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ON Semiconductor®

Designing Reliable Wi-Fi™

**Significant Improvements in Wireless Performance
and Reliability Gained with Combination of 4x4 MIMO,
Dynamic Digital Beamforming and Mesh Networking**



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Designing Reliable Wi-Fi

Significant Improvements in Wireless Performance and Reliability Gained with Combination of 4x4 MIMO, Dynamic Digital Beamforming and Mesh Networking

This white paper explains why wireless home networks are plagued by unreliable and spotty coverage, low data rates, intermittent outages resulting from interference and overall poor performance. In order to deliver intelligent high-speed performance, as well as consistent and reliable wireless connectivity, throughout the entire home, three essential ingredients are needed: 4x4 MIMO, dynamic digital beamforming and mesh networking. These technologies have been integrated into Quantenna's® High Speed (QHS) family of products, thereby delivering on the promise of reliable and fast Wi-Fi multimedia connectivity to all corners of the home.

Introduction

Wi-Fi has become the technology of choice for home networking and consumer devices. As a result, wireless networks are now required to support more bandwidth-intensive applications, such as wireless high definition (HD) video, HD television (HDTV) and Internet protocol television (IPTV) services. However, wireless home and enterprise networks frequently suffer from dead zones, unreliable bandwidth, poor coverage and signal interference (shown in Figure 1), which impacts the high level of performance needed for these advanced services. Video applications, in particular, are not very forgiving of poor reliability and performance, so new Wi-Fi designs must overcome these challenges to meet home networking demands and consumer expectations.

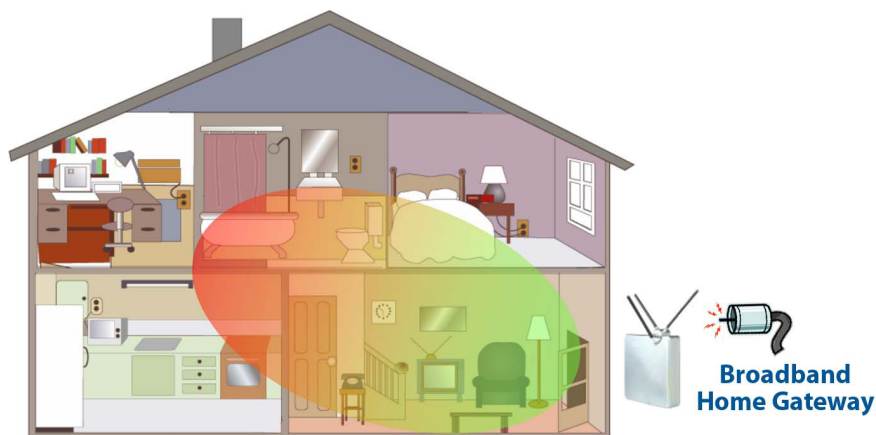


Figure 1. Dead Zones and Poor Coverage in Wi-Fi Home Networks

The reason for unpredictable and unreliable performance of existing 802.11 systems is the nature of wireless signal propagation and the fact that interference is pervasive in the unlicensed spectral bands where 802.11 operates. Specifically, the data rate and reliability of a Wi-Fi radio receiver improves as its received signal power increases, and decreases with more interference. Wi-Fi signals propagating through a home or an apartment experience a number of effects with respect to received signal power and interference, such as:

- The received signal power falls off inversely with the distance between the transmitter and receiver. Locations in the home far from a wireless access point receive less signal power, and therefore cannot support the high data rates possible at close-range.
- Signal reflections – also called multipath – from walls and other objects partially cancel the direct-path (line-of-sight) signal when their phases are not aligned. Multipath leads to fading and dead spots in various locations throughout the home.
- Interference from other wireless devices in the same or nearby frequency bands can saturate a receiver or cause excessive noise, thereby significantly degrading performance.
- Signals propagating through walls can experience significant power attenuation, depending on the wall material. In particular, a European home may have up to four concrete walls, which can cause signal loss of up to 50 dB in some rooms and makes it difficult to close the link between the access point and receiver.
- Apartment buildings, such as those in Japan, have thin walls, which result in minimal signal loss. However, interference from neighboring apartments is not attenuated either, and that interference may preclude good performance or jam the receiver, leading to intermittent outages and many dropped packets.

These signal propagation characteristics give rise to the home networking dilemma: Cutting the cord is highly desirable and Wi-Fi is pervasive and cost-effective, however, data rates

and reliability in existing Wi-Fi products are not yet good enough to provide a compelling solution for reliable wireless connectivity throughout the entire home.

