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MIMO Architecture The Power of 3

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MIMO Technologies

The buzz in WLAN today is multiple input/multiple output, commonly referred to as MIMO. The term MIMO covers a broad spectrum of technologies in the wireless space: smart antenna, space time block coding (STBC), spatial multiplexing (SM), cyclic-delay diversity (CDD), and maximal ratio combining (MRC) are all technologies that require multiple transmit and/or receive antennas. The goal of this paper is to help the reader cut through all the MIMO clutter and determine the optimal architecture for a WLAN MIMO system. To achieve this goal, we will focus on the key technologies that are most likely to become part of the IEEE 802.11n specification.

The trend in the IEEE standards committee point to multi-stream spatial multiplexing as the key component with transmit beam forming (TxBF), CDD, STBC, and MRC as optional features. But what do any of these technologies bring to the WLAN table? Is it throughput or is it range?

Spatial Multiplexing

SM provides a wireless system an opportunity to increase throughput without the use of additional spectral bandwidth. A simplified view of SM can be thought of as transmitting N unique data streams using highly directional antennas aimed at N different receive antennas. Each receiver detects a unique data stream resulting in an N fold increase in throughput. With sophisticated signal processing techniques it is possible to achieve a similar N -fold improvement using N (or more) omni-directional antennas. For example, in a standard WLAN 802.11g access point a second data stream can be transmitted from a second antenna. It is possible for a laptop with two receive chains to decipher the two (different) data streams, effectively doubling the throughput. A third antenna (at both the transmitter and receiver) can triple the data rate and so on. There is an upper bound, however. Analogous to solving an algebra problem of N unknowns from M independent equations ($M > N$), in SM systems the maximum number (N) of data streams is restricted to the number (M) of independent (uncorrelated) signals received. Here, uncorrelated signals are radio signals that took different physical paths (multipath) from a transmit antenna to the receive antennas. In other words, throughput improvement is limited by the number unique signal paths. Furthermore, the multipath conditions are completely dependent on the environment where the WLAN is deployed.

Transmit Beam Forming

TxBF is a technique to improve range of a wireless system and indirectly improve throughput. Sometimes referred to as "smart antenna technology", TxBF uses an array of transmit antennas with the same signal except that the magnitude and phase are adjusted at each transmitter such that a focused beam is generated. If a priori information about the location of the target receiver is known, TxBF would point its focused beam in that direction. It is easy to envision that such a focused beam will improve range because all of the radiated radio waves can be focused in the one direction of interest. TxBF can increase the average received signal power by the client by up to 4x.

Cyclic-Delay Diversity

CDD can be thought of as a variant of TxBF in that it reduces unintentional beam forming in the wrong direction. Depending on the physical environment where the WLAN system is deployed, a multi-transmit AP can accidentally create a focused beam. If this unintentional beam is pointing away from the intended client, the effective energy received by the client is severely degraded. To prevent this effect, CDD systematically adjusts the phase of the transmitted signals such that the unintentional beams are dispersed. Statistically, CDD results in the client receiving about half that of TxBF.

Maximal Ratio Combining

SM, TxBF, and CDC are for the multi-transmitter case. MRC is a technology utilized by the receiver with multiple antennas. The MRC algorithm determines how to optimally combine the energies from multiple receive chains such that the result is a coherent addition rather than destructive subtraction. This technology improves the range of a wireless system. As the distance between the transmitter and receiver increases, the strength of the received signal becomes weaker and more susceptible to corruption due to noise and interference. By having more than one antenna, the probability that at least one antenna receives uncorrupted data increases. The MRC algorithm puts the heaviest emphasis on that one signal with the least amount of corruption. Even when all the receivers' signals become noisy, the MRC algorithm can determine how to best combine all of the noisy signals such that a best estimate of the original data can be made.

