

# white paper

## INTRODUCTION

User demands on Wi-Fi networks continue to rise quickly across every segment of the industry, and as a direct result, great radio performance matters more than ever. Achieving that high performance is no small challenge in the face of high AP density, high client counts, and interference — requiring the use of every technology tool available to better control and improve radio behavior in the environment.

The latest generation of Wi-Fi chipsets are bringing a potentially useful new addition to the toolkit: transmit beamforming with explicit feedback (commonly referred to as “TxBF”). TxBF can offer gains under the right circumstances, but it has some inherent limitations that mean it cannot solve the performance challenge all by itself, despite some vigorous vendor marketing claims to the contrary.

Used in combination with adaptive antennas, though, TxBF can become an essential tool in a comprehensive approach to achieving maximum radio performance in today’s challenging environments.

Ruckus is continuing in its long tradition of pioneering work in the cost-effective application of smart antenna concepts to Wi-Fi, by enhancing our statistical optimization approach to radio performance with this combination of TxBF and adaptive antennas. As a result, APs equipped with our BeamFlex 2.0 technology, such as the recently launched ZoneFlex 7982 3x3:3 dual-band 802.11n AP, are setting new performance benchmarks for the industry.

This paper provides a thorough introduction to these smart antenna technologies, how they can be used together, and the results their combination makes possible in real-world WLAN networks.

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## GETTING THE BEST WI-FI PERFORMANCE POSSIBLE THROUGH BOTH BEAMFORMING AND ADAPTIVE ANTENNAS

### Understanding the Principles of Beamforming

This will take some explanation. One of the causes of vendor marketing excesses in this area is the simple fact that the concepts in multi-antenna technology can get complicated, especially for Wi-Fi buyers and users who may have strong technical backgrounds in other fields but who have little experience in the arcana of advanced radio-frequency engineering — in other words, the majority of you. We certainly don’t mean that observation as a slight to any of you, since it’s just fine with us that you leave the detailed engineering work in this area to the experts. No one would expect you to design your own compact fluorescent light bulbs or LCD televisions, either. The downside, though, is that it’s easy for vendors to mislead customers about RF behaviors while sounding vaguely credible, often without even realizing themselves that they’re completely disconnected from the real physics of wireless (since very few marketing people really understand how this all works, either), and certainly with little chance of savvy customers calling the technical foul.

Since these RF fundamentals matter so much now to the performance of your network, and to the experience of your users, we’re ready to take up the challenge of getting you enough knowledge to make good Wi-Fi network design decisions nonetheless. To build the foundation in “how stuff works” required to accurately assess claims and likely performance benefits for multi-antenna systems, we’re going to go back to the basics here, using lots of pictures and defining carefully the necessary jargon along the way to try to help make things very clear.

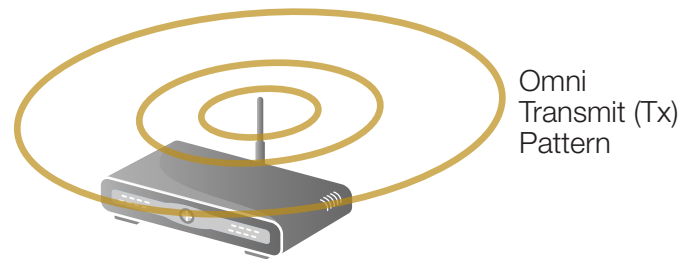
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We start with an old-fashioned single-antenna access point, shown in **Figure 1**, with a common omni-directional antenna, or an “omni”. When this device transmits, as the antenna’s name suggests, it sends the same signal in all directions in the horizontal plane (we’ll worry about what happens in the vertical direction in section 4). While this approach has a certain satisfying design simplicity, it has substantial performance disadvantages. The vast majority of this radio energy is completely wasted, since an access point can only talk to one client at a time. Beyond mere waste, this excess energy causes problems in the form of more self-interference in the WLAN, stepping on neighboring APs and their clients and reducing the possibility of channel reuse nearby. Meanwhile, the tiny fraction of transmit energy that actually reaches the client yields a lower throughput rate, as we’ll show shortly, than would be the case if the energy could be focused more tightly (since client throughput is directly related to available signal strength).

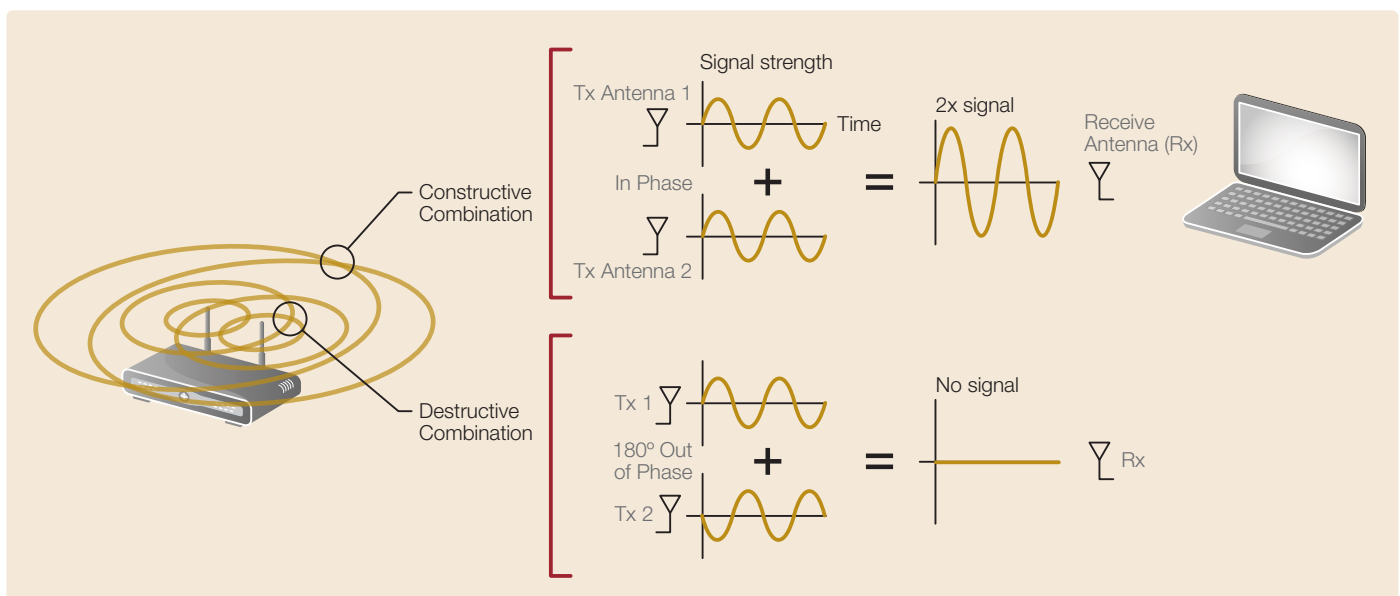
Next we introduce another omni antenna to begin to explore the options this might provide us for better control of the radio signal. As shown in **Figure 2**, the combination of two copies of the same signal transmitted from two neighboring omni antennas creates a set of intersecting troughs and peaks, much like the wave rings you would get by tossing two separate rocks into a still pond at the same time. In some locations, the peaks of the signal from transmit antenna 1 (“Tx 1”, in the jargon) line up in space and time with the peaks from Tx 2 — this is referred to as

**FIGURE 1:** Radio signal distribution pattern from an access point with one omni-directional antenna.



constructive combination. In other locations, the peaks of Tx 1’s signal are lined up with the troughs of signal from Tx 2, which yields destructive combination. If a receive (Rx) antenna is placed in the zone of perfect constructive combination, it would pick up roughly twice the signal strength of a single Tx antenna’s output, without doing any intelligent work on its own — its analog receive electronics simply sum the signals received automatically. In contrast, a zone of complete destructive combination would yield zero signal, a phenomenon useful in reducing intra-AP interference at the network level (more on this later). The repeating patterns in radio communication signals allow us to use the concept of phase to describe the peak or trough match-up relationship between two different signals.