Quantenna's Solution

Given the difficulties of Wi-Fi signal propagation and interference, Quantenna has integrated a trio of powerful complementary technologies to support intelligent high-speed performance and consistent, reliable performance over Wi-Fi networks. Quantenna's 802.11n solution combines 4x4 multiple-input, multiple-output (MIMO); dynamic digital beamforming; and mesh networking to provide very fast data rates to every room in the home.

4x4 MIMO

Systems with multiple antennas at the transmitter and receiver – also referred to as MIMO systems – offer significant increases in data rates, range and reliability without additional bandwidth or transmit power. These benefits are obtained by exploiting the spatial dimension associated with the multiple antennas. Specifically, utilizing several antennas at both the transmitter and receiver can create multiple independent channels for sending multiple data streams. The number of independent channels or, similarly, the number of data streams that can be supported over a MIMO channel is equivalent to the minimum number of antennas at the transmitter or receiver. Thus, a 2x2 system can support at most two streams, a 3x3 system can support three streams and a 4x4 system can support four streams, as illustrated in Figure 2. Some of the independent streams can be combined through dynamic digital beamforming and MIMO receiver processing, as shown in the red oval in Figure 2, which results in increased reliability and range. The reliability increase is shown in Table 1, which illustrates the probability of supporting one or two data streams at the maximum data rate (64 QAM) in 2x2, 3x3, and 4x4 systems. As the table indicates, a 4x4 MIMO system with dynamic digital beamforming and MIMO receiver processing supports two maximum-rate data streams 99 percent of the time. Other configurations are less reliable, since they have fewer antennas and thus fewer extra spatial dimensions that can be combined.

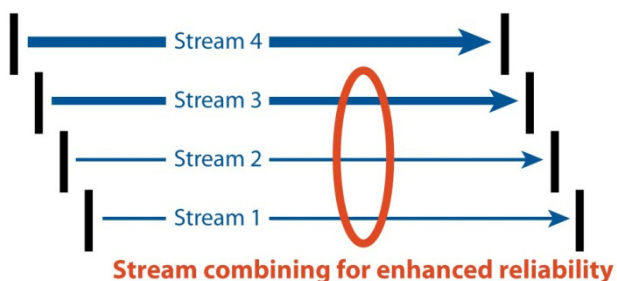


Figure 2. 4x4 MIMO System with Four Independent Data Streams

Table 1. RELIABILITY OF 64QAM FOR 2x2, 3x3 AND 4x4 MIMO IN 802.11n “B” CHANNELS

MIMO Configuration	2x2	3x3	4x4
Percentage of Channels Supporting 1 Max-rate Data Stream	99.5%	100%	100%
Percentage of Channels Supporting 2 Max-rate Data Streams	4.4%	68.1%	99%

Dynamic Digital Beamforming

Extra antennas at the transmitter, above the minimum required to support multiple data streams, are not very useful without dynamic digital beamforming. Dynamic digital beamforming applies optimal complex weights to each transmit antenna to steer the energy of the antenna array (noted in blue in Figure 3) in the independent spatial directions associated with the different data streams while simultaneously avoiding interference, as shown in Figure 3 for two data streams. This optimal weighting requires channel estimation at the receiver, and explicit feedback of the weights or channel estimates from the receiver to the transmitter. Implicit transmit beamforming where the weights are based on metrics such as minimizing packet error rate, also can be used. However, it is much less effective than basing the weights on explicit channel measurements. Dynamic digital beamforming is similar to switched-beamforming discussed in more detail below, but it is significantly more flexible because it is not limited to switching between fixed antenna patterns pointing in a single spatial direction. In particular, the transmit antenna array pattern can be optimally adapted to the spatial characteristics of the MIMO channel frequency response, the number of data streams and the receiver positions. This optimal adaptation provides significantly better throughput, range and reliability than switched beamforming or MIMO systems without dynamic digital beamforming. A 4x4 MIMO configuration supporting two data streams provides two extra transmit antennas for beamforming, which allows significant focusing of the energy in two directions. This feature not only improves reliability, but also reduces interference with coexisting systems, since steering energy in the direction of the desired receiver moves it away from other locations. For transmission of two data streams, a 3x3 system has significantly lower reliability since there is only one extra antenna to focus energy in the two required directions, and a 2x2 system exhibits negligible transmit beamforming performance gain as there are no extra antennas beyond the minimum needed. While dynamic digital beamforming works with any number of receive antennas, it is most powerful in a 4x4 configuration with MIMO receiver processing optimized with respect to the transmit beamforming weights.

