Introduction
Ruckus is well known for its BeamFlex adaptive antenna technology. Enterprise WLAN vendors often attempt to denigrate Ruckus innovations by embellishing their own beamforming stories, but their logic tends to be half-baked and gap-ridden. In this paper, we will provide a counterpoint to those “stories” and demonstrate the merits of BeamFlex.

We will assume that you have already read Cisco’s paper, or are at least familiar with Ruckus technology and the transmit beamforming alternatives offered by 802.11n products/standards and the basics of their functionality. If not, see resources in Appendix A.

All Beamforming Solutions Are Not Equal

CISCO RECENTLY PUBLISHED A WHITEPAPER TO DISCUSS THE TOPIC OF “BEAMFORMING.”

They got two things right:
1. The Title: All Beamforming Solutions Are Not Equal
2. The Concession: “the switched antenna approach to beamforming does provide some benefit”

Behind an excess of jargon, Cisco put forth a pseudo-technical defense of their marketing investment in beamforming, also known as ClientLink. While we appreciate Cisco’s flattery—their wholehearted focus on Ruckus—some mistakes aimed at Ruckus need fixing.

Starting with a Conclusion
Marketing is easy. Building RF features that truly impact real clients in everyday networks is the real challenge. We encourage end-users to review third-party testing that includes both Cisco and Ruckus products. Better yet, test both products in your own environment, with your expected client devices and applications. We trust the truth will set you free!

Part 1: Covering the Basics

Two Ways to Beamform
The first point of clarity to make about Cisco’s paper—and any “beamforming” argument—is that there are different fundamental categories of beamforming, including chip-based beamforming and antenna-based beamforming (e.g. BeamFlex). Most vendors are limited to offering whatever their chip vendor has included in the Wi-Fi chipset. By contrast, Ruckus can support both methods simultaneously, so there’s no need to worry about choosing one or the other.
The Truth About Cisco ClientLink
Cisco's ClientLink uses a type of chip-based beamforming with implicit client feedback. In theory, implicit transmit beamforming (TxBF) such as ClientLink allows an AP to create multiple downlink beams that constructively add together at the client to improve the overall signal. To do this successfully, the AP relies on what it hears from the client (the "implicit" feedback, which is really no feedback at all) to determine how best to steer the beams. This sounds plausible, but it has several real-world problems:

1. ClientLink is a chip-based MIMO technique that cannot be used on the same antenna at the same time as other chip-based MIMO techniques like Spatial Multiplexing (SM), Space-Time Block Coding (STBC), and Cyclic Delay Diversity (CDD), so TxBF comes with a tradeoff from the start.

2. In general, ClientLink forms its beams based on how the AP "hears" and not based on how the client "hears." In TxBF, the client’s hearing is what’s important (i.e. Cisco is on the wrong end). This can only be remedied through direct client participation (explicit feedback), which is why implicit feedback was not moved forward in the 802.11 standards.
   a. If clients have more than one antenna, there is an ambiguity as to which client antenna sent the uplink data.
   b. For beams to arrive in-phase (constructively) at the client, the client’s radio chains should be calibrated, because there are different active RF components in the receive and transmit RF paths (the AP does not know about those differences).
   c. Accurate AP calibration is necessary but not sufficient. Calibration during the manufacturing process is also difficult, error-prone, and expensive.

3. Implicit beamforming uses received signals to determine the relative signal offset for each downlink beam. Theoretically, this works fine for fixed clients, but for mobile clients, every downlink frame will be optimized for the client’s previous location, and not for its current location.

4. TxBF such as ClientLink requires incredibly precise phase and amplitude weights for constructive gain to occur exactly at the client location. When the weights are not accurate, destructive interference occurs and can actually reduce signal quality instead of improving it.

The Truth About BeamFlex
Ruckus’ BeamFlex technology is one of the key value propositions for Ruckus APs, which makes it a common competitive target. Here’s what they say, and how we respond.

