MU-MIMO – a practical example

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Introduction

Servicing a large number of clients that are using small packets with legacy Wi-Fi is inefficient because the overheads incurred by the preamble and other mechanisms tend to dominate. OFDMA is ideally suited for this scenario because it divides up the channel and services up to 37 users simultaneously, which amortizes the overhead. OFDMA improves system efficiency, but it does not necessarily improve throughput.

MU-MIMO creates spatially distinct separate channels between the transmitter and each of a small number of receivers such that each receiver hears only the information intended for itself, and not the information intended for other receivers. This means that the transmitter can, by superposition, transmit to a number of receivers simultaneously, increasing the aggregate throughput by a factor equivalent to the number of receivers being serviced.

Beamforming and MU-MIMO

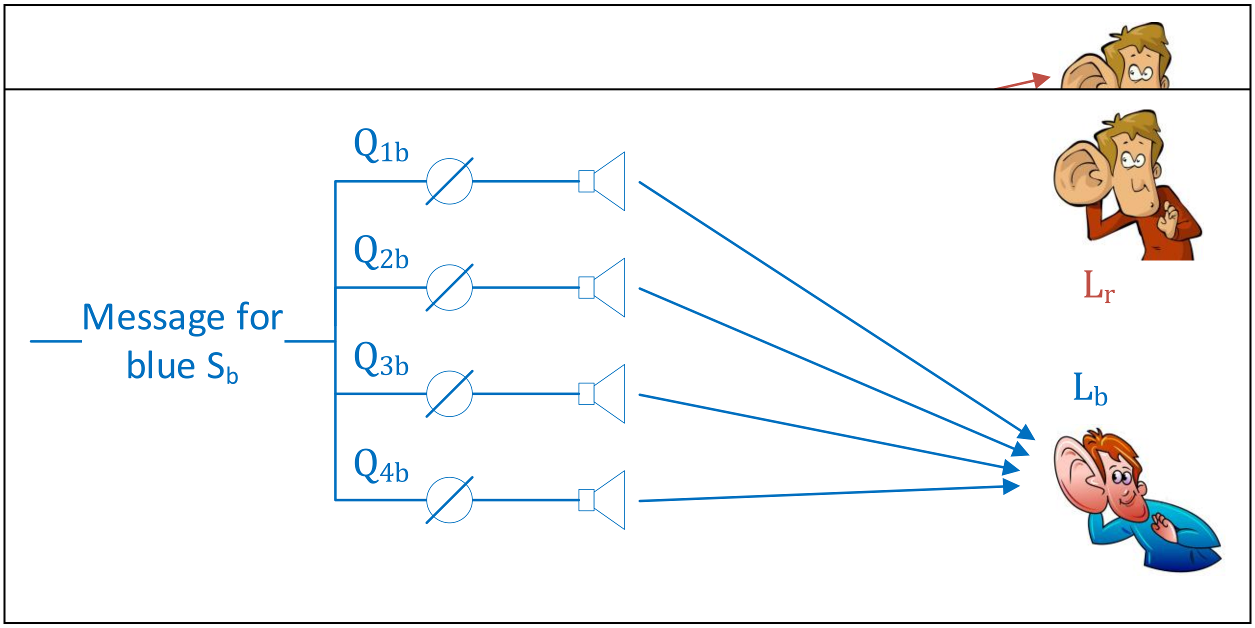
Beamforming radio waves using an array of phased antennas has been known for decades. More recently the principles have been used to produce MU-MIMO where the concept of multiple simultaneous beams to provide independent channels for each of the users.

The math behind MU-MIMO is complicated and it is often difficult to explain how MU-MIMO works to someone not familiar with the details.

for someone not familiar Similar principles apply in the audio domain where speakers can be phased to direct sound to a particular location. The idea is to adjust the phases of each speaker such that the sound adds constructively at the point where the listener is, and destructively at all other locations.