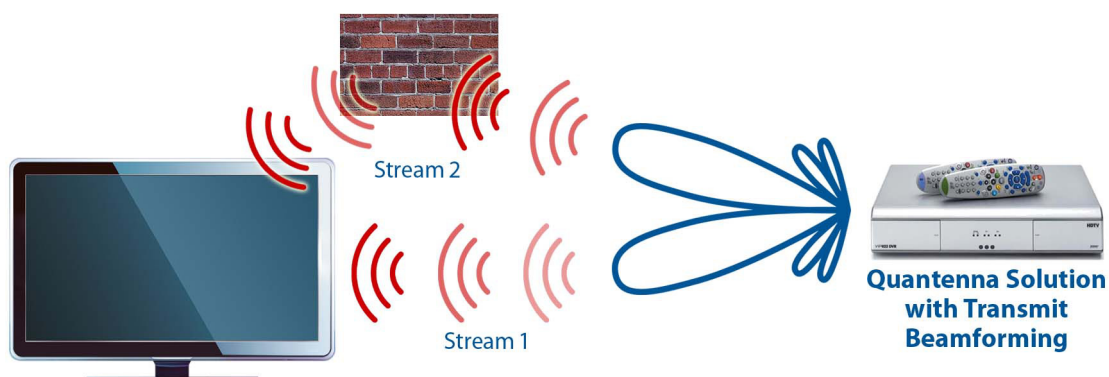


Figure 3. Dynamic Digital Beamforming in a 4x4 MIMO System with Two Data Streams

MIMO receiver processing is based on a principle similar to dynamic digital beamforming, but applied at the receive antenna array. Specifically, complex weights are applied to the receive antenna inputs to steer the receiver array pattern in the direction of the incoming data streams, as shown in Figure 4. MIMO receiver processing combined with dynamic digital beamforming optimally steers the data streams between the transmitter and the receiver. This steering provides increased throughput, reliability and range, and the performance improvement increases with the number of extra receive antennas beyond the minimum needed to support the transmitted data streams. MIMO receiver processing has an additional benefit over dynamic digital beamforming alone, as the complex weighting can be used to place nulls in the direction of interferers. For example, a 4x4 MIMO system with two data streams can null out up to two interferers. Although it is important to know that when the extra antennas are used for interference nulling there is less ability to steer the array in the direction of the incoming data streams. The receive antenna weights can be adapted to optimize performance through a combination of minimizing interference or maximizing received signal power based on the signal, channel and interference conditions. Ideally, the MIMO receiver processing and dynamic digital beamforming are combined to suppress interference effects, so that the transmitted signal occupies spatial dimensions that are orthogonal to those of the interferers.

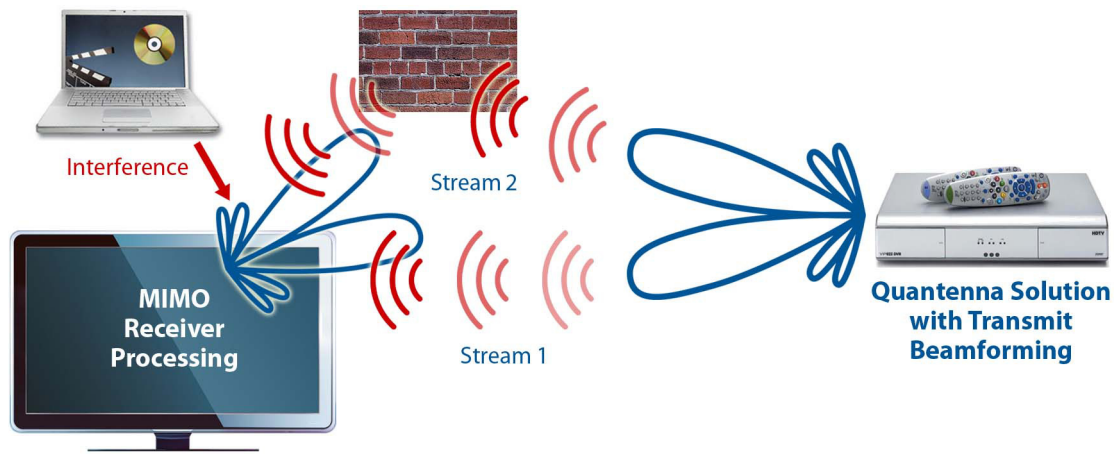


Figure 4. Dynamic Digital Beamforming and MIMO Receiver Processing in a 4x4 System with Two Data Streams