Space Time Block Coding

STBC is a technique typically used for asymmetric systems where the number of transmit chains is greater than one and the receiver has only one chain. A compact handheld device with room for only one antenna talking to an AP with multiple transmitters is a typical example of where STBC might be used. The multiple transmitters result in increased spatial diversity and hence improve signal recovery robustness. However, because only the AP transmits from multiple antennas, STBC only improves range in the downlink direction (AP to client). At the AP, each transmitter sends a known linear combination of each other's signals and the single receiver can algebraically determine what the original data stream is based on prior knowledge of each transmitter's linear combination formula.

MIMO Examples

The simplest spatially multiplexed MIMO system contains two transmit chains, two receive chains, and two data streams, mostly commonly denoted as 2x2 (Tx X Rx). One can improve performance by adding receive and/or transmit chains and incorporating any or all of the schemes already mentioned (TxBF, CDD, MRC, STBC). Furthermore, adding additional radio chains in either the transmit or receive path in conjunction with these schemes enhances performance. For example, a 2x3 with two streams is the next incremental improvement in MIMO topology. In the remainder of this paper, the basic 2x2, 2-stream system is the reference to which all other MIMO systems are compared.

In a typical usage model, it is reasonable for the access point (AP) to be able to transmit at a higher power as well as have more flexibility to physically place multiple antennas, whereas the client stations are typically battery operated devices and have restrictions on both power and physical size to place multiple antennas. Therefore, we will look at the uplink (client to AP) separately from the downlink (AP to client) direction.

Starting with the uplink, simulation results of the throughput vs. range is presented in Figure 1. Typical operating characteristics as defined by the ITU1238 model are given as: 11g band (2.4 GHz), 20 MHz mode, 50 ns rms delay spread, 3.1 dB path loss, 15 dBm power per transmit chain, 3 dB antenna gain, 5 dB system receiver noise, 12 dB shadowing margin, 4 dB (wooden) floor loss. As can be seen from Figure 1, the simulations show a ~20% increase in the average performance when going from a 2x2, 2-stream system to a 2x3, 2-stream system in the uplink direction.

Figure 1 Average PHY data rate vs. distance for 2x3 and 2x2 (2 streams) using the ITU1238 model

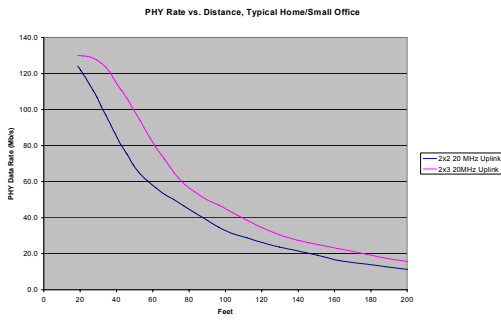


Figure 3 Measured data of a 2x3 and 2x2 uplink direction, both with 2 streams

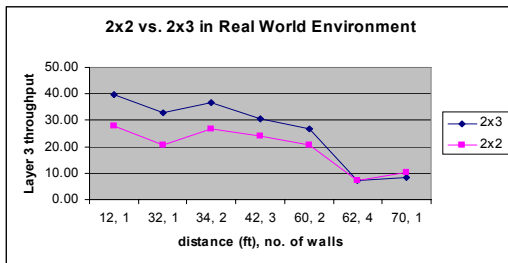


Figure 2 Chamber measurement comparing a 2x2 to a 2x3 system uplink throughput

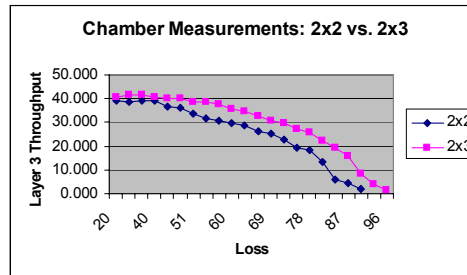
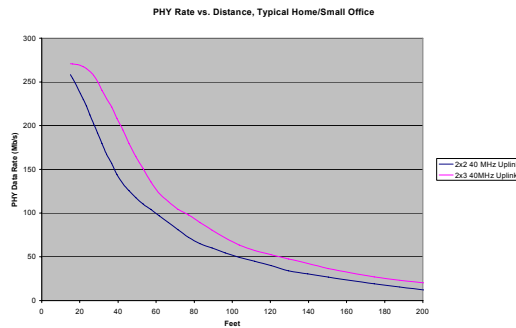