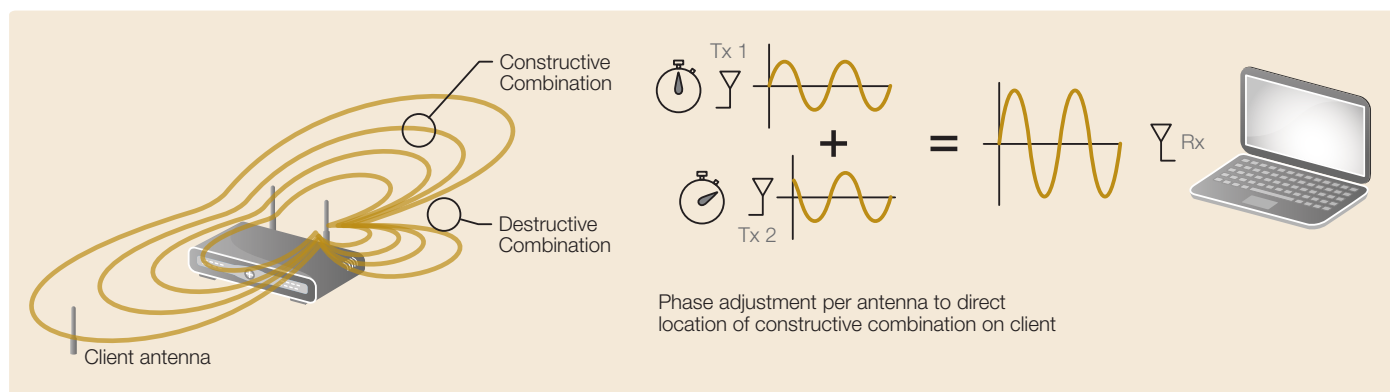
**FIGURE 2:** Fundamental concepts in multi-antenna processing for increased signal strength (technology often broadly categorized as “beamforming”)



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FIGURE 3: How signal phase control works in beamforming.



One way in which the phenomena of constructive and destructive combinations of multiple transmit sources can be put to productive use is through the addition of active control of individual transmit signal phases. This is the narrow (and most technically correct) definition of the term beamforming, and the type of multi-antenna processing that we mentioned at the outset is arriving in the current generation of Wi-Fi chipsets. In beamforming systematic manipulation of the phase of signals transmitted from multiple antennas is used to place zones of constructive combination that fall ideally at the location of the client of interest. We illustrate this in **Figure 3**. The depiction of the transmission pattern has been cleaned up here in order to show only the areas of strongest constructive combination, which is the common convention for showing “antenna patterns” — essentially the equivalent of geographic contour maps, where the lines in this case indicate levels of signal strength rather than height. You can see where the term beamforming arises, since the resulting patterns tend to have lobes of constructive combination areas that look somewhat like “beams” of energy shining out from the antenna array, much like the beam of a flashlight, that are “formed” by the system controlling the individual phases of the antennas. “Controlling phase” in this context means essentially “changing when you start transmitting.” Outside the lobes of the pattern as drawn are areas of destructive combination.

Phase is adjusted by the system to compensate for different travel times between each antenna and the client of interest, so that the signals from Tx 1 and Tx 2 arrive at Rx with their peaks aligned in time, maximizing signal strength at the client. So far, so simple. Things need to get a little more interesting to assess with clarity what’s being used in Wi-Fi today.

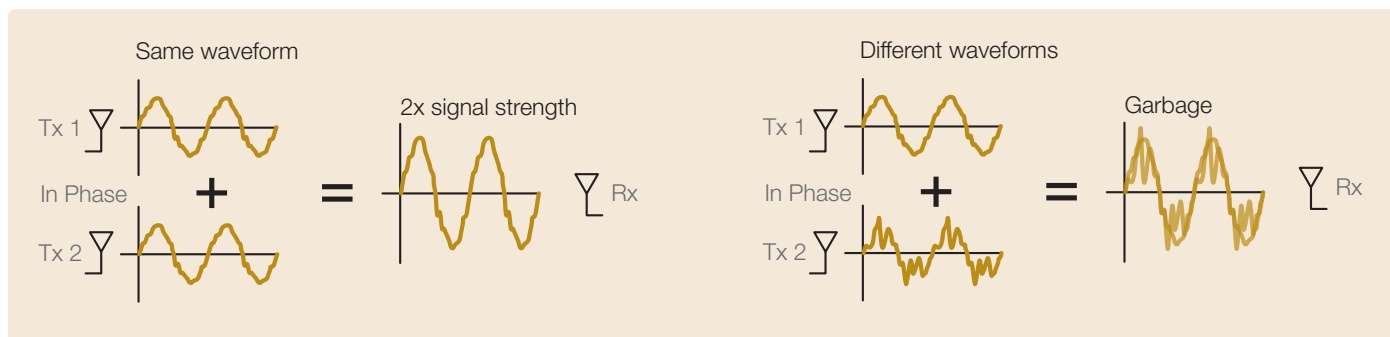
A key underlying requirement in beamforming is that both Tx 1 and Tx 2 are transmitting the same signal. To understand why that is important, we need a short word on the nature of the signals themselves. So far we’ve been using simple sinusoidal curves to depict our wireless signals, so they may appear to be just generic energy levels, and it might not be obvious why one segment of the orange curve couldn’t be combined at Rx with any other. The signal-shape reality of today’s encoded wireless transmissions is much more complex. In order to achieve high throughput, many bits are transmitted at the same time on a single signal “wave”, in a format called a constellation, where at a single snapshot in time each bit holds a particular place in a matrix in the real and imaginary number space. Fortunately for the many of you we’ve just lost with that last sentence, this particular batch of complexity is not important to understand fully in the context of evaluating multi-antenna processing technology. For sake of keeping things as simple as possible, we’ll show “real” wireless signals through squiggles we borrowed from the audio electronics world, in order to illustrate some key concepts.

We put this into practice first in **Figure 4**. Remember that the receive processing done by the client in a phase-based beamforming system is just simple summation of the signals received at any given time. **Figure 4** illustrates visually a point we can also make through a music analogy: if you had two audio speakers side by side blasting two different tunes (say, Bach’s Brandenburg Concerto #1 and Black Sabbath’s “Fairies Wear Boots”) at the same time, you’d hear essentially just noise. If they were both playing the same tune at exactly the same time, you’d hear a louder version of the tune. So to repeat: TxBF requires multiple copies of the same signal arriving in phase at the receiver.

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FIGURE 4: Phase-based beamforming can only be used with copies of the same signal.



The other key underlying requirement in beamforming is that the system knows where the client is, in an RF-signal-path sense of the term “where”, in order to choose phase adjustments to point or “steer” one of its beams in the right direction. In the Wi-Fi world there are two different approaches being used for educating the AP about client “location”:

**Implicit Feedback:** In the normal course of communication from client to AP, the AP can detect from its multiple antennas the different phases of arrival of a signal from the client on each of the AP’s antennas. This is roughly analogous to the way human ears process sounds that arrive at each ear at different times and therefore give an indication of the direction from which the sound came. It’s worth noting that for the same reason our ears can be deceived by sound bouncing off acoustically reflective surfaces, the AP’s impression of the client achieved by measurement of signal arrival phase differences is not a terribly reliable indication of actual physical location — because of signal reflection off surfaces in the environment in which the AP and client are operating. In implicit beamforming the phase differences are used as just that — phase differences that should be applied to the AP’s transmit antennas to achieve maximum constructive combination on the next transmit to that client.

The flaw in using the radio-space characteristics of the uplink from client to AP as a model for what should be used to manipulate signals in the downlink is that signal behavior can differ substantially between the uplink and downlink paths, largely because of the differing antenna geometries of APs and clients. We’ll show quantitatively in our subsequent section on performance assessment that beamforming with implicit feedback really just doesn’t work very well, for primarily this reason.

**Explicit Feedback:** To improve on the poor performance of implicit feedback, the alternative accommodated in the 802.11n

standard that is just now coming into infrastructure products and (eventually, it is hoped) clients in Wi-Fi involves communication from the client to the AP of what would work best for the client (in terms of the AP’s transmit phases and other settings), given the client’s current vantage point in the radio space. This is the variety of beamforming to which we referred in our introduction, commonly termed TxBF. Wi-Fi client adoption of this feature will be a gradual process over the coming years, so this approach faces some commercial challenges in practice. More technically, while it certainly improves the quality of the AP’s understanding of the characteristics of the best radio path to the client, it remains subject to the limitations intrinsic to small-antenna-count beamforming in the context of Wi-Fi networks. We elaborate on the nature of these limitations in the following sections.

One final note on this category: since the manipulation of signal phase must be done at the PHY layer (at the lowest level of hardware), both implicit and explicit beamforming functionality must be built into the Wi-Fi chipset. For this reason, these techniques are sometimes referred to as “chip-based beamforming” in the industry.

