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Choosing the Best 802.11n Solution for all HD Video Home-Networking Needs

Originally published in Aug. 2010 under the company name Quantenna® Communications, Inc.

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When deploying home networks, a recurring question is what kind of wireless technology is *good enough* for supporting multiple streams of HD video, while also delivering the lowest cost of deployment. Although there are several wired options for delivering compressed video in home networks, including MOCA, HPNA and PLC, they don't offer the same coverage and cost-effectiveness as wireless technology. Wireless 802.11n is the only solution capable of easily and economically reaching every corner of the home, and potentially replacing wired technologies to significantly extend home-networking coverage for a variety of consumer products, from TVs, residential gateways (RGWs) and set-top boxes (STBs) to game consoles, IP phones and mobile devices (see Figure 1).

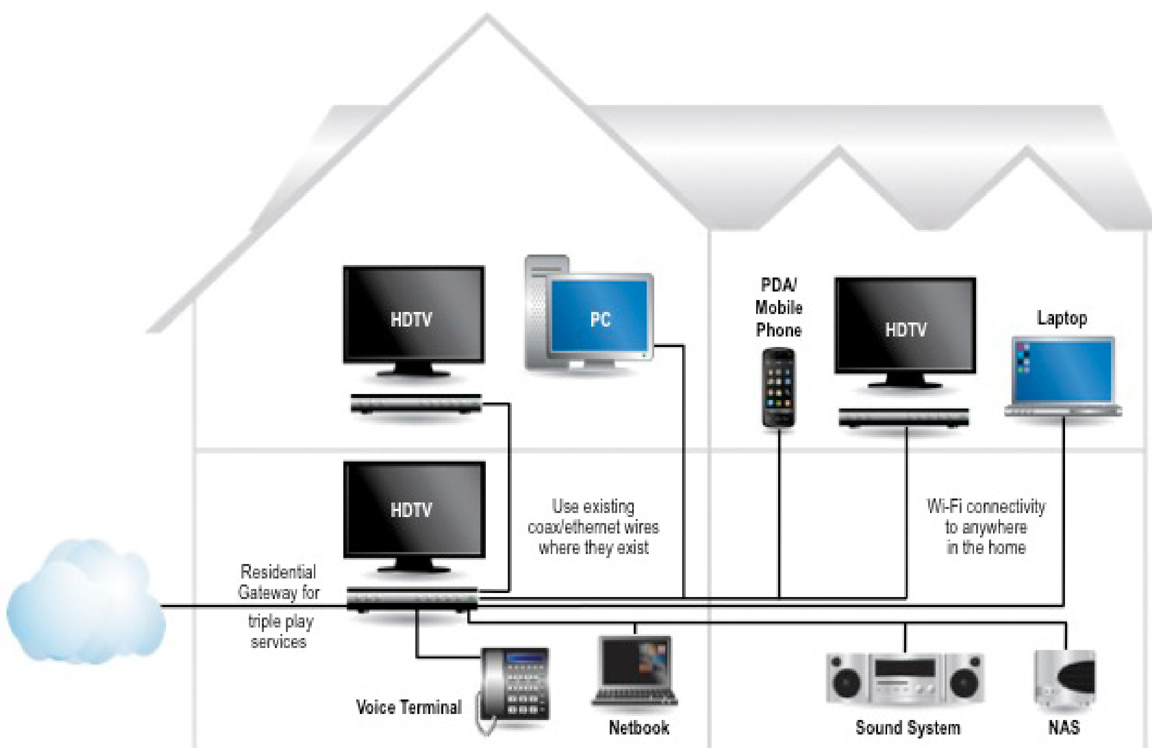

Figure 1. The Ideal Home-network Implementation with Logical Connections between Devices, Located in Multiple Locations Throughout the Home

Among wireless options, 802.11n is the only viable solution with the necessary performance and reliability for carrier-grade service deployment using all of these consumer products. This paper will look at the various 802.11n technologies that are available, and how they meet key requirements as both HD content and user expectations evolve and influence carrier services, roll-out strategies and the resulting consumer experience.

Requirements – Part 1: Signal Quality

Understanding What is "Good Enough" in Watching HDTV

Determining "viewing satisfaction" is a fairly complex and involved process with both objective and subjective components. Objective components are normally evaluated using long-term averages of statistical packet error measurements, which can be used to define, for example, a bad connection (low signal-to-noise ratio, or SNR). In this case, a typical consumer may observe a certain number of macro blocks appearing at random on a digital TV screen. One specific method that can help us quantify and evaluate these connection-quality scenarios has to do with measurements of long-term averages for packet loss ratio, also known as Packet Error Rate (PER). Consumers expect high-quality images at all times (for example watching TV for long period of time without any glitches). This expectation translates into very low packet error rate (PER) on the order of .01 percent to .001 percent–hence establishing the base parameter for watching quality HDTV.

