# Holographic Beam Forming and MIMO

By Eric J. Black, PhD, CTO, Pivotal Commware

## Demand Drives Spectral Efficiency

Mobile subscribers continue to demonstrate an insatiable demand for data. The next decade will experience the full impact of next generation 5G cellular networks with gigabit throughput, low-latency, and connectivity to billions of devices (IoT). The explosive demand for wireless access will surpass the data transfer capacity of existing broadband links.

Every cellular generation has offered new bands, lower latency, and faster data rates. What really defines wireless generations are the major technology shifts that set them apart. The transition from analog to digital communications marks the boundary between 1G and 2G. 3G introduced CDMA techniques for significant spectral efficiency gains. 4G LTE is nearly at the theoretical limits of wireless resource utilization, leaving little room for significant network improvement where frequency and time are the only free dimensions (Figure 1).

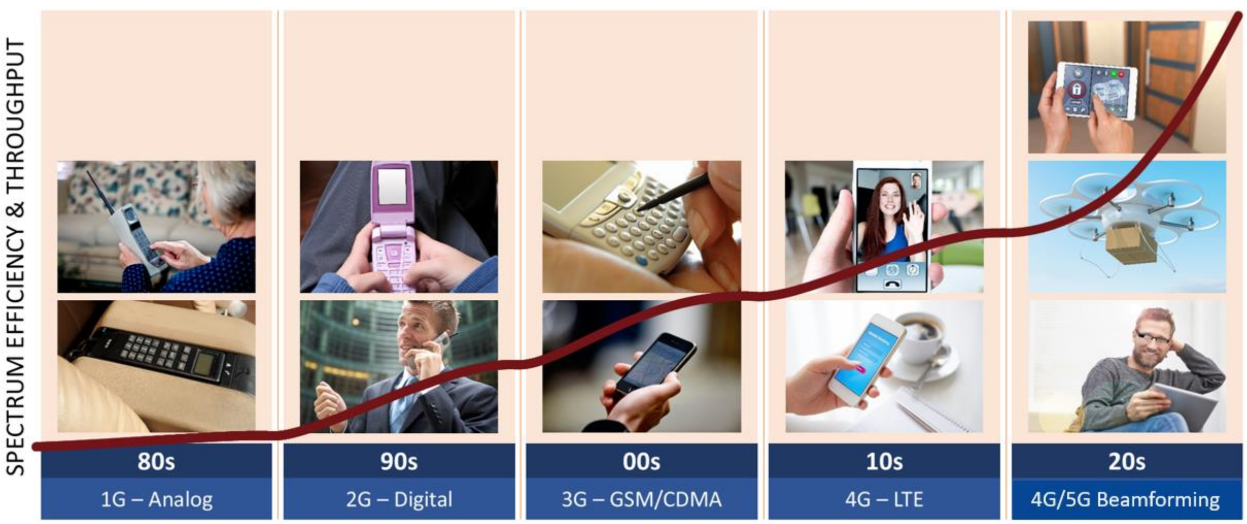



*Figure 1: Keeping pace with demand*

The wireless world is working feverishly to open a new degree of freedom -- space -- for explosively growing network capacity and performance. Actively leveraging the spatial dimension is frequently called Space Division Multiple Access (SDMA). As we shall see, SDMA is already here.

This paper will describe the benefits of electronic beamforming to 4G and 5G networks and compare two SDMA technologies: MU-MIMO and Holographic Beam Forming™ (HBF). Occasional reference will be made to conventional beamforming, i.e., phased array. Of them, HBF stands out as an excellent choice for the commercial market.

## Beamforming

Current cellular systems utilize antennas that form static 60 to 90-degree sector beams to spray energy like a medieval town crier (Figure 2). Subscribers listen for their code or timeslot. By contrast, beamforming permits a more focused communications protocol between base station and user. Highly directive beamforming enhances the signal to interference and noise ratio (SINR) of a communications channel. Signal strength is increased by focusing power at the intended recipient. Furthermore, beamforming hardens the channel by suppressing multipath components. Interference and noise are reduced by minimizing the angular field of view. Interfering signals from other co-channel systems outside the main beam are attenuated by beamforming.

Mobile operators can spend this SINR advantage in three ways: increase the coverage range, increase throughput by using higher order modulation schema (16 QAM to 64 QAM), or reduce transmit power. Beamforming preserves the spectral hygiene of the sector and allows for multiple concurrent transmissions using the same frequency without interference (as shown in Figure 3), thus allowing for abundant spectrum reuse with higher intensity signals delivered to both stationary and mobile users. Mobile operators can continuously reuse the same band of spectrum, at the same time, within a given spatial region.

