Understanding and Optimizing 802.11n

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Introduction: Wireless networks have always been difficult to implement and understand for both home users and network administrators. Wireless networking marries two equally complicated yet relatively unrelated technologies: networking technologies with radio frequency (RF) technology. Each technology has exclusive industry professionals, but rarely is expertise in both technologies available.

This document is designed to assist computer network users in deploying successful wireless network while sharing the education and reasoning behind the technology.

Related Parties: Wi-Fi® is a registered trademark made of the Wi-Fi Alliance created to give an easier to understand name for wireless networking/wireless local area network (WLAN) based on the IEEE 802.11 standard. To assist with the understanding of technologies, the following are brief descriptions of relevant companies, committees and alliances that are involved in specifying technology and policies relating to wireless networking products.

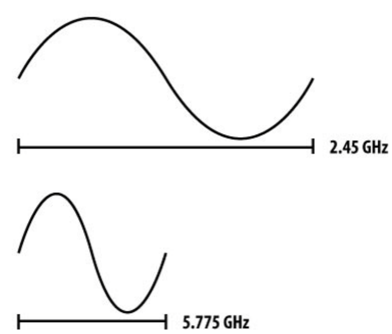
- **IEEE (Institute of Electrical and Electronics Engineers) –** IEEE is a professional association that creates electronics and electrical related technologies with aim to develop industry standards for use by manufacturers across the board. IEEE 802.11 is the standards group created and maintained by the IEEE as it relates to wireless networking. The letter after 802.11 (e.g. 802.11g) shows an amended standard governed under IEEE 802.11.
- **Wi-Fi Alliance / Wi-Fi CERTIFIED –** The Wi-Fi Alliance is a trade association that functions mainly to promote wireless networking and to ensure compatibility via a certification program amongst various wireless networking devices.
- **FCC (Federal Communications Commission) –** The FCC is an agency of the US government tasked with regulating non-federal/commercial use of radio spectrum. The FCC governs for the United States, while other countries have similar agencies regulating the usage and types of radio signals allowed to be used by the public.

These associations and agencies are just a few of the parties involved in establishing standards, rules, laws, etc. Throughout this document, it will become evident that the unique role each party plays has a serious effect on wireless network deployment.

Early WLAN History: This section provides a good background of 802.11 technology; however, understanding the history is not necessarily essential in determining how to successfully deploy an 802.11n network.

In June 1997, the IEEE 802.11 standard was officially ratified and released allowing manufacturers to design and produce products. Early products operated in the 2.4 GHz (2400 MHz) radio spectrum and were generally slow (2 Mbps) and not widely embraced. Issues with device interoperability, network/Internet penetration, slow performance and high cost prohibited mainstream adoption. To advance and improve the technology, IEEE subgroups worked on enhanced protocols. Namely, 802.11a and 802.11b groups worked concurrently on differing technical approaches to improve the standard.

Around mid-1999, both amended standards 802.11a and 802.11b were released. The 802.11b standard increased performance to 11 Mbps in the 2.4 GHz band and uses the same modulation technique (DSSS) as 802.11. On the other hand, the 802.11a standard increased performance up to 54 Mbps by utilizing the higher frequency 5 GHz radio spectrum as well as a different, more efficient and arguably more complex radio transmission technique (OFDM). While 54 Mbps is notably faster than 11 Mbps, the cost of 802.11a equipment proved to be more expensive, and the reduced ability for 5 GHz radio waves to penetrate obstructions such as walls made it less popular than the lower cost and longer range 802.11b technology. The figure to the right shows the higher frequency, tighter sine wave of 5 GHz.



