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EMBEDDED LINUX CONFERENCE

Wi-Fi 6 (Formerly IEEE 802.11ax) Deep Dive

Presented by
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Toradex

WITH YOU TODAY…

- Joined Toradex 2011
- Spearheaded Embedded Linux Adoption
- Introduced Upstream First Policy
- Top 10 U-Boot Contributor
- Top 10 Linux Kernel ARM SoC Contributor
- Industrial Embedded Linux Platform Torizon Fully Based on Mainline Technology
  - Mainline U-Boot with Distroboot
  - KMS/DRM Graphics with Etnaviv & Nouveau
  - OTA with OSTree
  - Docker resp. Podman

Marcel Ziswiler

Software Team Lead - Embedded Linux BSP

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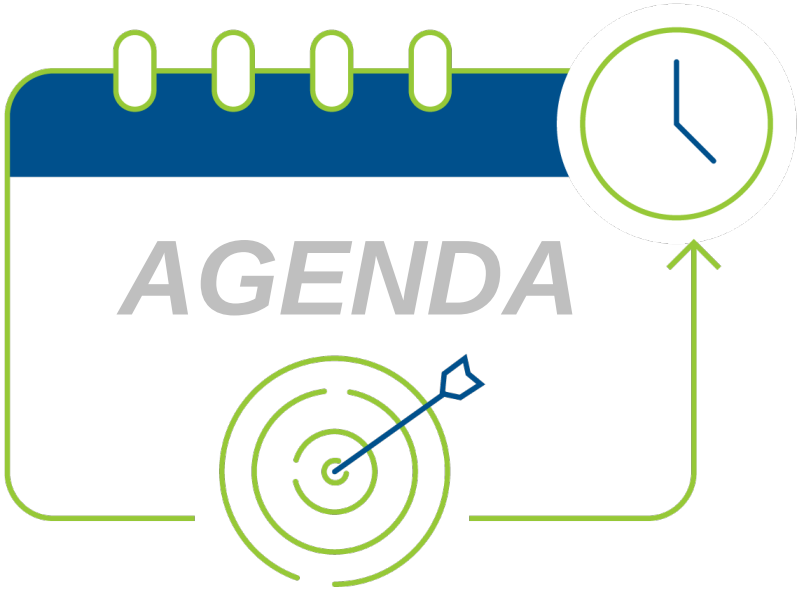
WHAT WE'LL COVER TODAY…

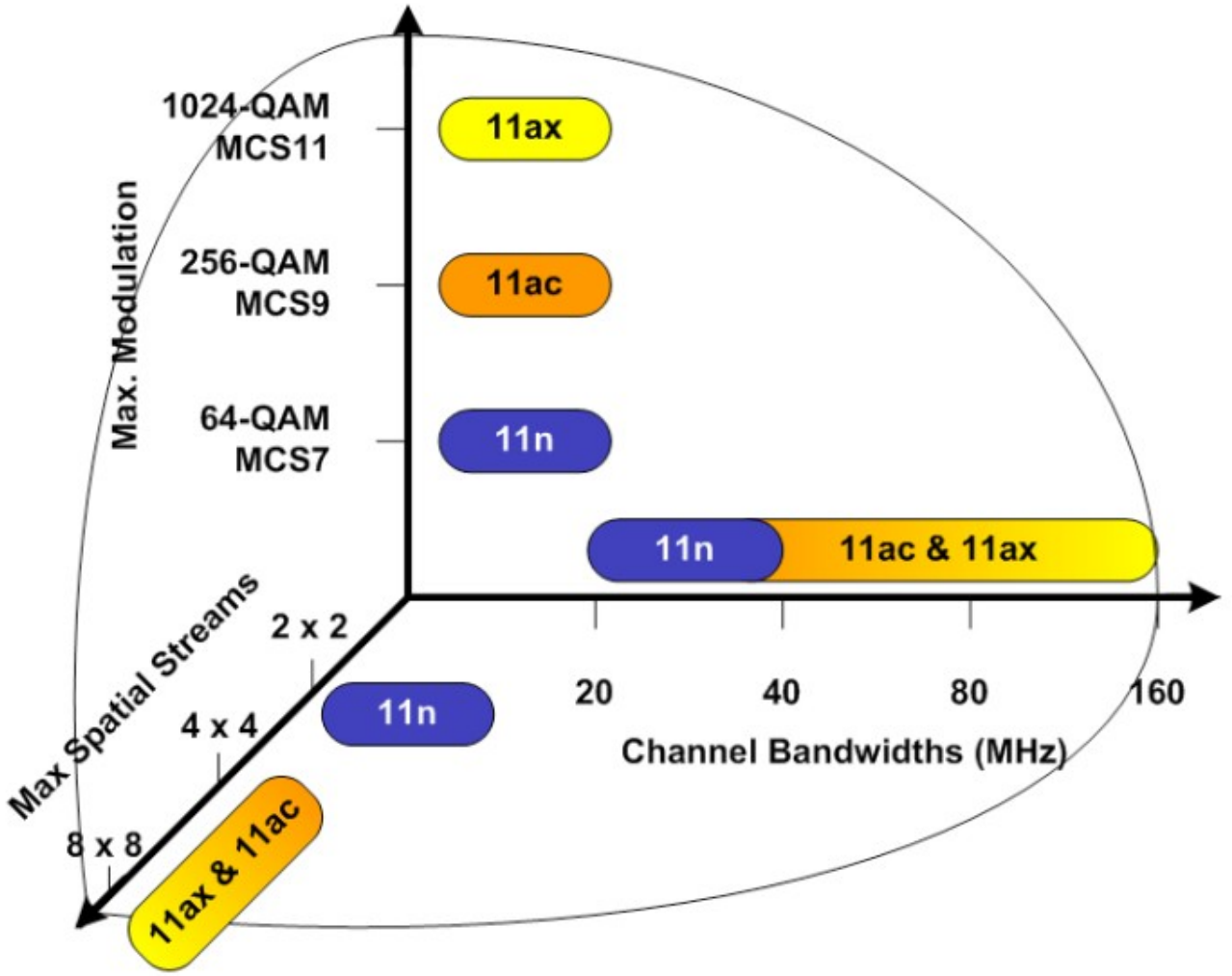
- Introduction to Wi-Fi 6
- Wi-Fi 6 OpenWrt
  Access Point (AP)/Router Landscape
  - Belkin RT3200/Linksys E8450 (MediaTek based)
  - Xiaomi Mi AioT Router AX3600 (Qualcomm based)
- Wi-Fi 6 Clients
  - Intel AX210NGW
  - MediaTek MT7921K
  - Qualcomm QCA6391
  - Realtek RTL8852AE
- Real-Life Configurations and Benchmark Demo Use Cases



Introduction to Wi-Fi 6

- Former IEEE 802.11ax standard
- Ratified early last year (February 1, 2021)
- Evolving Wi-Fi performance envelope (see diagram)
- However, developed to increase both overall efficiency and capacity
- **High-efficiency Wi-Fi**
- Overall improvements enhancing throughput per area targeting dense environments
- Higher spectral efficiency

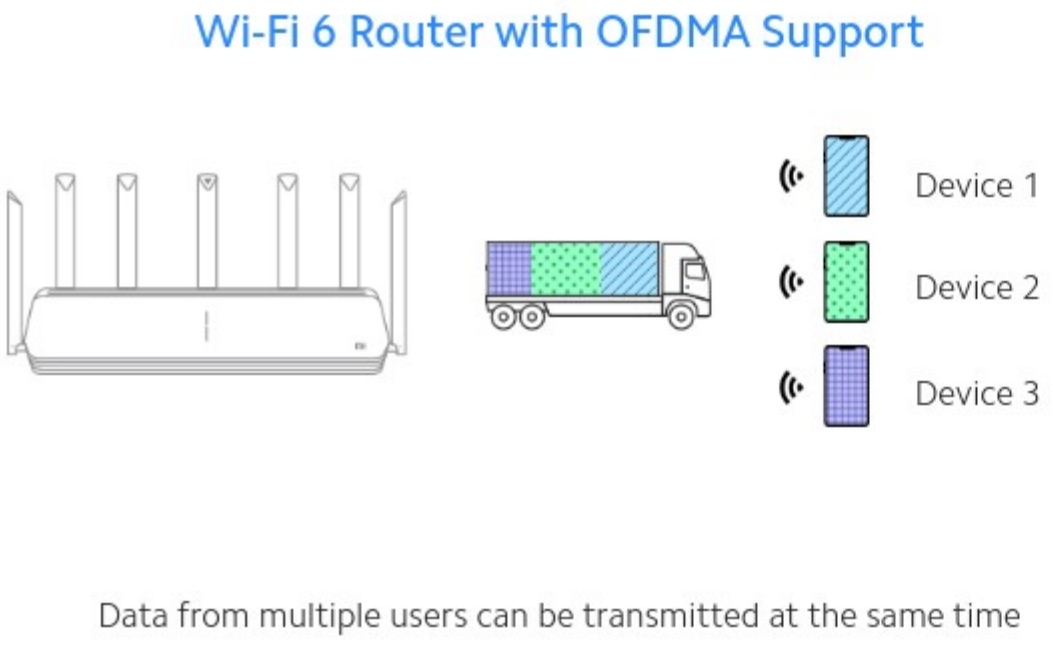
- **Wi-Fi 6E**: operation in unlicensed 6 GHz band