The average throughput of a 4x4 MIMO system with optimal transmit/receive array processing over a 3x3 system is shown in Figure 5. The green line indicates the average throughput of a 4x4 system with dynamic digital beamforming (precoding) and MIMO receive processing in a typical indoor channel (multipath reflections and attenuation through three separate walls). 4x4 MIMO is compared against a 3x3 system with switched-beamforming and MIMO receiver processing (the blue line, assuming a 7 dB antenna gain via switching) and a 3x3 system without any beamforming and MIMO receive processing (the red line, assuming a 3 dB omnidirectional antenna gain). The figure illustrates by how significantly a 4x4 MIMO system with optimal adaptive processing in the transmit and receive antenna arrays can improve range and throughput.

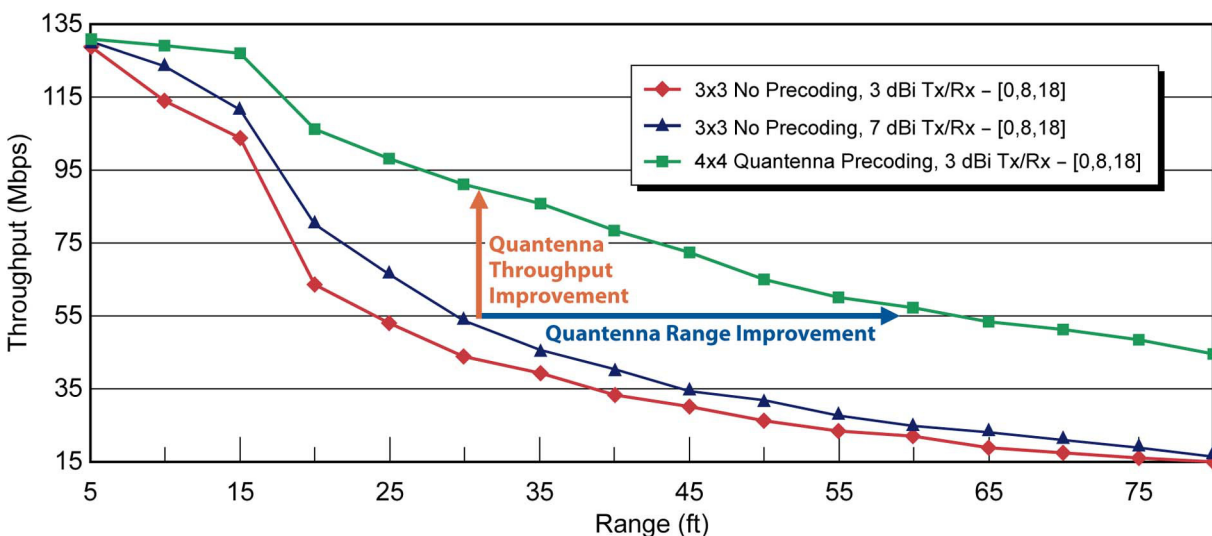


Figure 5. Average Throughput of Quantenna's 4x4 System Compared to 3x3 Without Dynamic Digital Beamforming

Mesh Networking

Mesh networking is the last ingredient to ensure consistent and reliable wireless connectivity throughout the entire home. As illustrated in Figure 5, the average throughput of MIMO systems, even with optimal transmitter and receiver processing, decreases with distance due to attenuation and path loss. Each home has its own unique propagation characteristics, which might include thick walls or floors with large attenuation. As a result, it is difficult to ensure reliable high-speed coverage for a home of any size, layout and construction from a single Wi-Fi access point. The basic premise behind mesh networking is to place one or more mesh elements at different locations in the home to route data from the access point to one or more receivers in hard-to-reach locations, as shown in Figure 6.



Figure 6. Mesh Networking for Consistent, Reliable Bandwidth Throughout the Home

This figure shows a high-rate, reliable connection between the transmitter and receiver 1, as would be expected in most locations throughout a typical home for a 4x4 MIMO system with dynamic digital beamforming and MIMO receiver processing. However, there may be some locations blocked by a high-attenuation wall or reflector, as is the case for receiver 2. This attenuation precludes a reliable high-rate connection from the transmitter to receiver 2. The solution is to place a 4x4 mesh element at an intermediate location between the transmitter and receiver 2. In this intermediate location, the mesh element will have a reliable high-speed connection to both the transmitter and to receiver 2, enabling a high-speed reliable link between them via routing. In applications with stringent latency requirements – such as video – the mesh element should support concurrent dual-band operation so that it can receive data from the transmitter while simultaneously relaying that data to receiver 2. This concurrent dual-band operation also is highly desirable in systems that support legacy 2.4 GHz devices while utilizing the low-occupancy 5 GHz band for video transmissions.