At the turn of the century and shortly thereafter, 802.11b products grew in popularity for home and business use. The first public "hot-spot" type networks were powered by 802.11b as were the first laptop PCs that used integrated WLAN technology. This and other popularity resulted in 802.11b being the first widely accepted WLAN technology. In 1999, around the release timing of 802.11b, the Wireless Ethernet Compatibility Alliance (WECA) was formed by a group of leading wireless product manufacturers to ensure product compatibility amongst manufacturers' 802.11b products. In 2002, WECA renamed itself the Wi-Fi Alliance. WECA and the Wi-Fi Alliance was successful in promoting and certifying interoperability between different manufacturers products, resulting in 802.11 wireless technology working well across brands and gaining mainstream popularity.

The popularity of 802.11b was undeniable; however, 802.11a enjoyed early commercial success in the market as a specialty technology designed for higher throughput applications and more specific applications like wireless bridging.

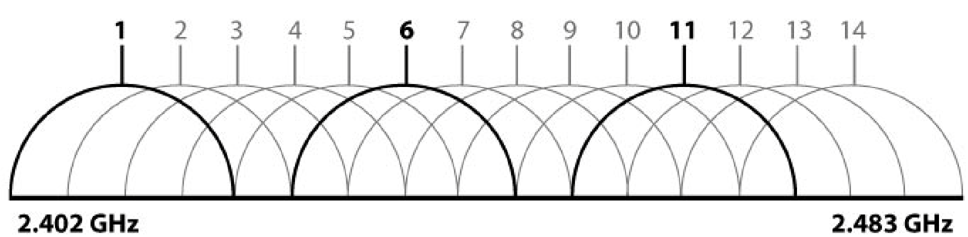
802.11g was the next major standard released in summer 2003 as a successor of 802.11b. The main technical goals of 802.11g were to improve performance while providing good range and backward compatibility with 802.11b. As such, 802.11g operated in the same 2.4 GHz spectrum as 802.11b, but it used the more efficient OFDM modulation technique of 802.11a. This allowed 802.11g to offer the increased performance (54 Mbps) of 802.11a while foregoing the reduced range of the higher frequency 5 GHz spectrum.

Furthermore, 802.11g was compatible with 802.11b technology so it worked with existing 802.11b devices and infrastructure. Ultimately, products that supported multiple standards (e.g. 802.11ab or 802.11ag) were released; these products referred to as dual band, offered independent radios and antennae for each band and allowed operation on either or both bands.

In regard to backward compatibility, wireless networking is a lowest common denominator technology; if an 802.11g product connects to an 802.11b device, both will operate under the lower specification of 802.11b devices. Additionally, backward compatibility can only occur in the same frequency band (2.4 GHz or 5 GHz).

2.4 GHz and 5 GHz – Congestion and Other Considerations: While the popularity of 802.11b and subsequent 802.11g grew, an apparent issue began to arise regarding radio spectrum congestion. The FCC states operation of 2.4 GHz devices on unlicensed bands in the United States should occur between the frequencies of 2401 and 2473 MHz, allowing for use of 72 MHz of spectrum. The 5 GHz unlicensed band ranges from ~5200 MHz to ~5800 MHz, or a range of around 600 MHz. It's worth noting that other countries allow for operation in slightly wider ranges, with the US being a bit more restrictive.

IEEE 802.11, 802.11b, 802.11a and 802.11g all use a channel based system to adjust the exact frequency the networks operate on. Although the 2.4 GHz spectrum is around 70 MHz wide in the US, the frequency used by a single WLAN device is 20 MHz wide. As such, channel numbers are used to specify at what area of the frequency a particular device's center operates. On normal home and business Wi-Fi networks, this channel is specified by the access point and not the wireless client devices. In the US, this creates 11 selectable channels with 5 MHz of separation, where channel 1 center frequency is 2412 MHz while channel 11 center frequency is 2462 MHz. Since the entire operation consumes 20 MHz, only three independent wireless channels can be used at the same time without interfering each other (Channels 1, 6 and 11), each with at least 25 MHz of separation. The graphic below shows all 14 channels available for 802.11 use in the 2.4 GHz band. In the US, channels 12, 13 and 14 are illegal channels per the FCC and are not supported in equipment sold in the US.



