

Chapter 6

Niche WiFi

WiFi has been primarily used as a networking technology for implementing wireless LAN in enterprise and residential domains, as well as connecting personal mobile devices, such as mobile phones, tablets, laptops, etc. to the Internet in homes, cafes, airports, and university campuses. These mainstream WiFi predominantly used the ISM bands 2.4GHz and 5GHz, with the new versions aiming to use the 6GHz band. In addition to these mainstream WiFi, IEEE has also released several 802.11 amendments that target some niche applications. These niche WiFi standards operate outside the mainstream bands, both at the very low end of the spectrum, i.e., below 1GHz, as well as at the very high end, i.e., 60GHz (see Figure 6.1). For example, 802.11af is targeting the exploitation of 700MHz spectrum recently vacated by TV stations due to their digitization, 802.11ah using 900MHz to connect emerging Internet of Things operating at low power, and 802.11ad/ay at 60GHz to support multi-gigabit applications at short range. In this chapter, we shall examine the features and techniques used by these niche WiFi standards.

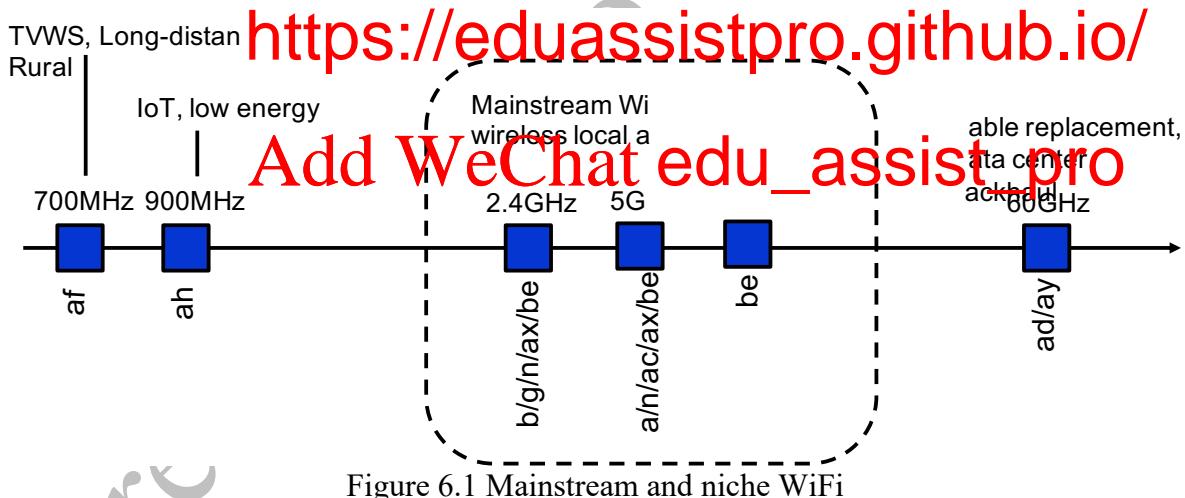


Figure 6.1 Mainstream and niche WiFi

6.1 802.11af (a.k.a. White-Fi)

When TV transmissions switched from analog to digital, they vacated a lot of spectrum in the licensed TV bands. The vacated TV spectrum is called the White Space. IEEE 802.11af [802.11af], which is also referred to as White-Fi (or Super-Fi), was designed to effectively exploit the white space for data communications.

6.1.1 Over-the-Air Television Channels

When TV was invented, it was using analog signals for transmitting and distributing programs over the air. Analog television channels used the spectrum between 30 MHz to 30 GHz. The channels are called High Frequency (HF), Very High Frequency (VHF), Ultra High

Frequency (UHF), and so on as shown in Figure 6.2. VHF is basically a *meter band* as the wave length is between 1 to 10 meters. UHF could be called *decimeter band* and so on.

Each channel uses 6 MHz in USA, 8 MHz in Europe, and 7 MHz at some other parts of the world. The numbering system for the VHF and UHF TV channels in USA is shown in Figure 6.3. Channel 37 is used for radio astronomy, hence excluded from TV transmissions. Also, some channels between 88 and 174 are reserved for FM radio.

At least one channel is skipped between two analog stations in neighboring areas to avoid interference. For example, if a small town has channel 2, then it will not have channel 3. Basically, all channels cannot be allocated to all cities and towns.

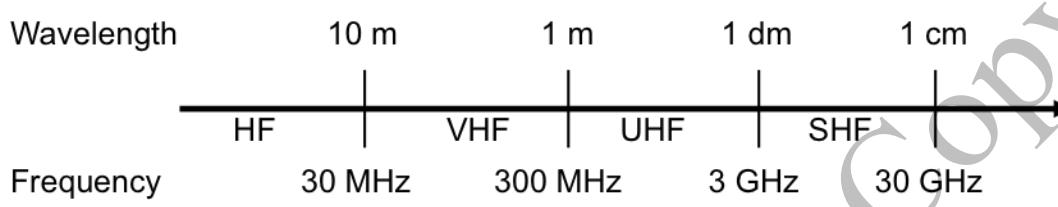


Figure 6.2 TV spectrum and channels

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Figure 6.3 TV V <https://eduassistpro.github.io/>

6.1.2 Digital TV

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Analog TV broadcast has been discontinued recently. The world has switched to digital broadcast due to many advantages. The main mantra for digital TV is that all pictures are represented as pixels and each pixel is represented by some bits. Once the pictures are converted to bits, it becomes like computer communications. Encryption, multiplexing, mixing with different services and types of data, etc. all become very efficient, just like computer communication networks.

Another main advantage of going digital is that we no longer need to provision for significant guard bands between occupied frequencies because interference from adjacent frequencies can be managed by sophisticated frame and error control techniques. Digital transmission also uses compression at the transmitter and decompression at the receiver, which further reduces spectrum usage for digital TV. Consequently, multiple digital channels can be transmitted within 6 MHz, which was previously used to transmit only one analog TV program. This bandwidth efficiency has freed up a lot of TV spectrum, which is dubbed as Digital Dividend.

There was a particular demand for this “new” spectrum in **700 MHz band** for Cellular, Emergency Services, and ISM. Consequently, governments were able to raise significant revenue by auctioning part of this spectrum to cellular companies while reserving the rest for unlicensed use. Similar practices happened in other countries.

Figure 6.4 illustrates the basic differences between 700 MHz and higher frequency. The wavelength in 700 MHz is much longer and hence it can travel far and penetrate many obstacles, such as buildings.

700 MHz has lower attenuation (1/7th to 1/9th of 1800/1900/2100 MHz), which means it requires lower transmission power and can provide longer mobile battery life for mobile devices. It can have larger cell radius, which means smaller number of towers. Such long-distance propagation is good for rural areas. It means providing cellular and wireless broadband services to rural areas become more cost effective and affordable. Because of these reasons, availability of new spectrum in 700 MHz is considered a very good opportunity for wireless networking.

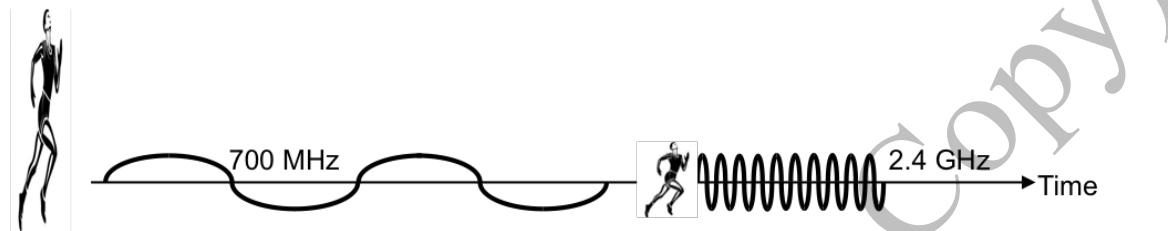


Figure 6.4 Differences between 700 MHz and higher frequency. A wave cycle in 700 MHz can travel much further than that in 2.4 GHz.

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6.1.3 Spectral White Spaces

A lot of spectrum is available at all locations and times. This is not fully used at a given time available for unallocated spectrum, allocated but under-utilized, adjacent cells, or spectrum available in the TV band.

is not fully used at a given time at a space may be due to interferences in

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Figure 6.5 shows that allocation does not mean it is used "white" because when spectrum usage is plotted in blue, the white gaps are the spectrum not used. Figure 6.6 shows a measurement conducted in Ottawa, Canada, for the UHF spectrum and we can see that most of it is white!

Well, it is clear that if we can use the white space, which appears to be in abundance, we can address some of the high demands for data. However, we must acknowledge that the white space that belongs to licensed spectrum poses interesting legal and policy issues, because the spectrum was already licensed for massive amount of fee to certain companies. Under previous ruling, those companies actually had the right to say no to the use of their spectrum whether they use it or not. Effective use of white space therefore requires new rules to be in place first.

