



IEEE 802.11 Evolution

Frequency Band	Version	Key Features
2.4 GHz 5 GHz 6 GHz		
	802.11be 2024	- PHY Data Rate: 46 Gbps (max) - OFDMA, 4096 QAM, WPA 3 - Up to 320 MHz (channel bonding) - MLO, MU-RU, R-TWT, 16x16 MU-MIMO
	802.11ax 2021	- PHY Data Rate: 9.6 Gbps (max) - OFDMA 1024 QAM, WPA 3 20, 40, 80, 160 MHz (channel bonding) 8x8 MU-MIMO DL/UL, TWT
	802.11ax 2019	- PHY Data Rate: 9.6 Gbps (max) - OFDM 256 QAM, WPA 3 20, 40, 80, 160 MHz (channel bonding) 8x8 MU-MIMO DL/UL, TWT
	802.11ac 2013	- PHY Data Rate: 6.93 Gbps (max) - OFDM, 256 QAM, WPA 2 80, 160 MHz channel bonding 8x8 MIMO, MU-MIMO DL
	802.11n 2009	- PHY Data Rate: 600 Mbps (max) - OFDM 64 QAM, WPA 3 20, 40 MHz channel bonding 4x4 SU-MIMO
	802.11g 2003	- PHY Data Rate: 54 Mbps (max) - OFDM, 64 QAM, ERP, WPA2 20 MHz channels 1x1 SISO
	802.11a 1999	- PHY Data Rate: 54 Mbps (max) - DSSS, CSMA/OFDM, 64 QAM, WPA 20 MHz channels 1x1 SISO
	802.11b 1999	- PHY Data Rate: 11 Mbps (max) - CCQ, QPSK, HR-DSSS, WEP 22 MHz channel 1x1 SISO

Notes:
1. Several permutations of the listed standards and technical specifications exist
2. For more IEEE 802.11 standards related information, visit IEEE.org



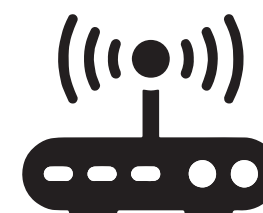
Typical Wi-Fi Eco-System

Smart Home Wi-Fi Network Attributes

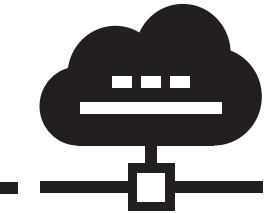
- Residential grade routers and peripherals often employ older generation Wi-Fi standards
- Typically offer asymmetrical upload/download speeds limited by coax or twisted pair cable connection (DSL)
- Basic Internet - web browsing, email, IoT devices, gaming, online banking/shopping, streaming content
- Work from Home - video conferencing, Google Docs, ...
- Wi-Fi routers often use factory default passwords simplifying unauthorized access
- Router employs no rules to manage Internet traffic
- Insufficient bandwidth to support large file transfers or cloud-based software
- Installing, downloading, accessing software and App is risky
- Best effort - No Service Level Agreement (SLA) with ISP
- Poorly managed home coverage using Wi-Fi extenders or Mesh systems