Subjective components of "viewing satisfaction" tend to involve time-dependent, event-driven statistical properties of the system. These errors are fairly hard to simulate or measure directly. However, their combined effects can be seen on a TV screen due to the presence of residual errors that appear for a short time period–only long enough for the eye to see them. The manifestations of these errors include degraded picture sharpness, color leakage and reduced contrast ratio. This is normally measured by sending a specific set of patterns to the TV so that a trained observer can view and assess the image quality, and then generate an opinion about image quality. After a group of observers scores the image quality, a Mean Opinion Score (MOS) is created. MOS was initially used in audio quality evaluation, and indicates the perceived quality of received media after compression and/or transmission. The methods used in subjective testing are detailed in various ITU-R recommendations. Two of these methods are:

- Double Stimulus Continuous Quality Scale (DSCQS): this is widely accepted as an accurate test method with little sensitivity to context.
- Single Stimulus Continuous Quality Evaluation (SSCQE): this is considered to be a more representative estimate for quality monitoring.

There are many parameters that could influence the subjective testing results, but on the wireless PHY side, these are limited to two parameters: i) linear dynamic range of the system, and ii) SNR margin. Both parameters are affected when the system is subjected to random interfering events occurring in the air.

Requirements – Part 2: Bandwidth and Data Rates

Bandwidth Expectations Now and in the Future

Data rate or capacity in the home is a product of time and bandwidth per user (i.e. how many Mbps and for how long), and it is continually rising with the move toward higher-quality flat-panel displays and video content with higher bandwidth and resolution. The growth in TV size, contrast ratio and color resolutions is driving demand for higher bandwidth, and higher dynamic range is also required in order to transfer quality HD content. Compression technologies such as H.264 are the vehicles for pushing HD content over the air. While most flat panels a few years ago displayed video content at 1080i-30 resolution, a large-scale shift has already occurred toward 1080P-60 resolution. At the same time, frame rates of 120/240 frames per second (fps) are becoming more commonplace and the movement toward 3D TV is already signaling a shift toward more bandwidth.

Even more bandwidth is needed for large screen sizes, in applications such as watching real-time sport channels. Viewing very high-quality HD content such as the Super Bowl on a 72-inch TV screen might require 30 Mbps or more of compressed H.264 performance. The result: while 8 Mbps to 12 Mbps performance for transporting compressed HD content may previously have been sufficient for a good viewing experience, speeds of 30 Mbps or higher will soon be required for a satisfactory viewing experience. For example, in our labs we have demonstrated that the use of very-high-speed H.264 encoders (with an average transfer rate of about 50 Mbps) enables compressed video to be displayed on a 60-inch flat-panel TV with a level of quality that is indistinguishable from that of uncompressed video from a Blu-ray source. (See CES 2010 report, included in References).

Do you Have a Teenager in the House? – Additional Bandwidth Requirements

Demand for video gaming with HD content continues to rise. With the advent of wireless technology using low-latency HD video encoding, all gaming gear can be stowed out of sight, in a central location, far from the flat-panel displays where the games are played. Today’s low-latency (sub-10 ms) video encoding/decoding technology requires that wireless technology deliver even higher bandwidth for low-latency HD video–as much as 60 Mbps for a fairly large size screen.

Summing up the Bandwidth Requirements for HD Video Home Networks

Summing up the bandwidth requirements for HD video home networks Two primary issues drive bandwidth requirements in the home: the amount of compressed video that is needed per HDTV, and how many TVs and wireless game consoles there are. Based on the analysis done here it is reasonable to assume a 30 Mbps video-encoding rate is needed per TV and about 60 Mbps for wireless gaming, understanding that some HD compressed sources may have much higher peak data rate than the average data rate. These rates are likely to be required across as many as three or four HDTVs as well as a variety of gaming gear. Service Providers (SPs) and Content Providers (CPs) should plan ahead so that they don't have to re-configure their offerings every few years, which means it would be reasonable to allocate a sustained 120 Mbps of compressed HD video rates in the downstream direction from a variety sources such as STBs, RGWs and NAS boxes. This sustained bandwidth might require an even greater peak data rate when planning ahead for total home network capacity.