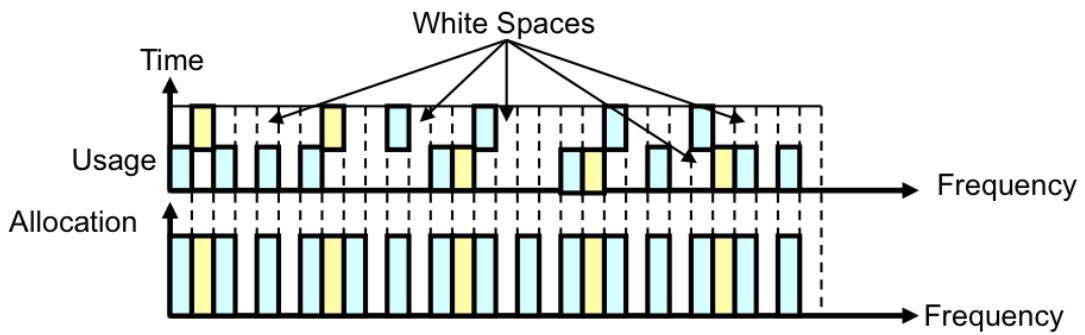


Figure 6.5 Concept of spectral white space. Allocation does not mean it is used.

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Figure 6.6 Spectral usage example from real m tawa].

6.1.4 TVWS Databases

It was agreed that the TVWS databases, a.k.a. geolocation database (GDB), which would hold information about which channel is free and when, would be operated by third parties. These databases do the following four things:

1. Get info from FCC database
2. Register fixed TVWS devices and wireless microphones
3. Synchronize databases with other companies
4. Provide channel availability lists to TVWS devices

Google was one of the third parties that acquired license to operate such databases, but it does not provide this service anymore. Figure 6.7 shows an example of what was available in the city of St. Louis (zip code 63130) using the Google database. We can see that there were 17 channels available at the time of accessing the WS database.

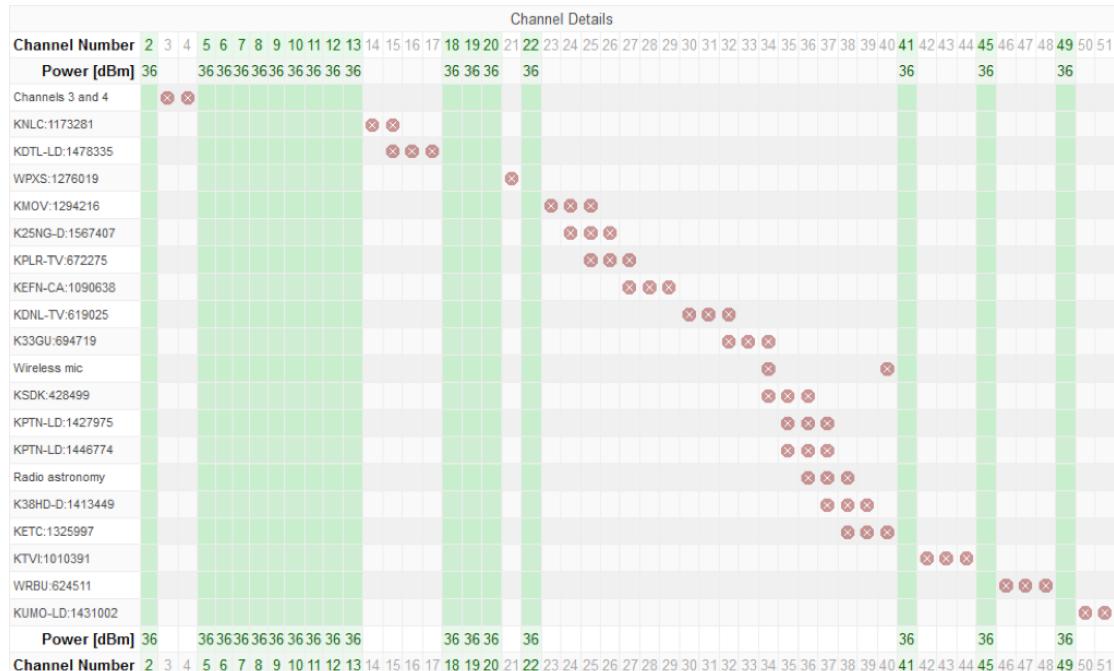


Figure 6.7 White space available near University of Washington in St. Louis.

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6.1.5 802.11af Database Operation

Recall that in whites available spectrum is Therefore, to implement developed for the LAN to obtain the channel GDBs, maintained by the third parties and distributed network.

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To achieve these objectives, a local cache or database called Registered Location Secure Server (RLSS) is maintained which stores the channel availability information learned from the public GDBs. This provides faster access to channel information. The idea is that all large companies and ISPs will have their own RLSSs, just like DNS cache or local DNS server.

To facilitate communication with GDBs and RLSSs, two new protocols are defined. One is called PAWS [PAWS2015], defined by IETF, which is used by the GDBs and the APs. PAWS is a general protocol that can be used by 802.11, or any other networks to query the spectrum in GDB. The other protocol is called Registered Location Query Protocol (RLQP), defined by IEEE, to be used *locally* between the AP and the stations. The use of these two protocols in accessing the white space databases is shown in Figure 6.8. The APs are called Geolocation Database Dependent (GDD) *enabling*, as they can interface directly with GDB, while the stations are called GDD *dependent*, because they cannot talk to GDB directly.

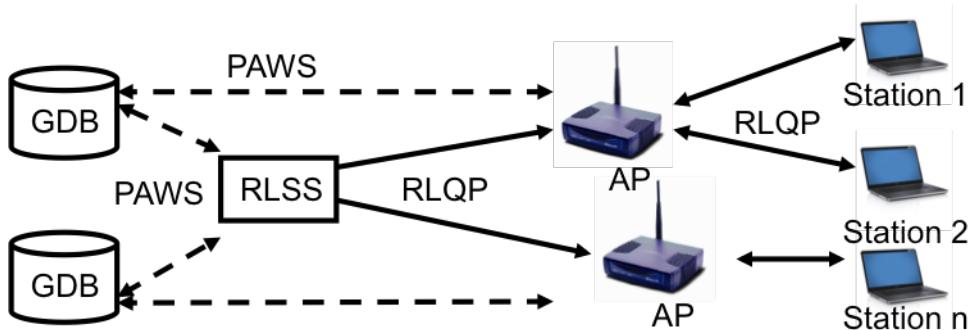


Figure 6.8 White space database access protocols.

6.1.6 Registered Location Query Protocol (RLQP)

RLQP is a protocol for exchange of white space map (WSM), a.k.a., Channel Schedule Management (CSM), among RLSS, APs, and stations. An example of message exchanges for RLQP is shown in Figure 6.9.

As we can see, AP uses CSM request and response to obtain the available channels first before these channels can be allocated internally with 802.11af network. Stations can be disassociated by the APs if necessary, such as if the channel becomes unavailable. Table 6.1 explains the meaning of all the other messages.

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Figure 6.9 Message exchange in RLQP.

Table 6.1 Description of RLQP messages

Message	Description
CSM Request	APs ask other APs or RLSS about white space map
CSM Response	White space map is provided
CVS	APs supply white space map to their stations and confirm that stations are still associated
CAQ	Stations ask AP if they do not receive the map within a

	timeout interval
NCC Request	Sent by stations to AP requesting use of a channel. AP may forward to RLSS
NCC Response	Permission to transmit on requested channel

6.1.7 Protocol to Access White-Space (PAWS)

There can be many different technologies, such as 802.11, 802.22, etc. that may work on white space and need access to WS databases. For a WS database provider it would then be necessary to design interfaces for all these different networking technologies. Instead, IETF has decided to come up with a single protocol, called PAWS, which is independent of any network technologies as well as the underlying spectrums. All WS networks will have to implement PAWS to access the WS databases and all WS database providers will have to implement PAWS to support WS networking.

PAWS has the concept of master and slave. Master device is one that can directly interface with the GDB using PAWS. A slave device is a WS networking device that cannot talk to a GDB directly, i.e., does not implement PAWS. Instead, the slave devices will need to communicate to a master device to find out spectrum availability. A device can act as both master as well as a slave. In Figure 6.10, the RLSS is a master device. The AP and BS are acting as both masters, as they can talk directly with the GDB, as well as slaves, because they can get spectrum information from RLSS. Some 802.11af clients, not shown in the figure, that must get channel information from the AP are slaves only.

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Figure 6.10 The master-slave concept in PAWS

How does the WS networking devices find out the addresses or URLs of the GDBs in the first place? There are several ways this could be implemented. One method could be to preconfigure devices with certificates to talk to some known database authority. Another could be using a listing server to list all national database servers.

