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

Presented by
Marcel Ziswiler
Software Team Lead - Embedded Linux BSP
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
Toradex
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
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

Wi-Fi 6 Router with OFDMA Support

- Data from multiple users can be transmitted at the same time

Traditional Wi-Fi 5 Router

- Only data from one user can be transmitted at a time

• 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 $4 \times 4 = 16$-QAM)
  • In case of 1024-QAM space is $32 \times 32$
  • 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 frequencies
  • 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)
## Status

### System

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hostname</td>
<td>OpenWrt</td>
</tr>
<tr>
<td>Model</td>
<td>Linksys E8450 (UBI)</td>
</tr>
<tr>
<td>Architecture</td>
<td>ARMv8 Processor rev 4</td>
</tr>
<tr>
<td>Target Platform</td>
<td>mediatek/mt7622</td>
</tr>
<tr>
<td>Firmware Version</td>
<td>OpenWrt 22.03.0-rc3 r19378-9f415792e1 / LuCI openwrt-22.03 branch git-22.140.66268-eff9568</td>
</tr>
<tr>
<td>Kernel Version</td>
<td>5.10.116</td>
</tr>
<tr>
<td>Local Time</td>
<td>2022-05-21 23:37:58</td>
</tr>
<tr>
<td>Uptime</td>
<td>0h 1m 23s</td>
</tr>
<tr>
<td>Load Average</td>
<td>0.21, 0.08, 0.03</td>
</tr>
</tbody>
</table>

### Memory

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Available</td>
<td>412.39 MiB / 482.98 MiB (85%)</td>
</tr>
<tr>
<td>Used</td>
<td>56.02 MiB / 482.98 MiB (11%)</td>
</tr>
<tr>
<td>Cached</td>
<td>13.06 MiB / 482.98 MiB (2%)</td>
</tr>
</tbody>
</table>
Belkin RT3200/Linksys E8450

Wireless Overview

- **radio0** - MediaTek MT7622 802.11bgn
  - Device is not active

- **radio1** - MediaTek MT7915E 802.11nacax
  - Channel: 124 (5.620 GHz)
  - Bitrate: ? Mbit/s

Associated Stations

<table>
<thead>
<tr>
<th>Network</th>
<th>MAC address</th>
<th>Host</th>
<th>Signal / Noise</th>
<th>RX Rate / TX Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master &quot;OpenWrt2&quot; (wlan1)</td>
<td>48:D8:90:FF:BD:94</td>
<td>fe80::80c0:e2f7:fb0a:1532</td>
<td>-56 dBm</td>
<td>1080.6 Mbit/s, 80 MHz, HE-MCS 10, HE-NSS 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1020.6 Mbit/s, 80 MHz, HE-MCS 10, HE-NSS 2, HE-GL 1</td>
</tr>
</tbody>
</table>
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 AloT 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

## Status

### System

- **Hostname**: OpenWrt
- **Model**: Xiaomi AX3600
- **Architecture**: ARMv8 Processor rev 4
- **Target Platform**: ipq807x/generic
- **Firmware Version**: OpenWrt SNAPSHOT r0-4a73ee4 / LuCI Master git-22.137.71281-d6dbedd
- **Kernel Version**: 5.15.40
- **Local Time**: 2022-05-30 18:26:34
- **Uptime**: 0h 9m 11s
- **Load Average**: 0.17, 0.27, 0.12

## Memory

- **Total Available**: 240.15 MiB / 407.46 MiB (58%)
- **Used**: 157.70 MiB / 407.46 MiB (38%)
- **Cached**: 21.48 MiB / 407.46 MiB (5%)
Xiaomi Mi AioT Router AX3600

- Gnome NetworkManager
  - Signal Strength: Good
  - Link speed: 1200 Mb/s (5.6 GHz)
  - Security: WPA3

- OpenWrt Status

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<td>Master &quot;OpenWrt2&quot; (wlan1)</td>
<td>FC:B3:BC:44:21:B8</td>
<td>?</td>
<td>-56/-105 dBm</td>
<td>1200.9 Mbit/s, 80 MHz, HE-MCS 11, HE-NSS 2</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1200.9 Mbit/s, 80 MHz, HE-MCS 11, HE-NSS 2</td>
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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

<table>
<thead>
<tr>
<th>x86_64: Client/Router</th>
<th>RT3200</th>
<th>AX3600</th>
</tr>
</thead>
<tbody>
<tr>
<td>AX210NGW</td>
<td>344/73</td>
<td>417/72</td>
</tr>
<tr>
<td>MT7921K</td>
<td>693/229</td>
<td>826/225</td>
</tr>
<tr>
<td>QCA6391</td>
<td>549/236</td>
<td>575/183</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Arm: Client/Router</th>
<th>RT3200</th>
<th>AX3600</th>
</tr>
</thead>
<tbody>
<tr>
<td>AX210NGW</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>MT7921K</td>
<td>171/213</td>
<td>186/220</td>
</tr>
<tr>
<td>QCA6391</td>
<td>640/216</td>
<td>607/174</td>
</tr>
</tbody>
</table>
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

- MediaTek Filogic 330

- Qualcomm Wi-Fi 6
  https://www.qualcomm.com/products/application/networking/features/wi-fi-6

- Realtek Semiconductor RTL8852AE
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