Gigabit Wi-Fi

by William Stallings

Just as businesses and home users have generated a need to extend the Ethernet standard to speeds in the gigabit-per-second (Gbps) range, the same requirement exists for the wireless network technology known as *Wi-Fi*. Accordingly, IEEE 802.11, the committee responsible for wireless LAN standards, has recently introduced two new standards[1], 802.11ac[2] and 802.11ad[3, 4], which provide for Wi-Fi networks that operate at well in excess of 1 Gbps. These two new standards build on previous work by the IEEE 802.11 committee, which has introduced numerous versions of the wireless LAN standard over the years (Table 1).

Table 1: IEEE 802.11 Physical Layer Standards

Standard	802.11a	802.11b	802.11g	802.11n	802.11ac	802.11ad
Year introduced	1999	1999	2003	2000	2012	2014
Maximum data-transfer speed	54 Mbps	11 Mbps	54 Mbps	65 to 600 Mbps	78 Mbps to 3.2 Gbps	6.76 Gbps
Frequency band	5 GHz	2.4 GHz	2.4 GHz	2.4 or 5 GHz	5 GHz	60 GHz
Channel bandwidth	20 MHz	20 MHz	20 MHz	20, 40 MHz	40, 80, 160 MHz	2160 MHz
Antenna configuration	1 × 1 SISO	1 × 1 SISO	1 × 1 SISO	Up to 4 × 4 MIMO	Up to 8 × 8 MIMO, MU-MIMO	1 × 1 SISO

The evolution of Wi-Fi from the Mbps range to the Gbps range has required the use of three key technologies to enable the higher data rate: *Multiple-Input, Multiple-Output* (MIMO) antennas, *Orthogonal Frequency-Division Multiplexing* (OFDM), and *Quadrature Amplitude Modulation* (QAM). In this article, we first introduce each of these technologies, with a brief mention of their evolution from simpler technologies, and then look at the two new Gigabit Wi-Fi standards.

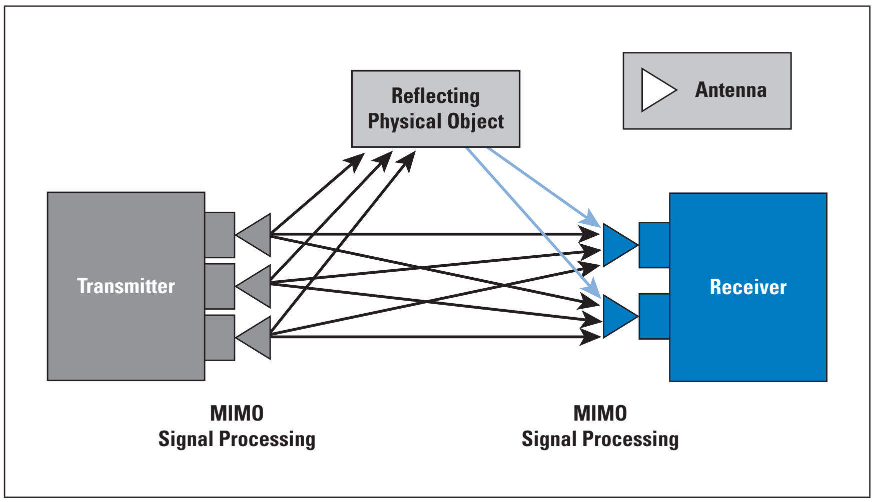
MIMO Antennas

In traditional two-way communication between two wireless stations, each station employs a single antenna for transmission and reception, referred to as *Single-Input, Single-Output* (SISO). In any wireless communication system, there are numerous forms of transmission impairments to deal with, and these impairments become increasingly significant at higher data rates. Of particular concern are noise and *multipath* effects. The latter term refers to the fact that a transmitted signal may reach a destination antenna by not just a direct path but by one or more paths that involve a reflection between source and destination.

These multiple arriving paths interfere with each other and make recovery of the data from the signal more challenging. One effective approach is to use multiple antennas, either at the transmitting end or the receiving end, or both.

In a MIMO scheme, the transmitter and receiver employ multiple antennas[5]. The source data stream is divided into n substreams, one for each of the n transmitting antennas. The individual substreams are the input to the transmitting antennas (multiple inputs). At the receiving end, m antennas receive the transmissions from the n source antennas via a combination of line-of-sight transmission and multipath caused by reflection (Figure 1). The output signals from all of the m receiving antennas (multiple outputs) are combined. With a lot of complex math, the result is a much better received signal than can be achieved with either a single antenna or multiple frequency channels. Note that the terms *input* and *output* refer to the input to the transmission channel and the output from the transmission channel, respectively.