1. We have “beamforming” too — BeamFlex is fundamentally different than chip-based beamforming. BeamFlex doesn’t require cooperation between antennas and thus works on top of any and all chip-based MIMO techniques, including Transmit Beamforming (TxBF), Spatial Multiplexing (SM), Space-Time Block Coding (STBC), or Cyclic Delay Diversity (CDD). BeamFlex provides gain for all of these.

2. BeamFlex is downlink only — All beamforming is primarily focused on downlink performance, but Ruckus APs also include many uplink enhancements as well, such as dual-polarized antennas with consistent 3D omni coverage patterns, maximal ratio combining (MRC), and high receive sensitivity resulting from low-noise hardware design, RF filtering, and high-quality components.

3. BeamFlex doesn’t scale — Ruckus is aware of no evidence to demonstrate this. Quite the opposite is true. BeamFlex reduces co-channel interference, improves signal quality, and adds aggregate capacity for the entire network. Ultimately, these improvements improve scalability. BeamFlex can support many hundreds of clients per AP.

4. BeamFlex causes hidden nodes — This argument works out nicely on paper, but it applies as much to TxBF as it does to BeamFlex. In the real-world, 802.11 standards encourage beamforming despite the small possibility of hidden nodes, and BeamFlex proves to work very well in high-density scenarios where hidden nodes would be most likely to occur.

5. Adaptive antennas have switching loss — With only one exception among the many BeamFlex implementations, BeamFlex does not contain switching components in the RF path and thus suffer no losses from such switching components.

6. Finding an optimal pattern takes too long — On the very first packet to each client, BeamFlex finds a beneficial pattern—compared to static omni antennas. From there, it narrows in on the best set of antenna patterns within milliseconds.

If you’re interested in the more technical side of this discussion to expand on these points, please keep reading. If not, let us leave you with a simple point. We believe that Ruckus’ BeamFlex innovations are easily demonstrated in the real-world. We encourage you to test Ruckus and Cisco side by side.
All Beamforming Solutions Are Not Equal

**DISCUSSION OF THE TOPIC OF “BEAMFORMING.”**

**Part 2: Getting Technical**

**The Flawed Premise(s)**
Cisco’s whitepaper—like most arguments against BeamFlex—begin with a flawed (though unspoken) assumption.

First, it gives the impression that BeamFlex and digital signal processing (DSP)-based beamforming (often called chip-based TxBF) techniques are categorically similar. The industry as a whole (as Cisco acknowledged itself) recognizes the merits of an adaptive antenna array; therefore, the non-BeamFlex vendors piggyback on the recognized advantages of BeamFlex by claiming alike technologies: “we have ‘beamforming’ too.”

Further, the same companies would like customers to believe that BeamFlex and DSP-based TxBF are two mutually exclusive versions of the same thing, called beamforming. The intended message to customers is clear: pick for yourselves which one is best, BeamFlex or chip-based TxBF.

What’s great about this position (for Ruckus) is that it’s really easy to prove false. BeamFlex and TxBF are radically different in function, benefit, and usefulness. But what’s more important is that product vendors with only DSP-based TxBF would like to suggest that Ruckus’ BeamFlex somehow prevents us from supporting chip-based TxBF as well. To these flawed premises, the simple response is this: Ruckus supports both. The benefits of BeamFlex sit on top of the benefits of chip-based beamforming. The gain of these techniques is cumulative. Why pretend that customers must pick one or the other when Ruckus provides both?

In fairness to Cisco, their claim is somewhat different. They seek to differentiate their proprietary version of DSP-based TxBF with the standards-based version of the same. But, they are still making the categorical leap by comparing their DSP-based TxBF (i.e. ClientLink) with BeamFlex (i.e. an adaptive antenna technology), instead of comparing ClientLink with standards-based TxBF, which is the more accurate compare/contrast exercise. It stacks up in this way:

*Cisco – ClientLink TxBF*

*Ruckus – BeamFlex + Standards-based TxBF*

<table>
<thead>
<tr>
<th>Beamforming Type</th>
<th>Ruckus</th>
<th>Cisco</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSP-based TxBF</td>
<td>Standards-based</td>
<td>Proprietary (ClientLink)</td>
</tr>
<tr>
<td>Adaptive Antenna</td>
<td>BeamFlex</td>
<td>None</td>
</tr>
</tbody>
</table>

Now that we are working from an accurate framework, away we go.

