IEEE 802.11ac: From Channelization to Multi-User MIMO

Oscar Bejarano and Edward W. Knightly
ECE Department, Rice University
Houston, TX
{obejarano,knightly}@rice.edu

Minyoung Park
Intel Corporation
Hillsboro, OR
minyoung.park@intel.com

Abstract—The IEEE 802.11ac amendment has been proposed to enhance the throughput of IEEE 802.11n beyond Gigabit-per-second rates. In this article we present an overview of the most important features proposed in the 802.11ac amendment including channel bonding mechanisms and Multi-User MIMO.

Keywords—IEEE 802.11ac, WLAN, Wireless Networks, Gigabit, Wireless Communications.

I. INTRODUCTION

Mobile data traffic is projected to experience an 18-fold increase between the years 2011 and 2016 due to the growth of mobile subscribers and bandwidth demands to support data-hungry applications [1]. Consequently, there is a need for devices and standards capable of coping with the next-generation mobile networks that require very high data rates to sustain video, voice, live gaming, and augmented reality applications, among others. To this end, the IEEE802.11ac task group (TGac) is working on an amendment that has the goal of reaching maximum aggregate network throughputs of at least 1 Gigabit-per-second (Gbps) on bands below 6 GHz, and excluding the 2.4 GHz band. In particular, the standard envisions a maximum MAC (Medium Access Control) throughput of at least 500 Mbps for a single user, and at least 1 Gbps in the case of multiple users. This represents an increase of five times the maximum achievable rate (per user) compared to the previous amendment, 802.11n [2]. In contrast to all previous amendments of the 802.11 standard, 802.11ac is aiming at improving total network throughput as well as single individual link performance [3]. Due to the significant increase achieved by 802.11ac, the term Very High Throughput (VHT) is also used to make reference to this new amendment. In Table I we present a summary of the evolution of the 802.11 standard by comparing some of the main characteristics of each generation. The table shows differences between 802.11 b, a, g, n, and ac.

Several modifications have been proposed in order to reach gigabit throughput rates. In this paper we explore the different features and enhancements that differentiate 802.11ac from previous standards. More specifically, we describe the key modifications to both the physical layer (PHY) and the MAC. While many of the specifications of 802.11n have been kept for 802.11ac (e.g., static and dynamic channel bonding and simultaneous data streams), these have been enhanced to allow support for wider channels as well as more data streams, among others.

The two main features that allow 802.11ac to achieve gigabit transmission rates are (i) static and dynamic channel bonding, and (ii) Multi-User MIMO. To enable these two features, substantial modifications are required at the PHY. For the most part, at the MAC level, the proposed changes are needed to guarantee compatibility with the modified physical layer. More specifically, key features proposed in the 802.11ac amendment include [4]:

- Mandatory support for 20, 40, and 80 MHz channels, and optional support for 160 MHz as well as 80+80 MHz channel widths (contiguous and non-contiguous, respectively).
- Additionally, it proposes a mandatory RTS/CTS mechanism for both static and dynamic bandwidth reservation [4].
- 802.11ac introduces Multi-User Multiple-Input Multiple-Output (MU-MIMO) by proposing a unique explicit feedback protocol that enables transmit beamforming. This is in contrast to previous standards where different single-user beamforming methods were introduced, but none of them were mandated for certification. This led to lack of interoperability among different manufacturers. Moreover, the number of spatial streams is increased from 4 in 802.11n to 8 in 802.11ac.
- In terms of modulation and coding schemes, 802.11ac mandates single spatial stream modulation of up to 64-QAM with 5/6 coding rate, and binary convolutional coding. It also allows higher constellation density (256-QAM with 3/4 and 5/6 coding rate), and the use of Space-Time Block Coding (STBC) and Low Density Parity Check Coding (LDPC) as an option. Moreover, the standard specifies the use of different frame aggregation schemes. In particular, it proposes mandatory use of frame aggregation to increase channel utilization and MAC efficiency.
- The 802.11ac amendment is being developed to address different types of usage models. The main categories are wireless display, in home distribution of HDTV and other content, rapid upload and download of large files to/from server, backhaul traffic, campus and auditorium deployments, and manufacturing floor automation [5]. Notice that 802.11ac stations are compatible with legacy devices. That is, the new amendment defines features in addition to 802.11n, which means that an 802.11ac conforming station can also support all the mandatory features defined in 802.11n.
In this paper we assume the reader is familiar with the 802.11 standard, otherwise we suggest first looking into [6].