Selecting MIMO Order for Next-Generation Wi-Fi® Needs: A Technical Discussion

Delivering on consumer expectations for wireless-HD video performance and reliability requires the right MIMO architecture plus enhancements that optimize connection strength and reliability for consumer entertainment and the viewing experience. The designers of next-generation Wi-Fi systems will have to resolve issues in several key areas, including:

Antenna Performance: Advantages of 4x4 over 3x3 and 2x2, and the Impact on PER and Viewing Experience for HD Video Applications

One of the key considerations for Wi-Fi system designers implementing MIMO technology is how many antennas to use for a given application. In other words, what should be the order of MIMO? A wireless MIMO channel is a multipath system, which means multiple reflections create many paths between all of the antennas. On the transmit side, any single antenna can transmit signals which can then be deflected and diffracted into many radio wave branches as each signal moves forward. On the receive side, any single antenna can be the recipient of many of these radio wave branches, in which case each antenna can be viewed as an independent "observer" that performs independent sampling, improving signal-to-noise ratio (SNR).

A wireless channel can be classified in terms of channel rank, or how many independent paths it can support between its transmit and receive antennas. The higher the channel rank (meaning more independent paths), the more the antennas can make use of these independent observation and sampling opportunities that improve SNR. Each independent path can carry one spatial stream. If the degree of correlations between some of the spatial streams increases, then they cannot carry independent data streams.

As the number of spatial streams increases, we have the opportunity to assign at least one antenna per spatial stream. Each spatial stream can carry a large amount of data–in the 802.11n protocol, the maximum amount is 150 Mbps in a 40 MHz bandwidth. As one would expect, not every spatial stream can carry 150 Mbps, and not every spatial stream has equal capacity or is truly independent. As such, sometimes the use of extra antennas may not yield additional throughput. Figure 2 shows how two spatial streams are multiplexed over an array of 4 x 4 antennas in order to utilize the capacity offered with only two available independent paths. The use of extra antennas (i.e., two antennas per spatial stream) benefits the signal reliability by an average factor of two and in some cases even more. At the receiver, reliability can be improved by employing an algorithm known as Maximal Ratio Combining (MRC), which optimizes the received SNR by enabling all four antennas to be used to recover the two spatial streams.

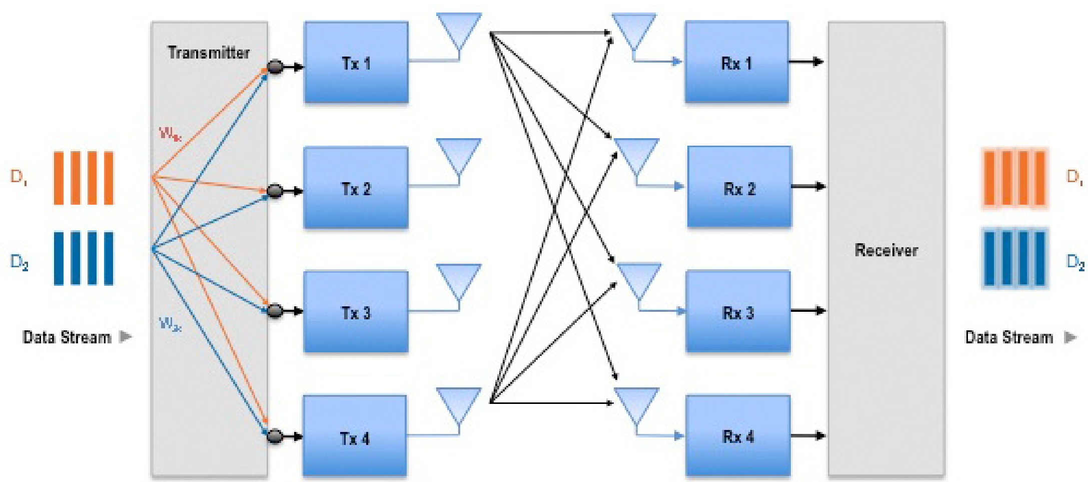

Figure 2. 4x4 MIMO with Multiplexing of two Spatial Streams

In order to achieve the maximum raw data rate of 150 Mbps per spatial stream, sufficient SNR must be available. Adequate SNR enables the receiver to decode the incoming signal, where each spatial stream has a 64 quadrature amplitude modulation (QAM) index. Support of a lower modulation index is required (i.e., 16QAM or QPSK) when the available SNR at the receiver is lower. As discussed earlier, on-time packet delivery is very important for IPTV reliability and, because of this, the User Datagram Protocol/Transmission Control Protocol (UDP/TCP) PER must be very low—generally in the range of .01 percent to .001 percent. This contrasts with web surfing, in which the UDP/TCP is set to about 1 percent PER. It is the combination all of these SNR and PER factors that determines what kind of data rate is possible per spatial stream for a given application.