IEEE 802.11 technologies are designed to pick up interference from other Wi-Fi devices and some additional wireless electronics, however this interference drastically reduces wireless performance and speed. Additionally, there are many wireless devices in the 2.4 GHz space that are not WLAN related, and they may or may not have been designed to handle interference. Devices like home cordless phones can operate in the 2.4 GHz space but are not designed to perform with interference. As a constant wave device with higher power limits than WLAN equipment, cordless phones can easily stop a wireless network from working altogether.

To conclude, with so many wireless LAN devices out there in addition to other equipment like cordless phones, baby monitors, microwave ovens (they emit radio waves in the 2.4 GHz space) and Bluetooth devices, wireless congestion is a serious issue for wireless networking devices. As device popularity has increased, usage of 5 GHz technologies like 802.11a has also increased, providing some refuge from overly congested radio spectrums. With about 10x the usable bandwidth and many fewer devices to compete with, much of the 5 GHz band is often interference free.

Wireless Performance in General (Not all Mbps are Equal): One of the most common confusions surrounding wireless networking devices is performance. Historically, interface speeds with computer related technologies have been highly accurate. For example, a 100 Mbps wired Ethernet connection is capable of regularly producing 100 Mbps data transfer speeds.

Wireless networking equipment involves much greater complexities. Unlike a wired Ethernet connection, wireless communications cannot be ensured. When a wireless device sends data to another wireless device, the sending device cannot determine if the receiving device acquired the message unless the receiving device positively confirms it. This is called an acknowledgement. While many issues can prevent two wireless devices from successfully communicating, here are a few:

- Devices are too far away from each other
- Another device was transmitting at the same time
- An external interference source caused excessive interference, etc.

To work around these issues, a wireless device sends data in small chunks with additional verification data (checksum/CRC). The client receives the small chunk and compares it with the verification data. If the verification is successful, the receiving device then sends a message (ACK) back to the original sending device informing it that the data was received successfully. Once that message is received, the sending device begins sending its next chunk of data. On top of this, only one wireless networking device in a network will communicate at any given time so there is additional technology and overhead to make sure that devices are only communicating in turn.

These advanced and tedious methods of sending data require a lot of overhead. Using 802.11g as an example, it offers performance of up to 54 Mbps. Of the 54 Mbps, roughly half of the wireless data being sent is overhead to support transmission. This makes actual data throughput roughly half of the maximum, or around 25-27 Mbps of actual, usable data throughput.

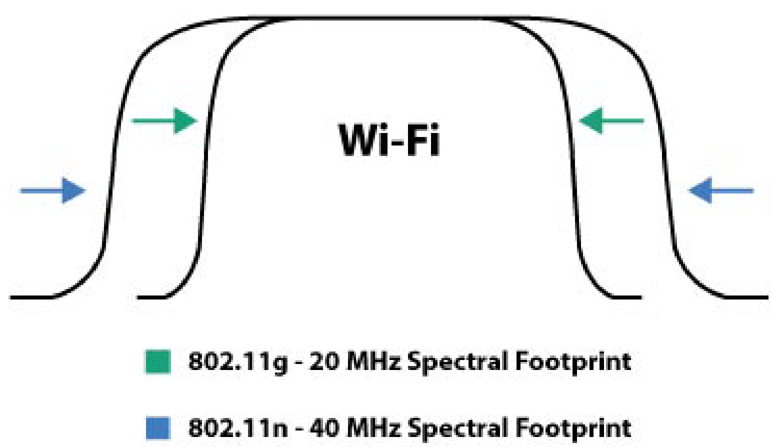
Finally, the rated performance (e.g. 54 Mbps) is assuming a link integrity that is pretty close to perfect. As a signal weakens or interference is increased, this speed is greatly affected. Wireless networking technologies are capable of transmitting very far given their power output. To achieve long range, the devices negotiate slower rates. The signal strength and negotiated speed is often displayed to users in the form of signal bars and/or link speed. The reported link speed always considers the additional overhead and does not indicate the speed at which data will actually be transmitted.

