Chapter 6

Niche Wi[illegible]

WiFi has been prima[illegible]rking technology for implementing wireless LAN in enterprise and resid[illegible]ell 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.

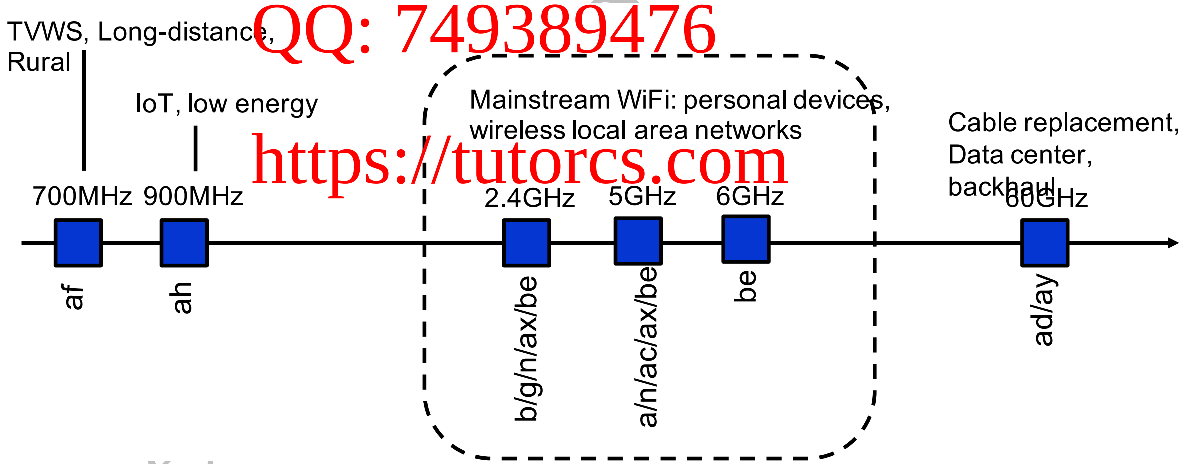


Figure 6.1 Mainstream and niche WiFi

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 numberi[illegible]HF and UHF TV channels in USA is shown in Figure 6.3. Channel 37 is [illegible]omy, hence excluded from TV transmissions. Also, some channels betw[illegible]eserved for FM radio.

At least one channe[illegible]n two analog stations in neighboring areas to avoid interference. For ex[illegible]wn has channel 2, then it will not have channel 3. Basically, all channe[illegible]d to all cities and towns.

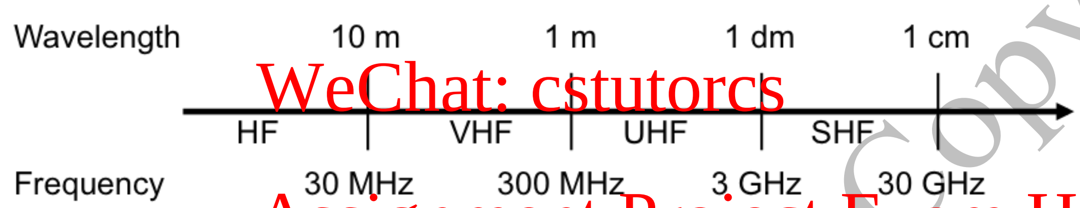


Figure 6.2 TV spectrum and channels

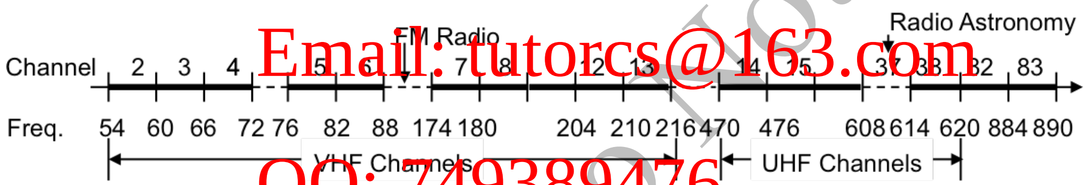


Figure 6.3 TV VHF and UHF channel numbers in USA. Frequencies are in MHz.

6.1.2 Digital TV

Analog TV broadcast has been discontinued recently in most parts of the world. 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 advantages 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 lowe[illegible] to 1/9th of 1800/1900/2100 MHz), which means it requires lower trans[illegible] can provide longer mobile battery life for mobile devices. It can have [illegible] which means smaller number of towers. Such long-distance propagatio[illegible] areas. It means providing cellular and wireless broadband services t[illegible] more cost effective and affordable. Because of these reasons, availability [illegible] 700 MHz is considered a very good opportunity for wireless networking[illegible]

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.

6.1.3 Spectral White Spaces

A lot of spectrum is allocated to certain services. However, the spectrum is not fully used at all locations and times. In general, white space is defined as any spectrum at a given area at a given time available for use on a non-interfering basis. The white space may be due to unallocated spectrum, allocated but under-utilized, channels not used to avoid interferences in adjacent cells, or spectrum available in the TV band due to digital dividend.

Figure 6.5 shows that allocation does not mean it is always used. It is called “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.