Query is a pull-based method. In pull-based, the master sends a query to the database each time it needs to know the availability of white space. For a master device, it may also be possible to receive push notifications from the GDB. The master can register with the GDB for such push notifications using its certificate and the database can push channel availability information whenever some new spectrum is available or availability of an old channel changes. Finally, to ensure security, all PAWS messages are encrypted.

Some sample PAWS messages and how they are exchanged are shown in Figure 6.11. As we can see, after the exchange of initialization messages, the registration messages are exchanged. It is only after the registration that the master device can send a query message to the database server and get a response. The master device can also send batch query to include requests for a set of slave devices located in different locations with different antenna heights etc. and get a batch response.

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6.1.8 802.11af channels and data rates

In 802.11af, a Basic Channel Unit (BCU) aka **Add WeChat edu_assist_pro** in the USA, this means that $W = 6 \text{ MHz}$. While the use of single channel bonding is optional. Two kinds of channel bonding are allowed. For contiguous channel bonding, $2W$ or $4W$ are allowed, i.e., 2 or 4 contiguous channels can be bonded together. This means that it is possible to have 12 MHz or 24 MHz contiguous spectrum as a single (bonded) channel.

802.11af uses a maximum of 256-QAM and 5/6 coding. It uses OFDM similar to 40 MHz in 802.11n, but down clocked by 7.5x. This gives a total of 144 subcarriers, of which 108 are data subcarriers. The down clocking increases the GI from $0.4\mu\text{s}$ to $3\mu\text{s}$, and the data interval from $3.2\mu\text{s}$ to $24\mu\text{s}$. As a result, the total symbol interval becomes $27\mu\text{s}$, which yields a maximum data rate of 26.67Mbps for a single stream and single channel link. Note that 802.11af supports MIMO with up to 4 streams, which can further boost the data rate. Table 6.2 shows the various data rates supported by 802.11af for a 6MHz channel.

Example 6.1

What is the maximum possible data rate achievable with 802.11af?

Solution:

Data rate with single stream and single 6MHz channel = 26.67Mbps

Data rate with 4 streams and 4 bonded channels = $4 \times 4 \times 26.7 = 426.7 \text{ Mbps}$

Table 6.2 802.11af data rates in Mbps: Single Stream, single unbonded (6MHz) channel

MCS	Modulation	Coding	Data Rate
0	BPSK	1/2	2
1	QPSK	1/2	4
2	QPSK	3/4	6
3	16-QAM	1/2	8
4	16-QAM	3/4	12
5	64-QAM	2/3	16
6	64-QAM	3/4	18
7	64-QAM	5/6	20
8	256-QAM	3/4	24
9	256-QAM	5/6	26.7

6.2. 802.11ah (a.k.a. HaLow)

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To achieve the long range, spectrum is shifted from and 5GHz) to sub-GHz. With the lower frequency, sub-GHz, signals can travel longer distances with less interference from other wireless devices and other infrastructure, which will hide many potential sources of interference. However, there is still congestion at sub-GHz as all other WiFi devices operate in this band. The number of devices that use sub-GHz are not many.

Hz, e.g. 2.4GHz stages for IoT. At

With lower frequency band, the achievable bit rate is low, but this is not an issue for IOT, because the sensors do not need to stream high definition video, but only short messages. With low data rate, we can also reduce MAC overhead, which is important for short messages. In fact, with MIMO, the data rate can be from 150 kbps to 78 Mbps per spatial stream (up to 4 streams are allowed), which is sufficient for all types of IOT devices. Finally, the low data rate allows APs to connect 4 times more devices than existing WiFi, which is very important for densely deployed IOT.

The spectrum allocation for HaLow is shown in Figure 6.12. We can see that different countries have allocated slightly different spectrum, but they are close to 900 MHz, just below the GHz mark.

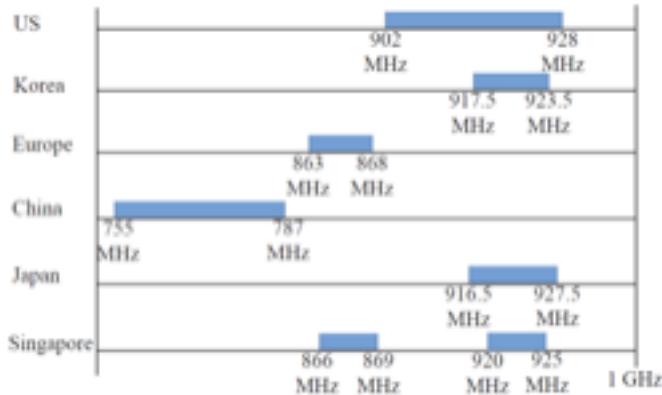


Figure 6.12 spectrum allocation for HaLow [802.11ah-bands]

6.2.1 Sample Applications

As the Figure 6.13 shows, the main application of 802.11ah is the neighborhood area network (NAN). The NAN is used to read various meters from houses as well as some municipality owned devices for monitoring smart cities, such as monitoring manholes, underground pipes, cables etc. The 802.11ah APs, which could be deployed on the streetlight poles, are then connected via wire to the cloud, where all the data ends up for processing by the data analytic.

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Figure 6.13 802.11ah supports neighbor hood area network (NAN)

6.2.2 802.11ah PHY

802.11ah PHY is actually built on top of 802.11ac PHY, but down clocked by 10x. This means each clock tick is now 10 times longer than 802.11ac, which will have a 10x effect on many aspects of the protocol.

First of all, 802.11ah will have 2/4/8/16 MHz channels in place of 20/40/80/160 MHz in 802.11ac. That is the channels are 10x smaller in MHz. However, the number of data subcarriers for 802.11ah channels are the same as the corresponding higher channel bandwidths in 802.11ac. For example, 20 MHz 11ac and 2 MHz 11ah both have 52 data subcarriers plus 4 pilots, which means 1/10th inter-carrier spacing in 11ah. The shorter spacing may mean higher inter-carrier interference, but as we shall see shortly, this is well compensated by longer symbol lengths.

802.11ah has 10x longer symbols, which allows 10x delay spread. Therefore, longer multipath can be accommodated within the symbol, which avoid inter-symbol interference even in long distance communication (longer distance means longer multipath).

In 802.11ah, all type of times, such as SIFS, are 10x longer. 802.11ah defines a new 1 MHz PHY with 24 data subcarriers. However, channel bonding is defined for two 1 MHz channels to form a single 2 MHz channel. All stations have to support both 1 MHz and 2 MHz channels.

With 1 MHz channel, 802.11ah defines a new modulation and coding scheme, MCS10, which is basically the previous MCS0, but after MCS0, every bit is transmitted twice. This allows 802.11ah to achieve long range as it can now sustain more errors. The rest of the MCS indices, i.e., the modulation and coding combinations remain the same, but the data rates are 10x lower from the corresponding MCS in 11ac. For example, for MCS 0 (BPSK with 1/2 coding), data rates for 11ac and 11ah, respectively are 6.5Mbps and 0.65Mbps for single stream 2/20MHz channels using the longer GI option.

802.11ah supports 4 spatial streams instead of 8 in 802.11ac. 802.11ah supports beamforming to create sectors, which can be used by a single AP to read meters from houses in different sectors more efficiently.

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Example 6.2

If we reduce the clock rate (symbols/s) to be the new symbol rate (symbols/s)?

Solution:

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802.11ac has a symbol duration of 3.6 μ s (for 400 n)

New symbol duration with a 10x slower clock = 36 μ s

New symbol rate = $1/(36 \times 10^{-6}) = 27,777$ sym/s

Example 6.3

In USA, 902-928 MHz has been allocated for 802.11ah. How many different channels can be used if 16 MHz channel option is used?

Solution:

902-928 MHz has a total bandwidth of 26 MHz. There is only one (non-overlapping) 16 MHz channel possible out of 26 MHz.

6.2.3 IEEE 802.11ah MAC

802.11ah MAC faces some new challenges due to IoT requirements and hence new features are introduced to address these challenges.

Large number of devices: IOT has to support many thousands of sensors in a very small area. For example, an 802.11ah AP in a NAN has to read many meters and city sensors. For this reason, it uses a Hierarchical Association Identifier (AID), which we will examine shortly.

Relays: Usually, in WiFi we do not use relays, but 802.11ah allows 2-hop relays. This will allow reaching houses in the neighborhood which may be far from a light pole or obstructed by metal infrastructure etc. The relays are installed by the network operators just like in cellular networks. These relays can be connected to mains power supply for sustained operation.

Enhanced power savings: 802.11ah allows all devices including the relays to sleep for extended periods, even for days. For example, meters can sleep for days. Stations can negotiate target wake times (TWTs) to facilitate such sleeps, which will be explained later in more detail.

Speed frame exchange: when stations wake up, they will be allowed to transfer all backlogs at a high speed and then go back to sleep.