802.11n History: IEEE 802.11n technology was officially released in late 2009, although 802.11n technology-based devices had been shipping since 2006. The 802.11n standard is by far, to date, the most complicated wireless networking standard; it is significantly more complex than 802.11a, 802.11b or 802.11g. As this document proceeds, it will focus on education so that one can deploy a properly optimized and configured 802.11n network.

Much of the complexity of 802.11n involves its various optional configurations and standards. Earlier 802.11 technologies did not offer this wide range of options.

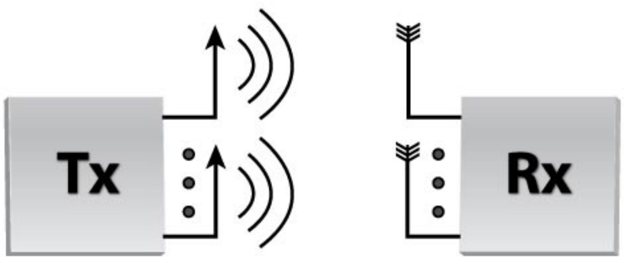
802.11n provides enhanced performance and range over prior 802.11 technologies. In its most basic form, 802.11n operates in the 2.4 GHz space while maintaining backward compatibility with 802.11g. Optionally, 802.11n devices can also operate in the 5 GHz space; such 802.11n devices are described as dual band.

Additionally, 802.11n adds two significant new technologies: MIMO (multiple input, multiple output – pronounced My-Moh) and 40 MHz wide channels. MIMO uses multiple antennae to transmit and receive data over multiple data streams, increasing performance and range significantly. The 40 MHz channel width allows for twice the usable radio spectrum to transmit data, essentially doubling performance compared to a normal 20 MHz channel width (often called Channel Bonding).



802.11n Performance (MIMO 2x2, 3x3, etc): MIMO allows for multiple antenna paths to be used to combine multiple signals for increased range and performance. The amount of antenna paths per device can be complicated to understand, but it has serious implications for performance. Many Wi-Fi equipment manufacturers choose to use terminology like 2x2 (two-by-two) to indicate what MIMO technology is in the product.

- 2x2 – 2 transmit antennas/paths and 2 receive antennas/paths
- 3x3 – 3 transmit antennas/paths and 3 receive antennas/paths



It is possible to have a different amount of transmit and receive antennas. As such, some 2x3 products exist on the market providing some benefit over 2x2 but not the same benefit as 3x3.

Explaining spatial multiplexing and the actual scientific benefit of MIMO is beyond the scope of this document, so the benefit of MIMO is simplified here into two categories: range and speed. Having more spatial streams does increase the range, but this document will mainly focus on speed impact.

Each 802.11n stream provides a maximum signaling rate of 150 Mbps (compared to the 802.11g single stream of 54 Mbps). It's crucial to note that to achieve 150 Mbps, the stream must operate at 40 MHz wide. Since 2.4 GHz spectrum is highly congested, running 40 MHz mode in 2.4 GHz is often difficult if not impossible to do (more on this in the next section). Thus a 2x2 product is capable of two 150 Mbps streams and would be considered a 300 Mbps wireless device and a 3x3 product a 450 Mbps device.

Finally, there are some 1x1 wireless devices on the market. These products utilize a single 802.11n transmit antenna and a single receive antenna. 1x1 devices are commonly used in portable electronics such as PDAs, mobile phones, etc. due to their limited size; installing multiple antennas is a challenge. The Wi-Fi Alliance allows certification for 1x1 client devices, but it does not allow certification of 1x1 access points. Even so, many uncertified 1x1 access point devices exist in the market, including some from Buffalo Technology. Such access point devices utilize 802.11n technology and are often called "N150", though they do not state Wi-Fi certification and sometime avoid mentioning 802.11n specifically. To summarize, 1x1 wireless client devices are extremely common while 1x1 access points are less prevalent due to the Wi-Fi Alliance specifications.