Table 1. Comparison of different IEEE802.11 Standards

<table>
<thead>
<tr>
<th>Feature/IEEE Standard</th>
<th>802.11b</th>
<th>802.11g/a</th>
<th>802.11n</th>
<th>802.11ac</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Data Rate per Stream (Mbps)</td>
<td>11</td>
<td>54</td>
<td>&gt;100</td>
<td>&gt;500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Assuming 80 MHz channels)</td>
<td></td>
</tr>
<tr>
<td>Frequency Band</td>
<td>2.4 GHz</td>
<td>2.4 GHz/5 GHz</td>
<td>2.4 GHz and 5 GHz</td>
<td>5 GHz</td>
</tr>
<tr>
<td>Channel Width (MHz)</td>
<td>20</td>
<td>20/20</td>
<td>20 and 40 (40 is optional)</td>
<td>20,40,80, 160, and 80+80 (last two are optional)</td>
</tr>
<tr>
<td>Transmission Technique</td>
<td>Direct Sequence Spread Spectrum (DSSS)</td>
<td>DSSS and Orthogonal Frequency Division Multiplexing (OFDM)</td>
<td>Orthogonal Frequency Division Multiplexing (OFDM)</td>
<td>Orthogonal Frequency Division Multiplexing (OFDM)</td>
</tr>
<tr>
<td>Maximum Number of Spatial Streams</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Beamforming Capable</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

II. CHANNELIZATION

One of the most important enhancements to the 802.11ac amendment is the support for wider channels as well as both static and dynamic channel access. We dedicate this section to describe these 802.11ac features.

A. Channel Widths Supported

The amendment mandates all devices to support 20, 40, and 80 MHz channels. In addition, it provides optional support for operation on 160 MHz channels. 80 and 160 MHz can be formed by a combination of two adjacent non-overlapping 40 and 80 MHz channels, respectively. The amendment also specifies that two non-adjacent 80 MHz channels can be used to form a 160 MHz one. More importantly, a device operating on non-contiguous 80+80 MHz should be capable of communicating with devices operating on contiguous 160 MHz if the former segments are placed in frequency to match the tone allocation of the latter case. In Figure 1 we show the channel allocation for the U.S. region.

B. Primary and Secondary Sub-Channels

Similar to 802.11n, channels consisting of 40 MHz or wider always require a primary 20 MHz wide sub-channel. Additionally, 80 MHz channels have a primary 40 MHz (which includes the primary 20 MHz) sub-channel and a secondary 40 MHz sub-channel. The same applies to 160 MHz and 80+80 MHz channels, which consist of a primary 80 MHz and a secondary 80 MHz sub-channels. In Figure 2 we depict this relationship between the primary and secondary sub-channels based on the different bandwidth options.

In all cases, the primary sub-channel is used for carrier sensing in order to guarantee no other device is transmitting. The presence of the 20 MHz primary sub-channel is also necessary to guarantee coexistence and backward compatibility with legacy 802.11 devices. Only the primary sub-channel performs full Clear Channel Assessment (CCA), which involves packet detection starting with the preamble. In contrast, the secondary sub-channel is not required to perform full CCA.

The CCA sensitivity of the primary sub-channel is -82 dBm for a valid 802.11 20 MHz signal, -79 dBm for a valid 802.11 40 MHz signal, -76 dBm for a valid 80 MHz signal and -73 dBm for a 160 MHz one. On the other hand, for the secondary sub-channel the sensitivity was improved from -62 dBm to -72 dBm for both 20 and 40 MHz channels, compared to 802.11n (and -69 dBm for 80 MHz channels). According to [7], an 802.11ac device should detect whether the primary sub-channel is busy within 4 µs with a probability greater than 90%. In contrast, on the secondary sub-channel the device has up to 25 µs to detect if it is busy with the same probability.

C. Static and Dynamic Channel Access

802.11ac extends the channel access policies proposed in 802.11n to the case of 80 and 160 MHz channels. In order for an 802.11ac station to be able to transmit an 80 MHz Physical Layer Convergence Procedure Data Unit (PPDU) two conditions must be true: (i) the primary channel follows EDCA (Enhanced Distributed Channel Access) rules so it needs to be idle for DIFS (Distributed Coordination Function Inter-Framing Spacing) plus the backoff counter duration, and (ii) all three secondary sub-channels must have been idle for a duration of PIFS (Point Coordination Function Inter-Framing Spacing) immediately preceding the expiration of the backoff counter [4].