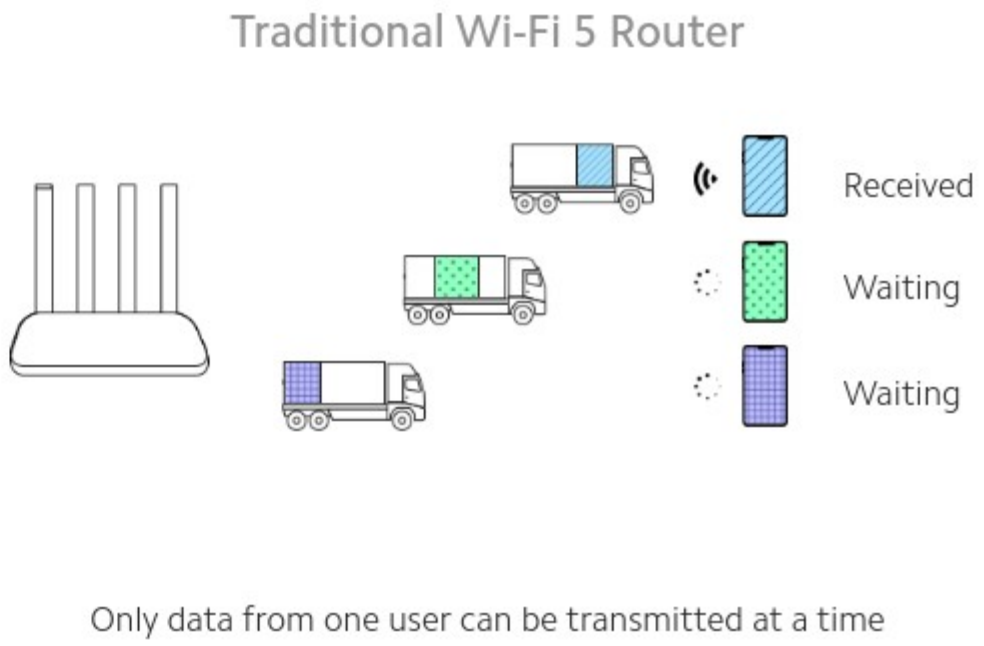


Source: Liang Jin, Spirent

Introduction to Wi-Fi 6 Main Concepts

- Orthogonal frequency-division multiple access (**OFDMA**)
  - Spectrum broken up into groups of sub-carriers called Resource Units (Rus)
  - Allows sharing each frame among users, improving efficiency, reducing contention

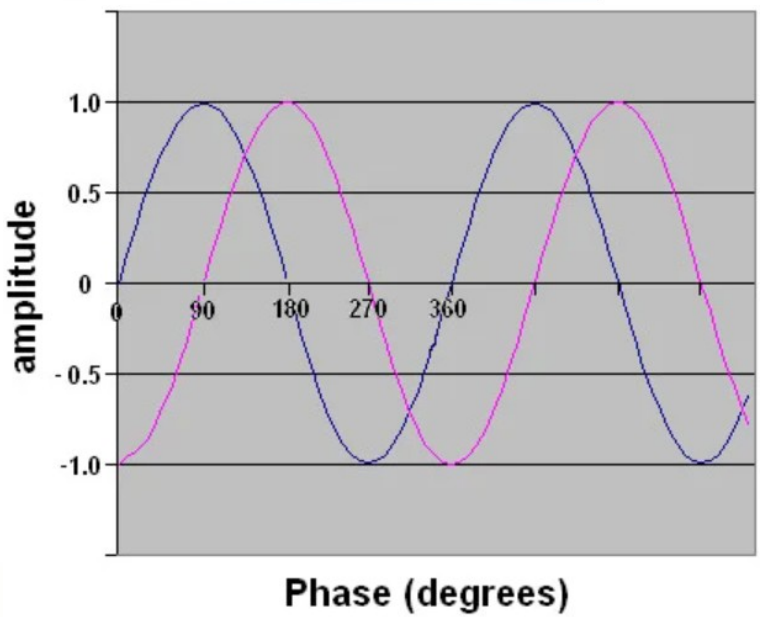


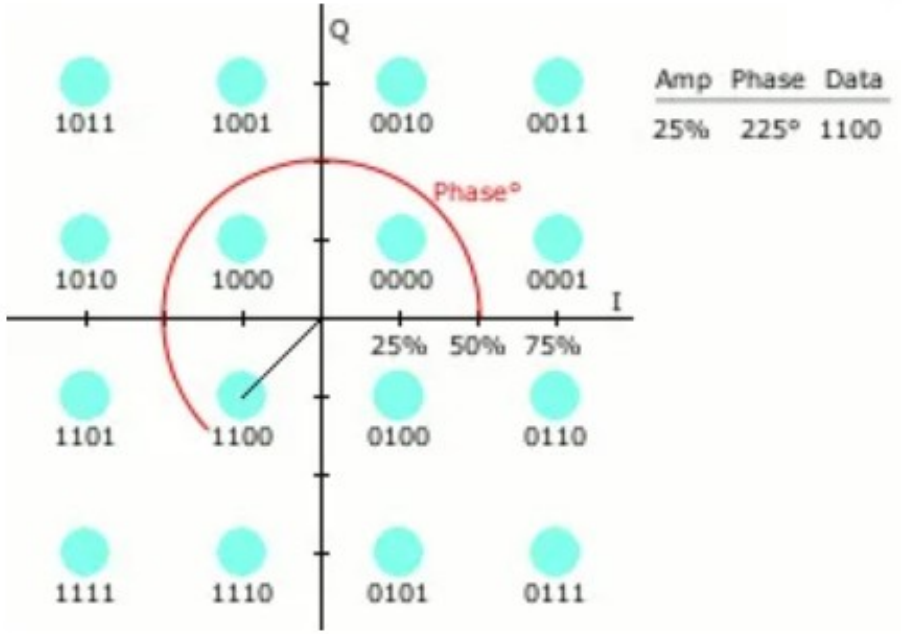


- Benefits at 2.4 GHz: managing low-rate IoT sensor devices
- **160 MHz** bandwidth channels

Introduction to Wi-Fi 6 Main Concepts (cont.)

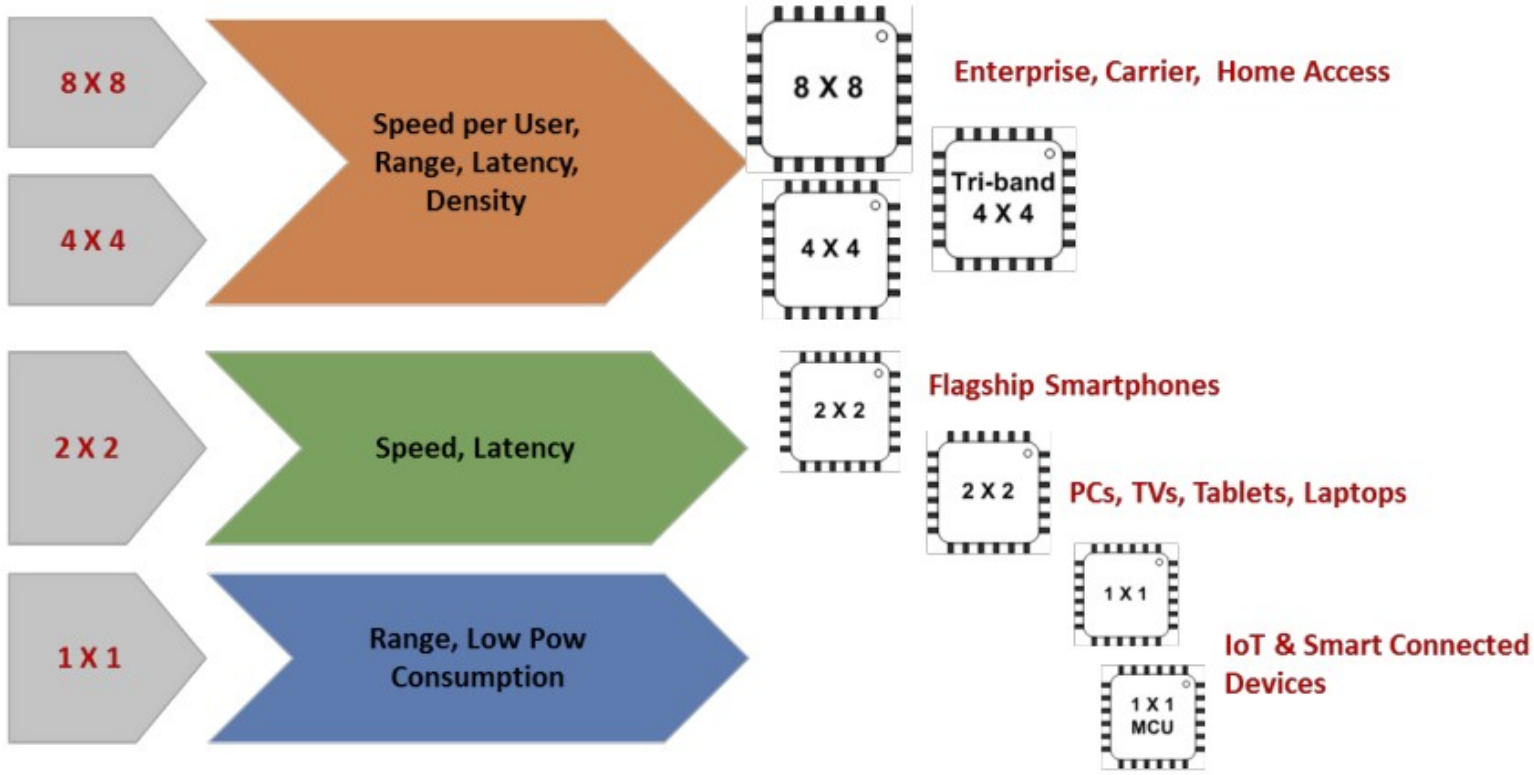
- Higher order 1024 quadrature amplitude modulation (**1024-QAM**)
  - Technique packing digital bits into radio signals
  - Using two so-called carriers (sine-waves) phase-shifted by 90 degrees (a quarter out-of-phase)
  - Modulated with output and phase variations (example 4x4=16-QAM)
  - In case of 1024-QAM space is 32x32
  - Delivering increased throughput
  - Up to 25% peak data rate increase over previous 256-QAM in Wi-Fi 5