At the time of writing, some 4x4 (600 Mbps max) wireless devices are available on the market, but they are specialty products used for high speed point-to-point linking.

MIMO configurations are also a lowest common denominator technology. Therefore, if a 2x2 device connects to a 3x3 device, the wireless communication between devices would occur at 300 Mbps.

The following table shows the maximum link rate for various configurations using both channel widths; please note that manufacturers always market products based on a 40 MHz maximum speed rate:

MIMO Configuration	Max Rate: 20 MHz Channel Width	Max Rate: 40 MHz Channel Width
1x1	65-72 Mbps	150 Mbps
2x2	130-144 Mbps	300 Mbps
3x3	195-216 Mbps	450 Mbps
4x4	260-288 Mbps	600 Mbps

Maximum speeds shown for 802.11n are independent of the frequency band on which the network operates.

Internal and External Antennas: As an essential component of all wireless devices to transmit data through electromagnetic waves, some antennas used are intended to increase the transmission and receiving capability of the wireless networking equipment, resulting in improved performance and range.

While many client devices such as phones and tablets have minimal space for large antennas, wireless access points can generally accommodate the use of sizable antennas. While internal antennas allow for a sleek, modern chassis design, external adjustable antennas provide distinct advantages:

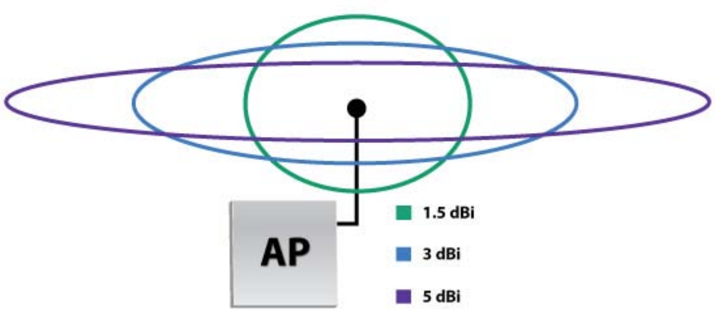
- External antennas are larger and are usually higher gain than internal antennas
- External antennas allow adjustability to tune polarity for optimal range and performance
- External antennas are sometimes removable and can be upgraded with better performing options

Non-adjustable internal PCB antennas
Very small ~1-1.5 dbi gain

Adjustable external high-gain antennas
Large ~5 dbi gain (more than 2x the power)

Configurable coverage
Ideal pattern for 2 story-home

Buffalo offers a variety of AirStation access points with internal and external antenna options; all AirStation high-performance models feature external antennas.
A key performance figure in determining how well input power is amplified is called gain, a measurement of an antenna's efficiency and directivity. This gain in decibles is called antenna gain and is expressed in dBi. Access point internal antennas usually carry signal gains of 1-1.5 dBi, while external antennas typically carry gains of 2-5 dBi. A 3 dBi gain advantage from external antennas represents double the transmit power, so the performance increase from external antennas can be quite significant. Some products include high-gain antennas that offer even larger dBi gains.



Vertical higher gain antennas have increased x-axis coverage at the cost of y-axis coverage

Antennas installed out of the box on consumer access points are almost always omnidirectional, meaning they radiate in 360 degree horizontal (x-axis) patterns. Adjusting the angle of the antenna provides the ability to change the vertical (y-axis) signal.