In the case that any of the secondary sub-channels is busy, the station can follow either static or dynamic channel access rules as dictated in 802.11n:
• Static Channel Access – Consider an 802.11ac station trying to transmit on 80 MHz. If the secondary sub-channel is busy the station will choose a random backoff period within the current contention window size to restart the contention process and attempt only until no interferer is present in any of the sub-channels. Notice that with a large number of legacy stations, the probability of accessing the medium with such a wide channel will be diminished.

• Dynamic Channel Access – The 802.11ac station may attempt to transmit over a narrower channel using 20 or 40 MHz instead. This will depend on each sub-channel’s CCA. This is clearly a more flexible approach that allows for more efficient resource allocation because the station can still transmit over a fraction of the original bandwidth. All transmissions always have to include the primary channel in order to inform the receiver of which channels the transmitter will use [8].

D. Implications of Channelization Rules on the MAC

Sub-channel collisions can occur due to the sensitivity level of the secondary sub-channel being higher than that of the primary. Consider the scenario where a legacy 802.11a/n station transmits on a 20 MHz channel and an 802.11ac station transmits on an 80 MHz one. If the legacy device’s transmission takes place on one of the secondary sub-channels of the 802.11ac station, and has a sensitivity between -82 dBm and -72 dBm, then the 802.11ac station will determine that the secondary sub-channel is idle and transmit an 80 MHz signal that in turn may collide with the transmission of the legacy device.

In 802.11ac, primary and secondary sub-channels have different rules for setting the Network Allocation Vector (NAV), specifically, when a station that is not the intended receiver overhears a packet in the primary sub-channel, it is decoded and based on the MAC header, the NAV setting is updated in order for that station to defer its transmission. In contrast, for wider channels, if the reception occurred on the secondary sub-channel, the device is not required to set the NAV [4]. This means that unless the physical carrier sensing mechanism is able to detect an ongoing transmission on a secondary channel, a transmission on that same channel may lead to a collision.

E. RTS/CTS Mechanism Enhanced

In the case that an 802.11ac AP is nearby other legacy APs, it is possible that the 20 MHz primary channel of any of the latter ones is anywhere within the 80 or 160 MHz of the former one. This means that the different APs and their clients can transmit at overlapping times on different sub-channels thus leading to collisions or deferrals [9].

To overcome this problem, 802.11ac defines a handshake to properly handle both static and dynamic channel allocation. This handshake consists of a modified RTS/CTS (Request-To-Send/Clear-To-Send) mechanism that provides information about the current amount of available bandwidth. We show how the enhanced RTS/CTS protocol works with the following example (depicted in Figure 3) [9]: Consider the scenario where an initiating AP wants to transmit data to an associated client through an 80 MHz channel. The AP first checks if the channel is idle. If it is, then it transmits multiple RTS in the 802.11a PPDU format (one RTS for each 20 MHz sub-channel). Therefore, it is expected that every nearby device (legacy or 802.11ac) can receive an RTS on its primary channel. Each of these devices then sets its NAV. Before the client replies with a CTS, it checks if any of the sub-channels in the 80 MHz band is busy. The client only replies with a CTS on those sub-channels that are idle, and reports the total bandwidth of the replicated CTS. Like with the RTS, the CTS is sent in an 802.11a PPDU format and is replicated across the different 20 MHz sub-channels that are idle.

Notice in Figure 3 the two different cases; In Figure 3(a) no interference is present at either the initiating AP or its client. On the other hand, in Figure 3(b) a nearby AP is already transmitting before the initiating AP starts, however it is only interfering with the client. Therefore, the client has to inform the AP by replying with a CTS only on the idle sub-channels.

Figure 2. Primary and Secondary Channel Selection [4]

Figure 3. Enhanced RTS/CTS Mechanism [9]
III. ENABLING MULTIPLE DATA STREAMS VIA DOWNLINK MIMO

Multiple-Input, Multiple-Output (MIMO) was first introduced to the IEEE 802.11 standards with the 802.11n amendment [2]. This technique consists of a physical layer scheme where both the transmitter and the receiver employ multiple antennas. The 802.11n standard supports a maximum of four MIMO streams that can serve a single user at a time (a technique known as single-user MIMO or SU-MIMO) with spatial multiplexing of up to four spatial streams. In contrast, 802.11ac is the first 802.11 amendment to introduce multi-user MIMO (MU-MIMO) to serve multiple stations simultaneously. Moreover, it increased the number of streams allowed for SU-MIMO from four to eight. We dedicate this section to provide a brief introduction of these two techniques, which are supported by 802.11ac. It is important to mention that the implementation of MU-MIMO and a technique we will explore in a later section known as transmit beamforming are necessary to achieve the maximum throughput gains targeted by 802.11ac. Notice that the amendment supports SU-MIMO for both uplink and downlink, but only downlink MU-MIMO is supported.