**ClientLink and DSP-based TxBF**
For IT managers, administrators, and engineers alike, 802.11n’s MIMO techniques can be both complex and confusing, which makes vendor marketing (admittedly) an opaque fog. Though this article is focused on adaptive antennas and TxBF, it’s important to mention that there are other transmit techniques available with MIMO, including Spatial Multiplexing (SM), Space-Time Block Coding (STBC), and Cyclic Shift Diversity (CSD) (aka Cyclic Delay Diversity).

Please note that only one chip-based technique can be used at a time for each antenna (i.e. it is either SM or STBC or CDD or DSP-Based TxBF). Any concurrent combination of these techniques requires several more antennas and radio chains. With any MIMO system, the merits of DSP-based TxBF must be weighed against the merits of these other transmit techniques. When a client device supports spatial multiplexing (different data streams on each antenna), the AP will usually prioritize spatial multiplexing above transmit beamforming (same data on each antenna with phase shifts) because the benefits are often greater.

BeamFlex can be used in conjunction with any of the above MIMO techniques. BeamFlex can also employ DSP-based beamforming using orthogonally polarized antennas, while ClientLink requires all antennas to have the same polarization. A client’s polarization can change based on its orientation (i.e. landscape or portrait mode), so this polarization diversity is quite important for consistent downlink and uplink performance.
All Beamforming Solutions Are Not Equal

DISCUSSION OF THE TOPIC OF “BEAMFORMING.”

TxBF and MRC

On the receive side, the major MIMO advantage comes from a combining technique called Maximal Ratio Combining (MRC). Cisco claims that ClientLink (a transmit-only technique) is superior to BeamFlex because of DSP-based MRC (a receive-only technique), which is both odd and illogical:

“...DSP-based beamforming (such as used in ClientLink 2.0) is superior (especially when supporting a network with many clients) and therefore preferred for the following reasons:

• DSP-based techniques are used in 11n chipsets to improve uplink performance. These same DSP techniques can also be used to improve downlink performance. Switched arrays only improve downlink performance.”

“Beamforming” is by definition a downlink technique (downlink TxBF from the AP does not improve uplink DSP techniques on the AP). Second, as we’ve already demonstrated, BeamFlex has a cumulative relationship with MIMO and DSP-based techniques. Like all enterprise WLAN vendors, Ruckus takes advantage of DSP-based receive techniques (e.g. MRC) to improve uplink performance. With dual-polarized, omni-directional antenna elements, our use of MRC (i.e. PD-MRC) is very effective at combining multiple received signals.

Primer on Standards-based TxBF

In 802.11n-2009, there were multiple chip-based TxBF options, but there were two major types of feedback (ways for the beamformer to calculate a steering matrix):

1. Explicit—the beamformee (receiver) sends steering feedback directly to the beamformer (transmitter), giving it instructions for optimizing the steered beams

2. Implicit—the beamformee sends training signals to the beamformer, which allow the beamformer to estimate the MIMO channel between the two stations and calculate its own steering matrix. No direct feedback is provided.

Explicit feedback works quite well with client participation. This is a bit like asking someone to scratch your back—giving instructions until they hit the right spot. Standards-based implicit TxBF requires client support because the beamformee must participate in the sounding and training process—and often calibration as well. But without direct feedback from the client, implicit beamforming does not work well in practice.

IEEE engineers agreed on the deficiencies of the implicit method and have removed it entirely from the 802.11 specs, beginning with the next-generation 802.11ac standard; instead, they will focus on explicit beamforming. Even still, it remains true that standards-based TxBF requires client support. This minimizes the real-world benefits today. But, let’s not insult the dozens of IEEE engineers designing the protocols. Client support for TxBF is required for good reason.