Figure 4 Simulated 40MHz mode operation for the average throughput vs. distance for 2x3 and 2x2 uplink



To substantiate the simulation results, chamber testing of a 2x3, 2-stream system was measured against a 2x2, 2-stream system. Figure 2 compares the two systems in a controlled chamber test. The graphs from this uplink experiment compare favorably with the simulation results (see Figure 1) in that a similar 20% improvement in throughput is measured.

Furthermore, a side-by-side comparison of a 2x3, 2 stream and a 2x2, 2 stream systems was performed in a real-world environment. The results are plotted in Figure 3. Again, there is agreement between the measured data and the simulation results of Figure 1. These data were collected using 20 MHz mode. However, the IEEE 802.11n standard will likely include an optional 40 MHz mode, effectively doubling throughput. Figure 4 depicts simulated performance comparing the 2x3 against the 2x2 configuration in this optional 40MHz mode. As in Figures 1-3, the ITU1238 model for the environment conditions were used.

Performance gain is significant in the 40 MHz mode for the 2x3 as well. As Figure 4 indicates, average throughput rates can be up to 40% better in the 30–40 ft range and better than 20% in the 60–100 ft range.

Now we will analyze the downlink direction (AP to clients). APs inherently have the flexibility to place more antennas and are able to radiate more power. Simulations were done to compare a 3x3, 2-stream system with the reference 2x2, 2-stream configuration. Similar to the simulation conditions already mentioned, the ITU1238 model was used: 11g band (2.4 GHz), 20MHz mode, 50 ns rms delay spread, 3.1 dB path loss, 20 dBm power per transmit chain, 3dB antenna gain, 5 dB system receiver noise, 12 dB shadowing margin, 4 dB floor loss. The result of the downlink simulations are presented in Figure 5.

Figure 5 Simulations of downlink throughput: 2x2 and 3x3 both with 2 streams

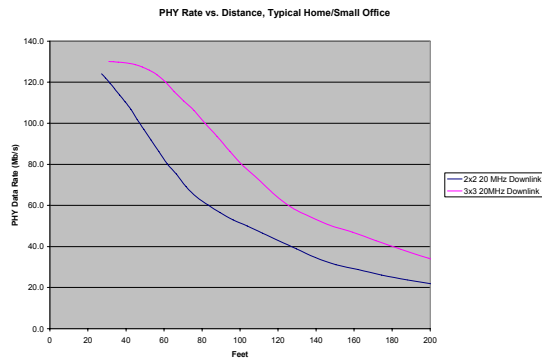
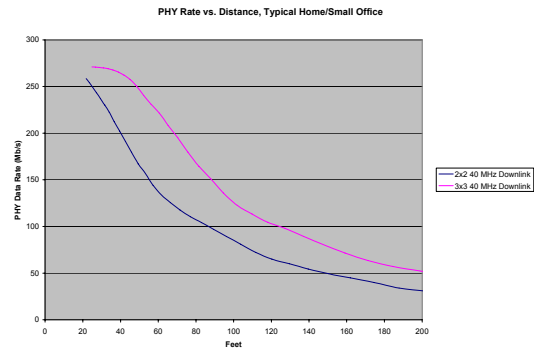


Figure 6 Simulation results for 40MHz mode: 2x2 and 3x3 downlink direction, both with 2 streams



It is evident from Figure 5 that the 3x3 configuration outperforms the 2x2 in downlink direction by better than 40% in the 20-100ft range.

Downlink simulated performance data for the 40MHz is given in Figure 6. As with 20MHz mode, significant improvement appears in the average throughput rate for the 3x3 configuration. Up to 50% improvement can be seen in the critical 50-80 ft range typical of the small office/small home environment.