6.2.4 MAC Protocol Versions

Two MAC versions are allowed in 802.11ah. Protocol Version 0 (PV0) is the same as that for b/a/g/n/ac. It can be selected to operate in the old MAC, but many of the advantages of the new MAC cannot be long range, energy saving etc. may not be achieved us with version 0. This version is optimized for IOT. The features for PV1 compared to PV0:

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Short headers: headers have been shortened for sh too much overhead.

thout incurring

Null Data packets: It is possible to transmit directly over the PHY with zero-length packet.

Speed frame exchange: many frames can be transmitted back-to-back when a station wakes up to reduce duty cycling.

Improved channel access: Time needed to access the channel shortened. Therefore, sensors that have urgent data can quickly access the network and start transmitting their data.

Next, these features are explained in more detail.

6.2.5 Short MAC Header

Figure 6.14 compares 802.11ah headers with the legacy 802.11 header. We see that in 802.11ah, High Throughput Control, QoS, and Duration fields are removed. Then there are only one compulsory address field instead of four and it is only 2-byte instead of 6-byte. The

Seq. field indicates whether the 3rd or 4th address fields, which are both 6-byte, are used. In summary, it saves 12-26 bytes.

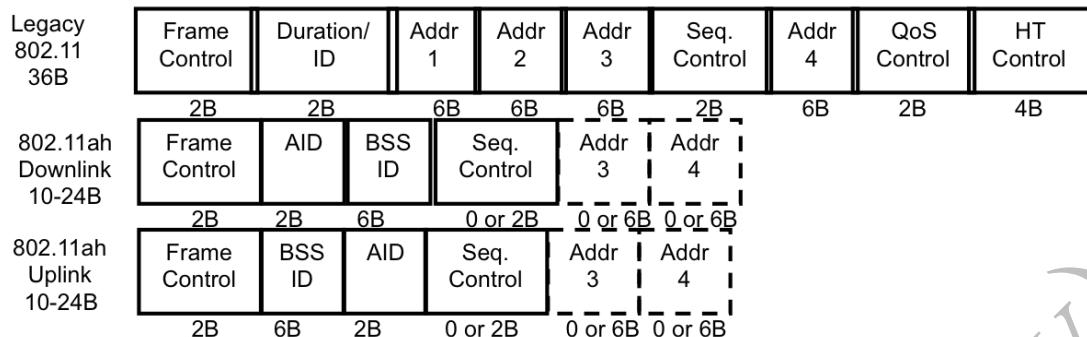


Figure 6.14 Comparison of 802.11ah headers with the legacy 802.11 header

Example 6.4

A garbage bin sensor uses 802.11ah to upload 10 bytes of bin-fill-level data once every hour. Compared to legacy 802.11 (a/b/g/n/ac), the bin sensor has to upload how many less bytes per day?

Solution: Assignment Project Exam Help

Legacy 802.11 MA

Total bytes uploaded

Total bytes uploaded <https://eduassistpro.github.io/>
 $1104 - 480 = 624$ le

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6.2.6 Null Data Packet (NDP)

There are many 802.11 packet types, such as ACK, RTS, CTS, etc., which has no data. However, the MAC header consumes too much overhead for these packets. 802.11ah removes the entire MAC header for these packets and identifies these packets via the modulation and coding scheme at the PHY. That is, ACK, Block ACK, CTS, etc, all use different MCSs.

6.2.7 Speed Frame Exchange

Initiator sends a frame with response indicator set to “long response”. Upon receiving this, the receiver can send data instead of ACK within a SIFS as shown in Figure 6.15. Frames are sent until there are no more frames or the TXOP limit is reached. The ACK can be sent at the end of all frames as a block ACK. This can be done at both ends, hence this scheme is also called “Bidirectional Transmit (BDT)”.

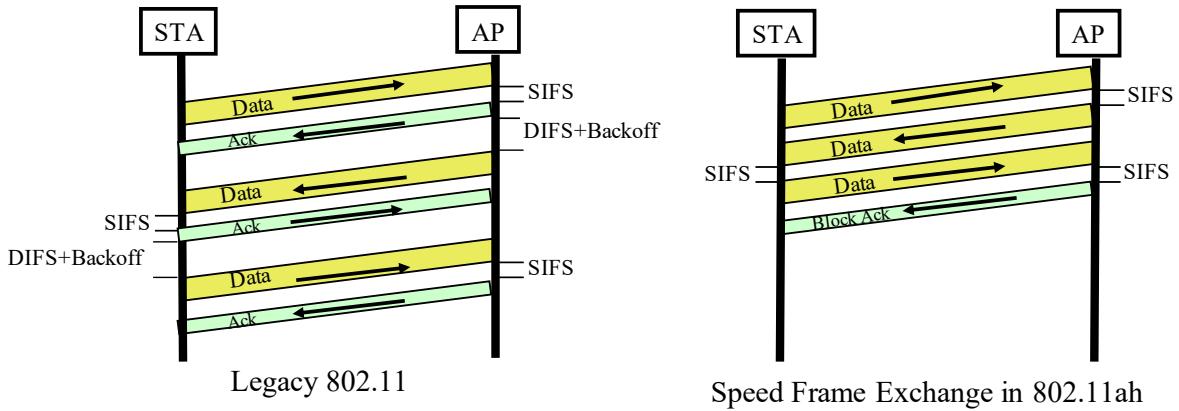


Figure 6.15 Speed frame exchange in 802.11ah

6.2.8 Types of Stations

There are three types of stations in 802.11ah based on how they handle Traffic Indication Map (TIM) that is transmitted within the beacon.

The first of the three types of stations are high traffic stations, also known as TIM stations, which remains awake all the time to listen to all beacons and the TIMs therein to transmit accordingly within restricted access window (RAW). The second type is an aperiodic low traffic station, also known as non-TIM station. This type of stations does not listen to beacons but negotiates a transmission opportunity with the AP and get a transmission opportunity. The third type is very low-traffic station, also known as a passive listener.

6.2.9 Page Segmentation

Announcing all buffered frames in each beacon would require a lot of bits in the TIM, especially for large 802.11ah networks connecting thousands of devices scattered in a neighborhood. To reduce the size of the beacon and better manage the contentions, AP divides the TIM stations in segments and announces only one segment at a time. Each station knows which segment it belongs to.

Every Delivery TIM (DTIM) interval, AP announces the TIM for the first segment as well as a *segment map* which indicates the segment that have pending data. All stations listen to the DTIM. Stations which belong to the first segment actually have to listen to the DTIMs only, because the rest of the beacons within the DTIM interval are for other segments. If a station is not in the first segment, then it will find out from the DTIM whether there is any data for its segment. If so, it will wake up for that beacon only and sleep for the rest of the time.

For example, if DTIM announces that there is data available only for the fourth segment, then a station which belongs to segment 2, will not wake up until the next DTIM beacon, because it knows that there is no data available for it. Figure 6.16 illustrates the transmissions of DTIM and other beacons.

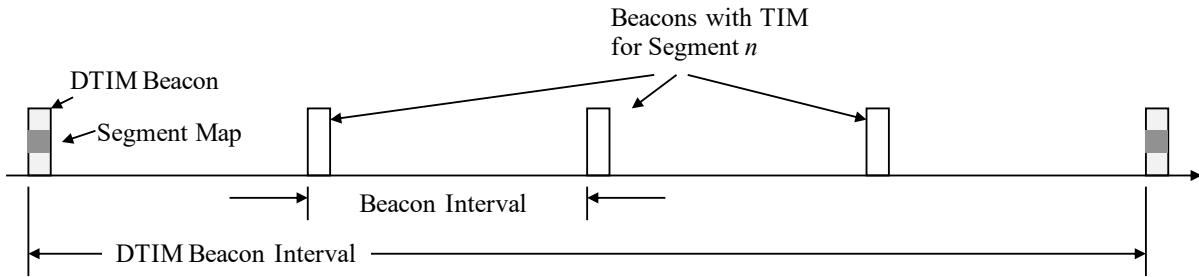


Figure 6.16 Transmissions of DTIM and other beacons in 802.11ah

6.2.10 Channel Access for TIM

Once a TIM station listens to the beacon for its segment, it can find out which slot it can use to contend for the channel. If the map indicates that the AP has buffered packets for a station, the station uses DCF (distributed coordination function) at that slot to send a PS-poll to get the packet. If a station has a packet to send, it listens to the map and uses DCF to send RTS at that slot.

Note that the TIM indicates which slots are allocated to which station, but the slots are not strictly reserved for individual stations. Rather a few stations are allocated the same slot. So, strictly speaking, there may be collision if two or more stations have data to send and they try to send at the same slot, which is allocated to one of them. However, small number of stations per slot reduces the chances of collisions. Under low load, its performance approximates TDMA (time division multiple access).

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6.2.11 Response In

Without any duration field in MAC header, 802.11ah can use NAV (Network Allocation Vector). RID is a new virtual timer similar to NAV. Like NAV, RID is also a time count down mechanism but it is different from NAV in many ways.