## The next fundamental building block: Spatial multiplexing

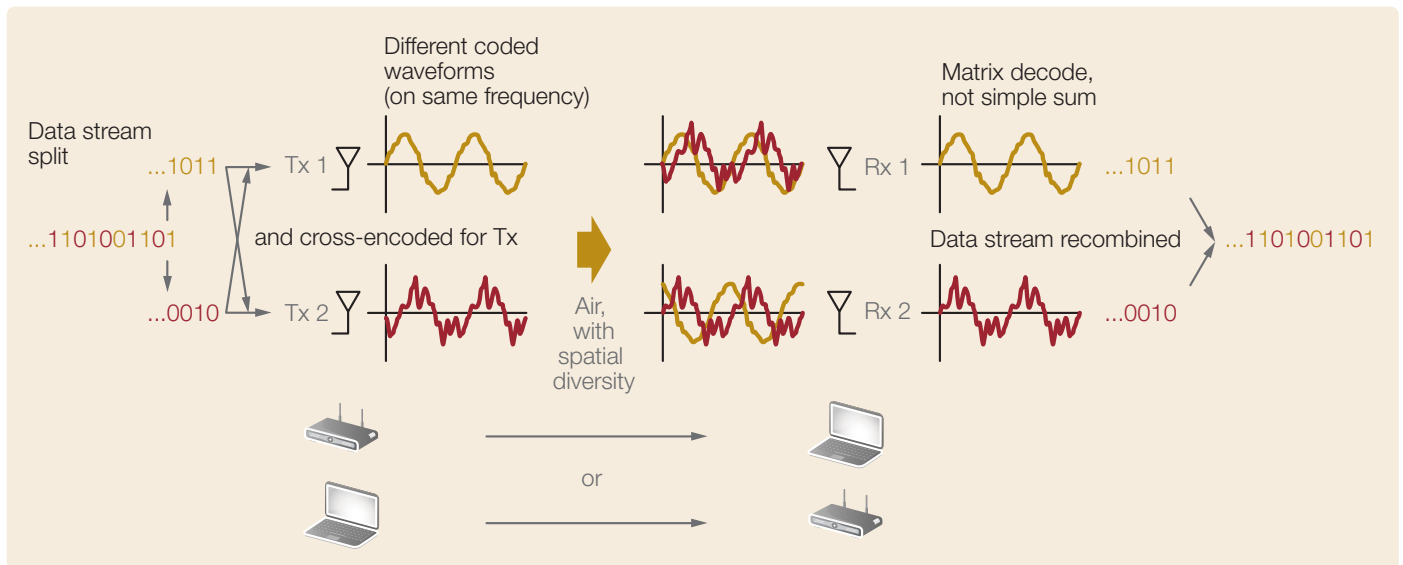
Phase-based beamforming was actually the simpler story. The more complex topic that is more essential to the high data rates defined in the 802.11n Wi-Fi protocol is **spatial multiplexing**, or SM. Note that in the Wi-Fi community the term **MIMO** is often used as a synonym for SM, which it’s not, really. Since we’re trying to sort things out clearly here, it’s worth cleaning this one up at the outset with a couple definitions:

**MIMO** = an acronym for “multiple input, multiple output”. Defined from the vantage point of the air between an AP and a client, the term refers simply to a system design where more than one

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FIGURE 5: How spatial multiplexing works.



transmit antenna put signals into the air (multiple input), and where more than one receive antenna extracts these signals from the air (multiple output). MIMO systems can be used to do a variety of different forms of multi-antenna processing, but not necessarily all at the same time, as we'll discuss below.

**SM** = spatial multiplexing. A system in which a single flow of bits is broken up into two or more streams that are transmitted into the air from Tx antennas separated in space (with one stream per antenna). These multiple streams are then extracted from the air by the same number of Rx antennas, also separated in space, and then recombined into the original single bit flow. SM requires a MIMO antenna architecture, i.e., multiple antennas on both client and AP. The point of the exercise is to get bits over the air interface faster through additional parallel "lanes" for traffic on the same spectrum.

Figure 5 illustrates how this works from a radio signal perspective. It may appear at first glance to break the rules for signal combination we introduced in section 2, since the blue and orange signals received on each client antenna look like our metaphorical Bach and Black Sabbath arriving at the same eardrum, just creating noise. The details of exactly how SM signals are coded on transmit and decoded on receive go beyond the scope of this paper and would require reviving matrix-math tricks you learned in the undergrad linear algebra class you've certainly forgotten by now. For our purposes here we can just say that the combination of special pre-encoding

and spatial diversity (signals differing based on where in physical space they are received) are leveraged in receive processing to disentangle the streams that got combined in the air between Tx and Rx. Note that this technology can be used by clients to send multiple streams to APs as well. Also note that without spatial diversity between the streams, decoding fails. This spatial diversity requirement will become important when we look at optimal tool selection for different radio jobs in a moment, as will the nature of the signals involved. As we've illustrated in Figure 5, spatial multiplexing requires that Tx antennas produce different signal waveforms in order for the system to code and decode the multiple streams. Phase-based beamforming requires the transmission of multiple copies of the same signal waveform, as we showed previously. With two transmit antennas (and two receive antennas on the other end of the air link, to complete the MIMO requirement for SM), it should be obvious that a system can do spatial multiplexing or phase-based beamforming, but not both at the same time.

To put the impact of this in context, we repeat for convenience in Figure 6 the well-known tabulation of bit rates defined for the various modulation and coding schemes in the IEEE's Wi-Fi standards series. The highlighted part of the 802.11n table emphasizes that all the more interesting rates require two or more spatial streams. In other words, sensible 802.11 systems will bias their designs toward maximizing the use of spatial multiplexing for clients that can support it.

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FIGURE 6: Importance of spatial multiplexing to higher 802.11n bit rates.

802.11 PHY RATES OVERVIEW												
802.11b		802.11a/g			802.11n							
									Peak Bit Rate, Mbps 20 MHz channel		40 MHz channel	
Modulation	Bit Rate Mbps	Modulation	Coding	Bit Rate Mbps	MCS Index	Spatial Streams	Modulation	Coding	800nsGI	400ns GI	800ns GI	400ns GI
DBPSK	1	BPSK	1/2	6	0	1	BPSK	1	7	7	14	15
DQPSK	2	BPSK	3/4	9	1	1	QPSK	1/2	13	14	27	30
CCK	5.5	QPSK	1/2	12	2	1	QPSK	3/4	20	22	41	45
CCK	11	QPSK	3/4	18	3	1	16-QAM	1/2	26	29	54	60
GI=800 ns					4	1	16-QAM	3/4	39	43	81	90
					5	1	64-QAM	2/3	52	58	108	120
					6	1	64-QAM	3/4	59	65	72	135
					7	1	64-QAM	5/6	65	72	135	150
					8	2	BPSK	1/2	13	14	27	30
					9	2	QPSK	1/2	26	29	54	60
					10	2	QPSK	3/4	39	43	81	90
					11	2	16-QAM	1/2	52	58	108	120
					12	2	16-QAM	3/4	78	87	162	180
					13	2	64-QAM	2/3	104	116	216	240
					14	2	64-QAM	3/4	117	130	243	270
					15	2	64-QAM	5/6	130	144	270	300
					...	3	...	...	...	...	...	...
					23	3	64-QAM	5/6	195	217	405	450
					...	4	...	...	...	...	...	...
31	4	64-QAM	5/6	260	289	540	600					
Note: 802.11a/b/g are all single stream												
Abbreviations												
MCS	modulation and coding scheme											
GI	inter-symbol guard interval											

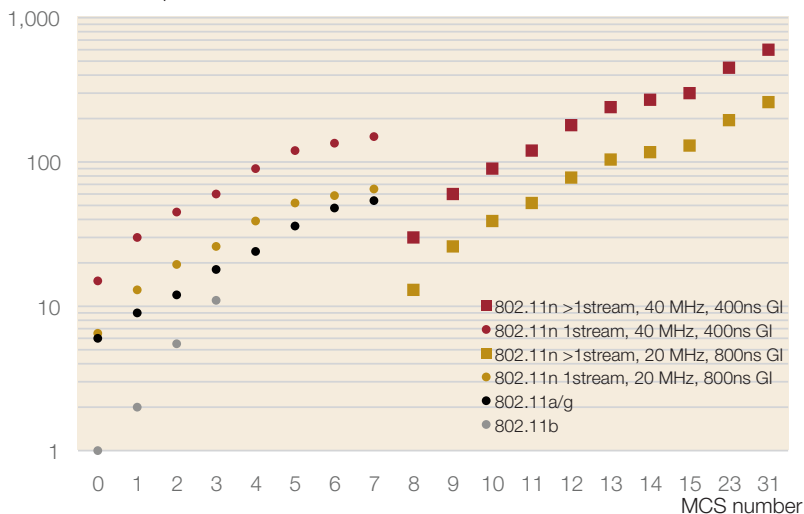
Note: 802.11a/b/g are all single stream

## Abbreviations

MCS modulation and coding scheme  
GI inter-symbol guard interval

and a graphical view:

Peak bit rate, Mbps





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### In Contrast: Understanding Adaptive Antennas

While we often use the term “beamforming” loosely, in the generic sense of “shaping radio energy in space,” to talk about the variety of multi-antenna processing we have employed in our APs to date, as a matter of convenience when we don’t want to have a long discussion about distinctions between different multi-antenna architectures, that’s not an entirely accurate term for what we have been doing, given the strict definition we introduced in section 2. As we illustrate in **Figure 7**, the approach we’ll call for the moment BeamFlex 1.0 involves digitally switching a selection from a large number of antenna elements to connect with the individual radio chains in the RF front end of off-the-shelf Wi-Fi silicon. A “radio chain” is the RF engineering term for the analog radio part between the chip doing the digital Wi-Fi protocol processing and the antennas. In BeamFlex 1.0 there is no analog adjustment of phase on each radio chain. Instead, an optimal combination of antennas is selected on a packet-by-packet basis to focus patterns of radio energy in the right radio-space ‘direction’ based on the inherent characteristics of the antenna elements themselves. The selection for a given client is based on the throughput last achieved with that client, confirmed through the ACK packet that is a standard part of the 802.11a, b, g, and n Wi-Fi protocols and that is supported by all clients today. [Note that some vendors attempt to compensate for their lack of intellectual property contributions in Wi-Fi by de-positioning BeamFlex as “non-standard” — which couldn’t be further from the truth. Our APs are absolutely 100% compliant with the 802.11 protocols, as proven by the Wi-Fi Alliance certification we receive on every model we sell, and require absolutely zero special behavior on the part of clients.]