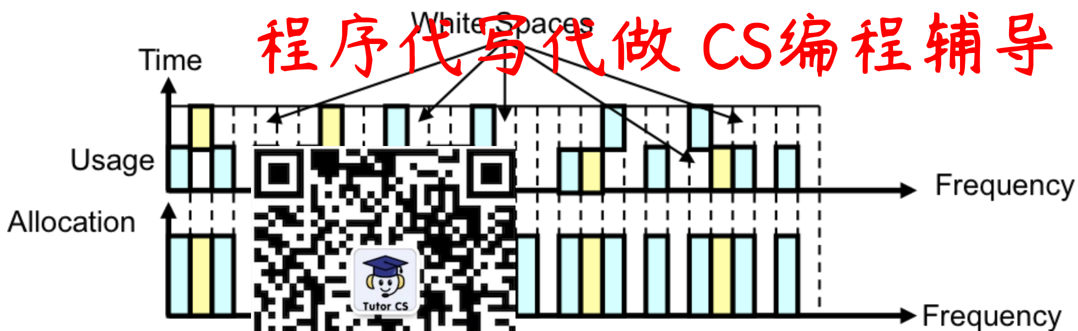


Figure 6.5 Conce[...]space. Allocation does not mean it is used.

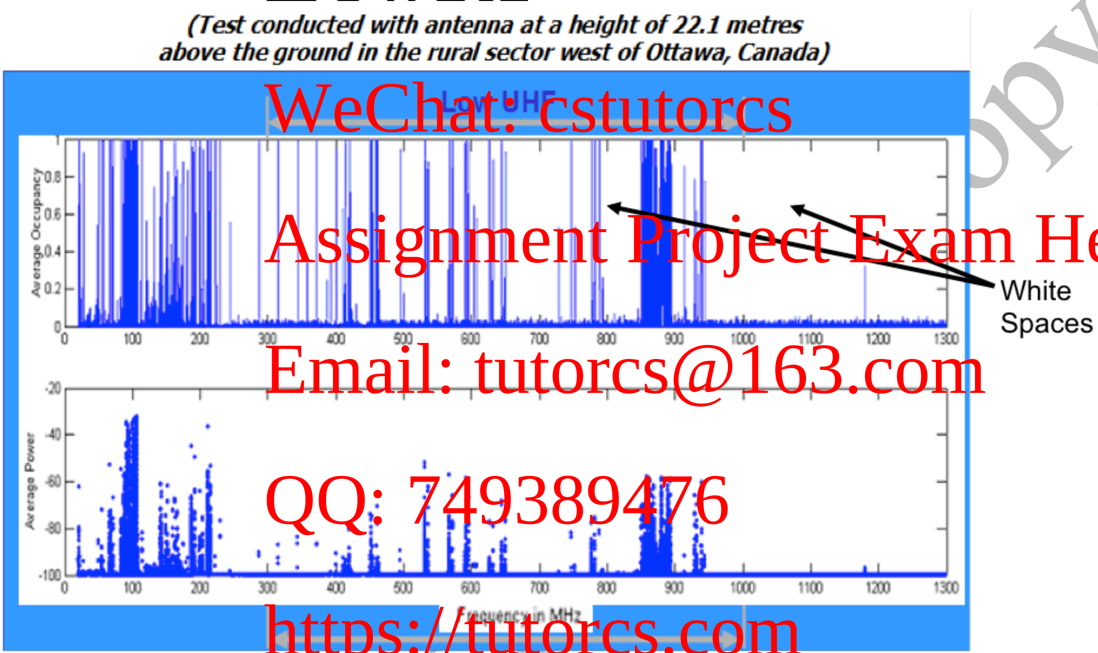


Figure 6.6 Spectral usage example from real measurements [TVWS-Ottawa].

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.

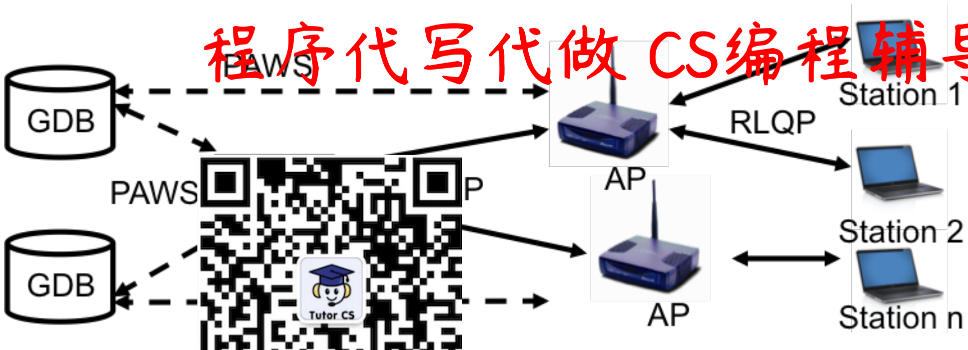
Figure 6.7 White space available near University of Washington in St. Louis.

6.1.5 802.11af Database Operation

Recall that in whitespace networking, the APs do not have a fixed set of channels, as the available spectrum is not known in advance, but rather must be found out dynamically. Therefore, to implement 802.11af, which uses white space, protocols and mechanism must be developed for the LAN to obtain the available channels from the white space databases, i.e., GDBs, maintained by the third parties and distribute such channels within the 802.11af network.

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.



Fi 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.