Figure 1: MIMO Scheme



MIMO systems are characterized by the number of antennas at each end of the wireless channel. Thus an 8 × 4 MIMO system has 8 antennas at one end of the channel and 4 at the other end. In configurations with a base station, such as a cellular network or a Wi-Fi hotspot, the first number typically refers to the number of antennas at the base station. There are two types of MIMO transmission schemes:

- *Spatial diversity:* The same data is coded and transmitted through multiple antennas, effectively increasing the power in the channel proportional to the number of transmitting antennas. This process improves the *Signal-to-Noise Ratio* (SNR) for cell edge performance. Further, diverse multipath fading offers multiple "views" of the transmitted data at the receiver, thus increasing robustness. In a multipath scenario where each receiving antenna would experience a different interference environment, there is a high probability that if one antenna is suffering a high level of fading, another antenna has sufficient signal level.

- *Spatial multiplexing:* A source data stream is divided among the transmitting antennas. The gain in channel capacity is proportional to the available number of antennas at the transmitter or receiver, whichever is less. Spatial multiplexing can be used when transmitting conditions are favorable and for relatively short distances compared to spatial diversity. The receiver must do considerable signal processing to sort out the incoming substreams, all of which are transmitting in the same frequency channel, and to recover the individual data streams.

Multiple-user MIMO (MU-MIMO) extends the basic MIMO concept to multiple endpoints, each with multiple antennas. The advantage of MU-MIMO compared to single-user MIMO is that the available capacity can be shared to meet time-varying demands. MU-MIMO techniques are used in both Wi-Fi and *Fourth-Generation* (4G) cellular networks.

MU-MIMO has two applications:

- *Uplink—Multiple Access Channel (MAC):* Multiple end users transmit simultaneously to a single base station.
- *Downlink—Broadcast Channel (BC):* The base station transmits separate data streams to multiple independent users.

MIMO-MAC is used on the uplink channel to provide multiple access to subscriber stations. In general, MIMO-MAC systems outperform point-to-point MIMO, particularly if the number of receiver antennas is greater than the number of transmit antennas at each user. A variety of multiuser detection techniques are used to separate the signals transmitted by the users.

MIMO-BC is used on the downlink channel to enable the base station to transmit different data streams to multiple users over the same frequency band. MIMO-BC is more challenging to implement. The techniques employed involve processing of the data symbols at the transmitter to minimize interuser interference.

OFDM, OFDMA, and SC-FDMA

The technologies discussed in this section all derive from one of the oldest techniques used in communications: *Frequency-Division Multiplexing* (FDM). FDM simply means the division of a transmission facility into multiple channels by splitting the frequency band transmitted by the facility into narrower bands, each of which is used to constitute a distinct channel. Common examples of FDM are cable TV, broadcast radio, and broadcast television.

A common application of FDM is *Frequency-Division Multiple Access* (FDMA), which is a technique used to share the spectrum among multiple stations. In a typical configuration, a base station communicates with numerous subscriber stations.

Such a configuration is found in satellite networks, cellular networks, Wi-Fi, and WiMAX. Typically, the base station assigns bandwidths to stations within the overall bandwidth available. Key features of FDMA include the following:

- Each channel is dedicated to a single station; it is not shared.
- If a channel is not in use, it is idle and the capacity is wasted.
- Individual channels must be separated by guard bands to minimize interference.

Thus, this scheme divides the available bandwidth into multiple nonoverlapping bands, or channels, as with FDM. The channels are allocated across multiple stations, thus allowing multiple access to the available bandwidth.

Orthogonal Frequency-Division Multiplexing (OFDM), also called *multicarrier modulation,* is a form of FDM in which a single data stream transmits over the available bandwidth, sending some of the bits on each channel. Thus, with OFDM, all of the channels are dedicated to a single data source.

Suppose we have a data stream operating at R bps and an available bandwidth of NB, centered at f. The entire bandwidth could be used to send the data stream, in which case each bit duration would be $1/R$. The alternative is to split the data stream into N substreams, using a serial-to-parallel converter. Each substream has a data rate of R/N bps and is transmitted on a separate subcarrier, with spacing between adjacent subcarriers of B. Now the bit duration is N/R.

The OFDM scheme uses advanced digital-signal-processing techniques to distribute the data over multiple carriers at precise frequencies. The relationship among the subcarriers is referred to as *orthogonality.* The result is that the peaks of the power spectral density of each subcarrier occur at a point at which the power of other subcarriers is zero. With OFDM, the subcarriers can be packed tightly together because there is minimal interference between adjacent subcarriers.