Laptop/Mobile Devices



Modem/Router



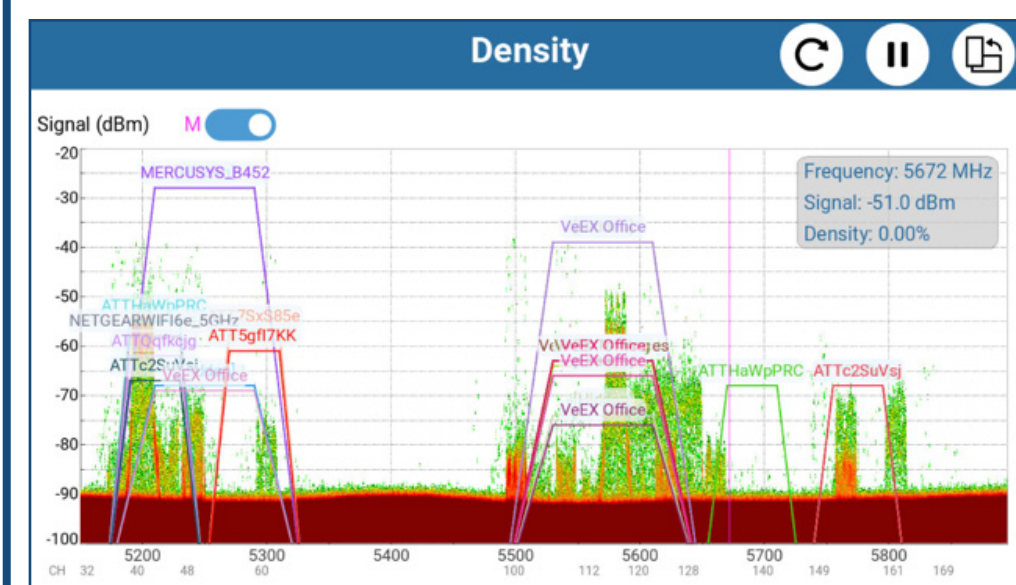
Internet Services

Business/Enterprise Wi-Fi Network Attributes

- Commercial grade routers and peripherals employing newer/latest generation Wi-Fi standards
- Symmetrical or asymmetrical rates depending on service: PON/FTTH, cable broadband
- Faster speed, better security and contention ratio
- IT team typically manages Wi-Fi network access to protect company and client data
- IT team manages router configuration (user passwords, firewall settings, and traffic priority)
- Static IP addresses for running servers, host company website, emails and support large file transfer
- Company controls software applications that can be downloaded/installed by each user and/or device
- VoIP providing affordable phone service over Wi-Fi
- Service Level Agreement (SLA) with ISP to guarantee QoS
- Typically provide a guest Wi-Fi network separate from main network