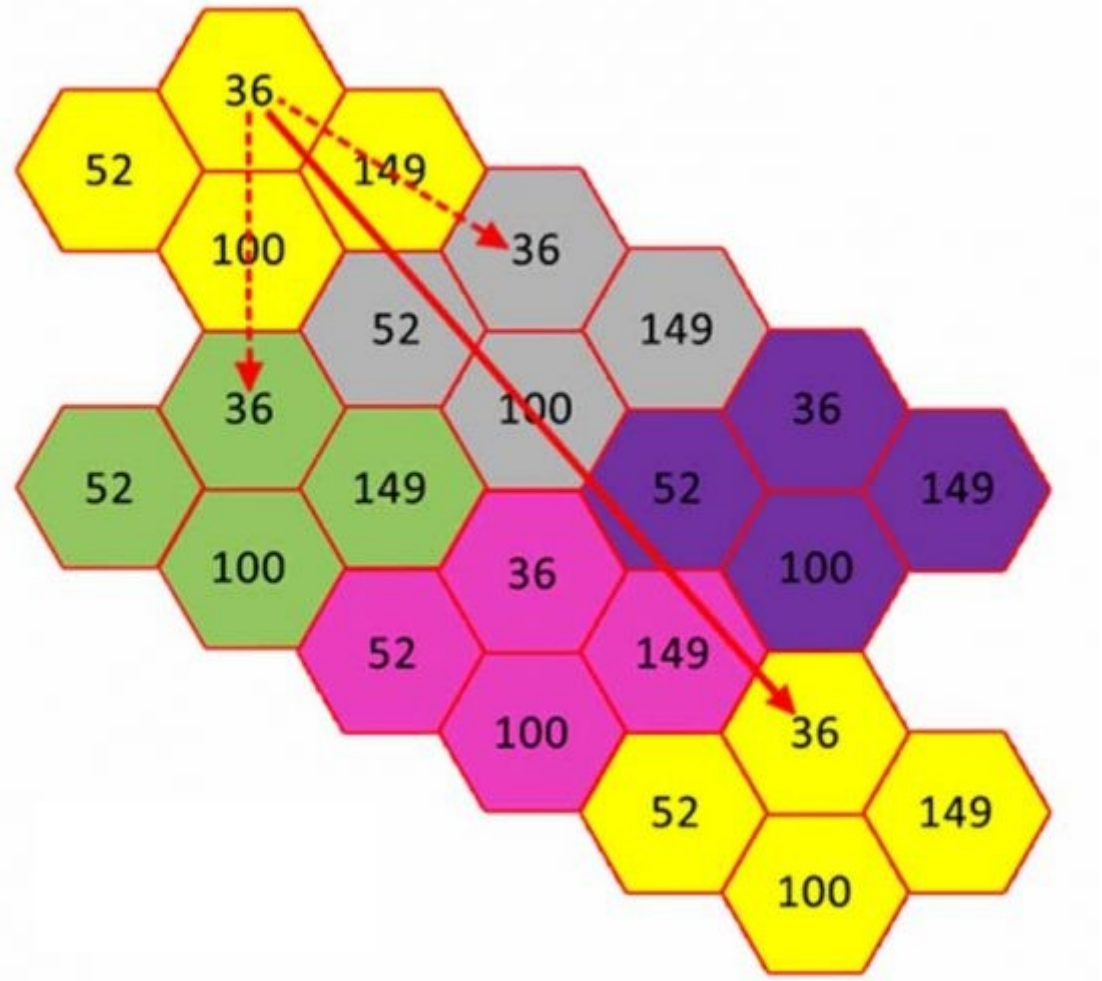
Introduction to Wi-Fi 6 Main Concepts (cont.)

- Up- and down-link multi-user multiple-input/multiple-output (**MU-MIMO**)
  - 8 streams in 5 GHz plus 4 streams in 2.4 GHz band for a total of up to 12 streams significantly boosting spectrum use
  - Works best with 8x8 channel state information (CSI) feedback aka sounding, but not mandatory
  - Best for stationary clients, but works with clients in motion as well
  - Flexibility:
    dual-band 8x8 may also
    operate as tri-band 4x4
  - Of course, the more streams, the more radios, the more power hungry it gets (and the more expensive)
  - Most client devices use 2x2 antenna configurations
  - IoT/smart devices do not all require high data rates, mostly 2.4 GHz band with 1x1 antenna configuration



Introduction to Wi-Fi 6 Main Concepts (cont.)

- Target Wake Time (**TWT**)
  - Orchestrating network traffic to minimize unnecessary chatter
  - Allows for different devices to schedule flexible check-in freque
  - Reduces contention
  - Dramatically reduces power consumption
- Basic Service Set (**BSS**) **Coloring**
  - Increasing capacity in dense environments requires frequency reuse across BSS
  - Technique to color aka mark traffic to be prioritized (basically a number included in PHY header)
  - Allows ignoring traffic on same frequency likely communicating due to overlapping Basic Service Sets (OBSS)
  - Improves reliability in dense environments

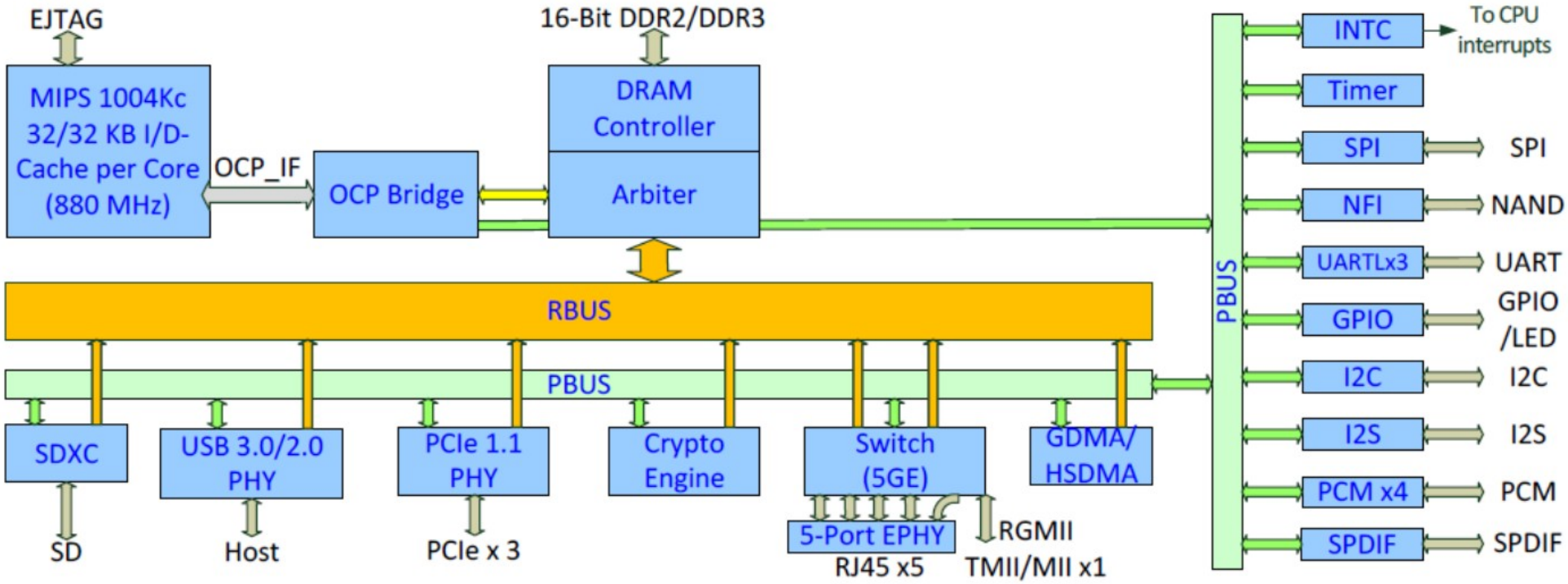


Introduction to Wi-Fi 6
Main Concepts (cont.)