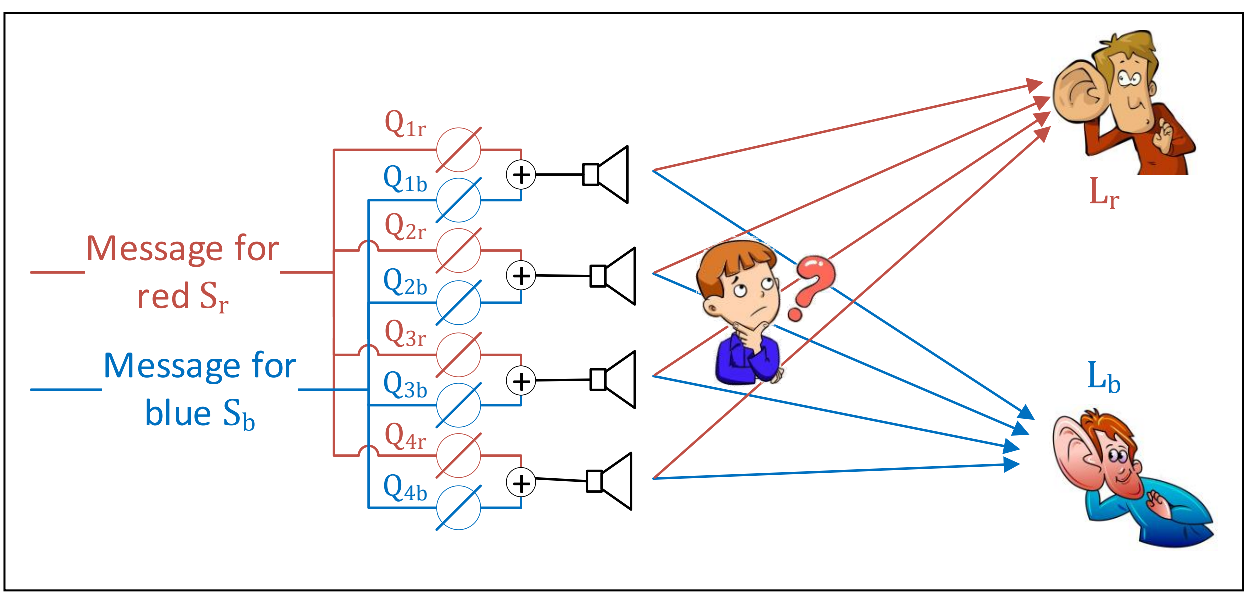
Consider a sound, S_r, played through an array of four speakers with the sound for each speaker adjusted by a phasor Q_{1r} through Q_{4r} so that the signal strength at the red listener, L_r is maximized, and the signal strength at the blue listener L_b is minimized.

$$L_r = Q_{1r}S_r + Q_{2r}S_r + Q_{3r} + Q_{4r}S_r$$



Similarly we select a set of phasors Q_{1b} through Q_{4r} to maximize the signal for listener L_b while minimizing it for listener L_r.

Using superposition, we can take each message, impose the appropriate phase adjustment, and add the signals just before they go into the speakers. This way we can send two different messages at the same time, but each listener will hear only the message intended for them.



Note the importance of spatial separation – L_b and L_r are hearing their respective messages because the phasors were optimized to deliver each sound to their specific location. If one of the listeners moves from his position, he will no longer hear his message.