A. Single-User MIMO

SU-MIMO exploits the presence of multiple transmit and receive antennas to improve both the capacity and the reliability of a transmission. By using space-time codes, a SU-MIMO system provides diversity gains thus increasing reliability. On the other hand, by combining different streams, it can also provide with significant multiplexing gains thus increasing link capacity [10]. This scheme is depicted in Figure 4(a). Observe that a multi-antenna station communicates with a single user at a time. That is, transmissions to different users are orthogonal in time in a time division multiple access (TDMA) fashion.

B. Multi-User MIMO

MU-MIMO is defined by the standard as a “technique where multiple stations, each with potentially multiple antennas, transmit and/or receiver independent data streams simultaneously [4].” That is, MU-MIMO allows stations having multiple antennas to transmit several data streams to multiple users at the same time, over the same frequency channel. For example, if an access point (AP) has four antennas it can serve four single-antenna users at a time, or two users each having two antennas by sending up to one stream per receiving antenna (over the same frequency). In Figure 4(b) we illustrate the basic idea behind MU-MIMO. Notice that the AP can serve several single- or multi-antenna users, simultaneously. Ideally, the number of simultaneous data streams enabled by MU-MIMO techniques is only constrained by the minimum number of antennas at either the AP or the receiver side (e.g., observe in Figure 4(b) that although there are five potential receiving antennas distributed among three different users, the AP has only four antennas for transmission).

In multi-user mode, the 802.11ac amendment supports up to four streams serving four different users simultaneously, or up to four streams per single user. Even further, the amendment specifies support for a different modulation and coding rate for each station being served in a downlink MU-MIMO transmission.

![Figure 4. Different MIMO Concepts: (a) SU-MIMO Beamforming and (b) Downlink-MU-MIMO Beamforming](image_url)

A MU-MIMO transmitting station requires knowledge of the Channel State Information (CSI) to all users in order to decrease the amount of inter-user interference generated by the multiple simultaneous streams. To achieve this, most existing approaches use a combination of strategies such as feedback, where the transmitting station obtains a measure of the CSI, and data precoding where that information is used to perform the inter-user interference cancellation at the transmitter side. 802.11ac specifies a single compressed beamforming method that relies on the use of explicit feedback to implement MU-MIMO (a technique known as MU-Beamforming).

C. Transmit Beamforming

802.11ac specifies a unique transmit beamforming method based on explicit feedback to enable both SU- and MU-MIMO. In particular, beamforming allows a station to transmit multiple simultaneous data streams to a single, or multiple users. Different beamforming methods were introduced in 802.11n but none of them were mandated for certification, which led to the development of multiple non-interoperable techniques by several chipset manufacturers [11]. As a consequence, the 802.11ac draft now defines a unique feedback protocol to guarantee interoperability.
between different beamforming implementations by different manufacturers. Although the sounding protocol proposed in 802.11ac closely resembles the explicit compressed feedback method proposed in 802.11n, it is not backward compatible with 802.11n devices [9].

In general, SU- and MU-MIMO beamforming techniques are employed by transmitting stations to steer signals based on knowledge of the channel in order to improve reception of PPDUs at a receiver. As the name indicates, in SU-MIMO beamforming, the different spatial streams transmitted are received at only one station. On the other hand, MU-MIMO beamforming implies division of the space-time streams among several receiving stations.

Beamforming is directly enabled by the support of “sounding.” Sounding is the term used to denote the process performed by the transmitter (e.g., the AP in a downlink transmission) to acquire CSI from each of the different users by sending training symbols and waiting for the receivers to provide explicit feedback containing a measure of the channel. This feedback is then used to create a weight or steering matrix that will be used to pre-code the data transmission by creating a set of steered beams to optimize reception at one or multiple receivers. The station sounding the channel and transmitting data using a steering matrix is known as the 802.11ac beamformer (VHT beamformer). On the other hand, the served 802.11ac station replying with the feedback is called the VHT beamformee. In Figure 4(b) we illustrate the concept of MU-beamforming. Observe that a multi-antenna AP serves a set of users by forming various beams each transmitting a different data stream.