Limitations of Implicit Beamforming

Interestingly, Cisco is the only vendor we are aware of to have developed a feature (i.e. ClientLink) based on implicit beamforming. At first glance, you might say this demonstrates Cisco expertise. But, in reading Cisco’s claims, they are deriving a downlink steering matrix (phase and amplitude weights) by reverse engineering MRC. They claim that this works sufficiently, with this reasoning:

“In Wi-Fi, the channel is reciprocal (the same from AP to client as from client to AP), which arises because reception and transmission happen on the same channel frequency and with the same antennas.”

Ruckus (and experts everywhere) agree that electromagnetic reciprocity from antenna to antenna can be assumed, but implicit TxBF depends on reciprocity between DSPs of both devices in the beamformed link.

Cisco argues that implicit beamforming works without client participation as long as the transmitter’s (Cisco AP) Tx and Rx chains are calibrated, but this neglects the asymmetry of active RF components on the receiver—where TxBF ultimately matters. It also runs completely counter to expert perspectives. Take this quote for example, from Eldad Perahia and Robert Stacey, respectively a PhD and MSc in electrical engineering:

“It is important to note that interference is not reciprocal. Furthermore, the channel between the digital baseband of one device to the digital baseband of another device includes transmitter and receiver RF distortions/impairments which are not reciprocal.”

In other words, the Tx and Rx path from antenna to baseband is not the same, which is why client calibration (or participation) is useful. The 802.11n-2009 specification affirms this by stating that “generally, calibrated radios in MIMO systems can improve reciprocity,” implying that without client calibration, full reciprocity should not be assumed, as Cisco does. Admittedly, it’s possible for the client device to be intentionally or unintentionally calibrated by design, bolstering the value of implicit techniques; but, this is an exception and not the norm. So, it’s possible that Cisco found an isolated client device that performs well in a lab and used it for marketing validation.

2 IEEE Std 802.11n-2009, Clause 9.19.1
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Perhaps the actions of the IEEE’s 802.11 working group—removing implicit beamforming entirely—speak the loudest. For more evidence on this topic, researchers from leading universities readily acknowledge the problem of non-reciprocity and the faults in implicit beamforming.\(^3\)

**AP-Only Calibration**
Cisco also claims that for ClientLink to work, only AP calibration is required and that they do this for each and every AP. However, an advanced RF calibration process must be done for each and every unit at its point of manufacture, and this process is both time-consuming and error-prone (which is why Wi-Fi devices sold in mass quantities are not calibrated). For a four-antenna device, Cisco’s manufacturers would need to calibrate each antenna connector against the other three, for a total of 12 sets (3x4=12). See Figure 3.

With 64 subcarriers per radio, multiplied by the number of channels used, and also multiplied by the radio bands (2G and 5G), it’s easy to see how complex this process would be by non-engineers on the assembly factory floor. Generally speaking, the complexity and cost of doing this would surely negate any possible benefits.

**Client Antenna Diversity**
Additionally, for beamforming to work successfully, transmitted signals from the AP must constructively combine at the client’s antenna(s). What happens if a client device has more than one antenna? In such a case, it is not possible for the AP to determine which client antenna(s) the AP heard from. Given that almost all notebooks and tablets as well as most mobile phones (even ones with a single Tx/Rx chain) have multiple antennas, ClientLink is becoming applicable to an ever-dwindling minority of clients—SISO devices without antenna diversity—such as the old iPhone4 with the well-documented “antennagate” problem.\(^4\)

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4 http://gizmodo.com/5589639/rim-and-nokia-respond-to-apples-antennagate-press-conference (RIM implies the use of multiple antennas, while Nokia claims it outright)
Destructive Interference with DSP-Based Beamforming

It’s also worth noting that the potential for destructive interference with DSP-based TxBF is quite large. If we consider a simple model in which two Tx chains and antennas are used for beamforming, the potential gain is 3 dB (double the power). However, if the transmit phase offsets are applied incorrectly (a huge risk with implicit beamforming), the result is signal cancellation and loss, known as destructive interference.