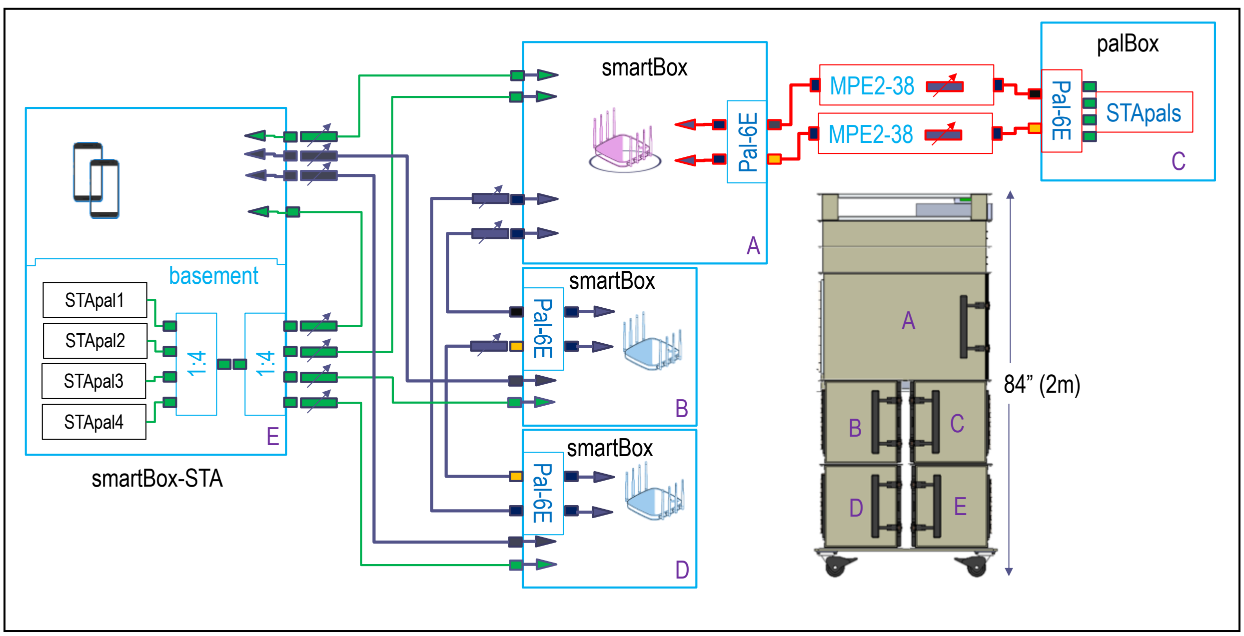
If a third person enters the picture and stands close to the speakers, he will hear the garbled sound of both messages simultaneously.

Consider this in the context of Wi-Fi where the speakers are replaced by antennas and the signal processing to control the phasors, and generate digital messages at a certain data rate, is done in the AP. Since both messages can be transmitted simultaneously one could theoretically double the aggregated data rate. The same approach can be used to service more clients simultaneously, so where is the limit? Practically, there are limits in the accuracy that the phasors can be set, there are reflections that cause "cross talk" and other imperfections that limit the gains in throughput that can be achieved.

Sniffing in the context of MU-MIMO is more complicated because of the spatial significance. Note that placing a sniffer close to the AP will achieve the same garbled message effect we discussed earlier. The sniffer probe must be placed physically close to the device that is being sniffed, and generally one sniffer probe is required for each device.

Practical testing

For this test we will use the octoScope STACK-MAX testbed which is capable of performing a wide variety of tests using the octoScope instruments. The Pal-6E is based on the Qualcomm Hawkeye chipset and can act in various modes including as an AP, a STA, a sniffer probe, or up to 256 virtual STAs.



The STApal is a fully contained STA based upon the Intel AX210 chipset, running either Windows or Linux on its own hardware platform, and is able to be used as a STA or a sniffer probe. The palBox contains 16 self-contained STApals which makes it useful for OFDMA and MU-MIMO testing.