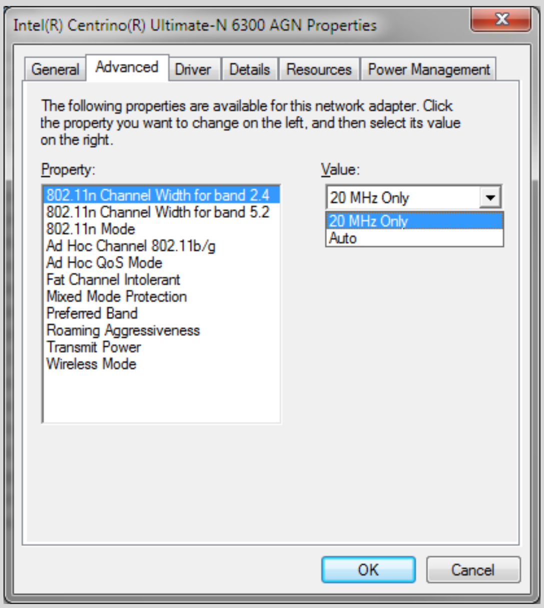
40 MHz Limitations: A great source of confusion for users of 802.11n equipment is the inability to achieve maximum speed with their devices. This is particularly so on the 2.4 GHz band. To avoid excessive interference, the Wi-Fi Alliance mandates for certification that Wi-Fi CERTIFIED® access point devices must ship by default in 20 MHz mode in the 2.4 GHz channel (40 MHz width is approved in 5 GHz devices).

Additionally, many manufacturers recommend not using 40 MHz wide channels in 2.4 GHz due to interference. Most 802.11n access point devices shipping at time of this publication are single-band 2.4 GHz only, with nearly all configured by default to use 20 MHz of space, which is not optimized to achieve maximum performance upon installation. Some products, most notably those with Apple Airport®, simply do not allow use of 40 MHz connections in 2.4 GHz in their wireless products. Additionally, 40 MHz mode is not supported if backward compatibility with 802.11b is required.

Various technologies exist in 802.11n to prevent operation of 40 MHz if neighboring networks stand to be too negatively affected. This is sometimes called “Safe Neighbor” technology. Generally, it’s good practice to only enable 40 MHz mode in 2.4 GHz if you are in an isolated area where neighboring networks won’t be negatively affected.

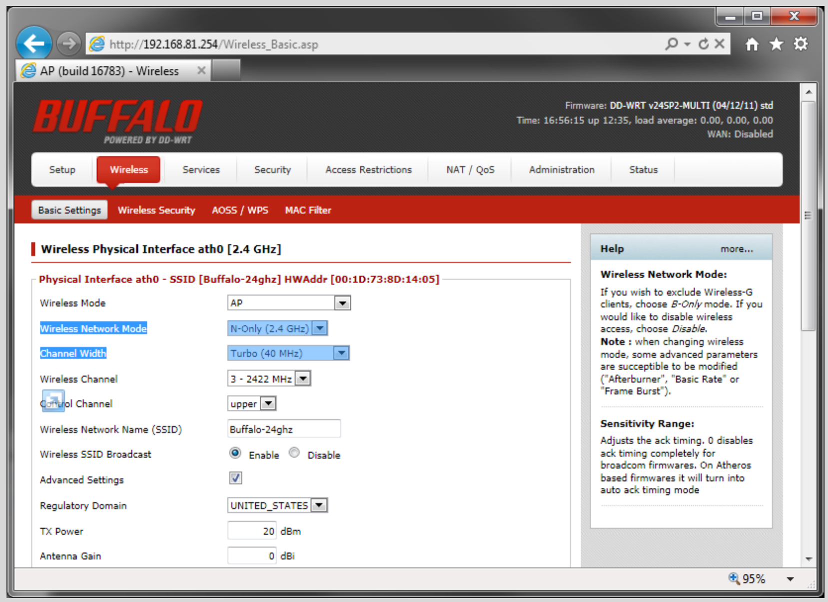
Optimization Opportunity: To achieve maximum wireless performance on 802.11n equipment, 40 MHz mode must be enabled and working. This requires checking both the wireless access point and clients to make sure they are configured to operate in 40 MHz mode. Be aware there is no guarantee that operating at 40 MHz will work, especially if neighboring access points are present. Provided is an example for adjusting an Intel® Centrino® client adapter and a Buffalo wireless router to support 40 MHz; different equipment will vary slightly.

Intel Client:



Under Properties->Advanced, change *Property* “802.11n Channel Width for band 2.4” from *Value* “20 MHz Only” to “Auto”.