RF Troubleshooting



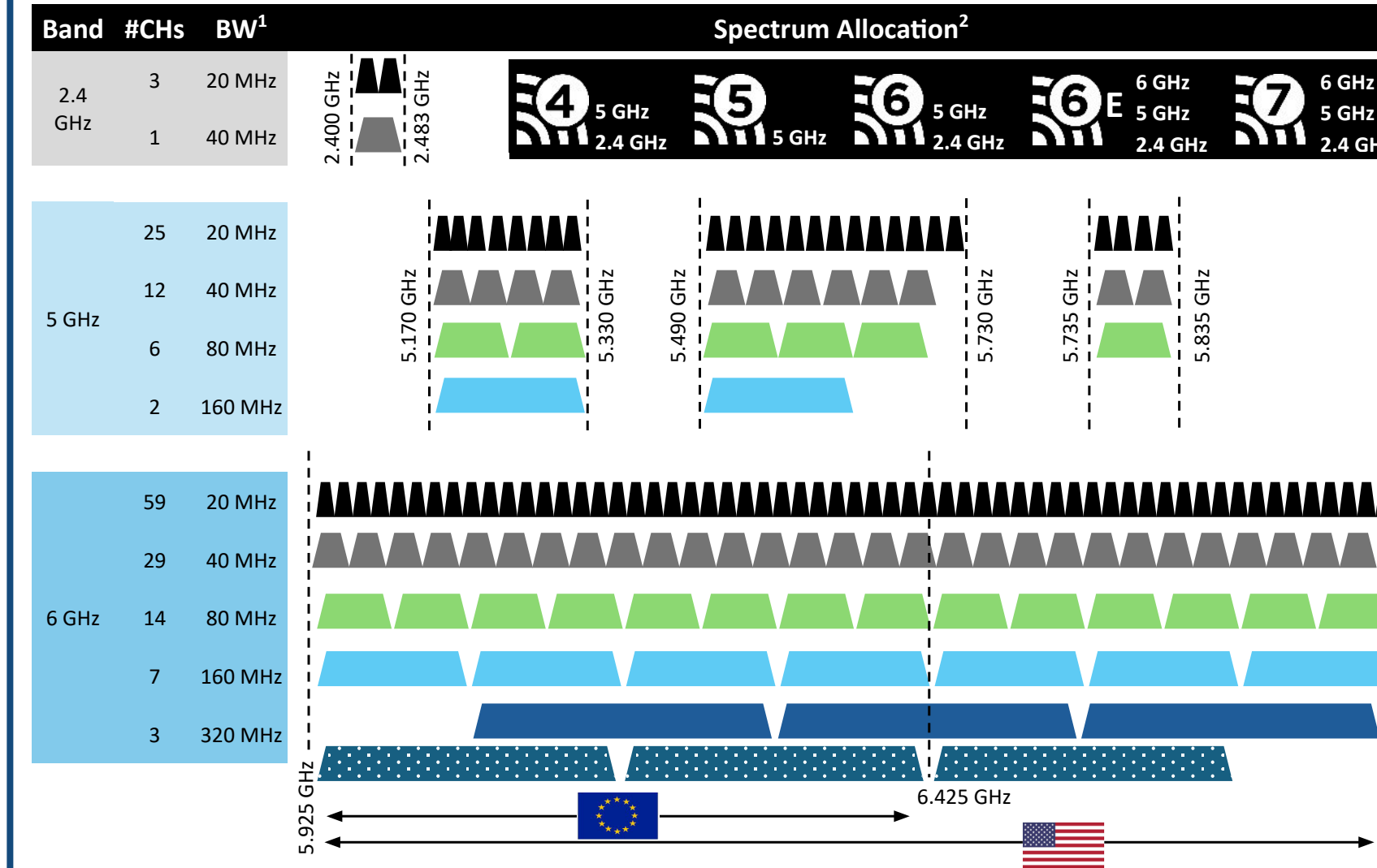
Overview

- The 2.4, 5, & 6 GHz Frequency bands are unlicensed and are highly susceptible to interference
- Microwave ovens, cordless phones, Bluetooth® devices, baby monitors, Zigbee®, and other devices are all potential interference sources which raise the overall noise floor, impacting network performance

Spectrum Analysis

- Use a Spectrum Analyzer to visualize the RF activity of Wi-Fi signals in their operating bands
- Identify Interference Sources: Detect Wi-Fi channels and intermittent non-Wi-Fi interference
- Monitor RF activity in real-time to detect congestion and noise levels
- Assess Channel Utilization: check bandwidth usage to optimize channel selection and reduce interference
- Differentiate Wi-Fi versus non-Wi-Fi Signals: Identify and mitigate non-Wi-Fi signal interference
- Use Signature Library: Recognize interference patterns and match them to known sources
- Evaluate Noise Floor & SNR: Identify high noise levels that impact performance and stability
- Optimize AP Placement & Power: Adjust AP location and power settings to minimize interference and optimize coverage

Channel Bandwidth



Notes:

- BW is defined as the bandwidth available per channel
- Spectrum determines the # of channels and varies by country - in the USA, the 2.4 GHz band offers 60 MHz, 5 GHz band offers 500 MHz, and 6 GHz offers 1200 MHz. In Europe, the 6 GHz band offers 500 MHz.
- 802.11be offers three super-wide 320 MHz channels in the 6 GHz band doubling the available bandwidth compared to 802.11ax