The results shown in these graphs are average throughput figures. Other articles have published similar claims. However, one key performance metric often overlooked is the minimum guaranteed throughput rates. As stated here, MIMO systems rely on the environment to produce uncorrelated signals at the receive antennas. A small change in the environment (rotating or moving the laptop) can prevent multipath components from reaching one of the receive antennas. If the received signals become correlated, the system will be forced to reduce the number of streams, resulting in reduced throughput. In other words, MIMO systems can have a large variation in throughput even at the same distance. By increasing the number of receive antennas, the probability that uncorrelated signals can reach the receiver increases. So, receivers with more antennas have a higher probability of maintaining higher number of streams and hence increased throughput.

COST OF MIMO

Without doubt, the performance of MIMO systems improves with additional diversity (i.e., more antennas). However, what is the cost of the improved performance in terms of power as well as the dollar amount?

The dollar cost and power dissipation are actually correlated. Each transmit chain requires the following: antenna, power amplifier (PA), RF mixer, RF filter, IF mixer, IF filter, baseband filter, DAC, and some incremental digital circuitry. Each receive chain requires the following: antenna, low-noise amplifier (LNA), RF filter, RF mixer, IF filter, IF mixer, baseband filter, ADC, and digital circuitry to process the spatially multiplexed signals. Each circuit component contributes to the power dissipation as well as dollar cost, which is why the two are highly correlated. The total cost (dollar amount and power) is roughly a function of the number of transmit chains, the number of receive chains, the number of data streams, and also the square of the number of data streams (computational complexity of extracting data streams follows the square of the number of streams). In other words, cost is proportional to f_c (fixed_cost, N, M, S, S2), where f_c is the linear combination function.

Performance of a MIMO system, on the other hand, has the tendency of diminishing returns. SM only works when the signal from each of the receive chain is statistically uncorrelated. At the 2.4GHz carrier frequency that 11n operates, the wavelength of the radio signals is $\sim 12\text{cm}$. Typical APs are 16-20cm wide. If the separation between each receive antenna are less than 12cm (one wavelength), the signals at those antennas will likely have some degree of correlation. The closer the spacing between antennas, the more correlated the signals get and result in diminished benefits of spatial multiplexing. Simply adding more antennas does not improve the performance linearly, but rather saturates up to the number of uncorrelated signals collected. Therefore, performance $\sim f_p (S \times [1 - e^{-(N+M)}])$, where S = number of streams (uncorrelated signals measured by the receive chains), N = number of Tx chains, and M = number of Rx chains.

Graphically, our model of the total system cost (power and dollar amount) and performance is compared in Figure 7. As the complexity of the MIMO system increases the cost grows exponentially while the performance saturates.

Figure 7 Relative cost and performance of MIMO systems

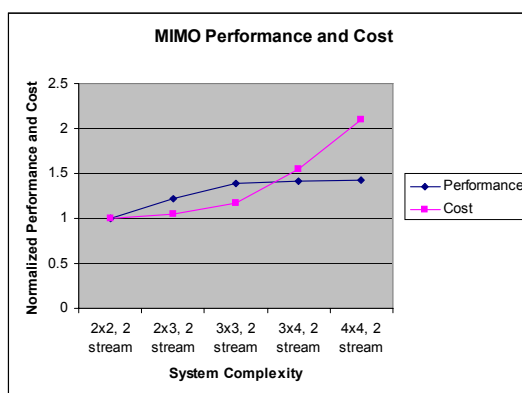


Figure 7 depicts the “bang per buck” curve. For configurations up to 3x3, the performance curve is above the cost curve. However, when the complexity of the MIMO system reaches the 3x4 configuration, the return on investment is not favorable.

Conclusion

MIMO systems are capable of improving throughput over range. However, the law of diminishing returns comes into play. For a two-stream MIMO system, the performance versus the total system cost is optimized with the AP configured as a 3x3 system while the client is configured as a 2x3 system.

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