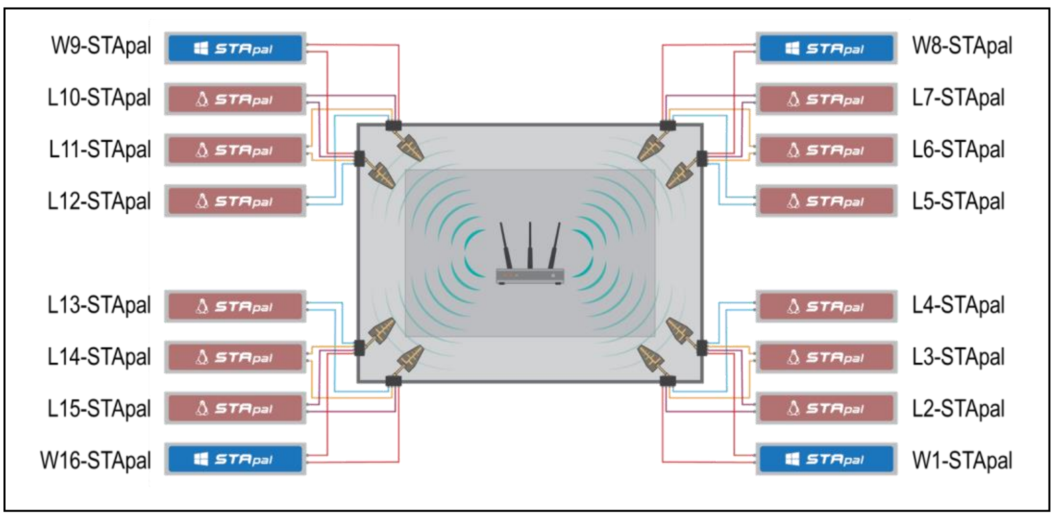
All of the test chambers are completely isolated from the outside world, and signal paths between them are controlled using fully shielded attenuators, so that reliable and repeatable measurements can be made. The chambers are lined with an RF absorptive foam to significantly reduce internal reflections and prevent standing waves. These measures make the environment suitable for MU-MIMO testing and the documents referenced (Kirsch, 2019), (Tefft, 2018), provide a PhD level academic analysis to prove this.

For this MU-MIMO test we will use only the portion of STACK-MAX marked in red in the diagram. This path connects signals from the Cisco AP in chamber A through to individual STApals in the palBox chamber C. The two Pal-6Es are effectively bypassed, and we will use the multipath emulator (MPE) in LOS, or IEEE Channel Model A mode.

We have seen that spatial separation is a requirement for successful MU-MIMO operation. The octoScope personal testbed achieves this by placing antennas in the corners of the anechoic test chamber to get the best spatial separation.

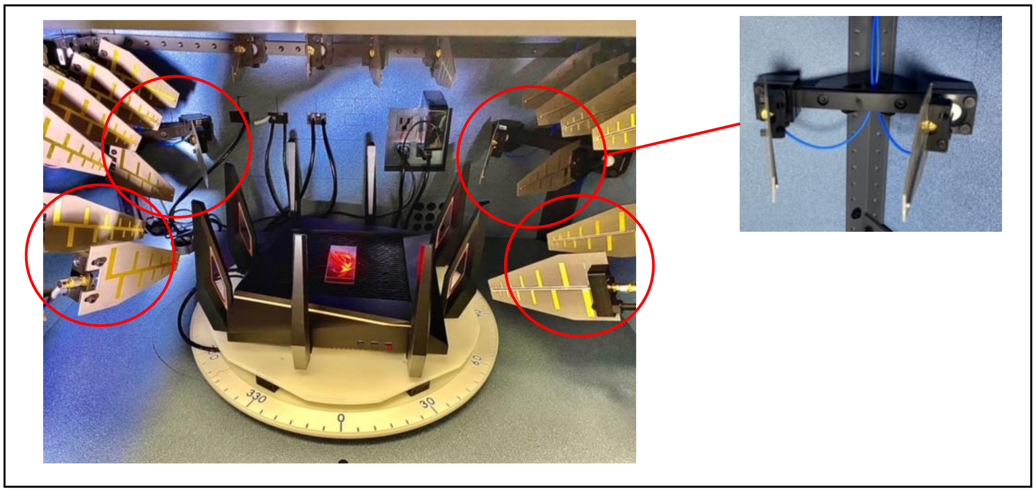
Each pair of antennas is fed into a group of four clients in the palBox as shown in the diagram below.

This allows four independent MU-MIMO streams to STAs in the four groups of four, allowing a companion STA in each group to be allocated as a sniffer probe if needed.