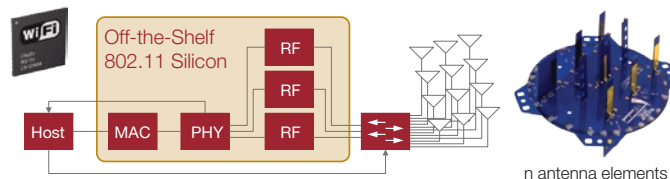
Of the many terms used in the general area of multi-antenna processing techniques (such as smart antennas, beam switching, beamforming, and so on), the most accurate classification of BeamFlex 1.0 would probably be in the category of adaptive antennas (AA). The statistical optimization engine that powers its superior performance is also managing a number of other variables at the system level, including rate selection and power control, so it is about more than just antenna adaptation itself, an idea to which we will return in a moment in the context of BeamFlex 2.0.

There are three primary functional advantages in our ability to use a combination of multiple antennas on individual Wi-Fi radio chains in AA: better antenna patterns, compatibility with spatial multiplexing, and more effective support for polarization diversity. We’ll look at each in turn.

#### Better antenna patterns

The baseline for comparison here is the kinds of beam patterns that can be created with phase-based beamforming — illustrated

FIGURE 7: High-level view of Ruckus BeamFlex architecture.



in **Figure 8**. This approach is limited to using only as many antennas as it has radio chains. With only two or three antennas at work, the shapes that can be created are fairly limited in structure, and they have consistent characteristics that diminish their utility in practice: they are symmetric, and their lobes or beams tend to be relatively narrow. The symmetry means that from the perspective of a target client, half the energy transmitted is wasted. From the vantage point of neighboring APs in the WLAN, this energy is worse than wasted — it means louder co-channel interference. The narrow widths mean they are pretty unforgiving about inaccurately pointed beams. If an AP’s estimate of the right phase combination to use for its antennas is a little off (either because it was using imperfect implicit feedback, or because the higher-quality explicit feedback forthcoming in Wi-Fi systems has gotten out of date because of delays in its use, high client mobility, or rapid changes in the environment like a door closing), the beam formed will fall where the client isn’t, and an area of destructive combination will fall where the client is, making the whole exercise worse than useless.

With AA, in contrast, highly asymmetric patterns can be achieved that have much more forgiving lobe shapes, and with huge variety across physical as well as polarization space (See **Figure 9**). Because the  $n$  elements of a Ruckus antenna matrix can be switched combinatorially to the radio chains of a Wi-Fi chipset, the number of possible patterns is  $2^n$ . Typical AP configurations contain thousands of possible patterns.

The asymmetry of these patterns provides very significant benefits when you look at a WLAN with many access points. As **Figure 10** shows, a typical Ruckus AA pattern has as much as 10 to 15 dB of inherent self-interference suppression over more than half of the total coverage area. As a result, Ruckus APs tend to be better neighbors of each other in a network than is the case for conventional approaches, whether they using TxBF or simple omni antennas alone.

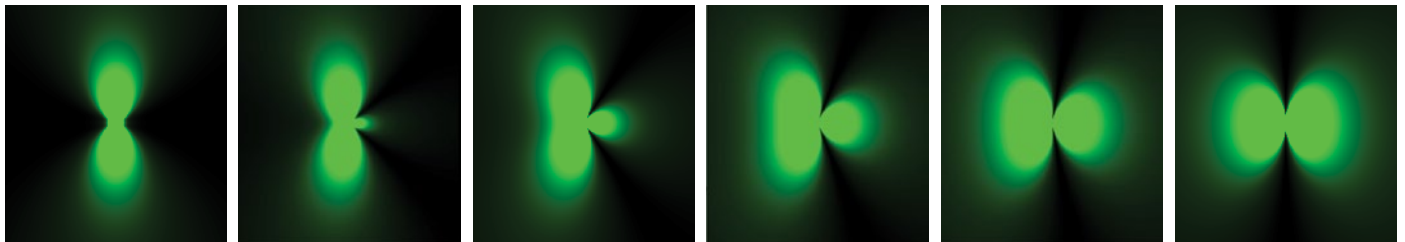
Finally, when combined with TxBF in BeamFlex 2.0, our asymmetric adaptive antenna patterns deliver better client connections while continuing to reduce self-interference, relative to TxBF operation alone. **Figure 11** illustrates how this works.

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FIGURE 8: Full range of patterns of constructive signal combination that can be achieved through phase-based beamforming, with two or three transmit antennas in a typical Wi-Fi AP's configuration (other patterns not shown are simple mirror images of these across a vertical axis).

Two Antennas



Three Antennas

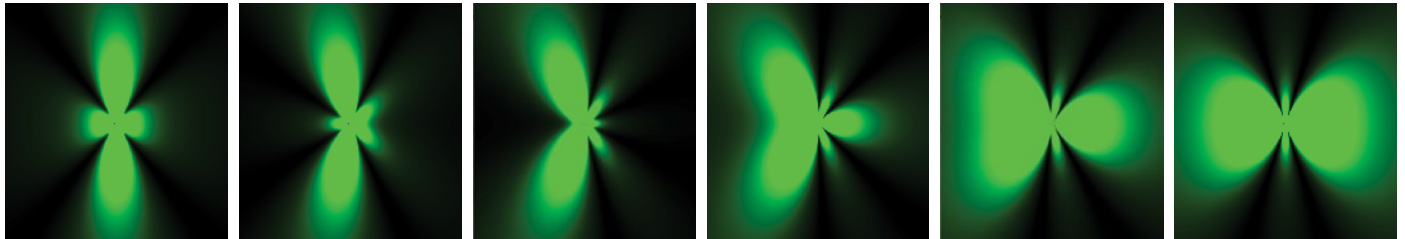


FIGURE 9: Sample of patterns of constructive signal combination that can be achieved through Ruckus BeamFlex (total variations available =  $2^n$ , where  $n$  = the number of elements in the AP's antenna matrix)

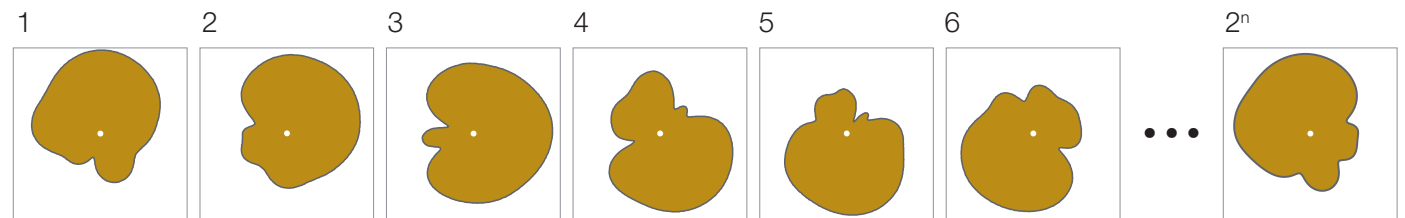
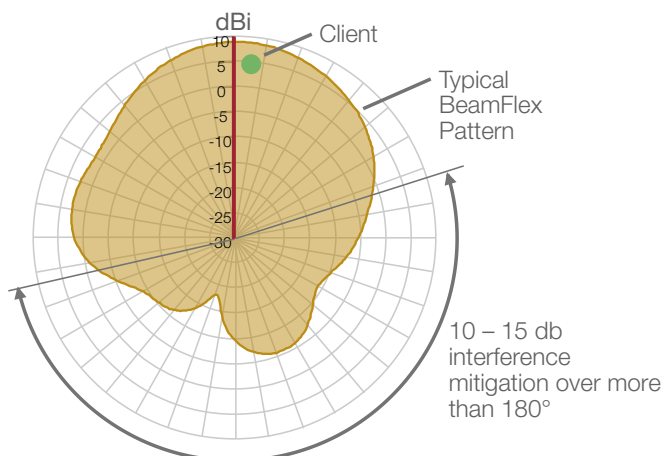


FIGURE 10: Typical BeamFlex antenna system pattern and inherent interference reduction.