The ability to increase the number of antennas per spatial stream is a major advantage of higher-order MIMO systems as compared to lower-order MIMO systems. This can be very important in home-networking models, which require two very robust spatial streams.

In addition to committing two antennas to each of these spatial streams, systems can employ other reliability-enhancing techniques. One of the most advanced techniques is to allow unequal modulation for each spatial stream (see Figure 3). Obviously, the ability to leverage the benefits of spatial streams increases as the number of antennas is increased.

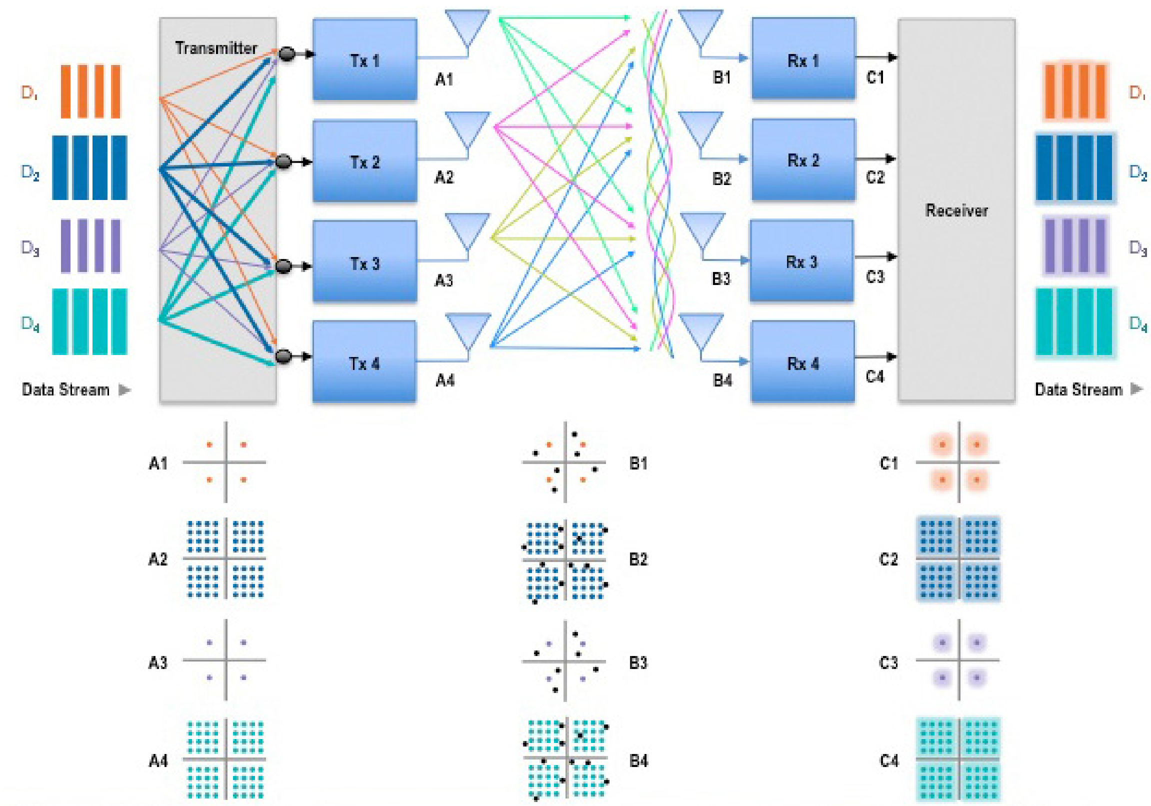

Figure 3. This Figure Illustrates 4 x 4 MIMO with 4 Spatial Stream Multiplexing. In this Example, due to this Spatial Signature, the Spatial Streams are not Equally Modulated. It is Shown that Streams 1 and 3 are QPSK Modulated (per Subcarrier-OFDM) and Streams 2 and 4 are 64QAM Modulated (per Subcarrier-OFDM)

Beamforming and its Application for HD Video Home Networks

Beamforming brings major advantages for optimizing wireless connections between transmitters and receivers. The way beamforming works is fairly straightforward. A MIMO receiver tries to estimate the channel matrix (the channel between the transmitter and the receiver) and tells the transmitter how to pre-compensate on a tone-by-tone basis, so that the received signal has the optimal SNR. If this is done dynamically, the MIMO receiver and transmitter can work together to estimate the adverse effects of any objects that would block or deflect the beam, and mitigate and/or pre-empt those affects by re-directing the beams from each of the transmitting antennas.