Common Wi-Fi Problems

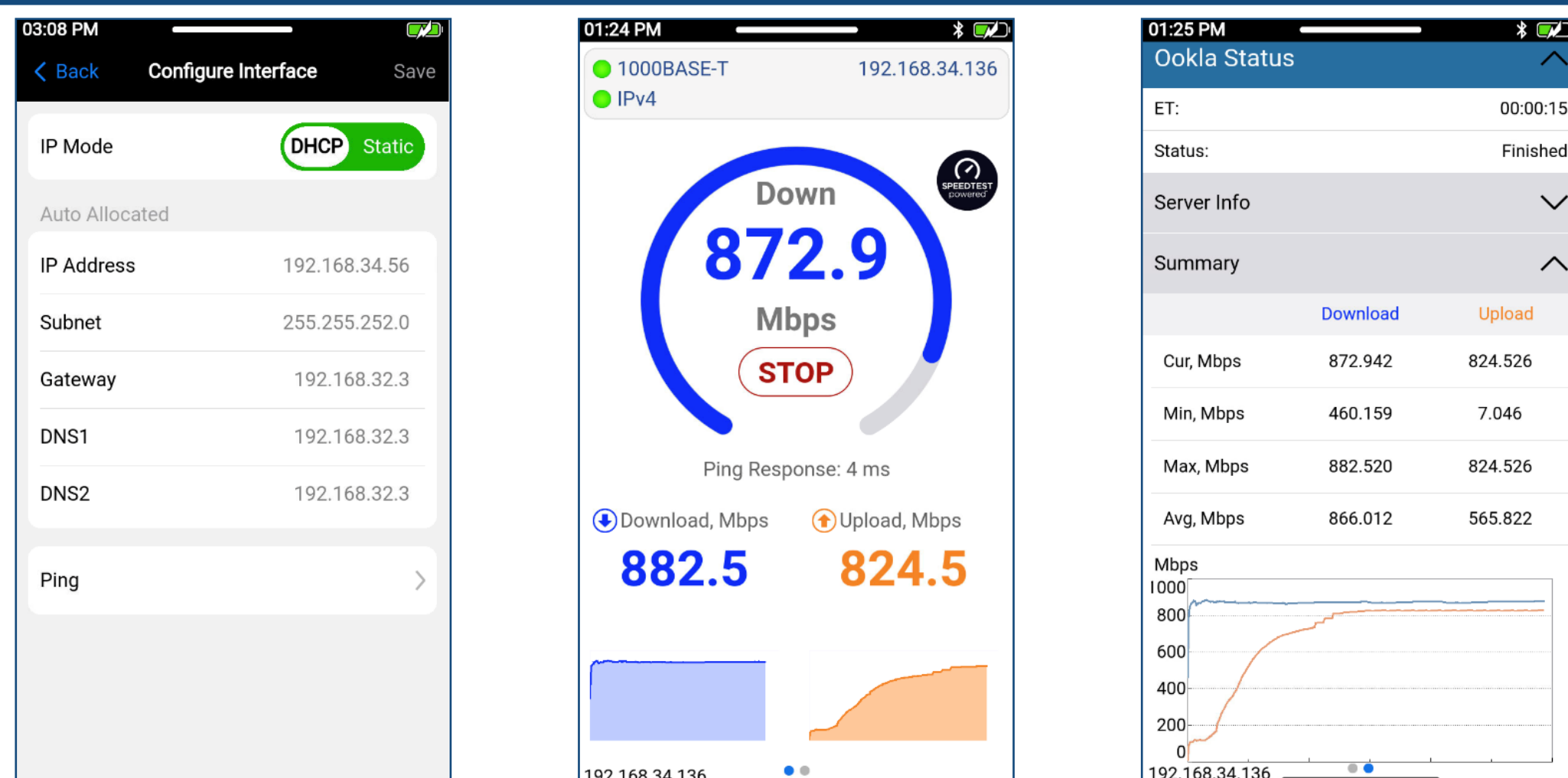
Complaint	Possible Causes & Potential Solutions
1. User/device cannot connect to Wi-Fi network	- Check if user is connecting to the correct SSID - Check password setting and related security credentials - Check if network is available including WAN connection - Check signal strength/SNR, coverage and dead zones - Check AP and client device configuration - Channel utilization and interference - Network services e.g., DHCP, DNS, Gateway status, ... - Check for legacy 802.11 devices - Check for excessive co-channel interference - Check for any PoE issues if applicable - power to AP
2. User keeps getting disconnected	- Check for signal level or SNR at client location - Check client device configured correctly - Check for non-Wi-Fi devices or interference sources - Relocate AP to improve signal level or SNR - Change AP to different channel to mitigate interferer
3. User cannot roam	- Check AP configuration e.g., security protocol - Check secondary AP coverage e.g., MESH systems
4. Wi-Fi network is very slow	- Check if there are too many APs on the channel - Check airtime utilization of channel for valid devices - Check airtime utilization of non-Wi-Fi devices - Check for rogue APs transmitting large files - Check for legacy devices which only support slow rates - Check WAN connection throughput (upload/download) rates using SpeedTest and compare to WLAN rate - Perform iPerf (TCP/UDP) test between devices or to an iPerf server on the network - TCP - measures throughput of your wireless network - UDP - measures packet loss and jitter to troubleshoot problems wrt latency sensitive applications