## Compatibility with Spatial Multiplexing

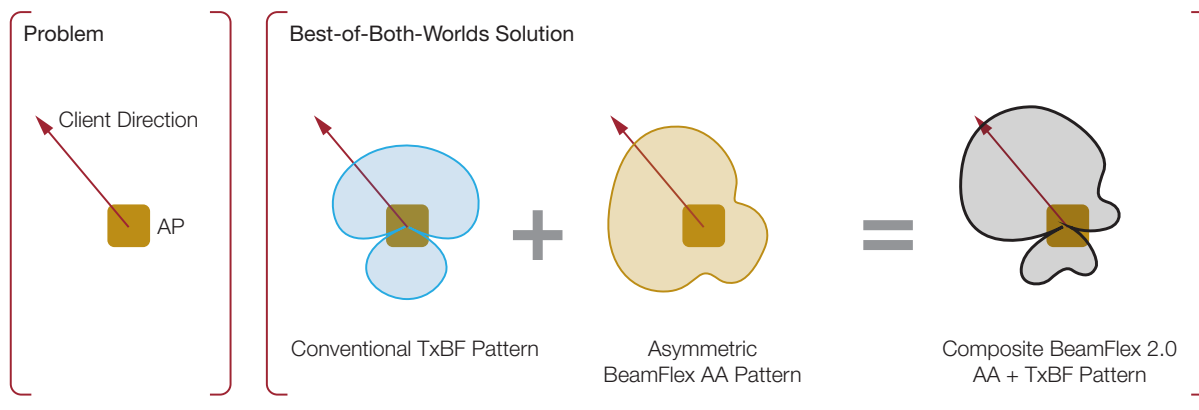
BeamFlex is the industry's only multi-antenna approach that can support both spatial multiplexing and constructive signal combination at the same time using only two transmit radio chains. An example of how this works is shown in Figure 12 below. [We'll note in the interest of full disclosure that it is technically possible to support the combination of SM and TxBF on an AP with four radio chains, but that configuration is not commercially viable in today's Wi-Fi market because of high hardware costs and power requirements beyond the limits of the 802.3af PoE source that is used for the vast majority of AP installations.]



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FIGURE 11: Advantages of BeamFlex AA and TxBF working in concert.



## Net Result:

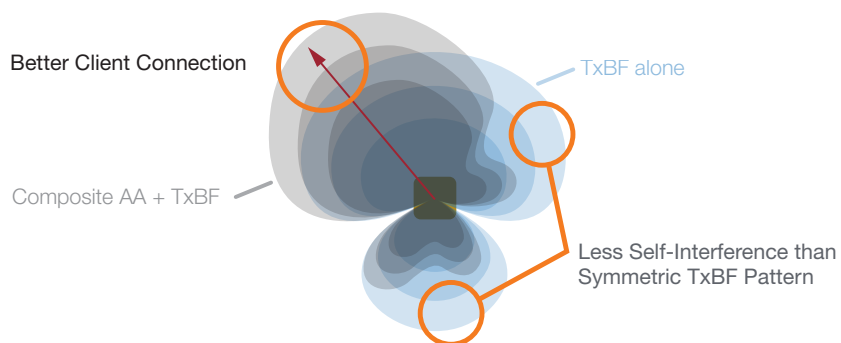
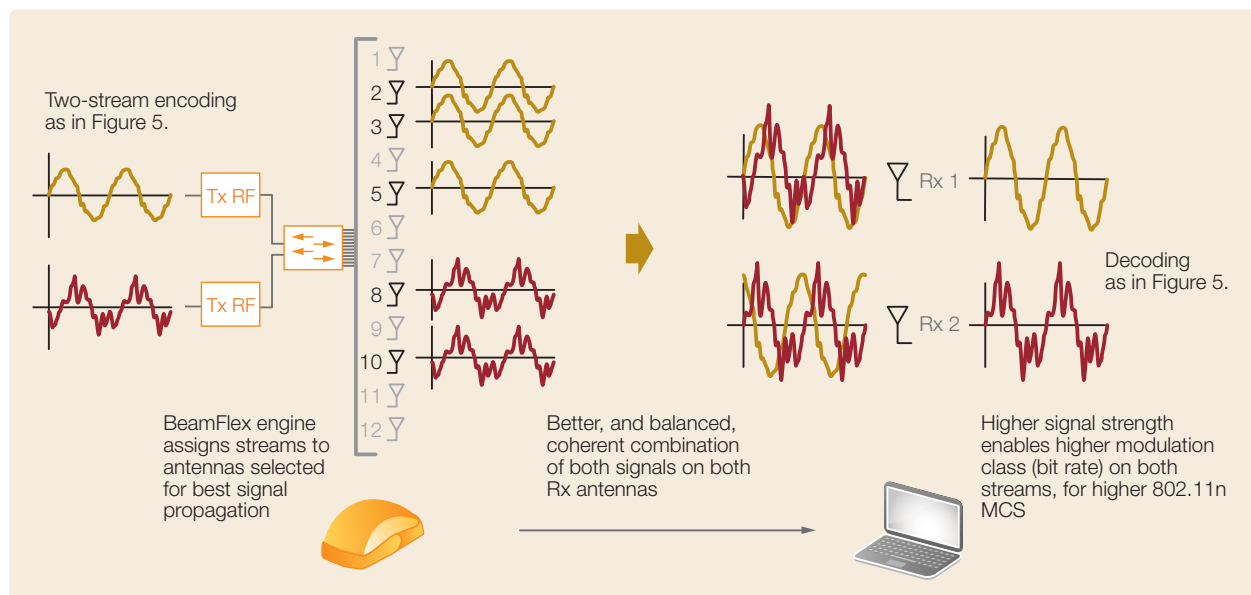


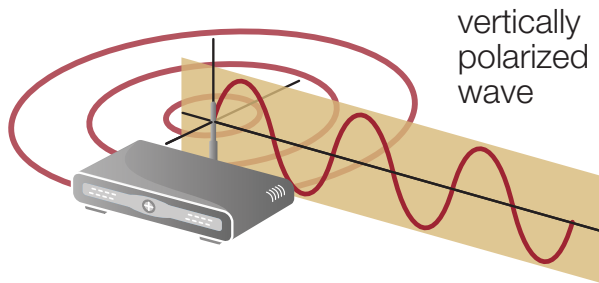
FIGURE 12: Ruckus' unique ability to enhance spatial multiplexing with adaptive antennas.



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FIGURE 13: Illustration of radio wave polarization.

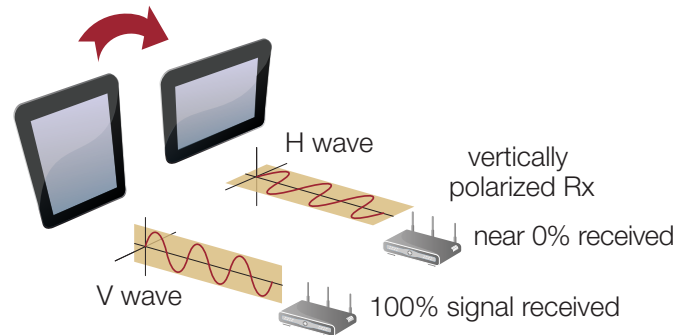


### Support for Polarization Diversity

To explain this final difference between AA and TxBF, we need to introduce one more fundamental RF concept, the idea of signal polarization — the understanding of which requires a little more discussion of how radios and antennas work. Recall our simple “omni” antenna from Section 1. In very simple terms, signal transmission from this antenna occurs because a power amplifier in the AP moves electrons in the antenna, and the motion of the electrons causes traveling disturbances in the electromagnetic field that surrounds them — an effect commonly known as radio waves. As the shape and configuration of our simple antenna example (repeated in Figure 13) suggests, the electrons’ motion is oriented vertically in the figure. This results in a configuration of the electromagnetic (or radio) wave that is known as vertical polarization — meaning that the energy in the wave oscillates in a vertical plane aligned with the direction of travel. Radio waves can have purely vertical or purely horizontal polarization, or oscillation around the direction of the travel that is at an angle somewhere between the two. To receive a signal, APs and client devices both apply essentially the reverse of the transmit physics. Instead of the current applied to the antenna that is used on transmit, on receive the antenna “picks up” the incident radio wave in the form of electron motion in the antenna that is stimulated by the electromagnetic field disturbance arriving at it. The tiny current in the receive antenna created by the electrons’ motion is detected by the sensitive electronics to which the antenna is connected and then amplified to permit processing of the signal. Antenna elements are usually specified as either vertically or horizontally polarized, which indicates which polarization of waves they can both transmit and receive.

Understanding both the transmit and receive physics at this simple level is required to grasp why the polarization of Tx and Rx must be the same: if the Tx signal polarization is vertical but the Rx antenna is horizontal (or vice-versa), the wave cannot excite electrons in the right direction on the receive side, and essentially no signal is detected.

FIGURE 14: Effect of polarization on connection quality.



Up until a few years ago, Wi-Fi networks were largely vertically polarized affairs. The vast majority of connected devices were laptops, and these were used generally in only one orientation, with the keyboard horizontal, and the display (which commonly houses the antenna) vertical. APs used vertically-polarized antennas, and all was well.