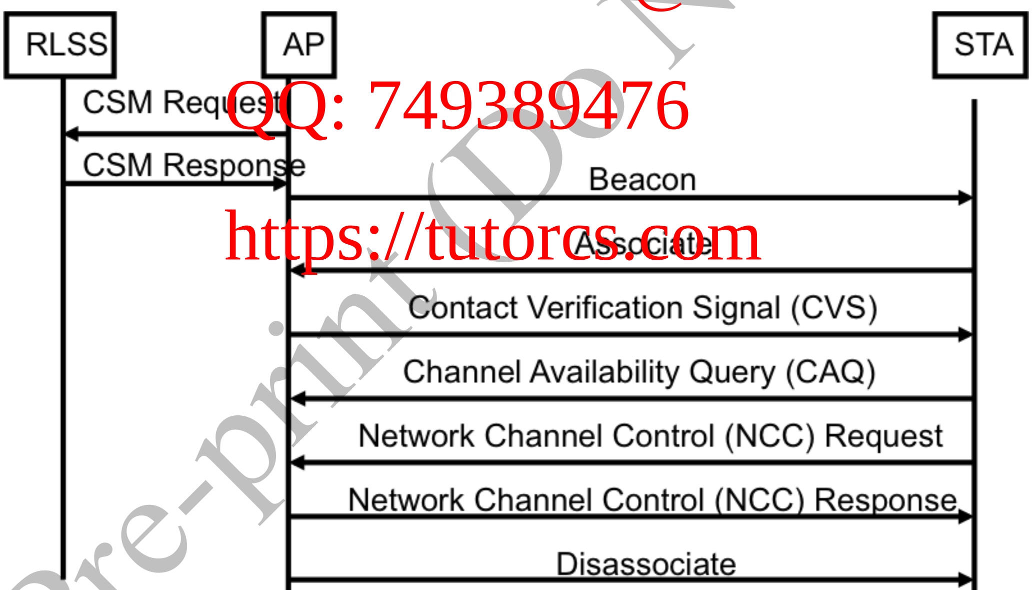


Figure 6.9 Message exchange in RLQP.

Table 6.1 Description of RLQP messages

Message	Description
CSM Request	APs asks 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 Ac[illegible]PAWS)

There can be many [illegible]es, such as 802.11, 802.22, etc. that may work on white space and nee[illegible]bases. For a WS database provider it would then be necessary to design [illegible]se different networking technologies. Instead, IETF has decided to com[illegible]rotocol, 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.

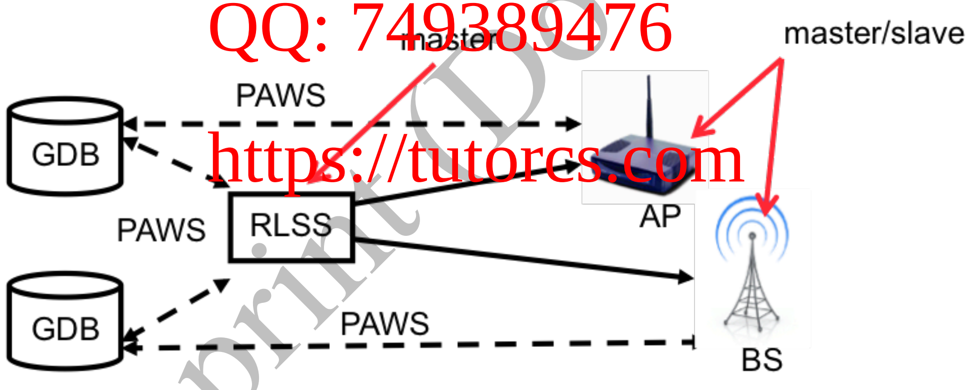


Figure 6.10 The master-slave concept in PAWS

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 s located in different locations with different antenna heights etc. and get a

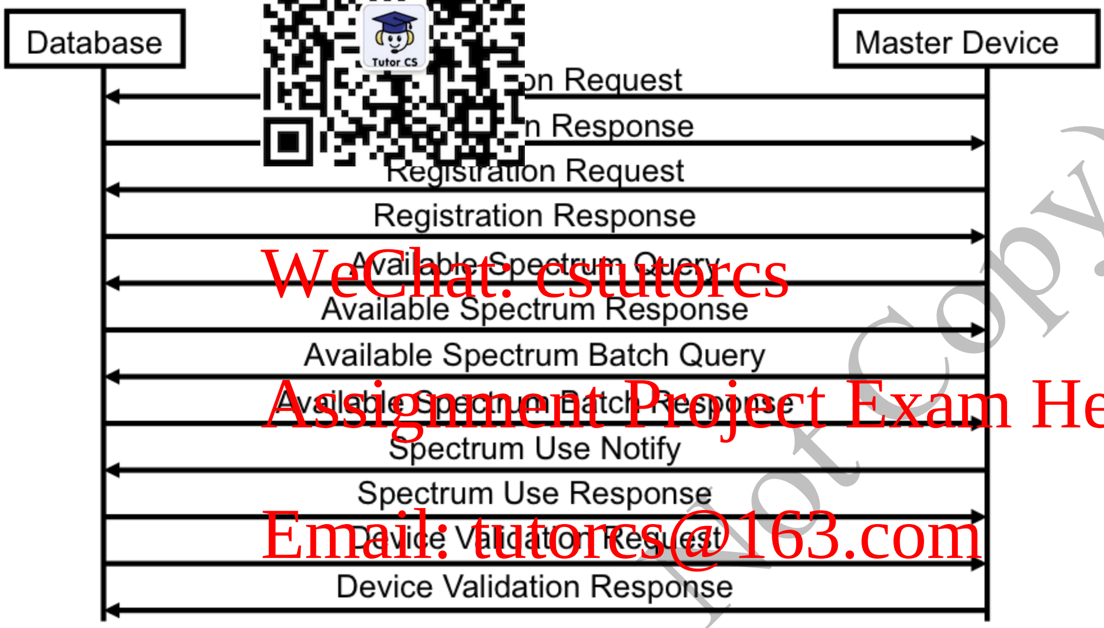


Figure 6.11 Message exchange in PAWS

6.1.8 802.11af channels and data rates

In 802.11af, a Basic Channel Unit (BCU), a.k.a. W, is one TV Channel. In the USA, this means that W = 6 MHz. While the use of single channel is default, 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 0.4μs to 3μs, and the data interval from 3.2μs to 24μs. As a result, the total symbol interval becomes 27μs, 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 = 4x4x426.7 = 426.7Mbps.