GLOSSARY OF TERMS

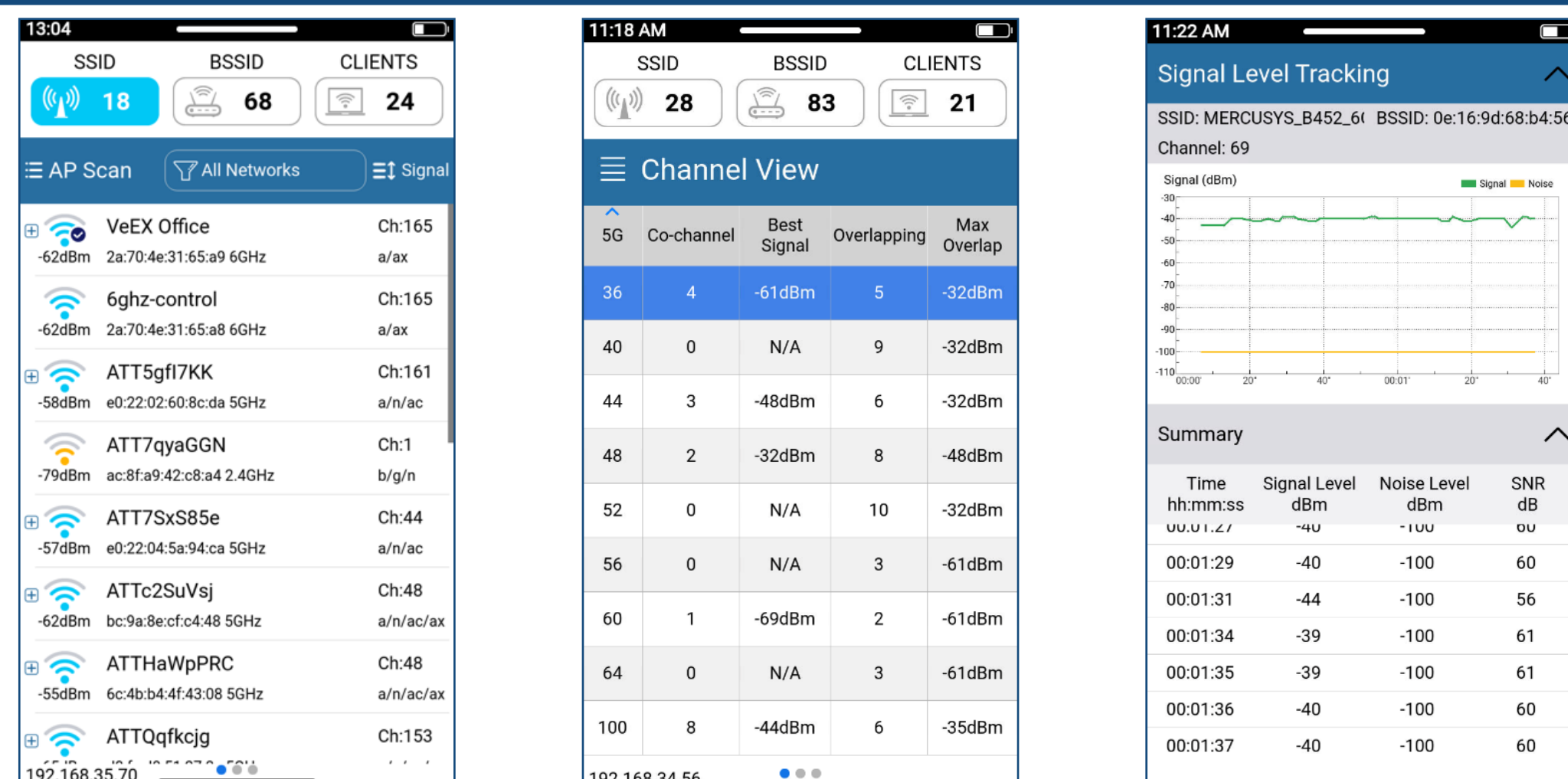
ACI	Adjacent Channel Interference	PSD	Power Spectral Density
AFC	Automated Frequency Coordination	PSK	Phase Shift Keying
AP	Access Point	QAM	Quadrature Amplitude Modulation
BSSID	Basic Service Set Identifier	QoS	Quality of Service
CCI	Co-Channel Interference	QPSK	Quadrature Phase Shift Keying
dBm	decibels relative to 1 milliwatt	RSSI	Received Signal Strength Indicator
DHCP	Dynamic Host Configuration Protocol	SISO	Single Input Single Output
DNS	Domain Name Server	SNR	Signal-to-Noise Ratio
DSSS	Direct Sequence Spread Spectrum	SSID	Service Set Identifier
HR/DSSS	High Rate/DSSS	TCP	Transmission Control Protocol
IEEE	Electrical and Electronics Engineers	TWT	Target Wake Time
MAC	Medium Access Control	UDP	User Datagram Protocol
MIMO	Multiple Input, Multiple Output	UNII	Unlicensed National Info Infrastructure
OFDM	Orthogonal Frequency Division Multiplexing	WAN	Wide Area Network
OFDMA	OFD Multiple Access	WEP	Wired Equivalent Privacy
OSI	Open Systems Interconnection	Wi-Fi	Wireless Fidelity
Ping	Packet Inter-Network Groper	WLAN	Wireless Local Area Network
PPPoE	Point-to-Point Protocol over Ethernet	WPA	Wi-Fi Protected Access