Simulation results confirm that beamforming yields a significant SNR enhancement, as shown in Figures 4 and Figure 5. In Figure 4, we illustrate the results of investigations into long-term PER averages for various MIMO configurations.

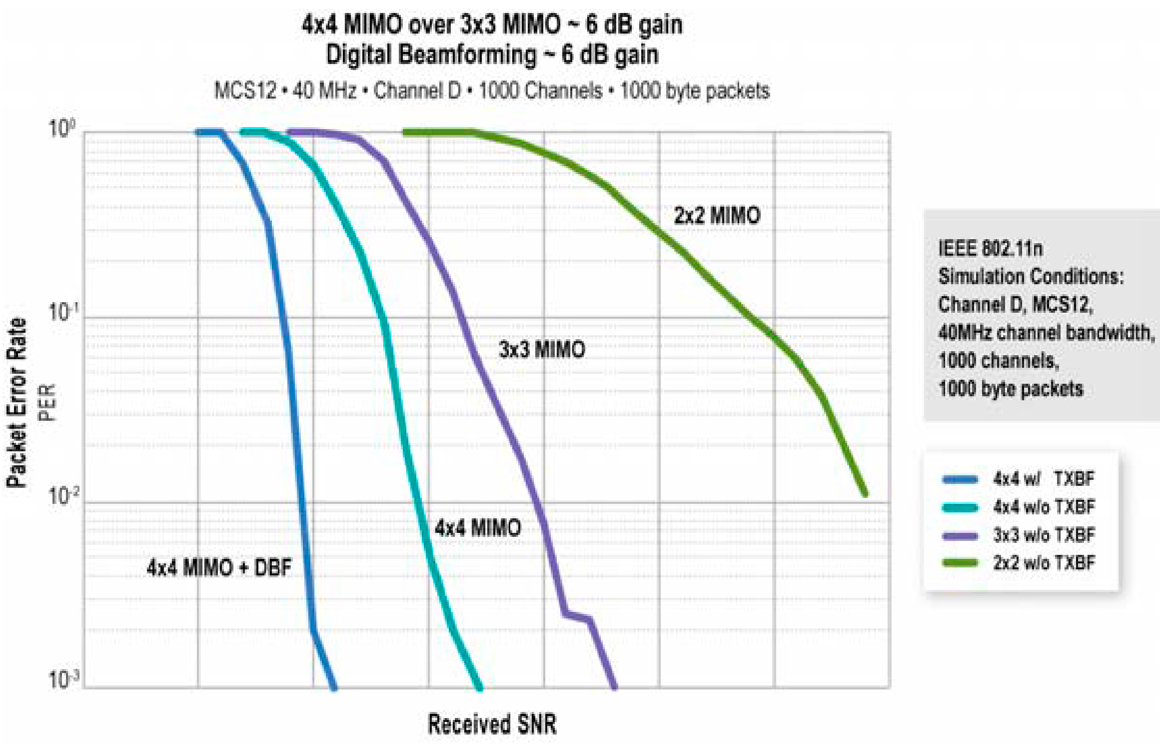

Figure 4. nxn MIMO Packet Error Rate for Various IEEE 802.11n Systems. 4x4 MIMO with Adaptive Beamforminghas 12 dB Advantage over 3x3 MIMO without Beamforming

Generally, correlated MIMO channels possess fewer degrees of freedom relative to ideal, fully scattered channels. For this reason, as the SNR decreases, the number of spatial streams also decreases, which reduces the multiplexing gain of the MIMO system. Figure 5 shows a comparison of various MIMO systems and their associated rate/reach curves for the same channel conditions. We focused on a fairly difficult channel model that consists of three 10 dB walls spaced very close to the transmitter, and evaluated the resulting data rates.