Table 6.2 802.11af data rates in Mbps: Single Stream, single unbo[illegible]l			
MCS	Modulation	[illegible]	[illegible]ate
0	BPSK	[illegible]	[illegible]
1	QPSK	[illegible]	[illegible]
2	QPSK	[illegible]	[illegible]
3	16-QAM	[illegible]	[illegible]
4	16-QAM	[illegible]	[illegible]
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)

IEEE 802.11ah [802-11ah] is also known as HaLow. The most interesting and historical change in 802.11ah compared to all previous versions is that this is the first time 802.11 is considering *wide area* networking, while all other versions were in the space of *local area* networking. Its ability to support *long range* is therefore the key difference.

To achieve the long range, spectrum is shifted from high frequency (above GHz, e.g. 2.4GHz and 5GHz) to sub-GHz. With the lower frequency, comes several key advantages for IOT. At sub-GHz, signals can travel longer distances with low power and penetrate buildings, roads, and other infrastructure, which will hide many future IOT devices. Also, there is less congestion at sub-GHz as all other WiFi devices work in either 2.4GHz or 5GHz. Also, number of devices that use sub-GHz are not many.

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.

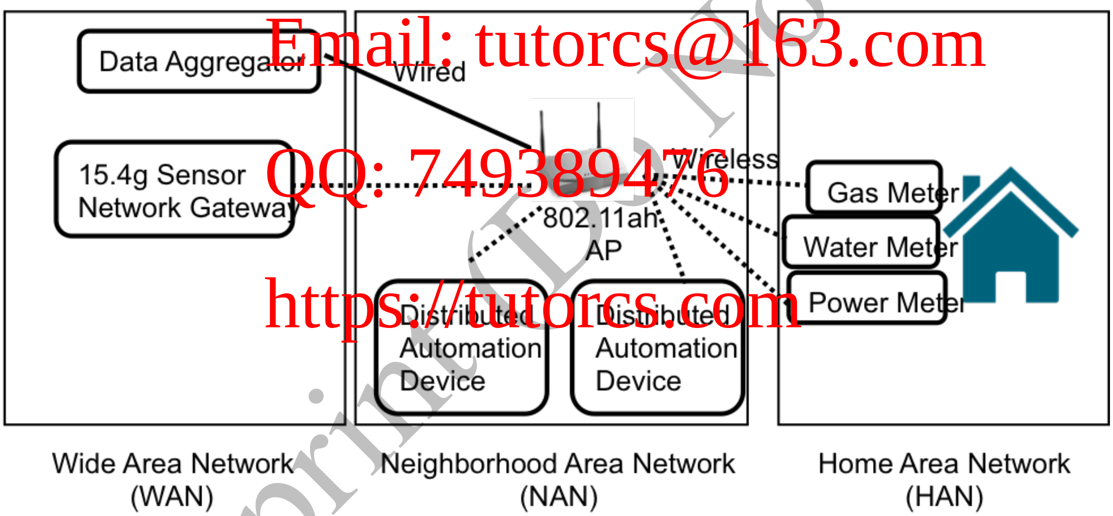


Figure 6.13 802.11ah sopports neighbor hood area network (NAN)

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 typ[illegible] IFS, are 10x longer. 802.11ah defines a new 1 MHz PHY with 24 data su[illegible] channel bonding is defined for two 1 MHz channels to form a single 2 [illegible] stations have to support both 1 MHz and 2 MHz channels.

With 1 MHz channe[illegible] 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 sued by a single AP to read meters from houses in different sectors more efficiently.

Example 6.2

If we reduce the clock speed of 802.11ac by a factor of 10, what would be the new symbol rate (symbols/s)?

Solution:

802.11ac has a symbol duration of 3.6 µs (for 400 ns GI).
New symbol duration with a 10x slower clock = 36 µs
New symbol rate = 1/(36 x 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 [illegible] relays, but 802.11ah allows 2-hop relays. This will allow reaching hous[illegible]od which may be far from a light pole or obstructed by metal infrastruct[illegible] are installed by the network operators just like in cellular networks. [illegible] 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 achieved. However, there may be situations where long range, energy saving etc. may not be very critical, such as connecting the entire indoor of an airport, which can be achieved using PV0. Protocol version 1 (PV1) is a totally new MAC not compatible with version 0. This version is optimized for IOT. There are four main advantages or new features for PV1 compared to PV0:

Short headers: headers have been shortened for short message transfers without incurring too much overhead.

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 inly 2-byte instead of 6-byte. The

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

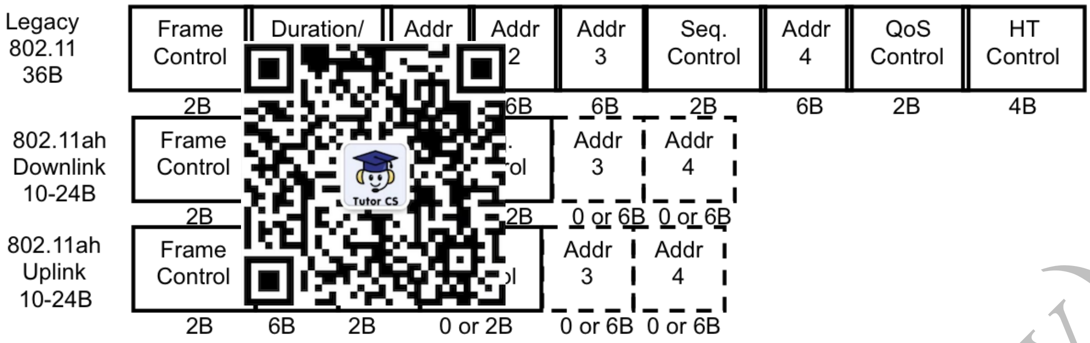


Figure 6.14 Comparison of 802.11ah headers with the legacy 802.11 header

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:

Legacy 802.11 MAC header length = 36 byte
Total bytes uploaded with legacy 802.11 = 24x(10+36) = 1104 bytes/day
Total bytes uploaded with 802.11ah = 24x(10+10) = 480 bytes/day (min)
1104 - 480 = 624 less bytes per day

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)".