Modem | Router Verification



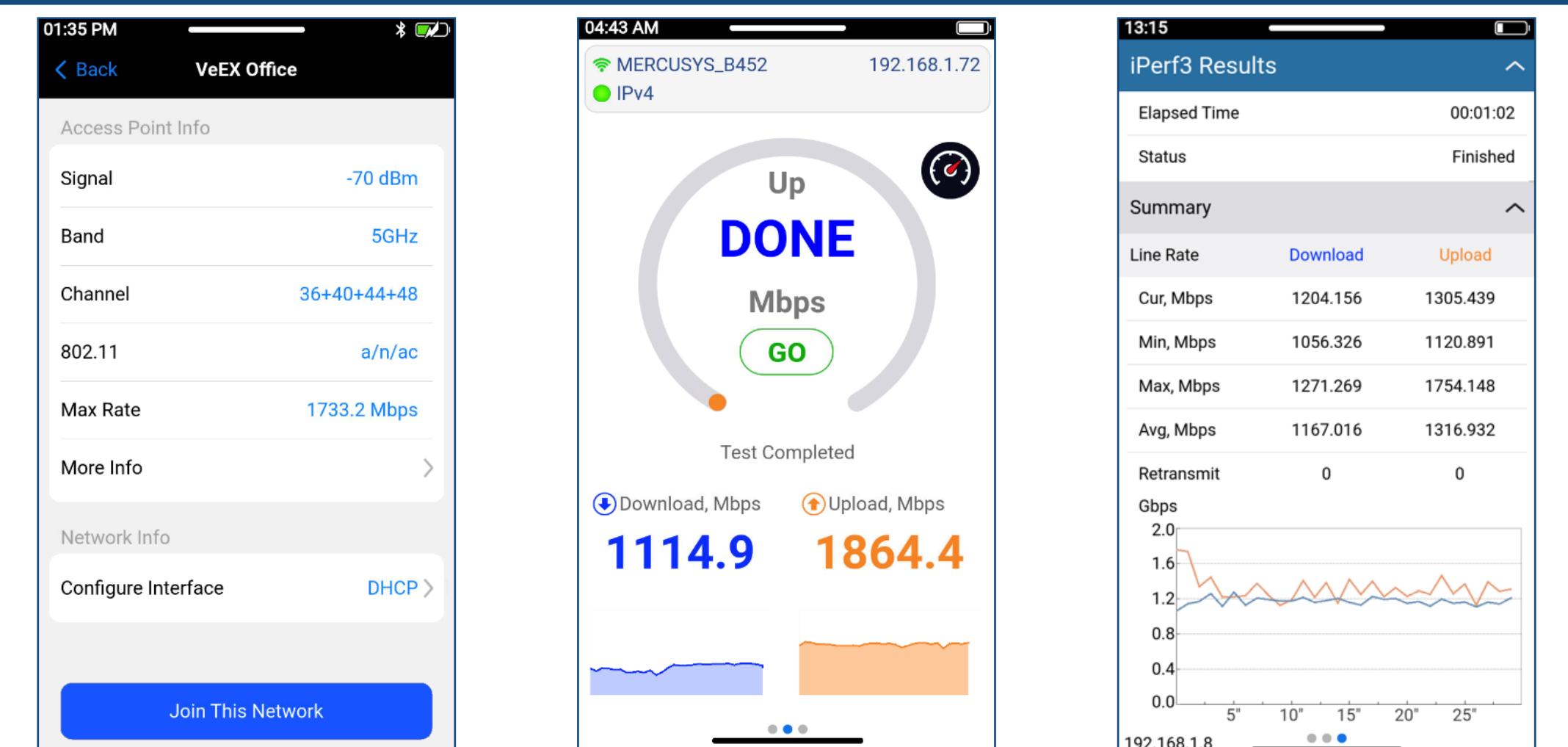
- All wireless APs (except mesh APs) use an Ethernet backhaul connection to the network
- Always test and benchmark the WAN connection speed performance prior to verifying Wi-Fi connectivity - Wi-Fi access can appear broken if the WAN connection to the Internet does not work correctly
- Check static IP address, or PPPoE credentials needed on your ISP's modem
- Plug an Ethernet cable into the router's LAN port and perform a Speedtest to an Ookla® server to verify connection to the Internet, and baseline the up/downstream line rates

Network Discovery | AP Survey



- Scan Wi-Fi network to identify valid and unwanted 802.11 a/b/g/n/ac/ax access points (APs), including slower legacy devices
- Verify SSID, BSSID, channels, clients, security settings, data rates, signal strength, noise levels, SNR, adjacent & co-channel APs
- Discover associated clients and non-associated clients, review MAC addresses, manufacturer details, and track client activity
- View channels to check contention ratio and identify heavily used channels (utilization %, # APs, co-channel AP count, signal strength)
- Poor signal coverage is one of the most common reasons for Wi-Fi connection problems - use signal and noise level measurements to survey the network to ensure proper Wi-Fi coverage

Internet Connectivity | iPerf & Speedtest®



- Emulate customer access by connecting to an AP using valid credentials (incl. WEP, WPA, WPA2, and WPA3 security protocols or portal logins)
- Review association and authentication status (assigned IP address, Gateway, DHCP server and DNS server details)
- Use tools like Ping and Traceroute verify Internet connectivity and connection to the Internet
- Perform speed test (Wi-Fi interface) against Ookla's Speedtest® servers to check TCP protocol performance (data transfer time, up/down rates)
- Use iPerf to qualify the maximum bandwidth between two devices over the network. TCP/UDP throughput tests offer insights into network speed, stability, and flags potential issues especially those relating to video streaming