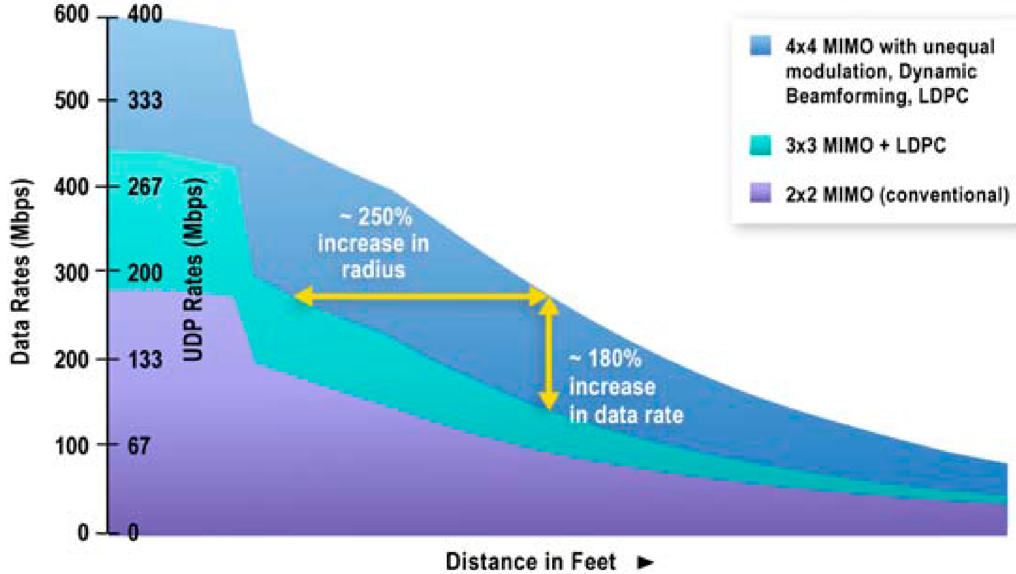

Figure 5. Typical Simulation Graph Used to Show Over-the-Air Bitrate. PER is Set to about 1%, and Packet Retransmission is Needed to Achieve Desired Reliability at the Expense of Delay. In this Model, at a Distance of 50 feet, the 4x4 System's Throughput Outperforms that of a 3x3 System by about 180%

Note that as the distance increases and the SNR decreases, the number of spatial streams also decreases. For a given a 4x4 system at sufficiently long distance and with enough attenuation, all versions of 4x4 MIMO systems will operate in one or two spatial streams. We should note that, in all of these analysis, the simulated data rate is the maximum possible data rate under the outlined condition. Later we will discuss the outage channel capacity as we look at a none-ideal interpretation of what is going on in the channel.

Performance Analysis: The Need for Understanding PER and its Statistical Distribution to Assess and Optimize Video Performance

PER and rate/reach curves are generated from long-term averages and, unfortunately, this is not sufficient for analyzing video-distribution quality. In home-networking video distribution, we must analyze very short time averages that are determined by the HD frame rate (i.e., 60 fps) of the video and the compression decoder depth (i.e., 5-100 ms), in order to eliminate various image artifacts. This basically means that channel conditions (channel matrix) have a broad statistical distribution. As a result, based on the characteristics of the wireless channel, we can experience any of a wide range of channel situations, with a corresponding impact on throughput. This leads to the next section and discussion of outage probability.

Outage Capacity and Outage Probability for Wireless Home Networks

In analyzing data rates it is not sufficient to only look at simulated rate reach curves, where the results are upper-bounded due to fixed assumptions about the channel. It is very important to consider the MIMO system's outage probability. Outage probability is the percentage of the channels that are not able to support a specific data rate. With ideal code, outage probability is equal to PER, and with non-ideal code, the outage probability is at the lower bound of PER. The analysis in Table 1 shows the outage probability for two cases using different MIMO systems with IEEE channel model B: 1) supporting 150 Mbps using one spatial stream with 64QAM, and 2) supporting 300 Mbps using two spatial streams with 64 QAM modulation index. The outage probability of a 3x3 MIMO system supporting two streams of 64 QAM is 31.9 percent, which means 31.9 percent of the channels would not provide "reliable" transmission for two streams of 64 QAM at the specific received SNR per chain−20 dB in this case. This is compared to a 4x4 system with an outage probability of 1 percent.

Table 1.

MIMO Configuration	2x2	3x3	4x4
Outage Probability of 1 Stream	0.5%	0%	0%
Outage Probability of 2 Stream	95.6%	31,9%	1%

The probability of achieving full channel capacity (more accurately known as ergodic capacity) is fairly low without the help of transmit beamforming. That is why we are looking at outage capacity. It is fairly difficult to achieve full capacity unless channel state information (CSI) is known to the transmitter. This is because the transmitted symbol (codeword) should be spanned over all possible channel conditions (matrices) over all possible locations, and the packet duration should be longer than coherence time. As a result, for transmit beamforming to be effective in achieving maximum capacity and full data rate, it must be adaptive. In other words, if the channel changes and the system does not adapt quickly and dynamically through adaptive beamforming, there would be capacity (data rate) loss and no chance of achieving maximum channel capacity and full data rate.