- Wi-Fi protected access 3 (**WPA3**) security protocol
  - Using pre-shared keys (PSKs) is inherently problematic due to the sharing part
  - Wi-Fi protected setup (WPS) used a weak 23-bit pin as part of the sign-up process
  - Simultaneous authentication of equals (SAE): more secure initial key exchange in personal mode
  - Wi-Fi device provisioning protocol (DPP): grant access to network using QR codes or NFC tags
  - 256-bit Galois/Counter Mode Protocol (GCMP-256)
  - 384-bit Hashed Message Authentication Mode (HMAC)
  - However, only 128-bit encryption mandatory in WPA3-Personal mode (192-bit in WPA3-Enterprise)
  - Wi-Fi certified enhanced open: using strong encryption even connecting to an open network
- 20-MHz-only channels targeting IoT sensors to use spectrum more efficiently
- Extending new features to congested 2.4 GHz band

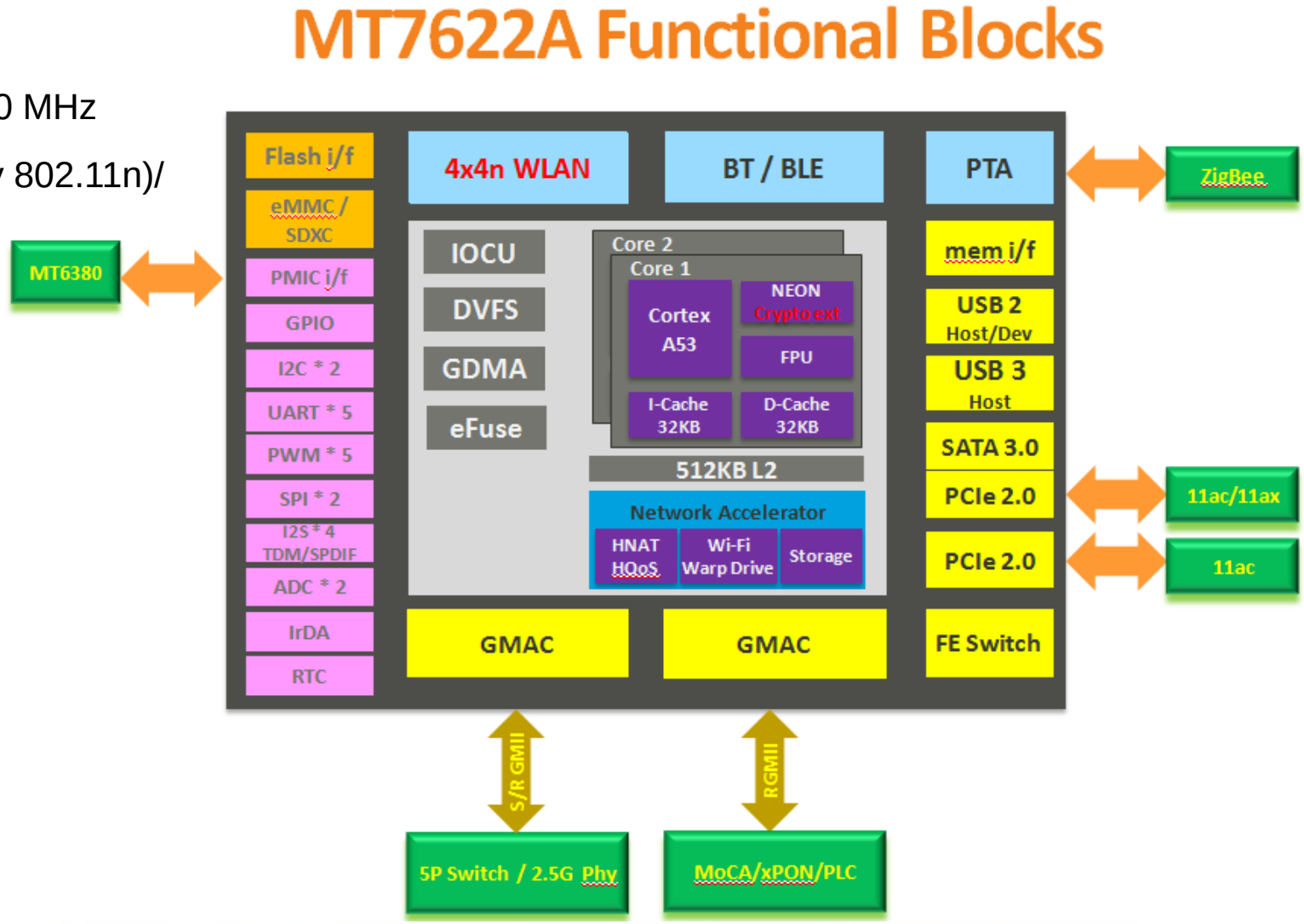
Wi-Fi 6 OpenWrt Access Point (AP)/ Router Landscape

- Only a few MediaTek based models officially supported since OpenWrt 21.02 (more in master/snapshots)
- Older RAMIPS MT7621AT or newer Arm MT7622BV based in combination with MT7911/MT7915 Wi-Fi 6 radios
- **MediaTek MT7621AT**
  - Dual 32-bit MIPS1004Kc core @ 880 MHz
  - Integrated 5 port GbE switch + RGMII
  - Network accelerator, HW NAT
  - 3x PCIe, 1x USB 3.0, 1x USB 2.0

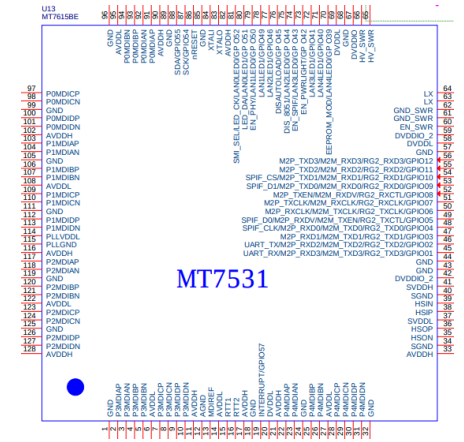


Wi-Fi 6 OpenWrt Access Point (AP)/ Router Landscape (cont.)

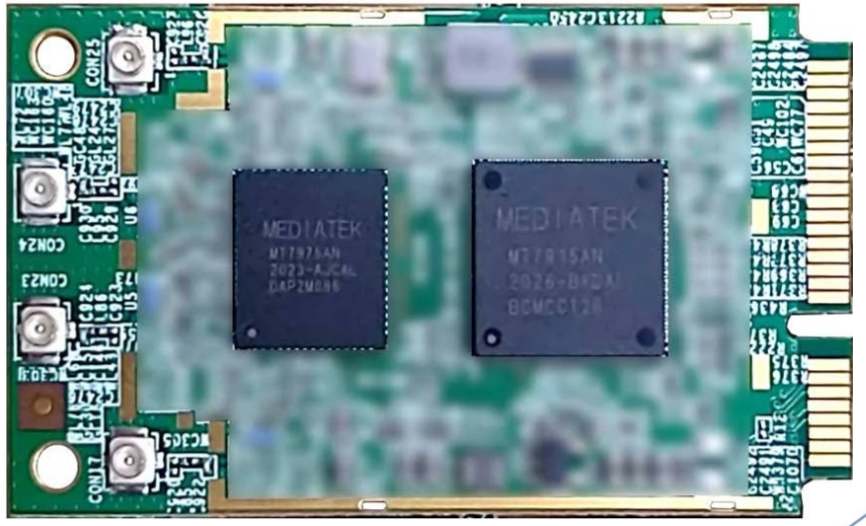
- **MediaTek MT7622BV**
  - Dual 64-bit Arm Cortex-A53 core @ 1350 MHz
  - Integrated 2.4 GHz 4x4 Wi-Fi 4 (formerly 802.11n)/ Bluetooth 5.0
  - Integrated 5 port Fast Ethernet switch, 1x HSGMII (1/2.5 Gbps) + RGMII
  - Network accelerator, HW NAT
  - 2x PCIe Gen2, 1x USB 3.0, 1x USB 2.0 (device/host)
  - SATA 3.0/eSATA Gen2



Wi-Fi 6 OpenWrt Access Point (AP)/ Router Landscape (cont.)



- **MediaTek MT7531BE**
  - 5 port GbE switch
  - 2500BASE-X for CPU port
- **MediaTek MT7911/MT7915**
  - Dual-band dual-concurrent (DBDC) 4x4 (MT7915A) or 2x2 (MT7915D) Wi-Fi 6 (formerly 802.11ax)
  - 20/40 MHz bandwidth in 2.4 GHz and 20/40/80 MHz bandwidth in 5 GHz
  - MAC/Base-band processor (BBP, e.g. requires external RFIC/FEM)
  - Bluetooth 5.1 (MT7915 only)
  - 32-bit RISC MCU
  - PCIe 2.1
- **MediaTek MT7975**
  - Radio Frequency Integrated Circuit (RFIC)/Front-End Module (FEM)