Explicit Beamforming Feedback in 802.11ac [4] – Every time a steering matrix is computed from new channel measurements, the current steering matrix is replaced for the next data transmission. With this method, a beamformee generates and replies to a predefined channel sounding packet with a compressed beamforming feedback matrix in the form of angles quantized according to [4]. The number of bits used for quantization is chosen by the beamformee based on the indication given by the beamformer of whether the feedback is for a SU-MIMO or MU-MIMO transmission. Notice that the method the beamformer uses to calculate the steering matrix is implementation specific and is not defined by the standard.

Protocol Description – The beamforming protocol proposed for 802.11ac works as follows. Before every beamformed transmission, the beamformer transmits a VHT Null Data Packet (NDP) Announcement frame that contains the addresses of the transmitter (AP) and the set of beamformees, as well as a sequence number that identifies the VHT NDP Announcement. The main purpose of this announcement is to notify the receive station that it should be ready to prepare a beamforming report frame. After SIFS (Short Inter-Frame Space), the AP transmits a VHT NDP frame in order to sound the channel. Based on the NDP frame, the station will prepare the information that will be carried by the beamforming report. The VHT NDP frame has the same format as the VHT PPDU but does not include a data field. Therefore, the targeted receptors only use a preamble to measure the channel between the AP and themselves.

More specifically, upon reception of the VHT NDP frame each beamformee removes the space-time stream CSD (Cyclic Shift Diversity) applied to the signals transmitted. The CSD consists of a signal shaping technique where different phase shifts are applied to the same signal across different transmit chains. After removing the CSD, the targeted beamformees are required to reply with a VHT Compressed Beamforming Frame. The first intended station replies immediately whereas the others have to wait to be polled by the AP (by using a Beamforming Report Poll). The most relevant information carried by the VHT Compressed Beamforming Frame is the following: (i) The VHT MIMO Control Field which contains the dimensions of the matrix, an indicator of the width of the channel in which the measurements used to create the feedback matrix were taken, and information indicating the size of the codebook entries. (ii) The VHT Compressed Beamforming Report containing the compressed beamforming feedback matrix in the form of two angles, as well as the SNR of each space-time stream averaged over all subcarriers used, and finally the (iii) MU Exclusive Beamforming Report carrying explicit information used by a multi-user beamformer in order to create the steering matrices.

Notice that when transmitting a VHT NDP Announcement frame having multiple stations as destinations (contrary to SU-MIMO where only one station is served at a time), any Beamforming Report Poll frame needs to be transmitted in order to retrieve a Compressed Beamforming Report from each of the stations. In Figure 5 we present an example of the VHT sounding protocol used when the AP deals with more than one VHT beamformee. In terms of power, regulation limits the transmit power based on the number of antennas used at the transmitter, therefore, transmit beamforming does not increase the maximum distance range [11].

The implementation of transmit beamforming is optional in the 802.11ac standard [9].

![Figure 5. Sounding Protocol with Multiple Beamformees](image)

IV. OTHER PHY AND MAC ENHANCEMENTS

Other modifications to the PHY and MAC have been proposed in the 802.11ac amendment. In this section we present three of the most relevant changes.

A. Higher Order Modulation

The Modulation and Coding Scheme (MCS) determines the modulation and coding that is used to transmit the data portion of the PPDU. At the PHY, the amendment includes
mandatory support for BPSK, QPSK, 16-QAM, and 64-QAM modulation schemes (thus keeping the same modulation, interleaving, and coding architecture of 802.11n), plus two additional (and optional) 256-QAM with 3/4 and 5/6 coding rates. 802.11n allows the use of unequal modulations, that is, a single user can receive at one MCS in one stream and at a different one in another stream [7]. In contrast, 802.11ac only supports unequal modulation in the multi-users case, not for single-user.

The use of a particular MCS is dependent on a combination of the channel bandwidth used for the data transmission as well as the number of spatial streams. While most channel bandwidth options can support the highest MCS (i.e., 256-QAM), these are not valid for certain specific number of spatial streams. Notice that some MCS are not valid due to the fact that some of the parameters such as the number of data bits per symbol need to be integers and for certain coding rates this is not feasible. For a complete list of the different supported combinations and the parameters for each MCS refer to [4].