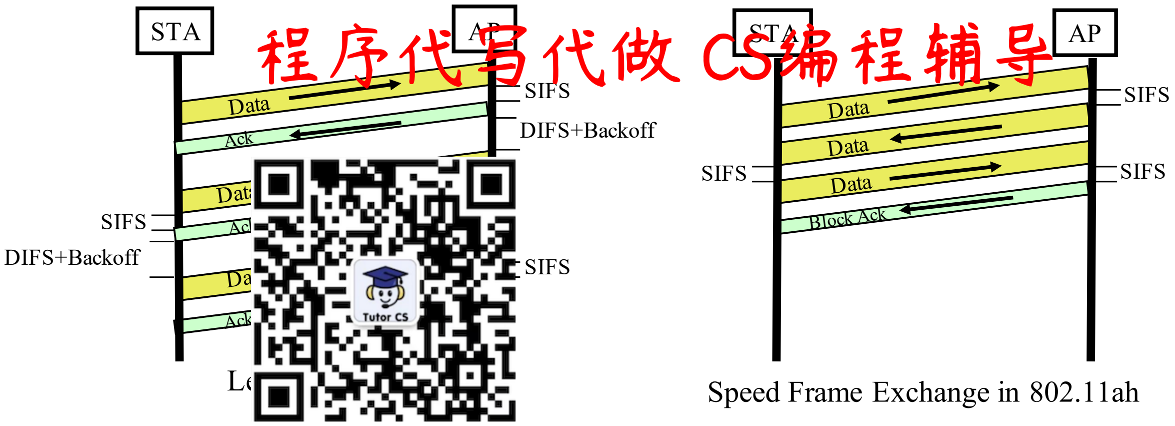


Figure 6.15 Speed frame exchange in 802.11ah

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 a restricted access window (RAW). The second type is a periodic low traffic station, also known as non-TIM station. This type of stations does not listen to beacons but negotiates a transmission time allocated in a periodic RAW. The third type is very low-traffic station, also known as unscheduled stations. They send a poll to the AP and get a transmission opportunity in response.

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 knowns 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.

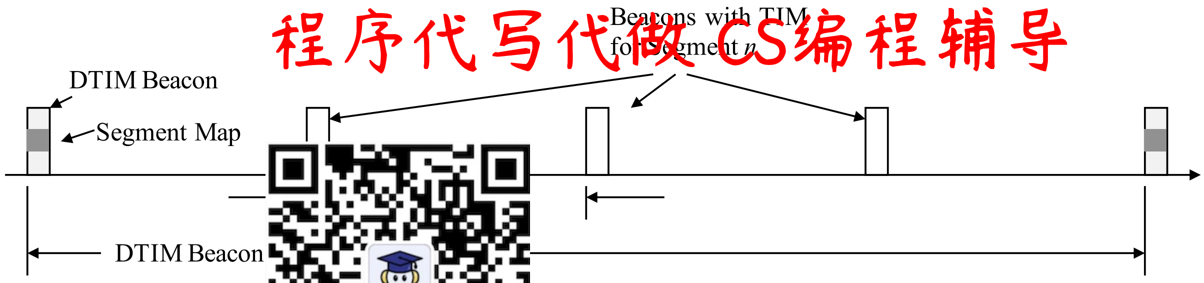


Figure of DTIM and other beacons in 802.11ah

6.2.10 Channel Acc

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 all of them. However, small number of stations per slot reduces the chances of collisions. Under low load, it performance approximates TDMA (time division multiple access).

6.2.11 Response Indication Deferral (RID)

Without any duration field in MAC header, 802.11ah can no longer use NAV (Network Allocation Vector). RID is a new virtual carrier sensing mechanism replacing NAV. Like NAV, RID is also a time count down mechanism but it is different than 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 ← SIFS + Ack or Block Ack time
- NDP Response: RID ← SIFS + NDP Frame time
- No Response (Broadcast frames): RID ← 0
- Long Response: RID ← 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 ea[illegible]work is divided into a few pages to better manage a large network. To a[illegible]gmentation procedure, we need to compare the TIM situation with that o[illegible].11 b/g/n/ac use 11-bit identifier, which allows 2007 stations to connect [illegible]0+ 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 ~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.