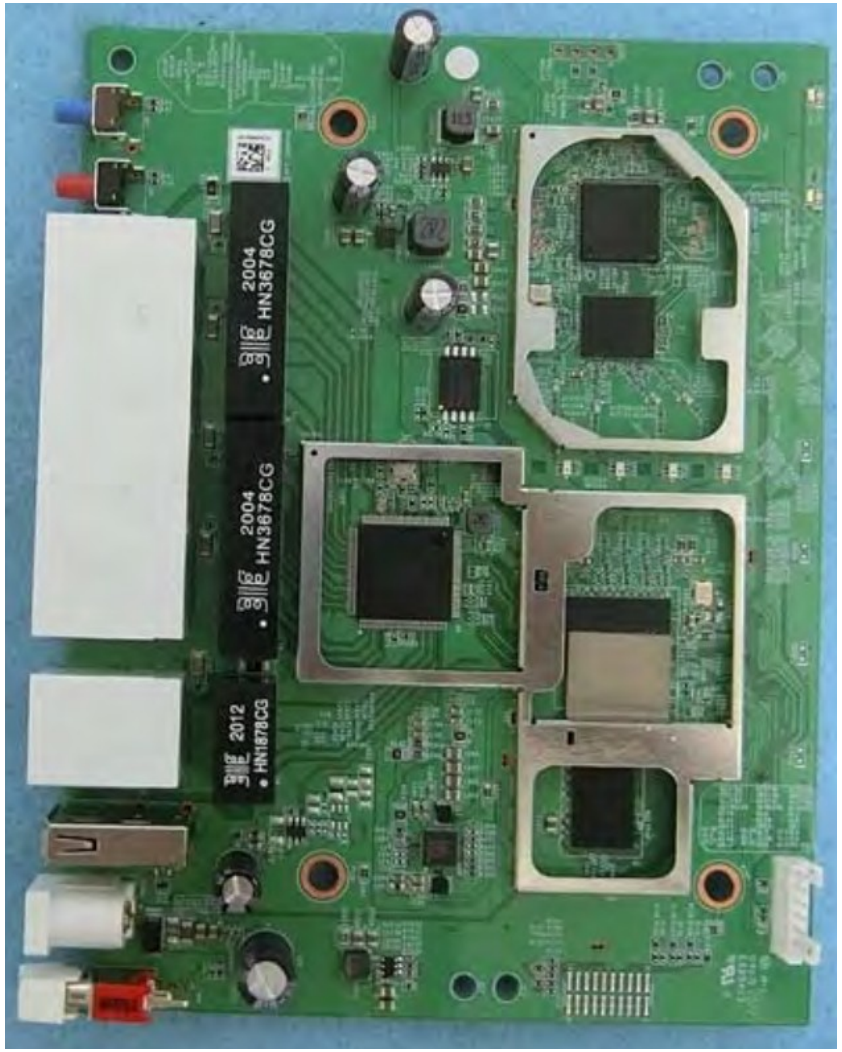


Belkin RT3200/Linksys E8450 (MediaTek based)

- **MediaTek MT7622BV SoC**
  - Dual 64-bit Arm Cortex-A53 core @ 1350 MHz
  - Integrated 2.4 GHz 4x4 Wi-Fi 4 (formerly 802.11n)
- **Fidelix FM35Q1GA-IB**
  - 128 MB SPI-NAND flash (requires ECC and wear leveling)
- **Winbond W634GG6NB-12**
  - 512 MB DDR3 RAM
- 1x USB 2.0 host port
- **MediaTek MT7915AN**
  - 5 GHz 4x4 Wi-Fi 6 (formerly 802.11ax)
- **MediaTek MT7531BE**
  - 5 port GbE switch (one of which usually WAN, rest LAN)
- 12 V DC, 2.0 A (regular barrel connector)

Belkin RT3200/Linksys E8450 (MediaTek based, cont.)

- Vendor firmware without proper flash ECC handling and wear leveling!
- UBI variant of OpenWrt requires replacing U-Boot with mainline version
- Maintainer created a convenient installer for this
- Remember to change Wi-Fi country code
- Change default CPU governor/scaling to avoid hangs on reboot
- Serial port header available (regular 3.3 V logic level)



Belkin RT3200/Linksys E8450

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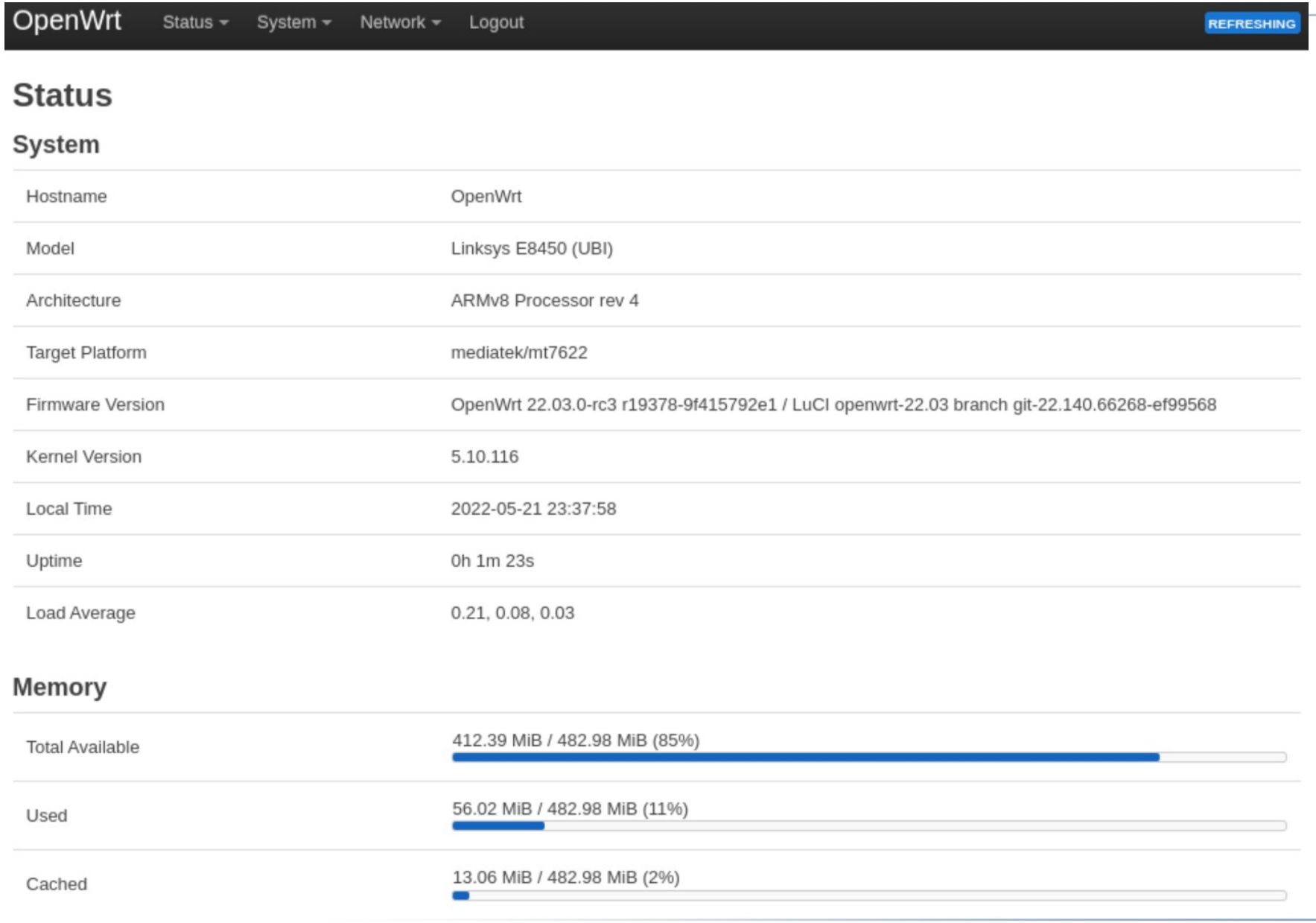