The avalanche of smart mobile devices on Wi-Fi networks has changed all this. They are used in any number of angles relative to horizontal, and more important, they are used in both landscape and portrait modes. Figure 14 indicates the problem this causes in simple terms: with vertically-polarized antennas in both a tablet and the AP with which it is communicating, rotating the tablet 90° will produce a horizontally-polarized wave that the AP can’t receive.

Fortunately, the situation is not quite as dire as all that, or there would have been much more mass revolt about the poor Wi-Fi performance of the whole smart mobile device class than has so far been the case. Multipath and reflections in the radio environment typically cause changes in the polarization angle of waves as they travel from client to AP and vice-versa, so a vertically-polarized AP will still be able to receive some vertical component of the signal. But this remains a legitimate concern when capacity demands on the network stipulate squeezing every available bit of productivity out of the channel being used.

There are a couple of different approaches to addressing this issue on the AP side — which is where the work must be done, given very tight constraints on antenna count and configuration on mobile devices. The first is an inelegant kludge, involving simply tilting omni antennas on a conventional AP, and the second involves use of our adaptive antenna designs to deliver much more effective diversity in practice.

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FIGURE 15: 3D coverage pattern from a single omni antenna.

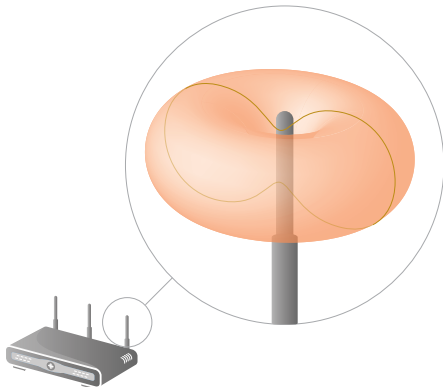


FIGURE 16: Major coverage-hole downside to the common technique of achieving “faux” polarization diversity by changing the fixed orientation of a small number of omni antennas.

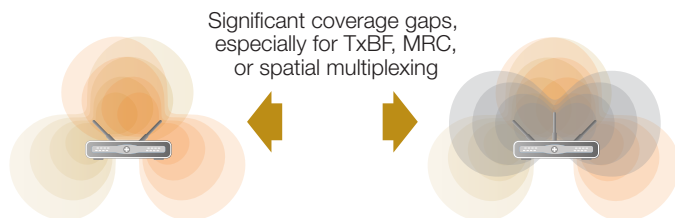
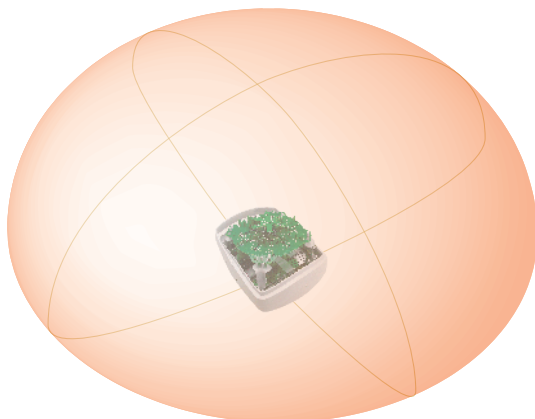


FIGURE 17: Ruckus AP aggregate coverage pattern, including adaptive polarization diversity throughout.



Once again, we have to introduce a little more detail in the behavior of our omni antenna in order to illustrate the differences between the common kludge and our proper AA solution. It turns out that the “omni” antenna example we’ve been using isn’t actually omnidirectional in the broadest sense of the term. In the horizontal plane, yes, but not in the vertical. As Figure 15 shows, the coverage pattern of an omni stick antenna is actually more like a donut in 3D space.

This means that if you attempt to provide Tx and Rx diversity by tilting antennas of this design, as we illustrate in Figure 16 (using an elevation view of the coverage patterns for clarity), you tilt the whole “donut” of coverage along with it — leaving potentially very large coverage holes in many areas for one or even both antennas. The fundamental mismatch in this configuration between the coverage of the multiple antennas will defeat the purpose of having more than one antenna in the first place: essentially any multi-antenna processing on transmit or receive will fail frequently, including TxBF, spatial multiplexing, and maximum ratio combining (MRC), the receive processing most commonly used in Wi-Fi to extract the best possible signal from multiple Rx antennas. Further, fixed polarization diversity of this nature, where it does actually achieve effective overlap from two antennas, significantly reduces the effectiveness of TxBF. If two signals with opposite polarization arrive at a receive antenna of arbitrary orientation, somewhere between 50 and 100% of the potential gain from the intended coherent signal combination will be lost because the Rx antenna can capture only one component (either vertical or horizontal, but not both) of the signals.

In contrast, Ruckus APs, equipped with a large number of adaptive antenna elements, cover a generally hemispherical aggregate pattern (illustrated in Figure 17), using combinations of vertical and horizontal polarization throughout, or not, as client orientation and path optimization dictate. Hence our AA approach can use polarization diversity in concert with spatial multiplexing and MRC, where it can provide material performance enhancement in today’s multi-orientation mobile-device world, and choose not to use polarization diversity to enhance the performance of TxBF where that is the most productive multi-antenna approach to employ.

## A proper multi-antenna processing taxonomy

To summarize the multi-antenna technologies we’ve reviewed here, and to set the stage for our final assessment sections 6 and 7, we present on the next page a thorough taxonomy of current approaches.

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Attributes	Implicit Beamforming	Explicit Beamforming (TxBF)	Adaptive Antennas (AA)	BeamFlex 2.0 AA+TxBF
802.11 protocols supported	a, b, g, n	n	a, b, g, n	a, b, g, n
adaptation	effectively open loop	closed loop	closed loop	closed loop
client behavior requirement	none	must send AP transmit characteristics 'recommendation'	none	as with TxBF
source of feedback	measurement of uplink signal from client	client's recommendation	standard client ACK packet on previous transmission	client reco for TxBF + ACK for AA
supports 802.11n spatial multiplexing	NO*	NO*	YES	YES
supports polarization diversity	NO	NO	YES	YES
typical SINR gain, Tx	none	3 dB	4–6 dB	8 dB
typical SINR gain, Rx	none	none	4 dB	4 dB
network self-interference reduction	none	none	10–15 dB	10-15 dB

\*would require 2 or more radio chains and antennas per spatial stream, a commercially impractical configuration given high hardware costs and power requirements exceeding 802.3af PoE limits

## Performance Gains

As we've developed a baseline understanding of how the various multi-antenna processing techniques work, we've noted a few characteristics that affect their performance. Now we pull these observations together, along with external validation, to quantify these technologies' typical performance gains in real networks. We'll discuss the key metrics and validation for each of the four categories in turn.

### Beamforming with Implicit Feedback

A number of vendors have embraced the chip-based approaches to beamforming over the past couple of years, largely just to add "beamforming" to their marketing materials, since we've done so much to popularize the idea. Given that the explicit version requires client functionality that still has not yet reached the market (more on this very important point in Section 8), all but a very limited subset of the entrants in the beamforming race are using implicit-feedback beamforming. As we saw in section 2, implicit beamforming suffers from fundamental flaws: the absence of any corrective feedback about whether or not a set of antenna phase decisions has been effective at all, the reliance on uplink characteristics to estimate the downlink (an unreliable metric), incompatibility with 802.11n spatial multiplexing rates

(without adding impractical numbers of RF chains), and patterns of coherent combination that are both sensitive to phasing inaccuracies and very symmetric (generating more concentrated co-channel interference to neighboring APs).

As a result, it's reasonable to expect at best modest performance gains. In fact, results we've seen from 3rd-party testing (See **Figure 18**) suggest that the gains can be closely approximated by the number 0. We exclude implicit beamforming from further analysis here for this reason.

### Beamforming with Explicit Feedback

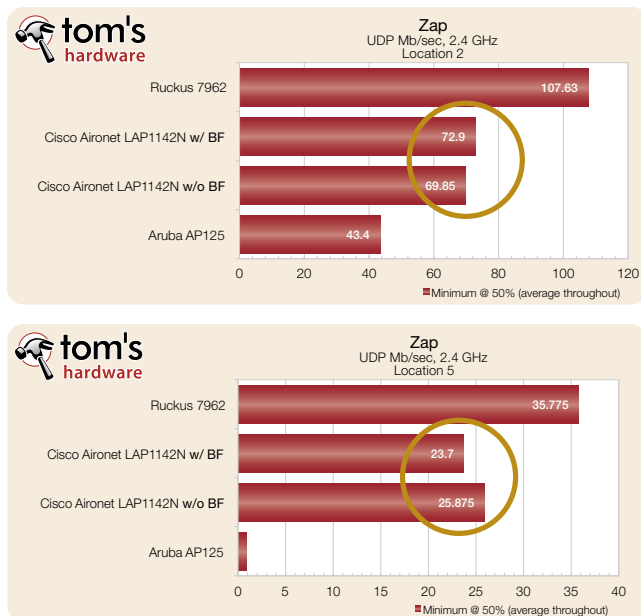
At this writing, very few vendors have brought APs to market based on the new generation of Wi-Fi chipsets that include explicit-feedback beamforming that is nominally part of the 802.11n standard. Since there are still no client devices on the market that support this technology, we have not seen any performance testing from third parties.

