freq: (6.135), ssid: (triband+mlo), rssi: (-55), event: (signal_quality_change)
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freq: (6.135), ssid: (triband+mlo), rssi: (-56), event: (signal_quality_change)
freq: (6.135), ssid: (triband+mlo), rssi: (-56), event: (signal_quality_change)
freq: (6.135), ssid: (triband+mlo), rssi: (-57), event: (signal_quality_change)
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freq: (6.615), ssid: (triband+mlo), rssi: (-64), event: (authenticating)
freq: (6.615), ssid: (triband+mlo), rssi: (-64), event: (signal_quality_change)
freq: (6.615), ssid: (triband+mlo), rssi: (-64), event: (roaming_end)
freq: (6.615), ssid: (triband+mlo), rssi: (-64), event: (scan_complete), scan: (12 BSSIDs found)
freq: (6.615), ssid: (triband+mlo), rssi: (-65), event: (signal_quality_change)
freq: (6.615), ssid: (triband+mlo), rssi: (-65), event: (scan_complete), scan: (10 BSSIDs found)
freq: (6.615), ssid: (triband+mlo), rssi: (-68), event: (signal_quality_change)
freq: (6.615), ssid: (triband+mlo), rssi: (-69), event: (signal_quality_change)
freq: (6.615), ssid: (triband+mlo), rssi: (-76), event: (roaming_start)
freq: (6.135), ssid: (triband+mlo), rssi: (-65), event: (authenticating)
freq: (6.135), ssid: (triband+mlo), rssi: (-65), event: (signal_quality_change)
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freq: (6.135), ssid: (triband+mlo), rssi: (-56), event: (signal_quality_change)
freq: (6.135), ssid: (triband+mlo), rssi: (-56), event: (scan_complete), scan: (15 BSSIDs found)