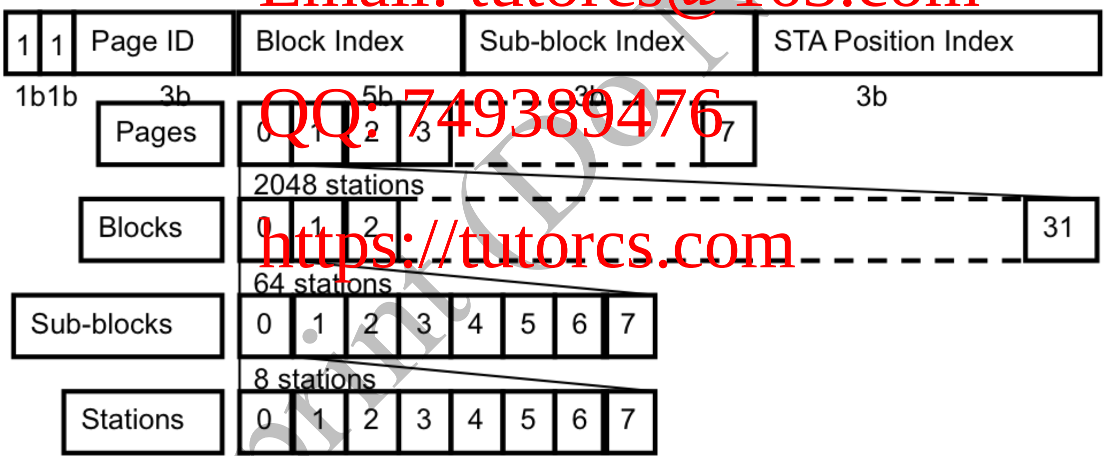


Figure 6.17 Association identifier for 802.11ah

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 [illegible]it than possible in a given slot. Therefore, a station tells the AP that it [illegible]mit using an Uplink Data Indication (UDI) bit in its frame. This helps th[illegible]h stations need access to slots in the next round, so it can calculate the slo[illegible]

Dividing stations i[illegible]ding 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 steps 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.

6.2.15 Other RAWs

We have seen how RAW works for allocating slots to TIM stations. The concept of RAW is extended to several other scenarios as follows:

Periodic RAW: Period and duration of PRAW are announced by AP for the periodic stations, i.e., stations that send data periodically.

Sounding RAW: This is used for sector sounding.

AP Power Management RAW: This is use 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 ... example shown in Figure 6.18, the AP knows from the TWTs of the two sta... be no point for it to remain awake for the next long period when both of ... sleeping. So, the AP goes to sleep and wakes up at the TWT of station 1 ... beacons.

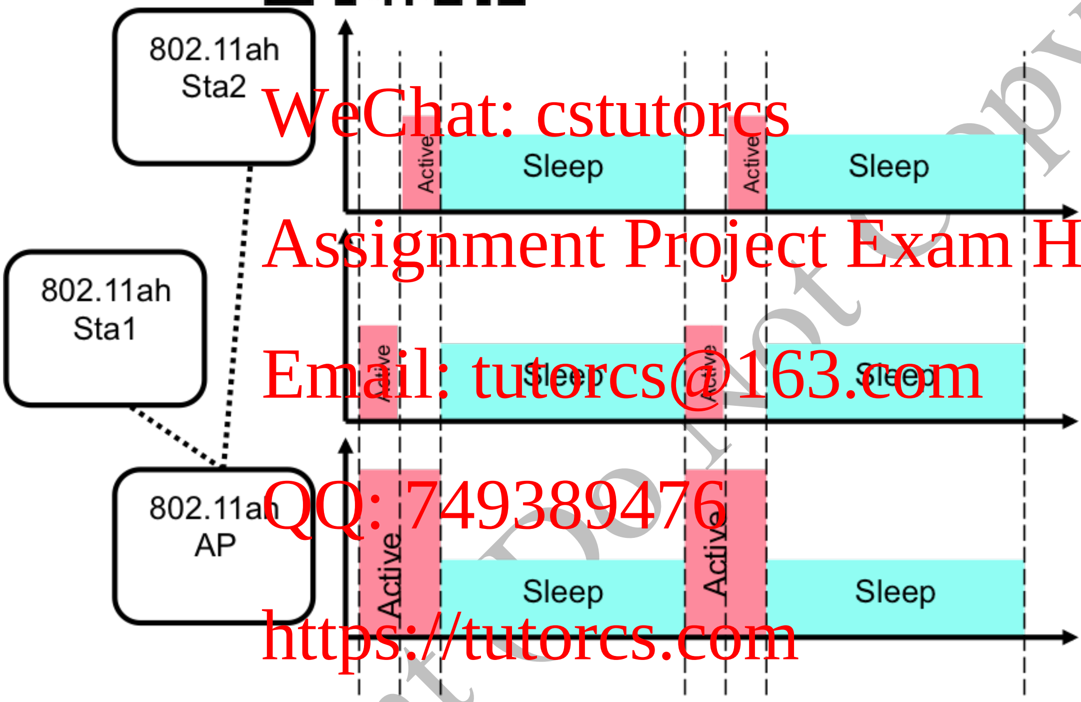


Figure 6.18 Use of target wake time (TWT) in 802.11ah.

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.

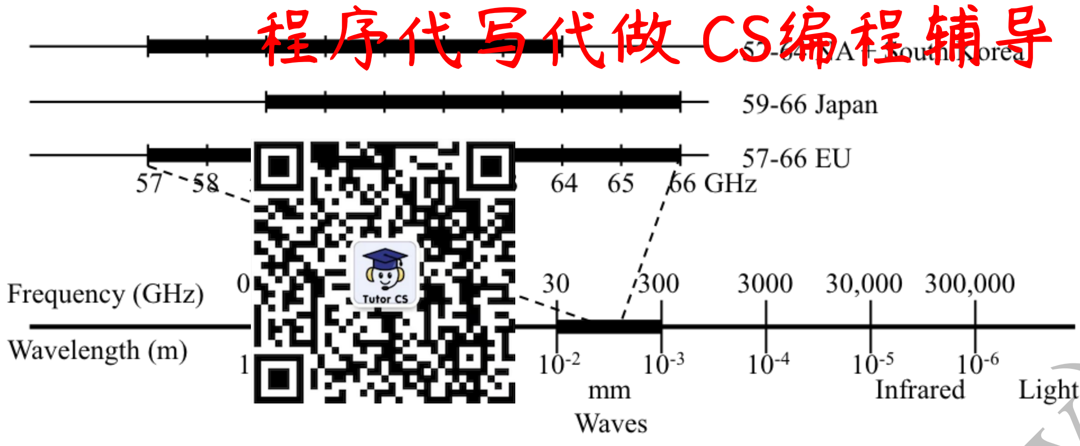


Figure 6.19 Frequency allocation in 60 GHz band

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.