We do have close working relationships with the chipset vendors who are enabling this next step in phase-based beamforming. In conversations far from the limelight of AP vendor marketing efforts, the engineering teams at the Wi-Fi chipset suppliers

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FIGURE 18: Example third-party comparative test results for implicit beamforming.

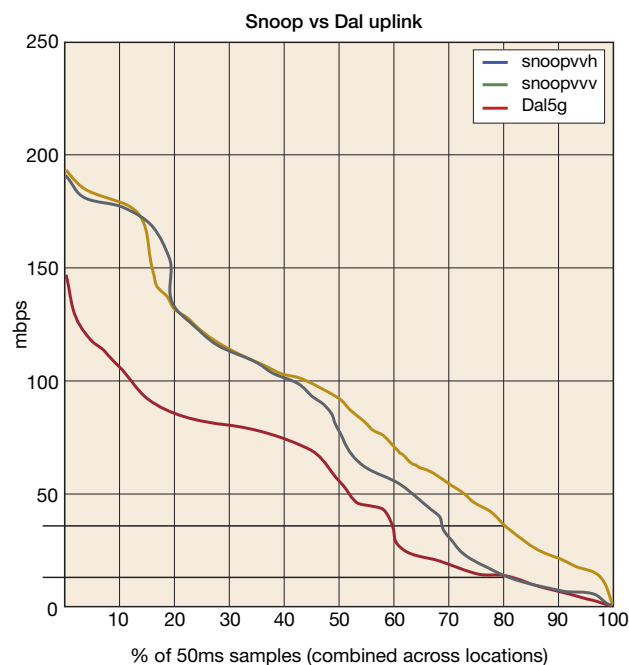


(many of whom have long histories in the area of multi-antenna processing techniques and therefore credible views on the subject) have provided us the following information:

1. For the same reasons we've outlined above (incompatibility with spatial multiplexing, limited beam-shaping degrees of freedom when you have at most three antennas, and the inaccuracy-sensitivity of the narrow beams thus formed), they have low expectations for the technical value of implementing the explicit beamforming part of the 802.11n standard.
2. In fact, their own lab testing has shown that the technique is only marginally more effective than implicit beamforming — yielding gains that range from a fraction of a dB to at most 3 dB.
3. It follows naturally that commercial implementation has always been a low priority for the chip vendors, and its entry into chips now was motivated almost exclusively by pressure from their larger AP vendor customers who wanted to add the capability to their sales story.

For the purposes of our quantitative comparison in the balance of this paper, we will give the technology a little benefit of the doubt and assume the chipset vendors' figure of 3 dB in performance gain is a reasonable expectation.

FIGURE 19: Throughput test results for iPads in a variety of orientations show that polarization diversity adds the equivalent of 4 dB SINR gain in the 80th percentile range.



## BeamFlex AA

We have a large number of external validation points from customers and other third parties that indicate our APs perform about twice as well as conventional APs from any of the others in real-world implementations. This can take the form of 2x the throughput for a given client distribution, 2x the coverage, and/or 2x the throughput in the face of interference. This kind of performance improvement can most easily be summarized as a 6 dB gain in link budget on the downlink, averaging across many different situations.

## Polarization Diversity

On the uplink, our support for polarization diversity in our AP designs has been shown to yield up to 4 dB of effective link budget gain at the 80th percentile, measuring throughput to iPad clients across a variety of locations and orientations (See Figure 19).

## Putting it all together

We summarize these performance perspectives in Figure 20. First off, for those of you wondering what happened to the 450 Mbps rate that 3-stream spatial multiplexing is advertised to deliver, please note the conditions assumed for this comparison.



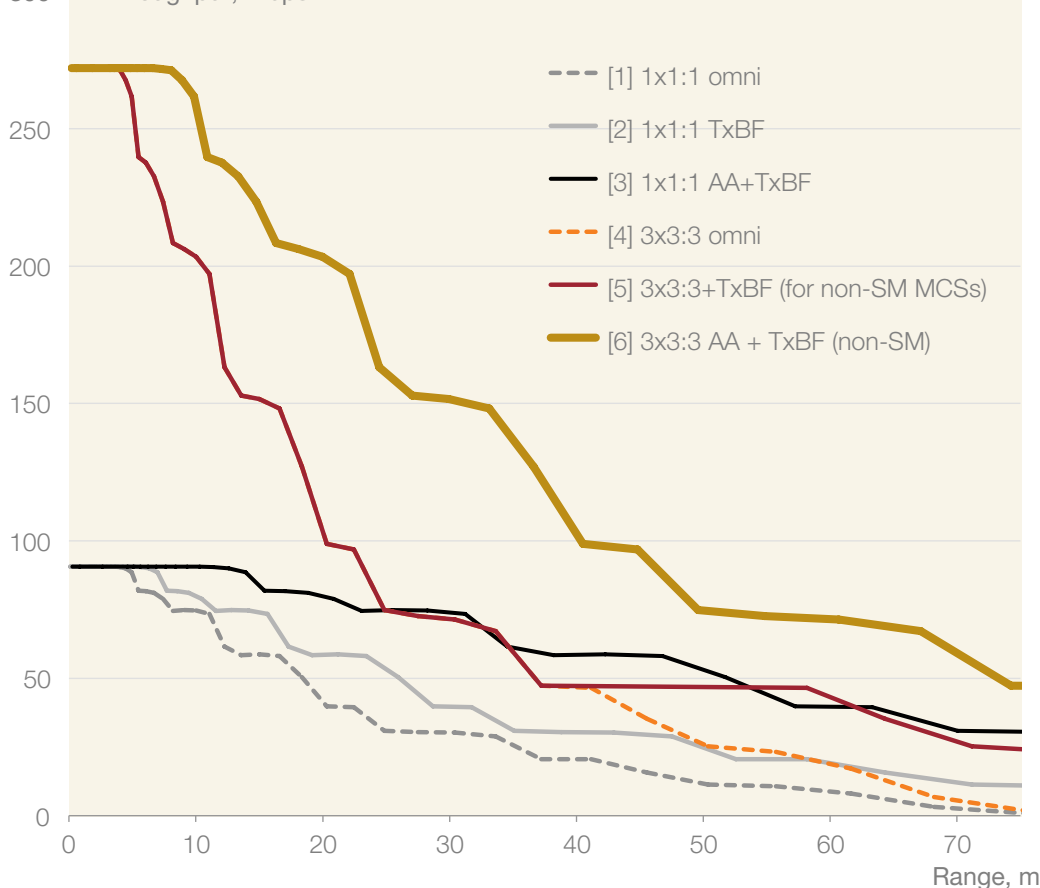
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FIGURE 20: Rate and range comparison of various multi-antenna technologies. See text for additional explanatory notes and sources.

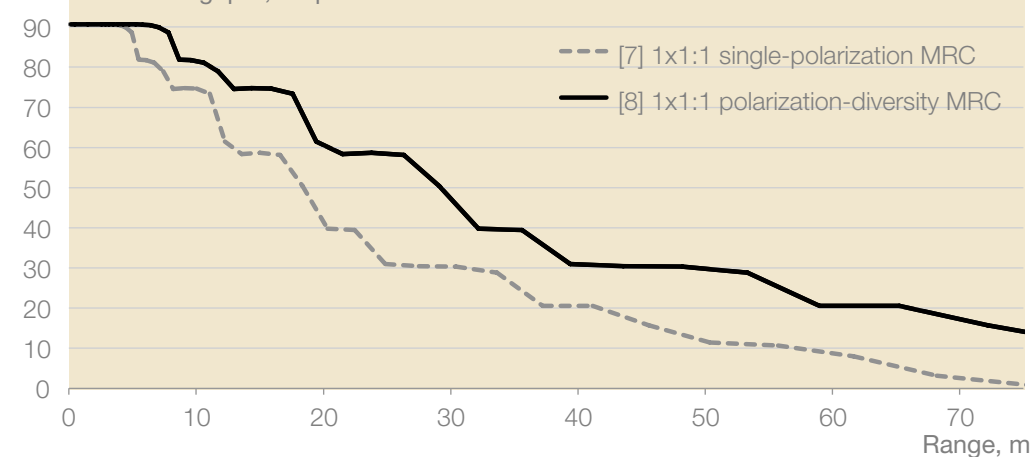
## RF Technology Comparison

300 DL Throughput, Mbps



## RF Technology Comparison

UL Throughput, Mbps



Notes on conditions: 5 GHz, 40 MHz channel, 800 ns guard interval, ETSI EIRP level, UDP traffic, medium level of Wi-Fi and other interference, near LoS link conditions, indoors.