freq: (6.135), ssid: (triband+mlo), rssi: (-57), event: (signal_quality_change)
freq: (6.135), ssid: (triband+mlo), rssi: (-55), event: (scan_complete), scan: (31 BSSIDs found)
freq: (6.135), ssid: (triband+mlo), rssi: (-55), event: (scan_list_refresh), scan: (31 BSSIDs found)
```

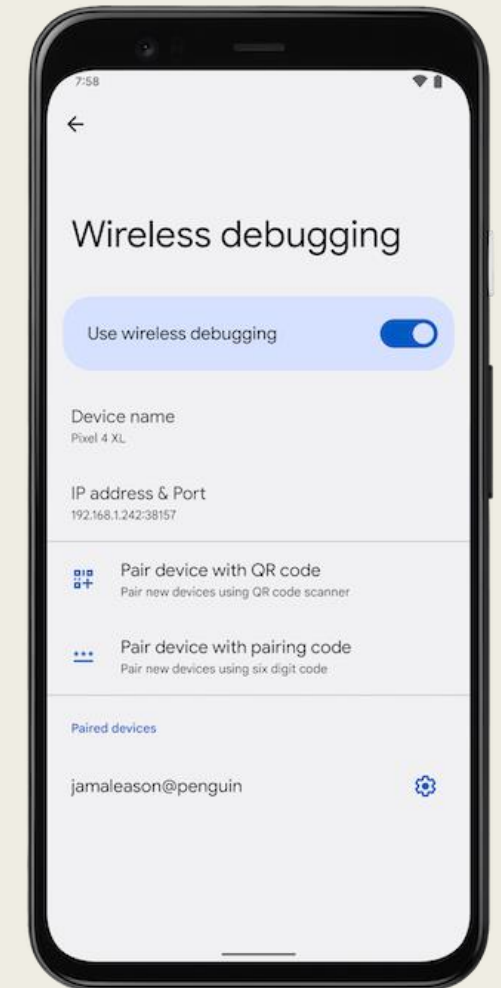
LSWIFI

- CLI-centric Wi-Fi scanning tool for Windows
- Live Wi-Fi connection analysis
- Captures Wi-Fi roaming events
- Log events to Remote Syslog Server
- <https://github.com/joshschmelzle/lswifi>

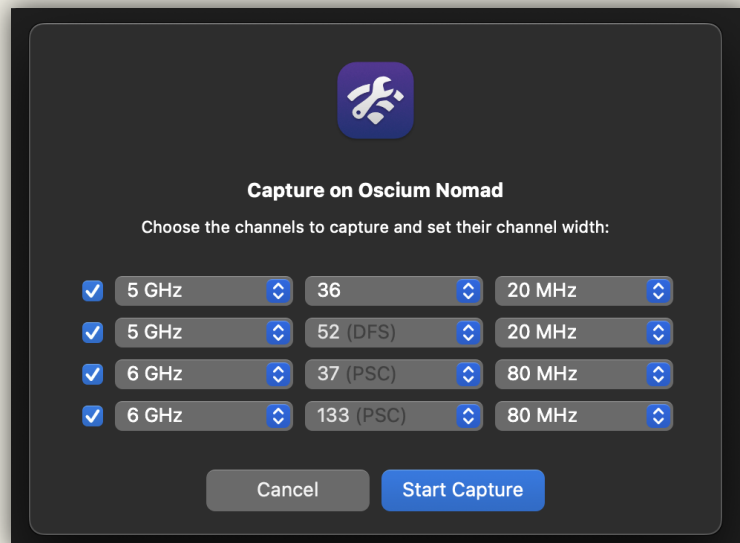
Android



- Enable Developer Options and USB Debugging
- Use adb (Android Debug Bridge)
- Real-time Logging with adb logcat
 - *adb logcat -b all | grep -i wifi*
- Record Wi-Fi Roaming Events
 - *adb logcat -b all | grep -i "roam\|BSSID\|RSSI\|handover" > wifi_roaming_log.txt*



Wi-Fi 7 Capture Solution

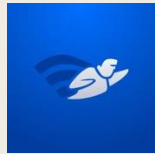


- **Oscium Nomad** – Wi-Fi Measurement Device
 - 4 Tri-band radios
 - Wi-Fi 7 capable
- **Intuitibits Airtool 2** – macOS app for capturing Wi-Fi traffic using your Mac's adapter
- Capture Wi-Fi packets on up to 4 channels simultaneously
- Save to PCAP or stream directly into Wireshark

<https://oscium.com/>

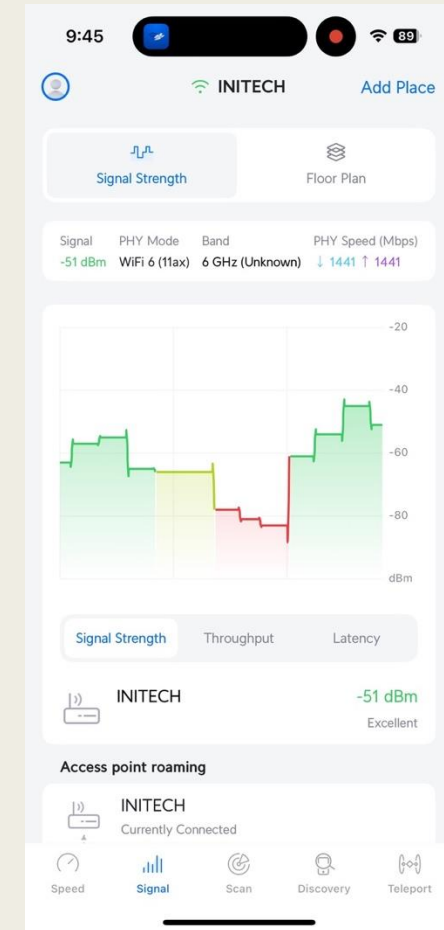
<https://www.intuitibits.com>

Real-time Roaming Analysis

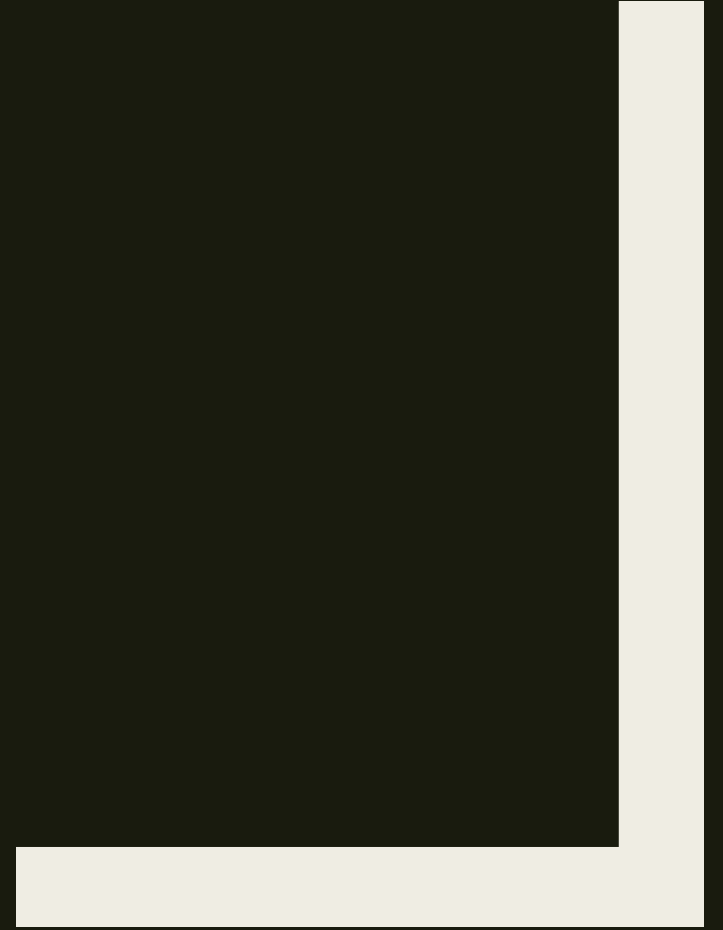


Ubiquiti WiFiman

- Android & iOS
- Live Roaming Analysis



DEMO





TESTING RESULTS & SLIDES

<https://github.com/jolla/roaming-wars>