Mesh networking is scalable, enabling large houses or even office buildings to achieve almost 100 percent coverage by adding more mesh elements at strategic locations. It also is adaptive,

meaning that if the end-to-end connection between a transmitter and receiver degrades due to intermittent interference, the mesh element can change frequencies or reroute through another element to maintain a reliable high-speed link between them.

Existing Solutions

The challenges associated with signal propagation in the home have been partially addressed in existing solutions using techniques such as receive diversity and switched-beam antennas. The diversity technique utilizes multiple receive antennas to coherently combine signal reflections, thereby mitigating the partial cancellation from multipath that gives rise to signal fading in the transmission of a single data stream. Switched-beam transmit antennas consist of an antenna array or other configuration that creates multiple directional antenna patterns, as shown in Figure 7. At any given time the beam is switched to the pattern giving the best connectivity to the receiver. The pattern selection ideally is based on channel estimates, or can use a less-accurate metric based on Media Access Control (MAC) level feedback such as Cyclic Redundancy Check (CRC) errors or received signal strength. If the pattern selection is based on MAC level feedback then the response time to channel changes is much slower than with dynamic digital beamforming, which can react immediately to changes in the channel.

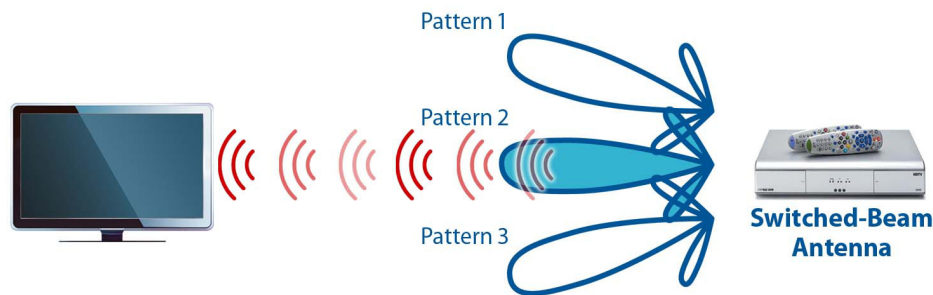


Figure 7. Switched-Beam Transmit Antenna

Switched-beam antennas are effective at increasing range for single-stream data transmission, since signal power is focused towards the best direction rather than uniformly in all directions, which is typical in omnidirectional antennas. This focusing of energy also reduces signal reflections and multipath fading, since less energy is directed towards reflectors. However, the focusing of energy in a single direction can degrade the performance of MIMO systems, which require multiple spatial dimensions to support multiple data streams. In particular, by focusing energy in a single direction, switched-beam transmit antennas reduce the spatial dimensions in a MIMO channel available for sending multiple data streams. As a result, a MIMO system with a switched-beam transmit antenna may not be able to support more than one data stream. Moreover, the switched-beam solution does not provide diversity gain, which increases SNR by 6–11 dB in a 4x4 MIMO system. Ultimately, while receiver diversity and switched-beam antennas can improve range and robustness for single-stream systems, they are not powerful enough to remove dead spots, unpredictable bandwidth

and intermittent outage in all homes while maintaining the high data rates of multistream MIMO systems.


Conclusion

In order to ensure the highest levels of consistency, reliability wireless connectivity in any home – regardless of its size, layout or construction – three essential ingredients are required: 4x4 MIMO, dynamic digital beamforming and mesh networking. The 4x4 MIMO system provides enough extra antennas to allow for substantial performance gains from dynamic digital beamforming and MIMO receiver processing. Dynamic digital beamforming uses explicit channel estimates to focus energy in the best directions to support transmission of multiple data streams with high channel gain and low interference, while enabling consistency over longer distances. This focusing of energy also reduces interference to other wireless devices. Complementary MIMO receiver processing provides maximum receive antenna gain in the directions of the incoming data streams and can null out interference. For particularly difficult-to-reach locations, mesh networking provides the necessary extension of bandwidth throughout the home by adding mesh elements in between transmitters and poorly-located receivers. These mesh elements maintain reliable high-speed connectivity to both the transmitters and receivers, thereby enhancing the link between them. Only with these three technical components – 4x4 MIMO, dynamic digital beamforming and mesh networking – can the promise of reliable and fast Wi-Fi connectivity throughout any home or office be realized.

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