Small antenna separation: 60 GHz has 5 mm wavelength. It means with lambda/4 separation rule, we can place antennas every 1.25 mm apart. This means large antenna arrays can be built in a single chip.

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

Low interference: At 60 GHz, signals do not travel very far, cannot penetrate 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 ba s, such as CSMA and RTS/CTS, do not work. Multicasting is also cause two stations separated cannot receive the same beam at the same tin ms are used.

Easily blocked: 60 (y blocked by humans, dogs, or any moving objects, making it necessary ynamic 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 Gaming: many interactive gaming uses uncompressed video, such as virtual reality-based games.

High speed file transfer: Very large files can be transmitted very quickly. For examples, full-length movies can be copied to a mobile device within a few seconds.

Wireless mesh backhauls: A large number of small cells are expected to be 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, ¾, 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	[illegible]	1732
QPSK	[illegible]	2079
16-QAM	[illegible]	2772
16-QAM	[illegible]	3465
16-QAM	[illegible]	4158
16-QAM	[illegible]	4504.5
64-QAM	[illegible]	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 = 1386/336 Msym/s
# of data subcarriers = 336
Data rate = $\log_2(64)$x(5/8)x336x(1386/336) = 5197.5Mbps

6.3.4 MAC challenges at 60GHz

MAC for 60GHz is a challenging problem for several reasons. The path loss at 60 GHz is significantly higher than conventional WiFi operating at much lower frequencies. For example, free space path loss is 28 dB higher than 2.4 GHz WLAN and 22 dB higher than 5 GHz WiFi. 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 with the beacon time (BT), within which only the PCP is allowed to transmit beacons. The rest of the beacon interval is divided into Association Beamforming Time (A-BFT), Announcement Time (AT), and Data Transfer Time (DTT).

As 802.11ad uses directional communication, the PCP needs to work out the direction for each of the member stations. This is figured out during A-BFT using antenna training.

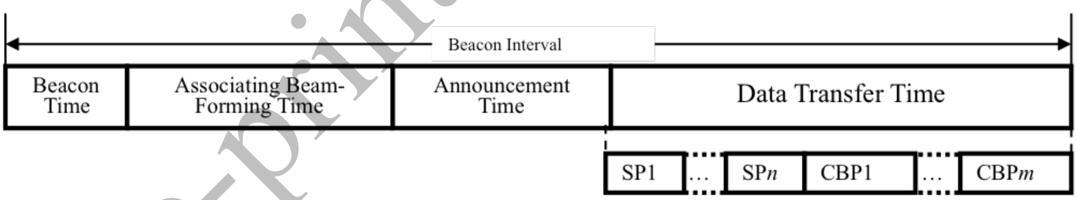


Figure 6.21 IEEE 802.11ad Beaconing

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 CBP (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 Trans[illegible]

Beacons transmitted [illegible] be received by all members. One way to achieve this would be to transm[illegible] using an omnidirectional antenna, so it reaches all directions. However [illegible] in this case would be too weak, which may not be correctly received b[illegible] 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

An 802.11ad PCP has a multi-sector antenna with every sector covering 45 degrees. During a Beacon Time (BT), how many beacons the AP should transmit to ensure that stations located at any direction can receive the beacon successfully?

Solution:

With 45-degree wide sectors, 360-degree coverage is achieved by 8 sectors. The AP therefore is required to send a total of 8 beacons (repeat the same beacons 8 times), one per sector.

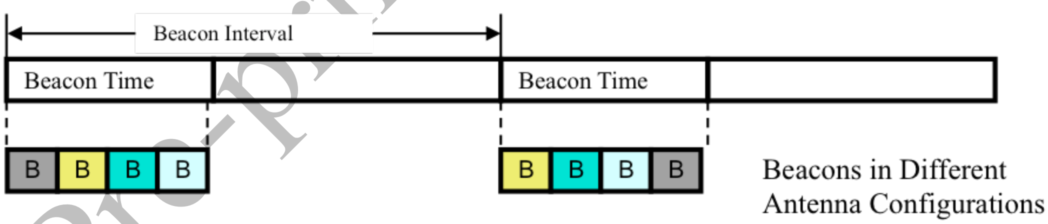


Figure 6.22 Illustration of 802.11ad beacon transmission for a four sector antenna; the beam is repeated sequentially over the four sectors.

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(N1xN2), where N1 and N2 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 op[illegible]d adopted in 802.11ad, is semi-exhaustive. In semi-exhaustive approac[illegible]tter evaluates all of its antenna sectors while the receiver stays in the [illegible]de. The pair of stations take turn to act as transmitter and receiver to con[illegible]gnment procedure. This reduces the complexity to O(N1+N2). For exa[illegible] 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.