Belkin RT3200/Linksys E8450

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Wireless Overview

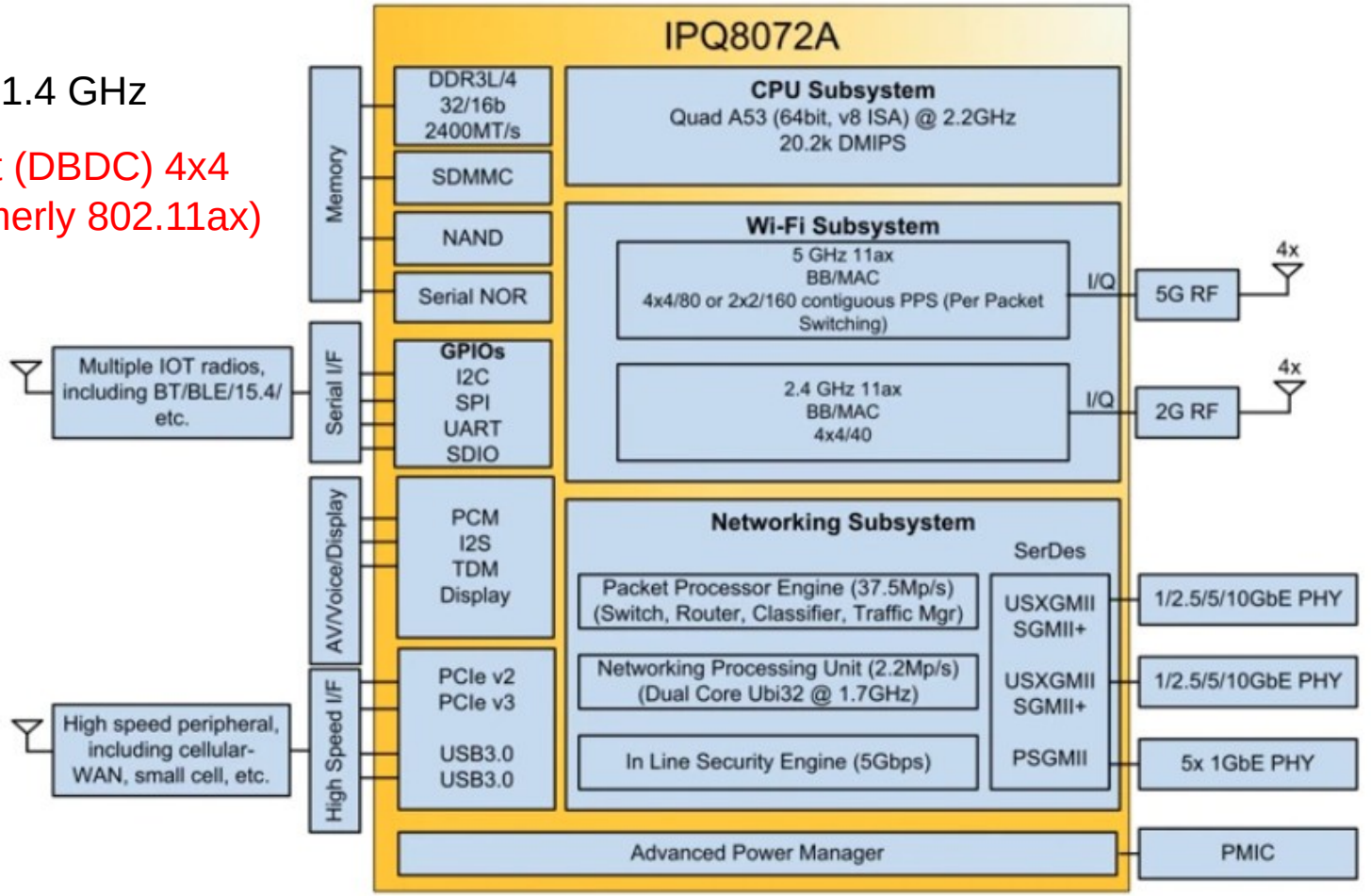
radio0	**MediaTek MT7622 802.11bgn** *Device is not active*	Restart Scan Add
disabled	**SSID:** OpenWrt2 | **Mode:** Master *Wireless is disabled*	Enable Edit Remove
radio1	**MediaTek MT7915E 802.11nacax** **Channel:** 124 (5.620 GHz) | **Bitrate:** ? Mbit/s	Restart Scan Add
--- dBm	**SSID:** OpenWrt2 | **Mode:** Master **BSSID:** C4:41:1E:F8:96:F5 | **Encryption:** WPA3 SAE (CCMP)	Disable Edit Remove

Associated Stations

Network	MAC address	Host	Signal / Noise	RX Rate / TX Rate	
Master "OpenWrt2" (wlan1)	48:D8:90:FF:BD:94	fe80::80c0:e2f7:fb0a:1532	-56 dBm	1080.6 Mbit/s, 80 MHz, HE-MCS 10, HE-NSS 2 1020.6 Mbit/s, 80 MHz, HE-MCS 10, HE-NSS 2, HE-GI 1	Disconnect

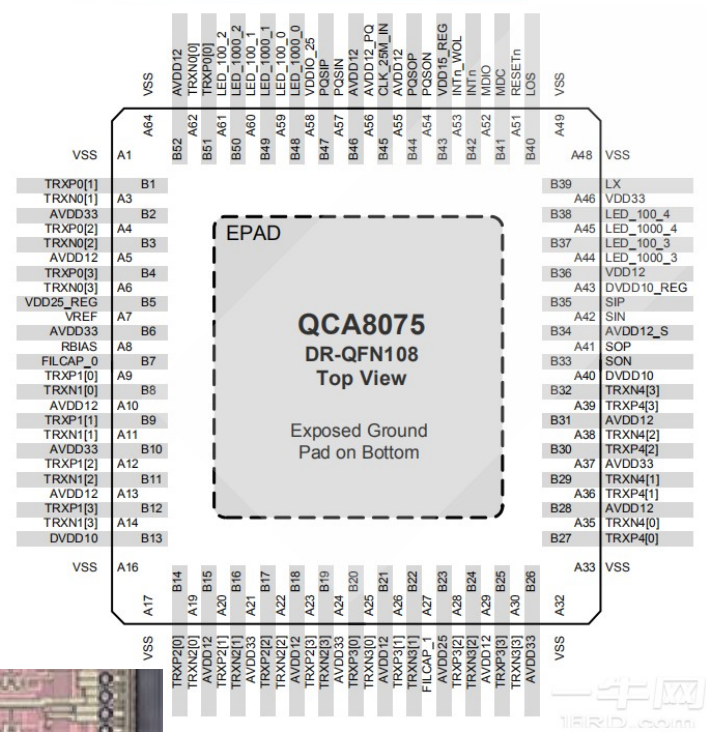
Wi-Fi 6 OpenWrt Access Point (AP)/ Router Landscape (cont.)

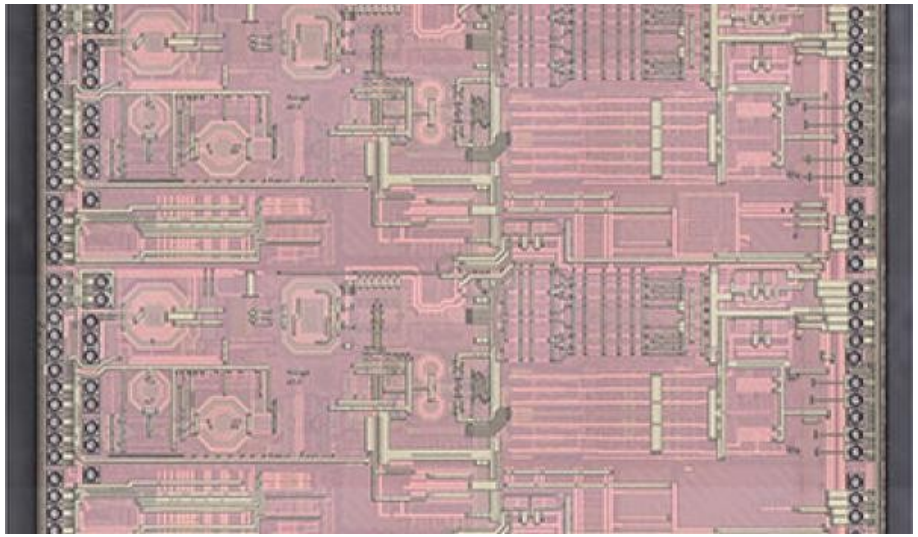
- Support for Qualcomm based models is work in progress
- **Qualcomm IPQ8071A (IPQ807x)**
  - Quad 64-bit Arm Cortex-A53 core @ 1.4 GHz
  - Integrated dual-band dual-concurrent (DBDC) 4x4 2.4 GHz and 4x4 5 GHz Wi-Fi 6 (formerly 802.11ax)
  - PCIe Gen3
  - Ethernet: 4x GbE, 2x 10GbE
  - USB 3.0



Wi-Fi 6 OpenWrt Access Point (AP)/ Router Landscape (cont.)

- **Qualcomm IPQ8075**
  - 5 port GbE transceiver aka PHY (not a switch)
  - Two integrated SerDes
    - 1x PSGMII or QSGMII to MAC
    - 1x SGMII to MAC or fiber (optional combo with copper port 4)
- **Qualcomm QCN5024**
  - 4x4 2.4 GHz Wi-Fi 6 (formerly 802.11ax)
  - PCIe
- **Qualcomm QCN5054**
  - 4x4 5 GHz Wi-Fi 6 (formerly 802.11ax)
  - PCIe
- **Qualcomm QCN9024**
  - 4x4 2.4, 5 GHz DBDC (80 MHz bandwidth)
  - PCIe Gen3