First, RID is done in PHY, while NAV was a MAC mechanism. As such, RID is set after the reception of PHY header, while NAV is set after the reception of a complete MAC frame. RID is set based on the 2-bit response indication field in the PHY header. With two bits, we have four combinations:

- Normal Response: RID \leftarrow SIFS + Ack or Block Ack time
- NDP Response: RID \leftarrow SIFS + NDP Frame time
- No Response (Broadcast frames): RID \leftarrow 0
- Long Response: RID \leftarrow SIFS + Longest transmission time
(Used with Speed Frame Exchange)

Note that although ACK is a type of NDP, it is treated separately from the rest of the NDP packets.

6.2.12 Power Enhancements

Enhanced power savings in 802.11ah is achieved in three ways, page segmentation, RAW, and target wake time (TWT). As we have seen earlier, page segmentation allows the stations to sleep longer as they do not have to listen to every beacon to find out whether they have a

packet buffered. Segmentation in 802.11ah is facilitated through a new hierarchical association identifier.

6.2.13 Hierarchical Association Identifier

As we have seen earlier, the whole network is divided into a few pages to better manage a large network. To appreciate the page segmentation procedure, we need to compare the TIM situation with that of legacy 802.11. 802.11 b/g/n/ac use 11-bit identifier, which allows 2007 stations to connect to the network. 2000+ bits are required in TIM to allocate slots to the stations.

802.11ah uses 16-bit identifier, which allows 8 times more stations to connect to the network. Therefore, the network is segmented into 8 pages of $\sim 2^{11}$ stations each. Actually, 2007 stations are allowed per page to be strict. Currently only page 0 is allowed. Page 1-7 are reserved.

Page 0 can serve a total of 2048 stations (a page has 11 bits). This is still too large. So, a page is divided into 32 blocks (a block has 5 bits), where each block can serve 64 stations. A block is then divided into 8 sub-blocks and each sub-block into 8 stations. This division is shown on Figure 6.17.

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Figure 6.17 Association identifier for 802.11ah

6.2.14 Restricted Access Window

802.11ah has both contention period and contention free period (CFP). However, due to large number stations possible under 802.11ah, it is not efficient or not possible to allocate one slot to one station. To make efficient use of the limited slots in CFP, the slots are allocated more intelligently using a mechanism called Restricted Access Window (RAW) as follows.

RAW allows a set of slots to be restricted to a *group* of stations. Now this group of stations are not allowed to attempt to transmit in other slots, which reduces the probability of stations attempting to transmit in a given slot. In essence, RAW is using CFP for some level of contended access to the channel by allocating multiple stations to the same group of slots. However, by keeping the number of stations low, it can achieve good performance. Using of this mix, i.e., **contention within contention free period** is a new concept brought forth in 802.11ah, but not seen in any legacy versions.

A TIM station can be allocated slots during RAW to transmit/receive packets. Access may be granted for transmission, reception, polling, etc. for one or a group of stations. A RAW schedule is transmitted at the beginning of RAW interval.

A station may have more data to transmit than possible in a given slot. Therefore, a station tells the AP that it has a frame to transmit using an Uplink Data Indication (UDI) bit in its frame. This helps the AP to find out which stations need access to slots in the next round, so it can calculate the slot allocations.

Dividing stations into groups and dividing time into slots for each group increases the efficiency under heavy load. At 100% load, RAW's utilization is close to 100%, whereas EDCF's performance drops to 0%, a classic phenomenon known as *congestion collapse*.

In general, for heavy load, reservation is good and for light load, random access is better. This is similar to having traffic lights on the roads. If traffic is very light, no need to put a traffic light. Drivers can simply arrive at the intersection and use their judgment and resolve the priority (in some countries there are 4-way stops to help drivers sort out who should go first). However, in intersections where traffic is heavy, it is better to use some form of reservations and allocations using traffic light to restrict the movement of group of cars at a time.

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6.2.15 Other RAWs

We have seen how the concept of RAW is extended to several

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Periodic RAW: Period and duration of PRAW are e periodic stations, i.e., stations that send data periodically.

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Sounding RAW: This is used for sector sounding.

AP Power Management RAW: This is used by AP to announce the time when it will be sleeping.

Non-TIM RAW: Non-TIM stations do not have heavy traffic. If all slots are allocated to TIM stations, then non-TIM stations will starve. Therefore, this RAW is designed to protect transmission of non-TIM stations

Triggering Frame RAW: This is used to allow stations to send power-save poll (PS-poll) frames indicating their need to transmit.

6.2.16 Target Wake Time

For non-TIM stations, which may sleep for very long time and send packets only once in a while, it is a waste for the AP to always include buffer information for this station in the beacon. Instead, such stations can specify a target wake up time (TWT), so the AP does not bother worrying about this station during the long sleep period.

Because the sleep period can be very long, it is difficult to exactly specify the duration in milliseconds or second accuracy. Instead the following three statistics are announced, the TWT, minimum wake duration, and the wake interval mantissa. AP sends an NDP to a station at its target wake up time containing buffering status. A station can then send a PS-poll and get its frames.

TWT also helps the AP to sleep. In the example shown in Figure 6.18, the AP knows from the TWTs of the two stations that there will be no point for it to remain awake for the next long period when both of the stations will be sleeping. So, the AP goes to sleep and wakes up at the TWT of station 1 and starts sending beacons.

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Figure 6.18 Use of target wake time (TWT) in 802.11ah.

6.3 802.11ad (a.k.a. WiGig)

IEEE 802.11ad [802-11ad] was released to make use of frequencies near 60GHz.

6.3.1 60 GHz Frequency Allocation

To address the continuous demand for more spectrum, new spectrum in the higher frequency bands are being considered for release. The frequency band of 30-300 GHz, which corresponds to wave lengths 1-10 mm, is called millimeter wave band. This band is currently mostly unused and is a good candidate to explore for new spectrum allocation.

7.9 GHz in 57-66 GHz has been allocated worldwide as license-exempt ISM band, which is now called 60 GHz band. Since different countries have some incumbent allocations in this band, the exact allocations are slightly different as shown in Figure 6.19. For example, the FCC in the US as well as Korea have allocated 57-64 GHz, but Japan has allocated 59-64 GHz and EU 57-66 GHz. At least 59-64 appears to be globally available in this band.

2-GHz channels will be considered in this band.

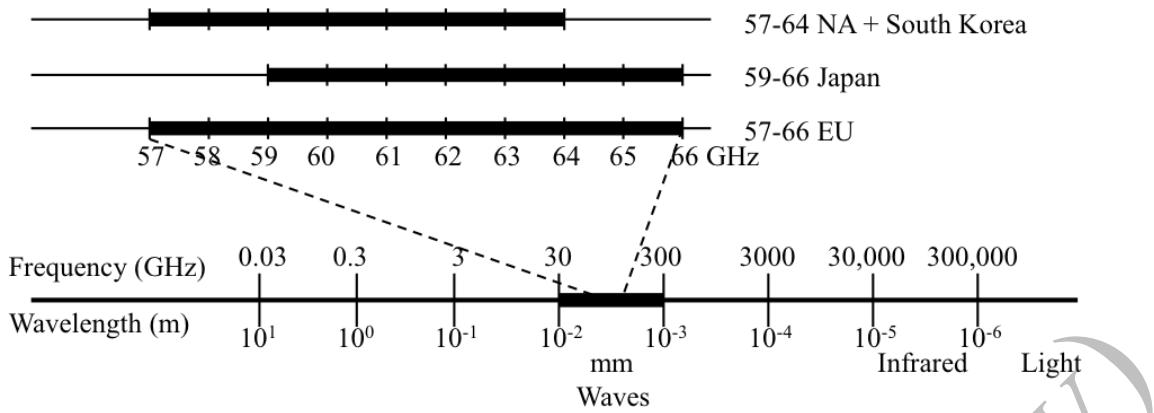


Figure 6.19 Frequency allocation in 60 GHz band

There are many advantages for this band:

Large bandwidth: It has a huge 7 GHz bandwidth. This means we can achieve 7 Gbps by using the very simply BPSK modulation. We can potentially reach hundreds of Gbps using more complex modulations, such as 256 QAM currently used in other bands.

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Small antenna separation: 60 GHz has 5 mm wavelength. It means with $\lambda/4$ separation rule, we can be built in a single large antenna arrays

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Easy beamforming: With large antenna arrays, beams can be steered at any direction quickly and with high accuracy.

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Low interference: At 60 GHz, signals do not travel through walls, and are very directional. This reduces interference with other 60GHz communications happening nearby. This is particularly efficient for urban environment where high density communications take place. For example, with existing 2.4 GHz and 5 GHz bands, WiFi signals from different apartments in the same building or even in adjacent buildings interfere with each other.

Directional antennas: at 60 GHz, directional antennas and beamforming are used to focus the power to the receiver to achieve the communication range (power attenuates quickly at this high frequency). As a result, spatial reuse of the same spectrum is possible.