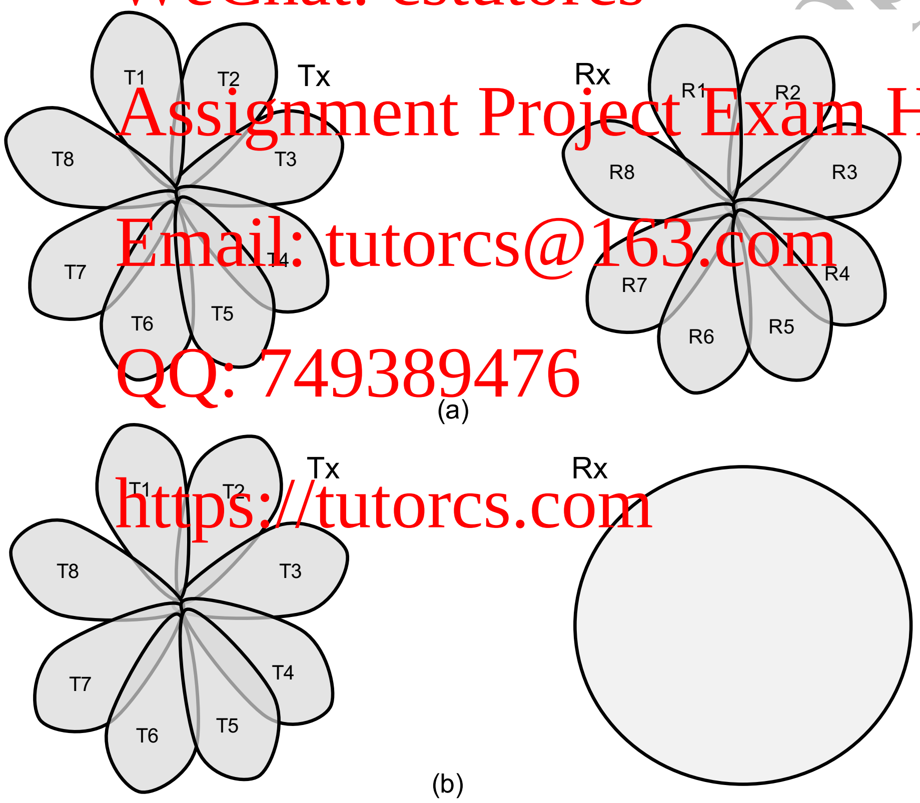


Figure 6.23 Illustration of sector training approaches: (a) exhaustive search vs. (b) semi-exhaustive search

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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 32x4 = 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 devic[illegible] want to beamform. STA1 has 16 different antenna configurations (i.e., [illegible]e beam to 16 different directions). STA2 has only 4 beam directions. For [illegible]enna approach, how many training frames are transmitted in total b[illegible] 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 rough direction and once the rough direction is established, they sweep that area more thoroughly for a more precise direction.

The first stage is called Sector Level Sweep (SLS), where the stations transmit in all sectors and identify the best sector for communication. The purpose of SLS is to find a coarse beam quickly. Note that the entire 360 degree is divided into a few sectors, so this process can be quick. For example, if we have four sectors for devices, then the total number of sectors that need to be probed is only 8 given the semi-exhaustive search option.

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.

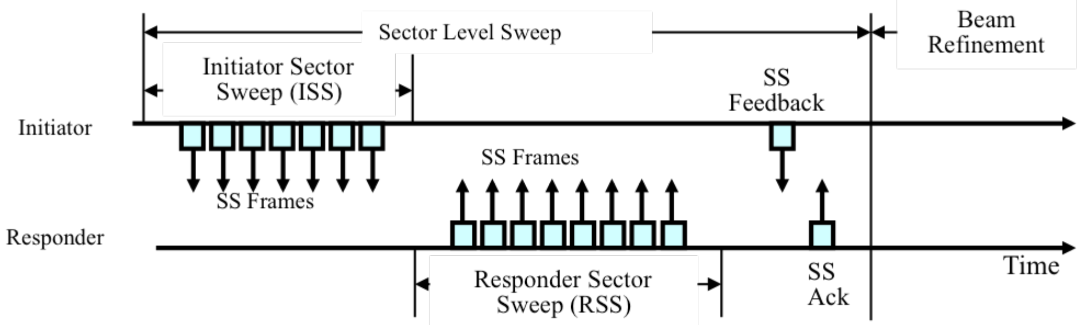

Figure 6.24 Sector-level sweep for 802.11ad antenna alignment

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 furthe[illegible] optimal sectors identified in SLS to find the optimal parameters in that s[illegible]arrower beam. Note that the narrower the beam, the stronger the signal s[illegible]P can be useful if devices need to achieve the highest possible data rates a[illegible] 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

Since wireless LAN clients or stations (STAs) mainly communicate with the access point (PCP in this case), let us first examine how the PCP-STA beams are formed.

The PCP-STA beamforming takes place during BT and A-BFT durations. During BT, the PCP transmits training frames on all its sectors while all STAs listen in omni-direction mode. Thus, during BT, the PCP acts as the initiator, while all stations serve as the responders. During A-BFT, roles of the PCP and the stations are reversed: the PCP becomes the responder listening in the omni-direction mode, while the stations assume 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 (RSSI) 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 e… s the frame transmitted by station A on its sector 1. What is the optimum … discovered after the SLS?

Solution:

The sector that produ… nal is selected as the best sector. For A, the strongest sector is 3 … ctor 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.

Table 6.5 SLS training details of Example 6.6

STA Pair	(A,B)	(A,E)	(B,E)	(B,F)	(C,D)	(A,F)	(E,F)
Sector Pair	(1,7)	(4,12)	(7,2)	(9,10)	(10,4)	(2,7)	(3,7)

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 channe[illegible]mum achievable data rate in excess of 170 Gbps.

6.5 Chapter Summ[illegible]

1. Mainstream [illegible]5GHz band: hugely popular and used in many consumer pr[illegible]phones, tablets, laptops, and wireless LANs. The following W[illegible]l 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, 256-QAM at a coding rate of 5/6.
8. PAWS is the protocol for accessing the white space databases.
9. 802.11ah uses 900 MHz band which can cover longer distances compared to other WiFi standards
10. 802.11ah is 802.11ac down clocked by 10x. It uses OFDM with 1/2/4/8/16 MHz channels; symbols are longer which can handle longer multi-paths
11. 802.11ah MAC achieves higher efficiency by reducing header, aggregating acks, using null data packets, and implementing speed frame exchange
12. 802.11ah can achieve higher energy saving by allowing stations as well as the AP to 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.

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