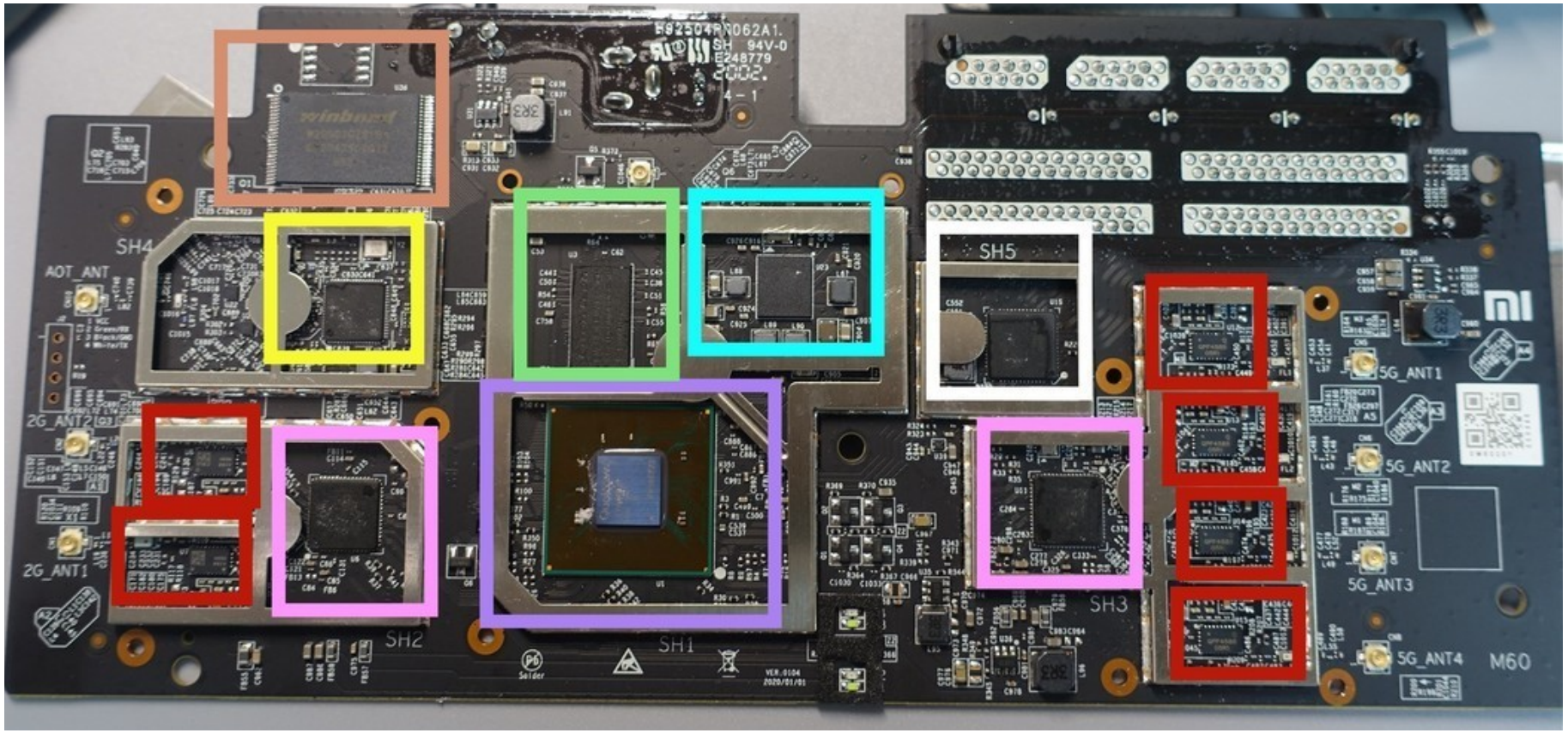


Xiaomi Mi AioT Router AX3600 (Qualcomm based)

- **Qualcomm IPQ8071A SoC**
  - Quad 64-bit Arm Cortex-A53 core @ 1.4 GHz
- **Winbond W29N02GZSIBA**
  - 256 MB raw NAND flash
- **EtronTech EM6HE16EWAKG-10H**
  - 512 MB DDR3L RAM
- **Qualcomm PMP8074** power management chip (PMIC)
- **Qualcomm Atheros QCA8075**
  - 4 port GbE PHY (one of which usually WAN, rest LAN)
- **Qualcomm QCA9889** AIoT exclusive dual-band 1x1 Wi-Fi 5 (formerly 802.11ac wave 2) chip
- **Qualcomm QCN5024** 2.4 GHz 2x2 Wi-Fi 6 (formerly 802.11ax)
- **Qualcomm QCN5054** 5 GHz 4x4 Wi-Fi 6 (formerly 802.11ax)
- 12 V DC, 2.0 A (smaller than usual barrel connector)

Xiaomi Mi AioT Router AX3600 (Qualcomm based, cont.)

- Vendor U-Boot has serial input aka RX locked
- Vendor firmware has SSH locked
- Known exploits to unlock
- Experimental builds may be installed
- Ath11k is very memory hungry
- Stock flash layout makes only use of half the space
- Serial port header available
  (1.8 V logic level!)



Xiaomi Mi AioT Router AX3600

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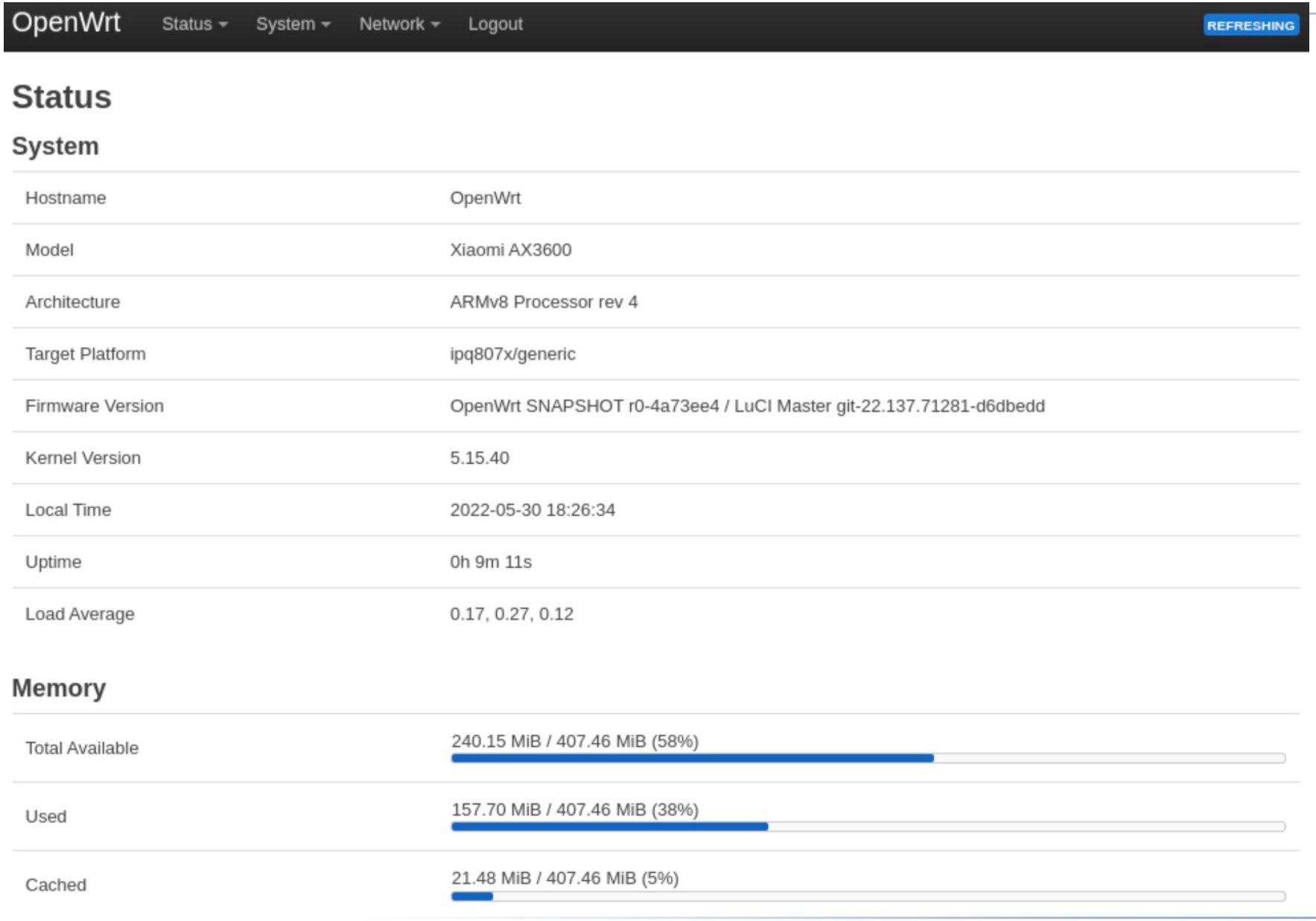


Xiaomi Mi AioT Router AX3600

- Gnome NetworkManager

Signal Strength	Good
Link speed	1200 Mb/s (5.6 GHz)
Security	WPA3

- OpenWrt Status

radio1

Type: 802.11nacax
Channel: 124 (5.620 GHz)
Bitrate: 1200 Mbit/s

SSID: OpenWrt2
Mode: Master
BSSID: 28:D1:27:4E:55:84
Encryption: WPA3 SAE (CCMP)
Associations: 1

Associated Stations

Network	MAC address	Host	Signal / Noise	RX Rate / TX Rate	
Master "OpenWrt2" (wlan1)	FC:B3:BC:44:21:B8	?	-56/-105 dBm	1200.9 Mbit/s, 80 MHz, HE-MCS 11, HE-NSS 2 1200.9 Mbit/s, 80 MHz, HE-MCS 11, HE-NSS 2	Disconnect

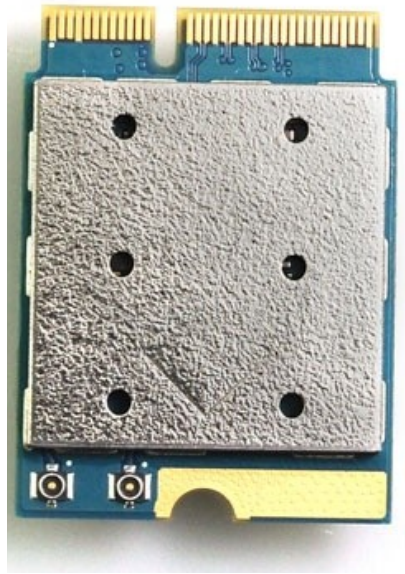
Wi-Fi 6 Clients

- **Intel AX210NGW**
  - 2x2 2.4, 5, 6 GHz (160MHz bandwidth)
  - Wi-Fi 6E (formerly 802.11ax) via PCIe
  - Bluetooth 5.3 via USB
  - M.2 2230 form factor, key A+E (also available as M.2 1216)
  - Linux driver: iwlwifi
    - Initial Wi-Fi 6 support merged in July 2018
    - AX210NGW support merged in February 2019
  - Kernel configuration: CONFIG_WLAN_VENDOR_INTEL, CONFIG_IWLWIFI, CONFIG_IWLMVM
  - Firmware: iwlwifi-ty-a0-gf-a0-72.ucode, iwlwifi-ty-a0-gf-a0.pnvm
  - Module parameters (e.g. put in /etc/modprobe.d/iwlwifi.conf)
    - options iwlmvm power_scheme=1
    - options iwlwifi power_save=0
  - Trouble getting it to run stable on non x86 embedded systems

Wi-Fi 6 Clients (cont.)