Inherent security: Because the signal power attenuates very quickly, it is difficult to intercept 60 GHz communications from outside the room. This provides an inherent high-level security

Some of the advantages of 60 GHz band can also work as disadvantages:

High attenuation: As explained earlier, 60 GHz has a very high attenuation. First, the attenuation increases with distance more rapidly than other bands due to the high frequency. Second, there is high Oxygen absorption at this band. The combination causes significant loss of signal power at short distances. As a result, communication range is limited to only 10

meters and very high transmission power is needed. High antenna gain is required for omnidirectional communication.

Directional deafness: Because all communication is highly directional, the conventional channel sensing based MAC protocols, such as CSMA and RTS/CTS, do not work. Multicasting is also more challenging because two stations separated cannot receive the same beam at the same time highly narrow beams are used.

Easily blocked: 60 GHz signals are easily blocked by humans, dogs, or any moving objects, making it necessary to deploy relays in dynamic environments.

6.3.2 60 GHz applications

Despite some of the disadvantages, 60 GHz has received a lot of attention. We have almost run out of spectrum in the lower frequency bands and 60 GHz provides very high-speed connectivity in a license-exempt band. Figure 6.2 illustrates some of the major applications envisaged for 60 GHz, mainly inspired by its extremely high-speed connectivity:

Cable replacement for TV: there are lots of cables behind a TV connecting the TV to the Blue-ray and DVD players etc. These cables can be replaced with wireless if 60 GHz is used due to its multi-gigabit transmission capacity required for such high-resolution uncompressed video communication.

Interactive Gamin

reality-based games

eo, such as virtual

<https://eduassistpro.github.io/>

High speed file transfer: Very large files can be tr
full-length movies can be copied to a mobile device

For examples,

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Wireless mesh backhauls: A large number of smal

e deployed in the

future to cope with the cellular traffic demand. These small cells require back-haul connectivity. 60 GHz can be used to provide highly directional wireless connectivity to provide back haul service to these cells.

6.3.3 802.11ad OFDM PHY and data rates

802.11ad was designed for single stream SISO communications with ~2GHz channels without any support for channel bonding. 802.11ad supports both single carrier and OFDM. With single carrier, data rates can vary between 385Mbps up to 8.085 Gbps depending on the modulation and coding. The OFDM, which is more complex to implement, is left as an optional feature for the vendors to implement.

For OFDM, 802.11ad uses a subcarrier spacing of 5.15626MHz and a total channel bandwidth of 1830.47MHz, which gives 355 subcarriers of which 336 are used as data subcarriers, 16 as pilots, and 3 as DC. The symbol interval is 336/1386μs. The modulations supported include SQPSK (staggered QPSK), QPSK, 16-QAM, and 64-QAM. Note that SQPSK can transmit only 1 bit per symbol. 802.11ad supports 5 different coding rates as follows: 1/2, 3/4, 5/8, and 13/16. OFDM data rates for 802.11ad are shown in Table 6.3.

Table 6.3 802.11ad OFDM data rates in Mbps

Modulation	Coding	Data Rate
SQPSK	1/2	693
SQPSK	5/8	866.25
QPSK	1/2	1386
QPSK	5/8	1732
QPSK	3/4	2079
16-QAM	1/2	2772
16-QAM	5/8	3465
16-QAM	3/4	4158
16-QAM	13/16	4504.5
64-QAM	5/8	5197.5
64-QAM	3/4	6237
64-QAM	13/16	6756.75

Example 6.5

What is the 802.11ad OFDM data rate for 64-QAM with 5/8 coding rate?

Solution:

802.11ad symbol rate = 38,336 Msym/s
of data subcarriers = 336
Data rate = $\log_2(64)$

6.3.4 MAC challenge <https://eduassistpro.github.io/>

MAC for 60GHz is a challenging problem for several reasons. WiFi operating at 60 GHz is significantly higher than conventional WiFi operating at 2.4 GHz. For example, free space path loss is 28 dB higher than at 2.4 GHz. At 60 GHz, path loss is 2 dB higher than at 2.4 GHz. Therefore, 802.11ad stations must have high antenna gain to overcome the high path loss. This is achieved with directional antennas, which can focus the energy toward the receiver through beamforming. The narrower the beam, the higher the antenna gain.

Directional communication, however, complicates the MAC design. The AP can talk to a STA (station or client) only if their antenna beams point to each other. Similarly, two STAs must point their beams to each other before they can exchange data in the ad-hoc mode. Therefore, the MAC has the responsibility to facilitate all stations to find the right beam directions at all times dynamically as they move and wish to communicate with different stations located at different locations. The problem becomes particularly challenging with many stations connecting to the network.

6.3.5 802.11ad MAC topology

The MAC topology of an 802.11ad is shown in Figure 6.20. In 802.11ad, BSS is called Personal BSS (PBSS), which defines the set of devices that wish to communicate with each other under the facilitation of a single control entity called PBSS Central Point (PCP). Although PCP controls transmissions within the PBSS much like the AP in previous 802.11 networks, we do not have a separate PCP device like we have an AP in other WiFi networks.

Instead, PCP is a function that may be assumed by any of the member devices. For example, if the TV is the most powerful machine around, it could be configured as the PCP inside a room to control other devices working within the 802.11ad network.



Figure 6.20 802.11ad wireless local area network

6.3.6 802.11ad Beacons

Beaconing is done slightly different than previous versions of 802.11. Beacons are transmitted every “Beacon Interval” as shown in Figure 6.21. All transmissions that happen within the beacon interval is called a “super-frame”.

The super-frame starts at Time (A-BFT), An

e PCP is allowed to activate Beamforming (TTI).

As 802.11ad uses directional communication, the PCP polls each of the member stations. This is followed by a training period for each station.

e direction for a training period.

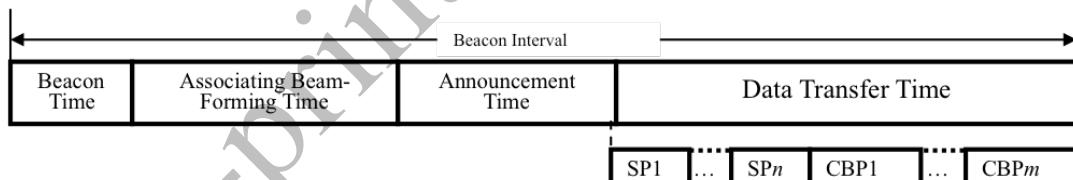


Figure 6.21 IEEE 802.11ad Beaconing

During AT, the PCP polls every member to find out their requirements. For example, member A might request for a 5 ms time slot to communicate with member B. Members send these type of non-data responses to the PCP during AT.

All actual data exchanges happen during DTT. Data frames are transferred either in dedicated service period (SP), or by contention in a contention-based period (CBP). During AT, the SPs are finalized for different stations similar to CTS/RTS in previous 802.11 versions.

Multiple transmissions may be scheduled on the same frequency at the same time if they do not interfere, which is called spatial frequency sharing (SFS). PCP asks stations to send results of “Directional Channel Quality” during an overlapping SP. The stations measure the channel quality and send them to PCP. PCP then knows which station pairs can share the same slot. SFS will be examined in more detail later in the chapter.

When DT starts, a series of SPs are first completed followed by CBPs (see Figure 6.4). During CBP, stations use the DCF function. All SP transmissions are controlled using the Hybrid Coordination Function (HCF) as defined in 802.11ac.

6.3.7 Beacon Transmission

Beacons transmitted by the PCP have to be received by all members. One way to achieve this would be to transmit a single beacon using an omnidirectional antenna, so it reaches all directions. However, the beacon signal in this case would be too weak, which may not be correctly received by all members. To ensure that beacons are received by everyone while still using directional transmission, the PCP must transmit the same beacon multiple times, one in every single direction.

Figure 6.22 shows that the PCP is transmitting the beacon in four directions (different colors represent different directions or antenna sectors), where the beam is 90 degree wide in each direction, so four antenna configurations cover 360 degree. Another PCP may decide to use narrower beams for beacon transmissions to achieve an extended range. In that case the beacon will have to be transmitted more than four times to cover 360 degree.

Example 6.6 Assignment Project Exam Help

An 802.11ad PCP has a multi-sector antenna with every sector covering 45 degrees. During a Beacon Time (BT), stations located at any direction can <https://eduassistpro.github.io/>

Solution:

With 45-degree wide sectors, 360-degree coverage is required to send a total of 8 beacons (repeat the sequence per sector).