OFDM has several advantages. First, frequency selective fading affects only some subcarriers and not the whole signal. If the data stream is protected by a forward error-correcting code, this type of fading is easily handled. More important, OFDM overcomes *Intersymbol Interference* (ISI) in a multipath environment. ISI has a greater impact at higher bit rates, because the distance between bits, or symbols, is smaller. With OFDM, the data rate is reduced by a factor of N, increasing the symbol time by a factor of N. Thus, if the symbol period is T for the source stream, the period for the OFDM signals is NT. This modulation scheme dramatically reduces the effect of ISI. As a design criterion, N is chosen so that NT is significantly greater than the root-mean-square delay spread of the channel.

A variant of OFDM is *Orthogonal Frequency-Division Multiple Access* (OFDMA). Like OFDM, OFDMA employs multiple closely spaced subcarriers, but the subcarriers are divided into groups of subcarriers. Each group is named a subchannel. The subcarriers that form a subchannel need not be adjacent. In the downlink, different subchannels may be intended for different receivers. In the uplink, a transmitter may be assigned one or more subchannels.

Subchannelization defines subchannels that can be allocated to *Subscriber Stations* (SSs) depending on their channel conditions and data requirements. Using subchannelization, within the same time slot a *Base Station* (BS) can allocate more transmit power to user devices (SSs) with lower SNR, and less power to user devices with higher SNR. Subchannelization also enables the BS to allocate higher power to subchannels assigned to indoor SSs, resulting in better in-building coverage. Subchannels are further grouped into *bursts,* which can be allocated to wireless users. Each burst allocation can be changed from frame to frame as well as within the modulation order, allowing the base station to dynamically adjust the bandwidth usage according to the current system requirements.

Subchannelization in the uplink can save user-device transmit power because it can concentrate power only on certain subchannel(s) allocated to it. This power-saving feature is particularly useful for battery-powered user devices.

Another variant of OFDM is *Single-Carrier FDMA* (SC-FDMA), which is a relatively recently developed multiple access technique with similar structure and performance to OFDMA. One prominent advantage of SC-FDMA over OFDMA is the lower *Peak-to-Average Power Ratio* (PAPR) of the transmit waveform, which benefits the mobile user in terms of battery life and power efficiency. OFDMA signals have a higher PAPR because, in the time domain, a multicarrier signal is the sum of many narrowband signals. At some time instances, this sum is large and at other times small, meaning that the peak value of the signal is substantially larger than the average value.

Thus, SC-FDMA is superior to OFDMA. However, it is restricted to uplink use because the increased time-domain processing of SC-FDMA would entail considerable burden on the base station. SC-FDMA performs a complex digital-signal-processing operation, which spreads the data symbols over all the subcarriers carrying information and produces a virtual single-carrier structure. This structure then is passed through the OFDM processing modules to split the signal into subcarriers. Now, however, every data symbol is carried by every subcarrier.

For OFDM, a source data stream is divided into *N* separate data streams and these streams are modulated and transmitted in parallel on *N* separate subcarriers, each with bandwidth *B*. The source data stream has a data rate of *R* bps, and the data rate on each subcarrier is *R/N* bps. For SC-FDMA, it appears that the source data stream is modulated on a single carrier (hence the SC prefix to the name) of bandwidth *N* x *B* and transmitted at a data rate of *R* bps. The data is transmitted at a higher rate, but over a wider bandwidth compared to the data rate on a single subcarrier of OFDM. However, because of the complex signal processing of SC-FDMA, the preceding description is not accurate. In effect, the source data stream is replicated *N* times, and each copy of the data stream is independently modulated and transmitted on a subcarrier, with a data rate on each subcarrier of *R* bps. Compared with OFDM, we are transmitting at a much higher data rate on each subcarrier, but because we are sending the same data stream on each subcarrier, it is still possible to reliably recover the original data stream at the receiver.

A final observation concerns the term *multiple access*. With OFDMA, it is possible to simultaneously transmit either from or to different users by allocating the subcarriers during any one time interval to multiple users. This transmission is not possible with SC-FDMA: At any given point in time, all of the subcarriers are carrying the identical data stream and hence must be dedicated to one user. But over time, it is possible to provide multiple access by allocating the bandwidth to different users at different times.

Quadrature Amplitude Modulation

To transmit digital data over an analog signal, such as a Wi-Fi radio signal, it is necessary to encode the data onto the signal by some form of modulation. The simplest approach is to provide two different signals to be transmitted during a bit time, with one signal element representing binary one and one representing binary zero. Thus, *Amplitude Shift Keying* (ASK) involves transmitting a constant-frequency signal but varying the signal amplitude between two values. With *Phase Shift Keyin*g (PSK), two different phase shifts of the same carrier frequency are used to represent the two binary digits. As the data rate increases, the length of each signal element representing a single bit shortens. That is, the signal element is shorter both in duration and in physical length while being transmitted. Thus, a short noise burst or a short transmission impairment of any sort affects more bits as the data rate increases. One standard way of coping with this problem is to encode more than a single bit in each signal element. For example, if four amplitudes are used instead of two, then each signal element can encode two bits. One of the most effective techniques for encoding multiple bits per signal element is *Quadrature Amplitude Modulation* (QAM).