- **MediaTek MT7921K**
  - 2x2 2.4, 5, 6 GHz (160 MHz bandwidth)
  - Wi-Fi 6E (formerly 802.11ax) via PCIe
  - Bluetooth 5.0 LE via USB
  - M.2 2230 form factor, key A+E
  - Linux driver: mt76
    - Initial Wi-Fi 6 support merged in May 2020
    - MT7921K support merged in January 2021
  - Kernel configuration: CONFIG_WLAN_VENDOR_MEDIATEK, CONFIG_MT7921_COMMON, CONFIG_MT7921E
  - Firmware: mediatek/{WIFI_MT7961_patch_mcu_1_2_hdr.bin | WIFI_RAM_CODE_MT7961_1.bin}
  - Stable and highest performance (on x86_64)

Wi-Fi 6 Clients (cont.)



- **Qualcomm QCA6391**
  - 2x2 2.4, 5 GHz DBDC (80 MHz bandwidth)
  - Wi-Fi 6 (formerly 802.11ax) via PCIe
  - Bluetooth 5.1 LE via UART/PCM
  - M.2 2230 form factor, key E (rather unusual)
  - Linux driver: ath11k
    - Initial Wi-Fi 6 support merged in November 2019
    - QCA6391 support merged in August 2020
  - Kernel configuration: CONFIG_ATH_COMMON, CONFIG_WLAN_VENDOR_ATH, CONFIG_ATH11K, CONFIG_ATH11K_PCI, CONFIG_CRYPTO_MICHAEL_MIC
  - Firmware: ath11k/QCA6390/hw2.0/board-2.bin
  - Stable and good performance

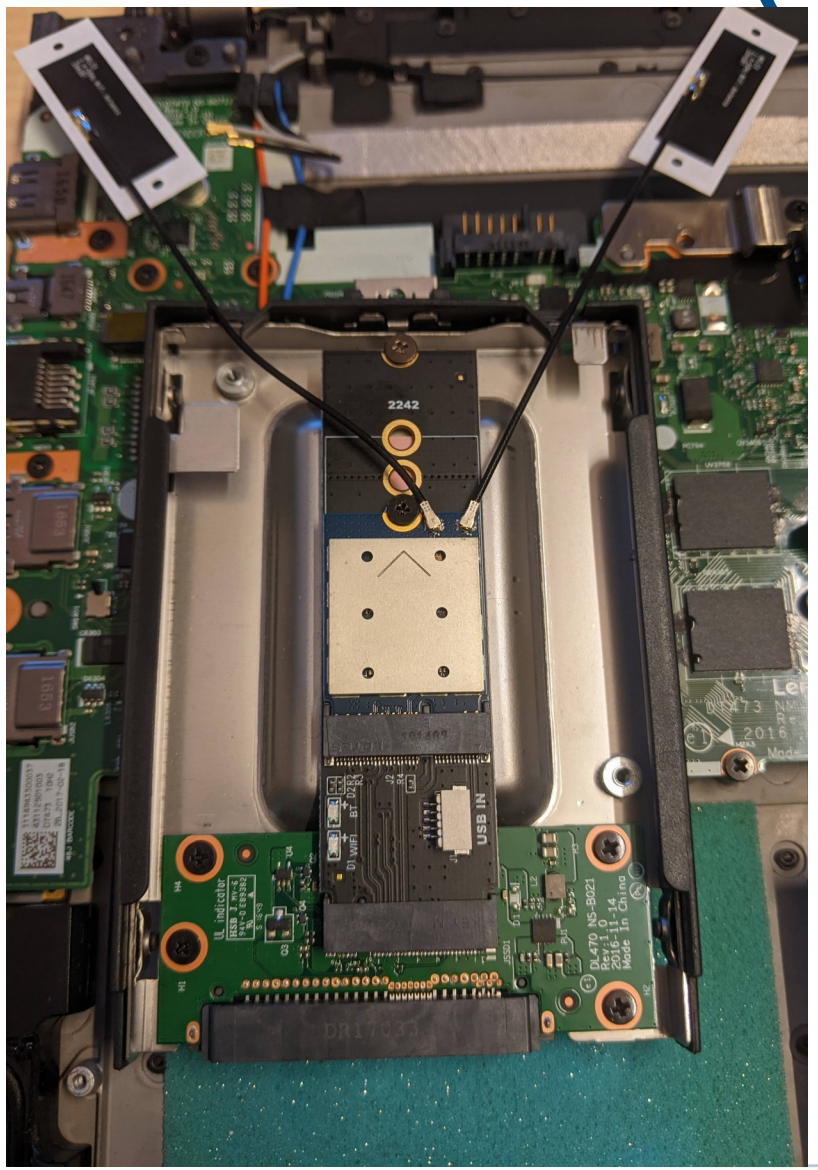
Wi-Fi 6 Clients (cont.)

- **Realtek Semiconductor RTL8852AE**
  - 2x2 2.4, 5 GHz DBDC (80 MHz bandwidth)
  - Wi-Fi 6 (formerly 802.11ax) via PCIe
  - Bluetooth 5.0 via USB
  - M.2 2230 form factor, key A+E
  - Linux driver: rtw89
    - Merged in October 2021
  - Kernel configuration: CONFIG_RTW89, CONFIG_RTW89_8852AE
  - Firmware: rtw89/rtw8852a_fw.bin
  - Have yet to try that one but reviews are rather mixed

Real-Life Configurations and Benchmark Demo Use Cases

- Initial support for Wi-Fi 6 (formerly 802.11ax) was merged into Linux kernel 4.19
- Only wpa_supplicant v2.10 (2022-01-16) added support for SAE (WPA3-Personal) AP mode configuration
- Requires OpenEmbedded/Yocto Project master branch
- Used two systems for my basic testing:
  - Lenovo Thinkpad T470p, Intel Core i7 (x86_64), 32 GB RAM, running Fedora 36 Silverblue
  - Verdin iMX8M Mini running image from OpenEmbedded/Yocto Project master branches with mainline Linux kernel
- Previously introduced two OpenWrt routers
- Previously introduced three M.2 cards
- 2 meter distance between client/router
- Make sure to set proper Wi-Fi country code
- 5 GHz connection may require time for initial radar detection in dynamic frequency selection (DFS) to complete
- Iperf3 from client to beefy server connected through Wi-Fi router
- AX210NGW kept crashing after a few seconds on Arm platforms (tried Apalis TK1 as well)

Real-Life Configurations and Benchmark Demo Use Cases (cont.)



Real-Life Configurations and Benchmark Demo Use Cases (cont.)

- Download/upload (e.g. iperf3 -R)
- Values in Mbits/sec
- Wi-Fi 5 shows much more consistent results across different clients/routers (from my experience)
- Likely not all clients/routers support all Wi-Fi 6 features (at least by default, further tweaking required?)
- Some Linux drivers are rather new, OpenWrt support also new resp. even still WIP
- 2.4 GHz: about 2x speed increase over Wi-Fi 5, 5 GHz: speed increase marginal resp. highly dependent

x86_64: Client/Router	RT3200	AX3600
AX210NGW	344/73	417/72
MT7921K	693/229	826/225
QCA6391	549/236	575/183

Arm: Client/Router	RT3200	AX3600
AX210NGW	N/A	N/A
MT7921K	171/213	186/220
QCA6391	640/216	607/174

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Q&A

References

- OpenWrt Wi-Fi 6 Devices
  https://openwrt.org/toh/views/toh_available_16128_ax-wifi
- MediaTek MT7622
  https://www.mediatek.com/products/home-networking/mt7622
- OpenWrt on Belkin RT3200 (Linksys E8450)
  https://openwrt.org/toh/linksys/e8450
- Qualcomm Networking Pro 600 Platform (IPQ8071A)
  https://www.qualcomm.com/products/application/networking/qualcomm-networking-pro-600-platform
- OpenWrt on Xiaomi AX3600
  https://openwrt.org/inbox/toh/xiaomi/xiaomi_ax3600
- Intel Wi-Fi 6E AX210
  https://ark.intel.com/content/www/us/en/ark/products/204836/intel-wifi-6e-ax210-gig.html
- MediaTek Filogic 330
  https://www.mediatek.com/products/broadband-wifi/mediatek-filogic-330
- Qualcomm Wi-Fi 6
  https://www.qualcomm.com/products/application/networking/features/wi-fi-6
- Realtek Semiconductor RTL8852AE
  https://www.realtek.com/en/products/product-hits/item/high-speed-wireless-internet-access

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