Cisco explains that with DSP-based beamforming with 4 antennas there are $10^{19}$ (4 billion x 4 billion) antenna patterns per subcarrier group,” which supposedly validates superiority. But if anything, this is further evidence that implicit beamforming is compromised. Without client calibration or participation, in the face of $10^{19}$ possible weights, how can the transmitter pick the absolute best amplitude and phase weight (the steering matrix) that combines constructively at the client’s DSP? Almost correct can actually be harmful with TxBF.

Conversely, BeamFlex is quite forgiving. By choosing an almost perfect directional antenna pattern with a reasonably wide beamwidth, signal quality is still improved from static omnidirectional antennas. BeamFlex has a lot of margin for error.

On Mobility

When it comes to DSP-based beamforming, experts disagree how frequently feedback is required for the beamformer to maintain accurate channel state information. Radio environments are notoriously dynamic and unstable, especially for mobile clients. Let’s presume for just a second that implicit beamforming actually works. What Cisco didn’t want to discuss is implicit beamforming with mobility. As the logic goes, implicit TxBF optimizes downlink transmissions based on the channel state of the last received frame from the client. This is fine for stationary clients. But for mobile clients, each downlink transmission is optimized at the client’s previous location instead of its current location.
Future Tradeoffs with DSP-Based Beamforming

Looking ahead, DSP beamforming is also at odds with multi-stream MIMO (i.e. MU-MIMO) systems in 802.11ac, which will sends simultaneous spatial streams to different single-stream clients, seeking to accomplish the exact opposite of transmit beamforming. That is, each antenna sends a different data stream to different receive stations. Each data stream must look as distinct as possible, creating signal nulls instead of peaks at each client.

Switching Loss for Antenna Arrays

Cisco makes a good point about the potential for antenna array switching components to cause RF loss. But, they point to “one type of switched antenna array,” and they build their case from there. One of the ways BeamFlex is truly innovative is that our dynamic antenna array does not follow these models. Thus there are BeamFlex implementations with no switching losses. So, either (a) Cisco knew this and hoped to mislead readers, (b) they made false claims without doing their homework, or (c) their researchers didn’t understand Ruckus technology.

Switching is Slow and Doesn’t Scale

Other vendors often like to claim that BeamFlex cannot switch quickly enough to handle busy networks, or cannot scale to accommodate very high densities of clients. Ruckus engineers often get a good laugh from this because they haven’t found any evidence offered for these claims. In fact, BeamFlex consistently proves the exact opposite: industry-leading performance in competitive testing and actual customer deployments with more than 100+ clients per AP. BeamFlex works for any and all connected client devices, legacy or new, SISO or MIMO, near or far. BeamFlex works for every user, every packet, and no high-speed, next-generation Wi-Fi technology threatens the effectiveness of its optimization speed and scalability.

Comparatively, Cisco’s ClientLink is guilty of scale limitations, as evidenced by Cisco’s own spec sheets. Let’s take their new 1600 (3x3:2) access point as an example. Spec sheets show that this AP supports a maximum of 128 clients per radio, and yet it only supports 32 ClientLink clients per radio. Easy math: only 1 out of 4 clients get ClientLink support. Their other APs have the same problem to varying degrees.

Finding the Right Pattern Takes Too Long

BeamFlex adaptation uses subsets of antenna patterns to determine the best overall antenna set. Thus, finding the best pattern doesn’t require an exhaustive search through all the available options. Cisco is partially correct that antenna adaptation takes more time (usually in the range of milliseconds)
than TxBF, but they neglect to mention that BeamFlex can find a beneficial pattern immediately, on the first packet to each client. Signal quality only improves after that as our algorithms narrow in on the best set of patterns and adapt to changing RF conditions. BeamFlex actually finds a statistically optimized set very quickly, based on the first few packets.