The MIMO system's ability to adapt is also influenced by its beamforming update rate, which becomes very important. Adequate beamforming update rate is required in order to deal with the dynamics associated with activities in a home environment that impact channel conditions — from people walking around the home to a fan running in the living room. One parameter that could influence the beamforming update rate is the memory depth of the H.264 (or equivalent) decoder and its ability to conceal some of the error conditions. High compression ratios require very deep memory (on the order of 100 ms). So, a good beamforming update rate should be designed to be between 20 ms and 100 ms, which also can be adaptive in this range, depending on channel conditions. Note that in all of our beamforming discussions we are assuming that the forward and backward channels are both being accurately estimated and, as a result, only explicit beamforming (which is the most reliable and accurate method) is considered. Implicit adaptive beamforming requires a lot of nonlinear estimation and calibration and ultimately could cause more harm than good if it is not accurate, even for a short time interval, as it will cause disruption in image quality.

Service-Deployment Cost Model

To deliver on the promise of the connected home, service providers must deliver reliable services at reasonable prices that can be enjoyed anywhere in any home. In order for service rollouts to be successful, the percentage of homes passed must be very high so that consumers will receive a similar level of service. Besides service providers, there are other stakeholders who want to see a reliable home network over which to distribute HD content, including such players as Apple, Sony, Microsoft and others.

From a cost perspective, the least expensive home-networking technology to deploy is Power Line Communications (PLC), which also provides a good deal of ubiquity. But in terms of reliability for home networking, PLC falls short due to challenges related to the availability and uncertain quality of electrical wiring inside homes. As a result, customers cannot be fully assured that they will have reliable service when they buy a PLC system; however, most agree that PLC is good for low-speed data connectivity. The remaining viable candidates for high-quality video distribution are wireless and MoCA technologies. Unfortunately, MoCA continues to be much less pervasive because not every home is wired with a coax network and, as a result, this technology will remain a niche solution and will not scale to broad deployment.

It is clear, therefore, that the only option moving forward is to devise a reliable wireless technology and do away with wires in the house. The ability to roll services out, ubiquitously, to any home, anywhere, without involving field technicians, can bring significant OPEX savings. For this reason, a key parameter to understand is what percentage of homes can actually benefit from the offered service, and what kind of upside exists for future upselling without the need to physically upgrade a system.

Based on the analysis presented in this paper, if we agree that the most likely home-networking bandwidth demands in the next three to five years will hover around 100 Mbps to 120 Mbps, then the questions are: what percentage of homes can be covered with that kind of bandwidth, and is there a way to upgrade bandwidth in the future. Wireless is the answer.

Figure 6 shows statistical measurements done by an independent company using an early second−generation Quantenna 4x4 MIMO solution with two spatial streams over many connections in nearly 20 homes of different sizes. The data for alternative, lower-order MIMO solutions is either interpolated or obtained from published results. If we consider 80 percent home coverage as a good starting point, the results show that, for a good PER of 0.001% for watching HDTV, the 2x2x2 (2x2 MIMO + 2 spatial streams) solution supports 10Mbps data rates, the 3x3x2 MIMO solution supports 55Mbps data rates, and the 4x4x2 MIMO solution supports 120Mbps data rates.