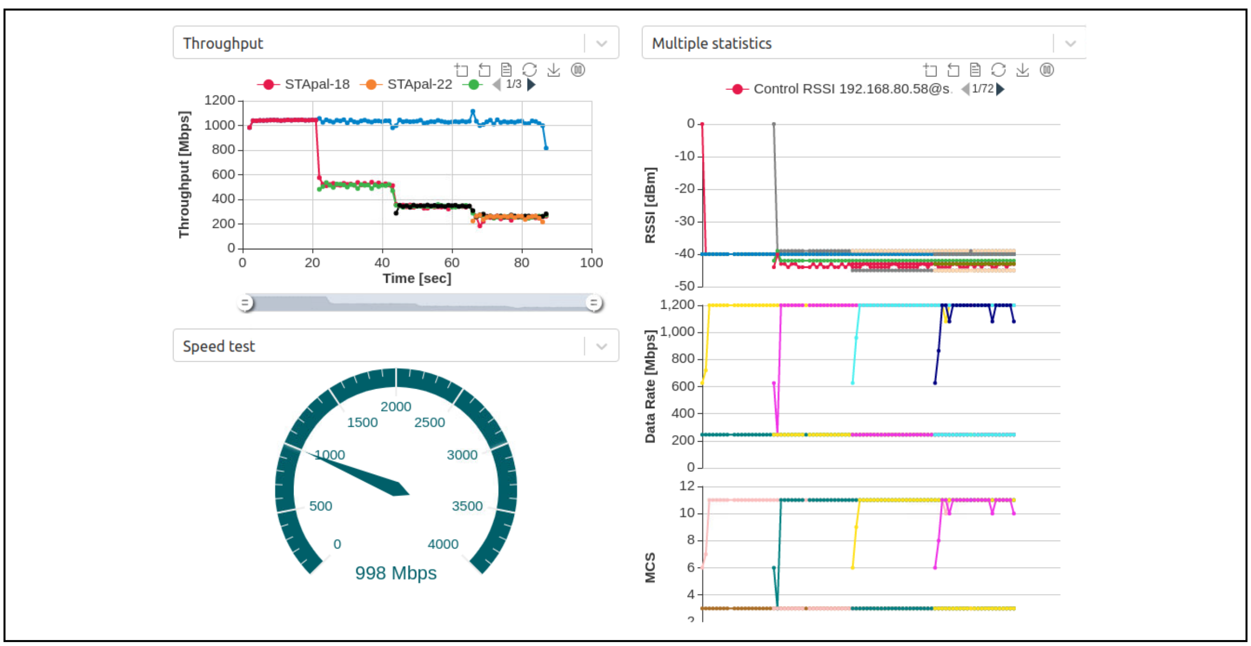


Practical testing

To demonstrate the MU-MIMO gains we place an AP in the center of the chamber and run UDP traffic to the STAs attached to the antennas in the box corners as shown in the diagram below.