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The peak 3-stream rate of 450 is raw bits in a 40 MHz wide 5 GHz channel at 400 ns guard interval (see our separate white paper Caveat Emptor for more details on translation from peak Wi-Fi claims to real-world usable throughput rates). We prefer to frame the analysis in a domain relevant to real-world net usable packet throughput (net of 802.11 protocol overhead and other factors) for real equipment. So our analysis depicts UDP traffic in 5 GHz, which cuts the peak three-stream rate down from the theoretical maximum of 450 to 272 Mbps. The other dimension of realism is client to AP range — we've assumed here ETSI requirements for EIRP (100 mW) and a healthy dose of interference and fading margin for busy indoor conditions (15 dB).

Now to explain each of the curves:

**[1] DL 802.11n 1x1:1 omni.** This is the low water mark, depicting the kind of performance expected from a conventional omni-equipped AP with no multi-antenna processing, communicating in downlink (DL) with a single-antenna client like a smartphone or a tablet.

**[2] DL 802.11n 1x1:1 + Explicit-Feedback Transmit Beamforming.** As we explained in section 2, the addition of explicit-feedback beamforming on a conventional 2- or 3-stream AP (the only practical model extant today) provides the system the choice of using TxBF or spatial multiplexing, but not both at the same time. With only 3 dB of incremental gain to offer, TxBF does not provide enough of a performance benefit to outweigh the data rate gains from SM in any case other than that for which SM is not an option, the 1x1:1 system. As can be seen, 3 dB doesn't buy a lot, in terms of either throughput increases or range extension — roughly a 30% increase.

**[3] DL 802.11n 1x1:1 with Adaptive Antennas + TxBF (BeamFlex 2.0).** Here we apply both adaptive antennas and TxBF to a single-stream client, yielding a 2x or better improvement in range or capacity from the combination.

This reflects the two spatial streams performance of an AP equipped with 2 omni antennas communicating with a 2 Rx equipped client such as a laptop. Note that the performance of the 2x2:2 system converges to that of the 1x1:1 system at longer range, as the realities of RF propagation reduce the ability to achieve spatial multiplexing with reliability. The performance of an AP with implicit or explicit beamforming capabilities would look exactly the same as this curve, because of the mutual exclusivity of spatial multiplexing and phase-based beamforming.

**[4] DL 802.11n 3x3:3 omni.** For this and the next two curves, we depict system performance with a high-end laptop on the client side, supporting three spatial streams. The baseline for this use case is a conventional AP with omni antennas and neither TxBF nor AA. Most of this curve is actually coincident with the next curve, [5], for reasons that will become clear in a moment. Note the descent of the 3x3 system's performance as a function of range. The higher modulation classes (based on 64 QAM, a very complex constellation) in combination with 3 spatial streams are only effective, in practice, at shorter ranges where there is enough diversity in the signal paths to accurately decode the three streams. Note that the performance of the 3x3:3 system converges toward that of the 1x1:1 system at longer range, as the realities of RF propagation reduce the ability to achieve SM with reliability even for 2 streams.

**[5] DL 802.11n 3x3:3 + TxBF for non-SM MCSs.** As we've noted, TxBF cannot be used simultaneously with SM. One can, however, consider its use for the non-SM MCS rates (0 through 7) in 802.11n, to enhance link budget under conditions (such as low diversity or long range) where SM is not possible. We've shown this effect in the right-hand side of curve [5], where it diverges from curve [4]. For speeds above 25 Mbps, roughly, SM would be employed and scenario [4] and [5] are the same.

**[6] DL 802.11n 3x3:3 + BeamFlex 2.0.** This adds BeamFlex AA gains on top of the SM-based rates in a 3-stream 11n channel along with TxBF gains for the non-SM MCSs on the right end of the chart. As with curve [3], the advantages in throughput at a given range driven by BeamFlex AA technology remain quite substantial.

**[7] UL 802.11n 1x1:1 Single-Polarization MRC.** This depicts the baseline performance in uplink from a single-antenna smart mobile device to a 3-antenna AP performing conventional MRC processing, assuming all 3 antennas have the same polarization.

**[8] UL 802.11n 1x1:1 Polarization-Diversity MRC.** Finally, we depict the results of introducing BeamFlex adaptive polarization on the multi-antenna AP Rx side, which allows polarization-diversity MRC (PD MRC) processing and yields around 4 dB of effective SINR improvement. As the curve shows, this can yield substantial (~2x) improvements in client throughput on uplink, which is commonly the limiting metric for network dimensioning in today's user-generated-content-rich application environment and therefore an extremely valuable improvement.

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Applications	Conventional Omni Antennas (no smarts)	TxBF	Adaptive Antennas (AA + PD-MRC)	BeamFlex 2.0 AA+TxBF
DL to mobile devices	No legitimate technical reason to continue using these under any circumstances	Useful, given client support	Higher SINR improvement than TxBF (and lower network self-interference) under all circumstances	Even better, given client support
DL to laptops		Useful at long range (where SM fails), given client support	Higher SINR improvement than TxBF (and lower network self-interference) under all circumstances	Even better where SM fails, given client support
UL from mobile devices or laptops		No help	Substantial gain from polarization diversity	Same as AA alone (no impact from TxBF addition)
Meshing		Helpful where SM fails	Higher SINR improvement	Even better where SM fails

## Using the Right Tool for the Job

As we noted at the start, the introduction of TxBF on the smart antenna scene does add a potentially productive new tool to our radio performance kitbag, but as we've shown in the balance of this paper, it's clear one has to be careful to understand for which jobs this new tool is well suited in practice. We've summarized our findings on the best application of the various multi-antenna approaches below.

## That's all fine, but where are the clients?

After all this heavy lifting, it's unfortunate that we must report there is a show-stopper issue in the way of realizing any benefits from TxBF in the near term. To explain, we need to step out of the realm of how the technologies themselves work, and into the matter of how the business of Wi-Fi equipment supply works.

We've mentioned that Wi-Fi infrastructure vendors have been pressuring the chipset providers to put TxBF — an optional feature in the 802.11n standard — into their recent chip releases, largely for the marketing benefit of "checking the beamforming box" on RFP feature lists. For the customers of the limited subset of chip vendors who have done so in response, they have been able to advertise that they support TxBF. With the launch of our ZoneFlex 7982 and 7321 products, we are joining this select

group, but with the twist of using it in combination with our adaptive antenna technology, as we do believe TxBF technology used in this way will provide value in certain situations, as we've shown.

There are two further steps that must be taken by the Wi-Fi industry in order for any benefits to be realized out in the real world of enterprise and carrier Wi-Fi networks, however. Client (i.e. mobile device) manufacturers and their chipset providers must implement the optional 802.11n feature on their side of the connection (in order to support the explicit feedback required to make transmit beamforming worthwhile at all), and then the Wi-Fi Alliance must add the feature to the multivendor interop testing done as part of their mandatory product certification requirements program, after having secured the participation of five infrastructure and five client vendors in support of the feature. At this writing (April, 2012), neither of these has happened, and there is currently no expectation that they will anytime soon, if ever, for the 802.11n standard. There is a version of TxBF included in the 802.11ac standard being implemented now, however, so this situation should improve as 802.11ac products come to market, currently expected in 2013.

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Meanwhile, with zero client support in the market, TxBF all by itself cannot provide any real value outside of AP to AP meshing, an application we are exploring now that our chipsets include the functionality. As an access technology, it is completely stalled in the Wi-Fi market by the absence of client support.

## In Conclusion

To recap: rapidly rising performance requirements on enterprise and carrier Wi-Fi networks dictate that you squeeze every available Mbps out of your infrastructure gear — using every RF technology you can to do so. Transmit beamforming with explicit feedback (TxBF) is a promising potential addition to the toolkit, but in reality subject to a number of constraints and disadvantages:

- the requirement for explicit client feedback in order to achieve any real performance gains, which has zero support in the market today and none on the way in the foreseeable future
- inherent incompatibility with the high-data-rate modes of 802.11n (i.e. spatial multiplexing)
- poor self-interference-generation characteristics in multi-AP networks
- inherent incompatibility (for any practical radio configuration) with crucial polarization diversity
- relatively modest RF performance gains, even where it is applicable.

In short, while several vendors are marketing TxBF as THE SOLUTION to the RF performance problem, all by itself it's not going to do much (if any) good any time soon.

Fortunately our well-proven adaptive antenna technology can deliver more gains, in both transmit and receive, while avoiding all of these issues — so there's no reason to give up on smart antenna technology and return to the simple omni-antenna reference-design implementations that continue to pollute both the enterprise and carrier network landscape with such mediocre Wi-Fi performance. You can reach well beyond the future promise of TxBF with Ruckus BeamFlex adaptive antenna technology you can put to work today — and then get the best of both worlds when Wi-Fi clients catch up with the TxBF idea.

See [www.ruckuswireless.com](http://www.ruckuswireless.com) for more information and a sales contact to learn how you can get started on the path to unrivaled Wi-Fi performance in your network.