QAM uses two basic principles for encoding digital data onto an analog signal: ASK and PSK. QAM takes advantage of the fact that it is possible to send two different signals simultaneously on the same carrier frequency by using two copies of the carrier frequency, one shifted by 90° with respect to the other. For QAM, each carrier is ASK modulated. The two independent signals are simultaneously transmitted over the same medium. At the receiver, the two signals are demodulated and the results are combined to produce the original binary input.

If two-level ASK is used, then each of the two streams can be in one of two states and the combined stream can be in one of $4 = 2 \times 2$ states. If four-level ASK is used (that is, four different amplitude levels), then the combined stream can be in one of $16 = 4 \times 4$ states. This modulation is known as 16-QAM. Systems using 64 (64-QAM) and even 256 states have been implemented. The greater the number of states, the higher the data rate that is possible within a given bandwidth. However, the greater the number of states, the higher the potential error rate due to noise and attenuation.

IEEE 802.11ac

IEEE 802.11ac operates in the 5-GHz band, as do the older and slower standards 802.11a and 802.11n. It is designed to provide a smooth evolution from 802.11n. This new standard uses advanced technologies in antenna design and signal processing to achieve much greater data rates, at lower battery consumption, all within the same frequency band as the older versions of Wi-Fi. The new standard achieves much higher data rates than 802.11n by means of enhancements in three areas:

- *Bandwidth:* The maximum bandwidth of 802.11n is 40 MHz; the maximum bandwidth of 802.11ac is 160 MHz.
- *Signal encoding:* The 802.11n standard uses 64 QAM with OFDM, and 802.11ac uses 256 QAM with OFDM. Thus, more bits are encoded per symbol. Both schemes use forward error correction with a code rate of 5/6 (ratio of data bits to total bits).
- *MIMO:* With 802.11n, the maximum number of antennas is 4 channel input and 4 channel output antennas. The 802.11ac standard increases this maximum to 8×8.

Two other changes going from 802.11n to 802.11ac are noteworthy. The 802.11ac standard includes the option of MU-MIMO, meaning that on the downlink, the transmitter can use its antenna resources to transmit multiple frames to different stations, all at the same time and over the same frequency spectrum. Thus, each antenna of a MU-MIMO access point can simultaneously communicate with a different single-antenna device, such as a smartphone or tablet, thereby enabling the access point to deliver significantly more data in many environments.

IEEE 802.11ad

IEEE 802.11ad is a version of 802.11 operating in the 60-GHz frequency band. This band offers the potential for much wider channel bandwidth than the 5-GHz band, enabling high data rates with relatively simple signal encoding and antenna characteristics. Few devices operate in the 60-GHz band, meaning that communication experiences less interference than in the other bands used for Wi-Fi. However, at 60 GHz, 802.11ad operates in the millimeter range, resulting in some undesirable propagation characteristics:

- Free space loss increases with the square of the frequency, so losses are much higher in this range than in the ranges used for traditional microwave systems.
- Multipath losses can be quite high. *Reflection* occurs when an electromagnetic signal encounters a surface that is large relative to the wavelength of the signal; *scattering* occurs if the size of an obstacle is on the order of the wavelength of the signal or less; and *diffraction* occurs when the wavefront encounters the edge of an obstacle that is large compared to the wavelength.
- Millimeter-wave signals generally don't penetrate solid objects.

For these reasons, 802.11ad is likely to be useful only within a single room. Because it can support high data rates and, for example, could easily transmit uncompressed high-definition video, it is suitable for applications such as replacing wires in a home entertainment system, or streaming high-definition movies from your cell phone to your television.

Prospects for Gigabit Wi-Fi

Gigabit Wi-Fi holds attractions for both office and residential environments, and commercial products are beginning to roll out. In the office environment, the demand for ever greater data rates has led to Ethernet offerings at 10 Gbps, 40 Gbps, and most recently 100 Gbps. These stupendous capacities are needed to support blade servers, heavy reliance on video and multimedia, and multiple offsite broadband connections. At the same time, the use of wireless LANs has grown dramatically in the office setting to meet needs for mobility and flexibility. With the gigabit-range data rates available on the fixed portion of the office LAN, gigabit Wi-Fi is needed to enable mobile users to use the office resources effectively. IEEE 802.11ac is likely to be the preferred gigabit Wi-Fi option for this environment.

In the consumer and residential market, IEEE 802.11ad is likely to be popular as a low-power, short-distance wireless LAN capability with little likelihood of interfering with other devices. IEEE 802.11ad is also an attractive option in professional media production environments in which massive amounts of data need to be moved short distances.

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