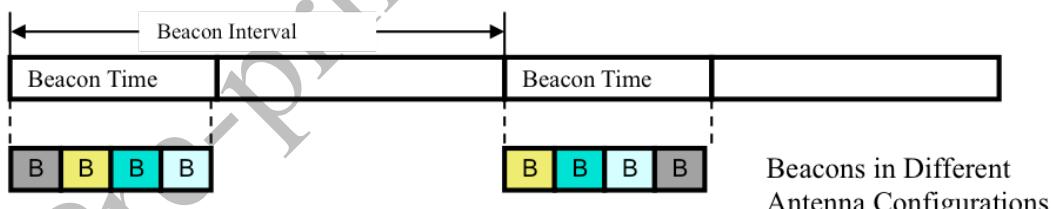


Figure 6.22 Illustration of 802.11ad beacon transmission for a four sector antenna; the beam is repeated sequentially over the four sectors.

6.3.8 Antenna sector search options

As all communications in 802.11ad are directional, the communicating pair must work out their antenna configurations, i.e., they must align their sectors or select their best pair of sectors, before they send data packets to each other. There are two fundamental options available for selecting the best sector pairs, exhaustive search and semi-exhaustive search.

In the exhaustive search, every single pair is evaluated first to find the best performing pair. Exhaustive search is highly time and energy consuming as it has a complexity of $O(N_1 \times N_2)$, where N_1 and N_2 represent the number of antenna sectors in the transmitter and receiver, respectively. For example, 1024 sector pairs will have to be evaluated if both stations have 32-sector antennas.

A more practical option, which is indeed adopted in 802.11ad, is semi-exhaustive. In semi-exhaustive approach, only the transmitter evaluates all of its antenna sectors while the receiver stays in the omni-directional mode. The pair of stations take turn to act as transmitter and receiver to complete the sector alignment procedure. This reduces the complexity to $O(N_1 + N_2)$. For example, only a total of 64 sectors need to be evaluated if both stations have 32-sector antennas. Figure 6.23 illustrates the difference between exhaustive vs. semi-exhaustive approaches of antenna alignments.

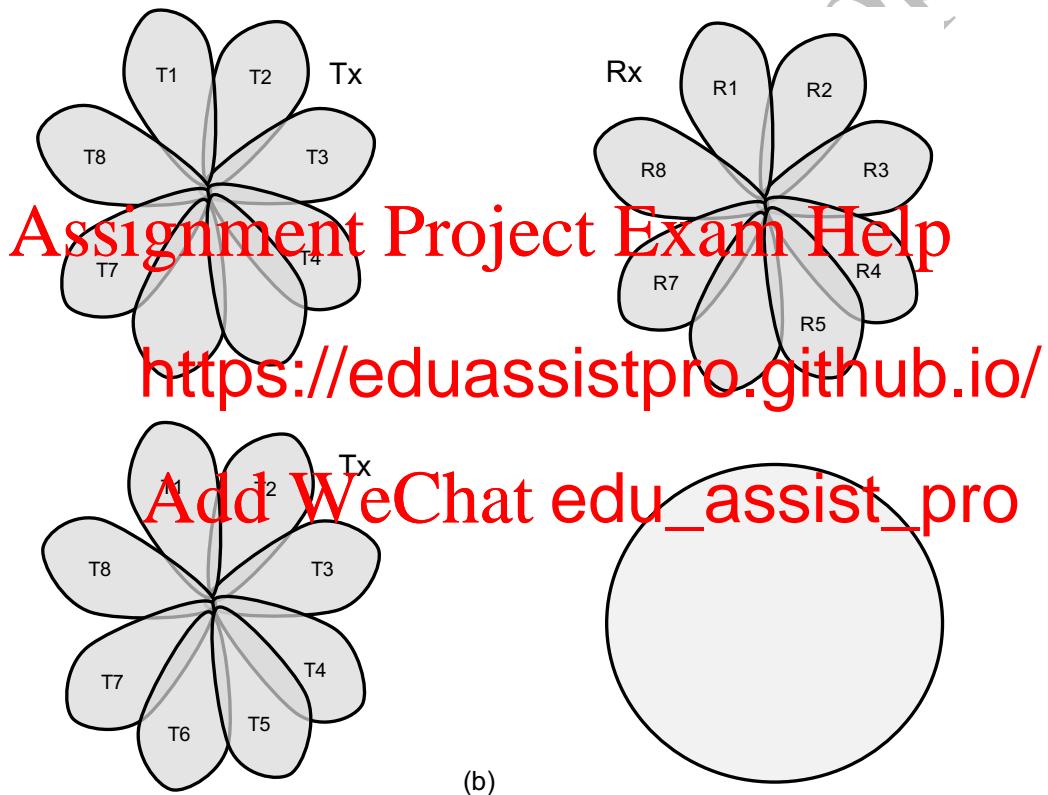


Figure 6.23 Illustration of sector training approaches: (a) exhaustive search vs. (b) semi-exhaustive search

Example 6.7

Two 802.11ad devices, STA1 and STA2, want to beamform. STA1 has 32 different antenna configurations (i.e., capable of steering the beam to 32 different directions). STA2 has only 4 beam directions. For Exhaustive Search, how many training frames are transmitted in total by these two devices before they discover the optimum beam pairs for communication?

Solution:

Total combinations of antenna configurations between the two stations is $32 \times 4 = 128$. Therefore, 128 training frames are transmitted, one per specific pair of antenna configurations, before the best combination (pair) is finally selected.

Example 6.8

Two 802.11ad devices, STA1 and STA2, want to beamform. STA1 has 16 different antenna configurations (i.e., capable of steering the beam to 16 different directions). STA2 has only 4 beam directions. For Omni-direction Antenna approach, how many training frames are transmitted in total by these two devices before they discover the optimum beam pairs for communication?

Solution:

STA1 first transmits 16 training frames while STA2 is listening in omnidirection. Then STA2 transmits 4 frames while STA2 is listening. Total frames transmitted: $16+4 = 20$.

6.3.9 802.11ad Beam Training

IEEE 802.11ad adopts the semi-exhaustive search approach in aligning the antenna beams between devices. The beam alignment is achieved in two stages. In the first stage, stations quickly figure out a that area more thor

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The first stage is cal and identify the best sector for communication. Th quickly. Note that the entire 360 degrees is divided int quick. For example, if we have four sectors for dev need to be probed is only 8 given the semi-exhausti

Figure 6.24 illustrates the SLS process. First the initiator transmits a Sector Sweep (SS) frame over all sectors sequentially identifying the sector ID in the frame. When the initiator is transmitting sector sweeping frames, the responder is receiving in the omni-directional mode. After the initiator completes frame transmissions over all of its sectors, the role of the two devices are reversed, i.e., the previous responder now becomes the initiator and vice versa. The initiator then acknowledges the sector number of the responder for which it received the highest signal strength. The responder acknowledges using an SS ACK frame and communicates the strongest sector number for the initiator. Now both devices know which sectors they need to use for communicating with each other.

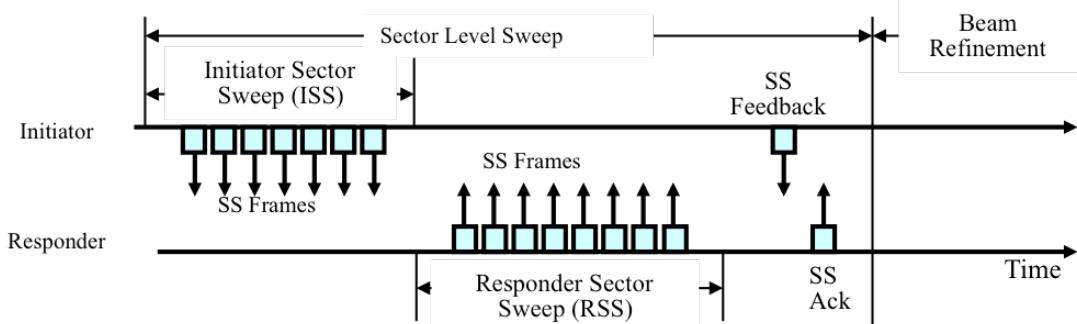


Figure 6.24 Sector-level sweep for 802.11ad antenna alignment

After the SLS, the devices can choose to further refine the beam within the optimal sector by initiating an optional second stage called Beam Refinement Procedure (BRP). Basically, in BRP, devices further search through their optimal sectors identified in SLS to find the optimal parameters in that sector to identify a narrower beam. Note that the narrower the beam, the stronger the signal strength is. Thus, BRP can be useful if devices need to achieve the highest possible data rates available in 802.11ad. SLS and BRP are illustrated in Figure 6.25.