B. Coding Techniques

Forward Error Correction (FEC) is enabled in 802.11ac. Two different schemes are proposed for this. The first one is Binary Convolutional Coding (BCC) and it is mandatory. On the other hand, Low Density Parity Check (LDPC) coding is optional. FEC is used by 802.11ac with a coding rate of 1/2, 2/3, 3/4, or 5/6. Furthermore, Space-Time Block Coding (STBC) is also an optional feature of the amendment. Compared to 802.11n, the new standard proposes fewer modes that only include 2x1, 4x2, and also 3x2, and 4x3 as extension modes [9]. Each different mode corresponds to a different combination of transmitting and receiving antennas. For example, a 4x2 STBC mode indicates that 4 antennas are used at the transmitter whereas only 2 are used on the receiver side.

C. Frame Aggregation

At the MAC, the standard specifies the use of different frame aggregation schemes, and capability negotiations to indicate channel width for example, as well as VHT frame formats to enable the operation of the new PHY enhancements. In particular, it proposes mandatory use of frame aggregation via A-MPDU (Aggregate-MAC Protocol Data Unit), which was introduced in 802.11n. A-MPDUs are enhanced in 802.11ac by increasing their size thus packing several MPDUs within a single PPDU. This in turn increases channel utilization and MAC efficiency.

V. Conclusion

In this paper we present a detailed description of what we consider are the most important enhancements proposed in the 802.11ac amendment. These modifications are key to attain the performance gains dictated by this new amendment. We identify the changes to the channelization techniques as well as the multi-user MIMO capabilities as the paramount strategies for reaching gigabit wireless transmissions. Moreover, we have presented a comparison of the capabilities of 802.11ac stations with those of legacy devices.

REFERENCES


**Oscar Bejarano** received a B.S. degree from The University of Texas at Austin, TX, in 2009, and a M.S. degree from Rice University, Houston, TX, in 2011. Since then, he has been pursuing a Ph.D. degree in the Rice Networks Group at Rice University; all degrees have been in Electrical and Computer Engineering. His current research interests include MAC layer protocol design for MU-MIMO networks.

**Minyoung Park** received B.S. and M.S. degrees from Yonsei University, Seoul, Korea in 1993 and 1995, respectively and Ph.D. degree from The University of Texas at Austin, TX, USA in 2005, all in Electrical Engineering. From 1995 to 2001, he worked as a Senior Research Engineer at LG Electronics Inc. Since 2005, he has been a Wireless System Architect at Intel Corporation. His research interest is in physical and MAC layers of wireless communications systems.

**Edward Knightly** is a Professor of Electrical and Computer Engineering at Rice University in Houston, Texas. He received his Ph.D. and M.S. from the University of California at Berkeley and his B.S. from Auburn University. He is an IEEE Fellow, a Sloan Fellow, and a recipient of the National Science Foundation CAREER Award. He received the best paper award from ACM MobiCom 2008 and serves on the IMDEA Networks Scientific Council.
Table 1. Comparison of IEEE802.11 Standards

<table>
<thead>
<tr>
<th>Feature</th>
<th>802.11b</th>
<th>802.11g/a</th>
<th>802.11n</th>
<th>802.11ac</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Data Rate per Stream (Mbps)</td>
<td>11</td>
<td>54</td>
<td>&gt;100</td>
<td>&gt;500 (Assuming 80 MHz channels)</td>
</tr>
<tr>
<td>Frequency Band</td>
<td>2.4 GHz</td>
<td>2.4 GHz/ 5 GHz</td>
<td>2.4 GHz and 5 GHz</td>
<td>5 GHz</td>
</tr>
<tr>
<td>Channel Width (MHz)</td>
<td>20</td>
<td>20/20</td>
<td>20 and 40 (40 is optional)</td>
<td>20,40,80, 160, and 80+80 (last two are optional)</td>
</tr>
<tr>
<td>Transmission Technique</td>
<td>Direct Sequence Spread Spectrum (DSSS)</td>
<td>DSSS and Orthogonal Frequency Division Multiplexing (OFDM)</td>
<td>Orthogonal Frequency Division Multiplexing (OFDM)</td>
<td>Orthogonal Frequency Division Multiplexing (OFDM)</td>
</tr>
<tr>
<td>Maximum Number of Spatial Streams</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Beamforming Capable</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
![Figure 1. Channel Allocation in the U.S. [7]](image-url)
Figure 2. Primary and Secondary Channel Selection [4]
Figure 3. Enhanced RTS/CTS Mechanism [9]
Figure 4. Different MIMO Concepts: (a) SU-MIMO Beamforming and (b) Downlink-MU-MIMO Beamforming
Figure 5. Sounding Protocol with Multiple Beamformees [4]