**BeamFlex is Downlink Only**
First and foremost, beamforming techniques are for the transmit side. As an adaptive antenna technique, yes, BeamFlex (like TxBF techniques) has a downlink focus. However, the same antenna and RF design expertise that created BeamFlex has been applied to all aspects of receiver optimization in Ruckus access points. This includes completely custom antenna design, high-quality filtering, low-noise PC board design, and much more. These engineering priorities translate into several benefits:

- High-gain antennas with uniform 3D coverage patterns and consistent performance in all directions
- Industry-best receive sensitivity, which improves throughput at range, decreases errors and loss, and improves overall network capacity and performance
- More balanced, symmetrical RF links between APs and clients, which usually have low output power and poorer RF performance as a result of power, size, and cost constraints

The same antenna structure used for BeamFlex also provides dual-polarized antenna elements for receive, which optimizes uplink performance. Dual-polarized antennas (in 360 degree 3D coverage patterns) enable the DSP to maximize the benefits of MRC, indoors and outdoors regardless of a mobile client’s orientation. So BeamFlex optimizes downlink performance to poor performing client devices, while smart engineering provides the uplink complement.

**BeamFlex Causes Hidden Nodes**
Hidden node discussions are always interesting, because in order to understand all the mechanics of hidden nodes, it’s important to look at the whole scope of Wi-Fi contention protocols. Cisco focuses on the possibility for dynamic antenna arrays to create a hidden node based on the scenario in Figure 8, in which Device A and Device C can’t hear one another (assuming Device B is the AP). However, this problem is solved by an RTS/CTS exchange prior to uplink transmissions by the client. Or it isn’t solved at all (by anyone—Cisco, Ruckus, or otherwise).

Cisco suggests that directional downlink transmissions, such as those from Device B (the AP) to Device A may create a hidden node scenario with Device C. If this was a real problem, it would hold true for all beamforming solutions, including standards-based explicit as well as Cisco’s own ClientLink. Explicit beamforming is in the 11n standard and is also being moved forward into the 11ac standard means that this is not a real issue.

However, in practical experience, Ruckus demonstrates very high performance at range, with high client densities, and with busy networks (which is the theoretical scenario in which hidden nodes are most likely to occur). Despite the theories, as Wi-Fi contention plays out in the real-world, this hidden node concept is a non-issue.

But, this does raise some interesting questions about contention and interference in multi-AP networks. What happens to Wi-Fi contention in 3D space between neighboring cells? Let’s look at a simple illustration (imagine this illustration on a much greater scale with far more devices) and see what happens. See Figure 9.
Educated Wi-Fi engineers everywhere know that one of the most difficult design challenges today is to reduce co-channel interference caused by APs and clients in neighboring cells (read a design guide from any vendor and you will find this topic). This can also be thought of simply as contention, which is designed to prevent two devices from transmitting at the same time, causing a collision. Even the best Wi-Fi designers can’t eliminate co-channel interference, so the goal is to reduce it.

Now, looking back to our illustration, Device A is connected to Device B. Device C is connected to Device D (as it would be in a real-world scenario). When Device B sends a downlink frame to Device A with omni-directional antennas (non-Ruckus), Device C must wait (because it hears Device B and follows Wi-Fi rules), even though it has data to send to Device D. If Device C could send that data to Device D at the same time as Device B to Device A, it would be using the channel twice as efficiently (because Device D does not hear Device B, and thus would not experience interference). However, with omni-directional antennas, what occurs is called co-channel interference, and it is a waste of precious capacity and aggregate performance.

The omni-directional interference scenario plays out in real networks everyday, reducing capacity, causing errors, and aggravating engineers. On the other hand, with directional transmit patterns from BeamFlex, Device B transmits to Device A and Device C is kept out of the conversation, so it can continue receiving from or transmitting to Device D without hindrance. Admittedly, signal isolation is never perfect, so BeamFlex can’t eliminate co-channel interference. But, it can certainly reduce the contention impact from neighboring cells. This is one reason why Ruckus delivers higher capacity for each user and as a system than our omni-directional-antenna-using friends.

A Final Word
Marketing efforts aside, implementation and evaluation in the real-world will expose any flaws in ours or Cisco’s arguments and technologies. We encourage testing.

Really. Test it for yourselves and let US know what works.

Appendix A

For more information about beamforming, antennas, Wi-Fi, and 802.11n, check out these other materials:

| Tom’s Hardware Testing | http://www.tomshardware.com/reviews/beamforming-wifi-ruckus,2390.html |