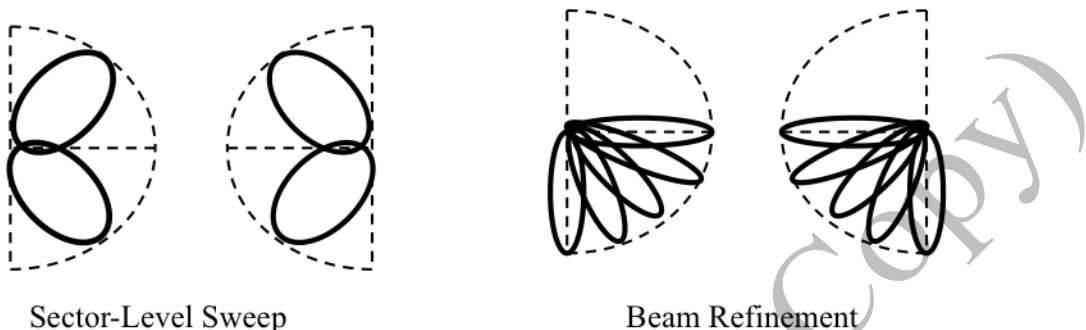


Figure 6.25 Beam refinement procedure during antenna alignment in 802.11ad

6.3.10 PCP-STA Beam Training

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Since wireless LAN clients or stations (STAs) mainly communicate with the access point (PCP in this case), 1

The PCP-STA beam training (BT) is a process where the PCP transmits training frames on all its sectors while the STAs receive them in omni-direction mode. During BT, the PCP acts as the initiator, while all STAs respond in a multi-direction mode. During A-BFT, roles of the PCP and the stations are reversed. The PCP becomes the responder and the stations take the initiator role.

Given the existence of multiple stations in a wireless LAN, there has to be a protocol to ensure that only one station carries out its SLS at any given time while all other stations refrain from transmissions. This is achieved via slotting the entire A-BFT period into N finite time slots. Each STA selects a slot randomly and transmits its training frames on all its sectors during that slot. A consequence of random slot selection is that it may lead to collision if two or more stations select the same slot. In fact, the probability that a station will be able to randomly select one of the N slots without colliding is $(1-1/N)^{M-1}$, where M is total number of stations attempting SLS during the same beacon interval. Collisions would damage the frames and hence the stations involved in the collision will not receive any feedback from the PCP about the training outcome. The stations which do not receive any feedback, can try SLS again in the next beacon interval. Note that only SLS is completed during BT and A-BFT; BFP is optional and may only take place during DT.

Table 6.4 SLS training details of Example 6.5

Transmitted Sector	A.1	A.2	A.3	A.4	B.1	B.2	B.3	B.4
RSSS at Responder (dBm)	-70	-62	-50	-64	-49	-71	-75	-80

Example 6.9

Table 6.4 shows the received signal strength (RSS) at the responder for each transmitted training frame from the beam training initiator during SLS. There are four sectors for both initiator and responder, and the number after the station letter denotes the sector number. For example, row 1 shows the frame transmitted by station A on its sector 1. What is the optimum beam (sector) pair discovered after the SLS?

Solution:

The sector that produces the strongest signal is selected as the best sector. For A, the strongest sector is 3 (-50 dBm). For B, sector 1 produces the strongest signal at A (-49 dBm). The optimum beam pair for (A,B) therefore is (3,1).

6.3.11 Spatial frequency sharing

An important advantage of highly directional beams is that 802.11ad can potentially schedule multiple transmissions on the same frequency at the same time if their paths do not intersect. This is achieved in 802.11ad as follows. First, the PCP asks every station to send their results of any STA-STA beamforming that they may have performed. PCP then has the complete knowledge of beam pairing among all the stations within its PBSS. PCP then can work out which station pairs can share the same time slot without interfering with each other.

STA Pair						(A,F)	(E,F)
Sector Pair	(1,7)	(4,12)	(7,2))	(3,7)

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Example 6.10

In a given PBSS, all stations have 12 antenna sectors with 30-degree transmission angle. Table 6.5 shows the beam pairs learned from beam training among 6 stations, A to F. For example, the first row of the table shows that A would use its sector #1 to communicate with B while B would use its sector #7 to communicate with A. If a communication, SP1, between A and B has already been scheduled, can SP2, a new communication between E and F, be spatially shared with SP1, i.e., be allocated during the same time slots without interference?

Solution:

No. During SP1, B will transmit on its beam #7, which is the same beam number found to be optimum to communicate with E (Row 3 in the table). Therefore, B's transmissions to A during SP1 will affect E. SP2 therefore cannot be spatially shared with SP1 without interference.

6.4 802.11ay

802.11ad only supports single stream and cannot bond channels (each channel is 2.16GHz wide). As we have seen in Table 6.3, a maximum of ~7Gbps can be achieved for a single channel and single stream with 802.11ad. To push the data rates in the 60GHz band, IEEE is about to release an extension, named 802.11ay [802-11ay], which will support 4 streams and bond up to 4 channels, pushing the maximum achievable data rate in excess of 170 Gbps.

6.5 Chapter Summary

1. Mainstream WiFi operates in 2.4/5GHz band: hugely popular and used in many consumer products, e.g., mobile phones, tablets, laptops, and wireless LANs. The following WiFi standards are used for these mainstream applications: IEEE 802.11a/b/g/n/ac/ax (11n=WiFi4, 11ac=WiFi5, 11ax=WiFi6)
2. Niche WiFi introduced at both sub-GHz and 60GHz
3. Sub-GHz: 802.11af (700 MHz TV Whitespace: long-distance) and 802.11ah (900 MHz: IoT, sensors networks, home automation, large number of connections)
4. 60GHz: 802.11ad (7Gbps; already penetrated some niche products) and 802.11ay (upcoming; 270+Gbps cable replacement, backhaul, etc.)
5. Analog to Digital conversion of TV channels has freed up spectrum in 700 MHz band, which is called White Space.
6. 700MHz allows long-distance communication, which is useful for rural areas
7. IEEE 802.11af White-Fi can achieve up to 426.7 Mbps using OFDM, 4-stream MIMO, 200-QAM and a coding rate of 5/6.
8. PAWS is the protocol for accessing the white space databases.
9. 802.11ah uses compared to other WiFi standards
10. 802.11ah is 1/2/4/8/16 MHz channels; symbols are longer which can handle null data packets, and implementing retransmissions
11. 802.11ah MAC achieves higher efficiency by using null data packets, and implementing retransmissions
12. 802.11ah can achieve higher energy saving by sleep using Target Wakeup Time and Restricted Access Window mechanisms
13. 60 GHz, a.k.a. mmWave, has large bandwidth, small antenna separation allows easy beamforming and gigabit speeds but short distance due to large attenuation
14. In 60GHz WiFi, multiple transmission can take place on the same frequency at the same time, which is known as Spatial Frequency Sharing.

References

[802-11af] A. B. Flores, R. E. Guerra, E. W. Knightly, P. Ecclesine and S. Pandey, "IEEE 802.11af: a standard for TV white space spectrum sharing," in *IEEE Communications Magazine*, vol. 51, no. 10, pp. 92-100, October 2013, doi: 10.1109/MCOM.2013.6619571.

[802-11ah] "IEEE Standard for Information technology--Telecommunications and information exchange between systems - Local and metropolitan area networks--Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 2: Sub 1 GHz License Exempt Operation," in *IEEE Std 802.11ah-*

2016 (*Amendment to IEEE Std 802.11-2016, as amended by IEEE Std 802.11ai-2016*), pp.1-594, 5 May 2017, doi: 10.1109/IEEEESTD.2017.7920364.

[802.11ah-bands] Weiping Sun, Munhwan Choi and Sunghyun Choi, "IEEE 802.11ah: A Long Range 802.11 WLAN at Sub 1 GHz," *Journal of ICT Standardization*, Vol. 1, 1–25, 2013, doi: 10.13052/jicts2245-800X.125.

[802.11ad] "IEEE Standard for Information technology--Telecommunications and information exchange between systems--Local and metropolitan area networks--Specific requirements-Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band," in *IEEE Std 802.11ad-2012 (Amendment to IEEE Std 802.11-2012, as amended by IEEE Std 802.11ae-2012 and IEEE Std 802.11aa-2012)*, pp.1-628, 28 Dec. 2012, doi: 10.1109/IEEEESTD.2012.6392842.

[802.11ay] Y. Ghasempour, C. R. C. M. da Silva, C. Cordeiro and E. W. Knightly, "IEEE 802.11ay: Next-Generation 60 GHz Communication for 100 Gb/s Wi-Fi," in *IEEE Communications Magazine*, vol. 55, no. 12, pp. 186-192, Dec. 2017, doi: 10.1109/MCOM.2017.1700393.

[TVWS-Ottawa] C. Stevenson, et al., "Tutorial on the P802.22.2 PAR for: Recommended Practice for the Installation and Deployment of IEEE 802.22 Systems," https://grouper.ieee.org/groups/802/802_tutorials/06-July/Rec-Practice_802.22_Tutorial.ppt [accessed on 20 Oct

[PAWS2015] V. C. Dabholkar, "Performance Analysis of IEEE 802.22.2 (TVWS) over Fading Channel with IEEE 802.11a/b/g/n," in *Proceedings of the 2015 International Conference on Advances in Computing, Communications and Informatics (ICACCI)*, pp. 1-6, 2015, doi: 10.1109/ICACCI.2015.7280350.

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End of Chapter 6