Buffalo Router:



Under Wireless->Basic Settings, change *Wireless Network Mode* to “NG-Mixed” or “N-Only” and change *Channel Width* to “Turbo (40 MHz)”.

40 MHz operation in the 5 GHz spectrum is rarely an issue and is most often enabled by default on all products that are dual band.

Importance of Best Channel: To ensure the best overall wireless performance, a wireless network should be configured to operate on the clearest channel. This also increases the likelihood of sustaining 40 MHz channel widths. Expensive devices called spectrum analyzers can measure the RF noise generated by any device in a given spectrum. This gives a snapshot into the energy being produced and would allow for the most optimal channel selection. However, spectrum analyzers are extremely expensive and generally difficult to use. However, there’s an easy and free alternative that’s almost as good.
Any PC or Mac® computer with wireless networking support can actually make for a pretty good spectrum analyzer. However, it is limited to only see the interference caused by wireless networks, not other 2.4 GHz noise sources like Bluetooth devices, microwave ovens, cordless phones, etc. However, wireless networks are some of the most important devices to consider since the wireless devices in your network actively follow what other wireless networks are doing and adjust accordingly.

Optimization Opportunity:
There is great free software that turns any Windows® or Mac computer into a decent Wi-Fi spectrum analyzer. Below are recommendations:

PC: **InSSIDer** - http://www.metageek.net/products/inssider/
Mac: **KisMac** - http://kismac-ng.org/
Linux: Linux offers the most impressive assortment of extremely capable surveying tools

The analyzer software installs easily and is relatively self-explanatory. It provides an active view into the wireless networks in range, what channels those networks are on and at what signal strength those networks operating. Networks with a stronger signal will interfere more than those with a weaker signal.

Using the analyzer software near the access point, locate the clearest channel area and set your access point to that channel. Some access points use an automatic channel setting feature to automatically perform this task, but in a simpler fashion. Also, most automatic features just check for the clearest channel once at the time of installation. Because new wireless networks are frequently deployed and existing wireless networks may change channels, it's a good idea to regularly inspect your environment and search for the clearest channel.

Which Wireless Devices to Purchase? With so many different wireless technologies to purchase on the market today, having a good understanding of the devices you will use and your goals is important. This document will conclude with some overly generalized advice:

- Purchase an access point (or wireless router) that is compatible with the devices on your network. There's a good chance you don't have any client devices with a 3x3 (450 Mbps) radio, so buying a 3x3 router may be unnecessary. However, you do have the option of purchasing aftermarket, usually USB wireless client adapters to replace internal wireless cards.

- The 2.4 GHz band is very congested. If you live in an urban area, consider a dual band access point. Many PC and Mac computers and even tablets now have built-in dual band client support. The quality of your connection and performance, especially at close range will improve on 5 GHz. Please note that distance of the 5 GHz range will not be as far as 2.4 GHz, however, a dual band access point/wireless router will allow you to operate both networks simultaneously so you can enjoy the best of both worlds. Client devices that support dual band may not say 5 GHz, but if they list 802.11n and 802.11a as supported standards; this indicates they support 802.11n in 5 GHz.

- To achieve the full, marketed performance of any wireless device, you will need to operate at 40 MHz with minimal interference; otherwise, performance will degrade to various degrees.

- If long range is desired, there are many long range access point devices and client adapters on the market. Look for amplified products or products with high gain antennas installed. Most consumer and small office grade equipment transmits at ~50mW. Buffalo AirStation High Power Wireless Routers & Access Points user power amplifiers and high gain antennas to transmit more power than competing products.

  Note: Increased power from amplification does not increase range proportionately with unamplified client devices, however gain from higher gain antennas is mutually beneficial.

Conclusion: Modern 802.11n wireless networks vary heavily depending on equipment used as well as configuration. Understanding the technology, regulations and limitations surrounding wireless networks can help tremendously in obtaining good performance out of your network.