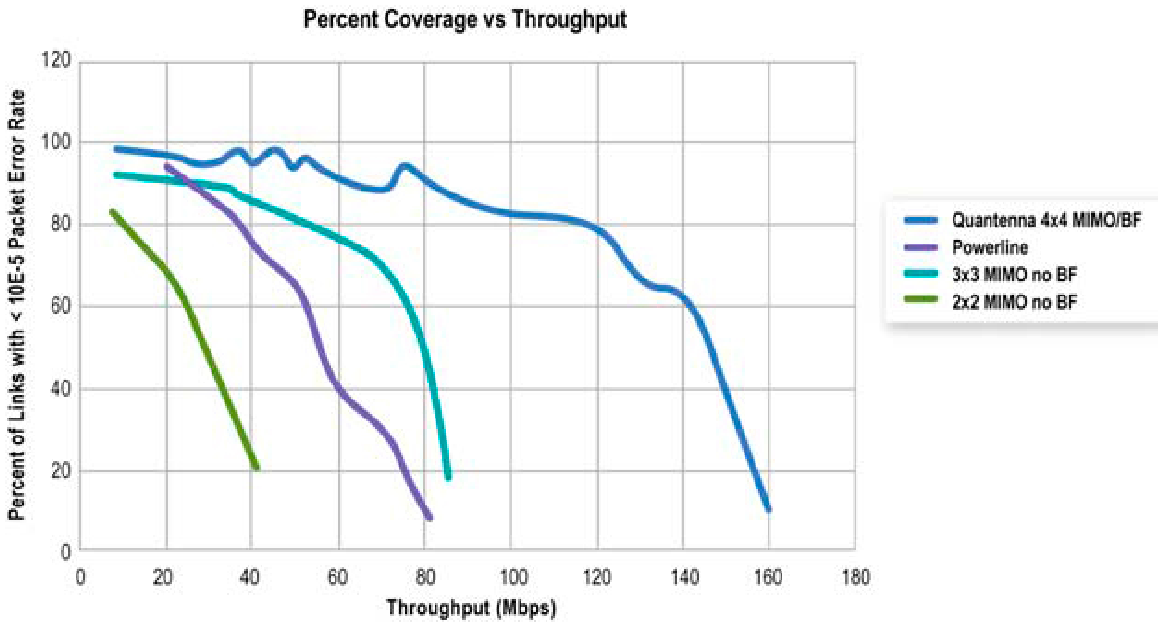

Figure 6. 17 Homes – All Room Connections Tested

At first glance, it may be difficult to reconcile the difference between statistical measurement results of Figure 6 and the measured results of Figure 5 that are typically found in published literature. We first note that the data rate measurements of Figure 6 were evaluated at a PER of 0.001%. Aside from differences in PER criteria, this discrepancy can be further explained with the help of Table 1 where we discussed the outage probability: when we increase the number of homes in our statistical study, we are essentially offering more channels over which the codewords must span. This explains why there is such a large gap between various MIMO systems, which may not have been obvious in the rate/reach curve.

It is very clear that neither 2x2 nor 3x3 MIMO offers sufficient performance for a long-term home−networking solution, and that 4x4 MIMO solutions are the superior alternative. The only remaining question is whether 4x4 systems are cost-effective relative to 3x3 systems. Generally speaking, 3x3 systems are about 15 percent to 20 percent smaller than 4x4 systems. Over time, we expect economies of scale to bring the cost of goods (COG) delta between a 3x3 system module and 4x4 system module to below $1.

How To Get to 100% of All Homes Covered

The new generation of 4x4 MIMO technology (with 4 spatial streams capable of unequal modulation, plus LDPC and dynamic beamforming) will provide even better coverage than alternative solutions that have been tested per Figure 6, and we would expect to exceed

120-150 Mbps over 95% homes. The remaining very large homes (i.e. 7000 sq. ft.) can easily use a single mesh node with frequency re-use capability to achieve near 100% coverage in all homes across the globe.

Summary

In this paper we analyzed which 802.11n MIMO system has “good enough” performance for HD video distribution, and why 802.11n 2x2 systems are non-starters due to significant SNR problems that preclude adequate performance. We’ve also shown how 3x3 solutions deliver inferior performance as compared to 4x4 solutions with DBF. Two questions remain:

- Is 3x3 system “good enough” for HD video distribution? If not, then
- Is 4x4 +DBF, a cost-effective solution?

The answer to the first question is “ NO in most cases.”

We have shown that, while an advanced 3x3 MIMO system performs substantially better than a 2x2 MIMO system, the percentage of home covered and total number of video streams supported is “not good enough” for large scale rollout and hence its arrival is too little too late. The justification for this statement comes from the irrefutable performance delta between a 4x4 system with DBF and low-density parity check (LDPC) as compared to earlier 3x3 solutions. Plus, 4x4 solutions will continue to benefit from ongoing integration improvements, much like Gigabit Ethernet (GE) physical-layer (PHY) devices did as they eclipsed earlier 10/100 Base−T market solutions. We expect the long-term cost difference between a 3x3 system and a 4x4 system to be no more than $1.

Consumers expect the same quality in their wireless connections as they do from wired Ethernet. The latest generation of 4x4 MIMO solutions delivers this performance, including full HDTV quality with 1080 p and higher video resolution, all the time, anywhere in the home. It meets the so-called “Gold Standard” for carrier deployment of wireless entertainment networking, delivering up to four HD video streams at more than 100 Mbps data rates, over 100 feet, with near-zero PER data transfers, regardless of signal impairments and dead zones that are typical in the home. Ongoing advances will deliver further improvements in throughput, reach and reliability.

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