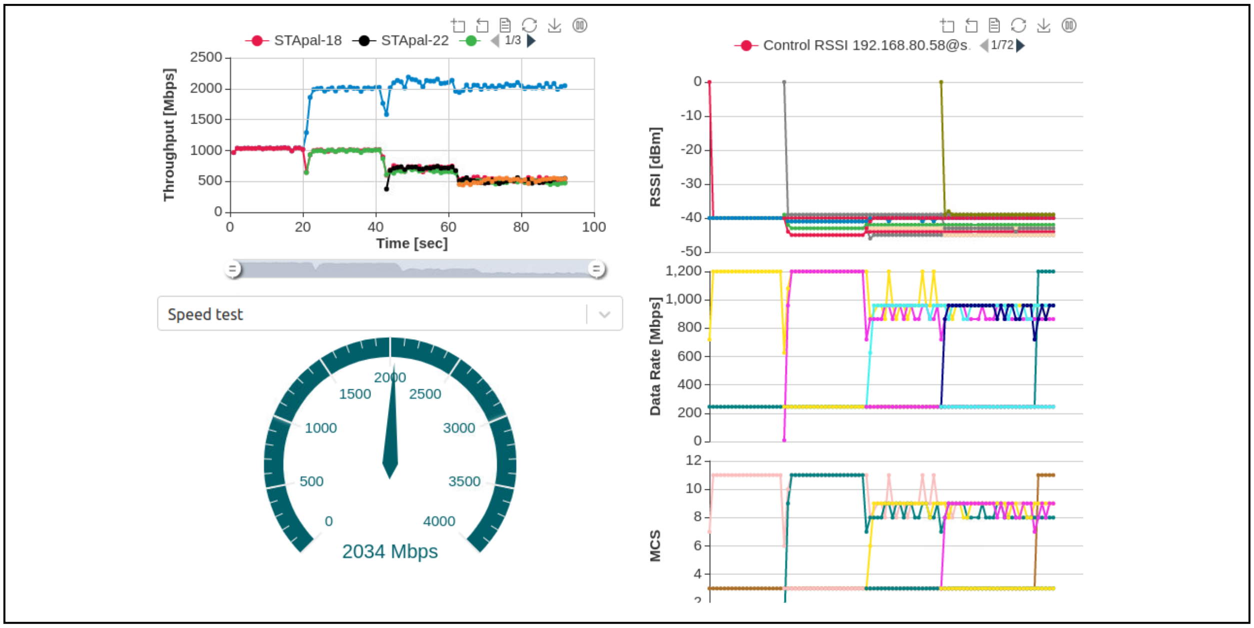


First we do this with MU-MIMO switched off and we start with one STA and we note that the throughput is just a little over 1000 Mbps, a little less than the 1200 Mbps of the PHY rate. After 20 seconds we introduce another STA and see that the aggregate throughput stays at the 1000 Mbps, but that the two STAs share the channel and each STA is achieving 500 Mbps. 20 seconds later we introduce a third STA. Again the aggregate throughput stays the same at 1000 MBps, and the three STAs share the channel to get a little over 300 Mbps each. Introduction of the fourth STA follows the same pattern with the aggregate remaining unchanged, and each STA receiving 250 M bps.



We repeat the experiment, this time with MU-MIMO switched on.

Starting with one STA we achieve the familiar 1000 Mbps. After 20 seconds we introduce the second STA and note the aggregate has increased to 2000 Mbps which is significantly higher than the PHY rate. We also note that each STA is still receiving nearly the 1000 Mbps it was before. Unlike the previous experiment where the STAs shared the channel, in this experiment they are each able to fully utilize their own channel independently of the other.



Adding a third STA increases the aggregate to 2300 Mbps. Here the gain is not quite so dramatic, but each of the three STAs is still receiving 760 Mbps. Addition of a fourth STA results in a slight decrease of the aggregate throughput to 2100 Mbps – nevertheless each STA is receiving 525 Mbps, a two-fold increase over SU operation.

The table below summarizes the results.

		Individual device throughput (Mbps)	Aggregate throughput (Mbps)	MU-MIMO gain
4 clients	MU-MIMO off	250	1000	
1 client	MU-MIMO on	1000	1000	1
2 clients	MU-MIMO on	1000	2000	2
3 clients	MU-MIMO on	760	2300	2.3
4 clients	MU-MIMO on	525	2100	2.1

Conclusion

MU-MIMO exploits the spatial separation of receivers to direct independent messages to each of the receivers simultaneously. This allows for much more efficient use of the medium and increases the aggregate data that the network can deliver.

Spatial separation of the stations is key to successful operation. In an open area spatial separation is easy to achieve, but interference from nearby networks tends to cloud reliability of the results and care must be taken to ensure that path losses are similar for each STA.

We have demonstrated that MU-MIMO can be achieved in a relatively small anechoic chamber by placing antennas in the corners of the chamber. The best MU-MIMO gain is achieved with two STAs. Adding additional STAs gives further gain, but to a more limited extent.

References

[1] Kirsch, D. J. (2019). *SMALL ANECHOIC CHAMBER CHANNELS Estimating Channel Capacity from a Chamber Model.* University of New Hampshire. https://www.octoscope.com/English/Collaterals/Whitepapers/octoScope_WP_UNH_MIMO-OTA_dissertation_summary.pdf

[2] Tefft, J. (2018). *NEAR-FIELD MIMO CHANNEL MODELING WITH APPLICATIONS TO SMALL ANECHOIC CHAMBERS.* University of New Hampshire. https://www.octoscope.com/English/Collaterals/Whitepapers/octoScope_WP_NearFieldMIOChannel_201812.pdf