*Figure 2: Town crier -- low gain, low capacity, low spectral efficiency*

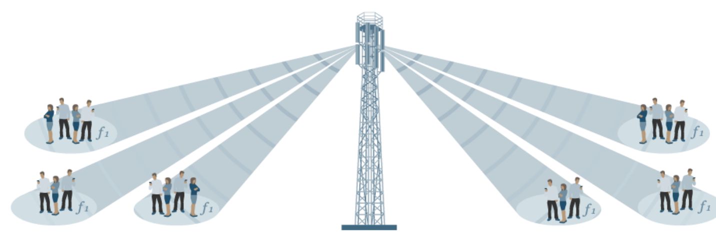


*Figure 3: Beamforming: maximized throughput, increased spectral efficiency*

Dynamic beamforming antennas also offer additional advantages. In 4G networks, for example, optimal coverage patterns for a cell are rarely sector-shaped and never static due to urban canyons, commuter traffic and special events. Today, simple remote electrical down-tilt is widely deployed and showing the capacity benefits of reconfigurable coverage. Dynamic beamforming allows a mobile operator to manipulate the shape of coverage in azimuth, elevation, and gain and to reposition it electronically. High-speed beamsteering also benefits backhaul and fronthaul applications, including fixed broadband wireless, by obviating the need for precise and high-cost alignment procedures. This is crucial for small cells, which are often mounted on municipal furniture that can twist and sway in the wind. If it's fast enough, say, less than a microsecond, then beamsteering allows front and backhaul links to maintain perfect alignment automatically, which ensures maximum throughput.

Beamforming and electronic beamsteering also deliver on the promise of self-optimizing 4G networks (SON). Imagine the beam of one underutilized cell site reaching out to provide extra capacity to another cell site that is either maxed out or impaired. This could occur automatically and instantaneously – without truck rolls. With artificial intelligence (AI), network optimization could be underway constantly, utilizing an array of available key performance indicators – without humans.

But that's today. What about 5G? The space dimension used by beamforming – as opposed to frequency and time -- is already employed in 4G networks with the concept of a cell. Wireless systems are responsible for fixed areas of coverage and attempt to optimally use the frequency/time resources available on a per-cell basis. The boundaries between cells where the antenna coverage overlaps are contested and so intercell interference coordination (ICIC) is used. A cell-based system must waste resources on ICIC for the users present in areas of overlap and thus never reaches ideal data rates.

5G will herald the widespread use of dynamic SDMA because SDMA antennas and their coverage patterns are defined in software. This Software-Defined Antenna (SDA) is game changing. Once coverage areas can be adjusted on the fly, it becomes possible to shift the regions of intercell interference to locations where no users are present. This in turn allows the cell to dedicate its full throughput to users within its coverage area. This concept could be taken to an extreme level in 5G, where the wireless system will employ beamforming to generate personal "cells" on a nearly per-user basis. Each beam will have uncontested access to the full wireless resource set and thus enable explosive growth in wireless capacity needed for 5G. Each SDMA beam will have capacity exceeding current 4G macrocells.

Two significant technologies are aimed at enabling these advanced beamforming capabilities. Let us begin by comparing MU-MIMO with HBF.

## MIMO TECHNIQUES

MIMO comes in many flavors so it is worthwhile to define a simple taxonomy. We will define boundaries between MIMO basics, which is common to all MIMO platforms, Single User or SU-MIMO, and Multi User or MU-MIMO. The term Massive-MIMO has been used with both SU and MU systems and really just means 'lots of radios' with no clear delineation between what is 'massive' and what is not.

*MIMO Basics*

MIMO is a digital signal processing technique that pays no respect to the physical hardware upon which it is implemented. Indeed, MIMO's greatest strength is in generally maximizing the capacity of a given wireless implementation.

MIMO and 'MIMO-like' devices abound.. Taxonomically, all MIMO devices are composed of multiple antenna elements whose antenna elements are backed with a digital to analog converter (DAC), analog to digital converter (ADC), or both. Their waveforms are directly synthesized or digitized and all beam processing takes place in the digital domain.

Secondly, MIMO relies on channel reciprocity for computation of transmit coefficients (channel sounding). This reciprocity dependence brings a few key caveats:

1. MIMO relies heavily on time division duplexing (TDD). The large frequency division duplexing (FDD) band splits commonly used in modern cellular band allocations do not show sufficient reciprocity under general conditions to function.
2. MIMO is range-limited. Excessive time of flight for RF propagation leads to a time evolution in the channel that breaks reciprocity. This is usually a non-issue in low frequency cellular applications but is a problem for high gain, long range communication systems.
3. High frequency millimeter wave (mmW) bands do not easily support MIMO because the channel evolves too quickly. The channel coherence time is proportional to wavelength employed and the

inversely proportional speed of objects in the coverage area. At 30 GHz with a car moving at 5 m/s, the channel can move from peak to null in 2 milliseconds (ms). The channel would then need to be re-characterized to assure reciprocity less than once every 1 ms. The MIMO system would be stuck channel sounding and never sending data with such rapid channel evolution.

Finally, MIMO supposedly does not rely on diversity strategies. However, in practical systems, MIMO relies on diversity all the time. In theory, the capacity of a MIMO system is linearly proportional to the number of antenna pairs "N" and the only requirement to achieve this capacity is a "sufficiently rich scattering environment" that carries the critical task of assuring the orthogonality of the N channels. Understanding what a sufficiently rich scattering environment is and how rare it is to find one – typically never -- is central to understanding the challenges seen in MIMO systems.

*SU-MIMO*

Single User MIMO is widely deployed in cellular networks today but interestingly, most of its benefits come from classic polarization diversity. In SU-MIMO, multiple antennas are present both at the base station and end user to maximize data rate between them.

In commercial 2x2 SU-MIMO (two antennas in the handset and two at the base station) deployments, the two antenna ports are connected to small arrays with orthogonal polarizations. Frequently a left-slant and right-slant configuration are used. This polarization diversity scheme predates MIMO by over 100 years and has long been known to nearly double the capacity of a wireless system as the two polarizations are orthogonal from the outset. MIMO algorithms can easily exploit this configuration but it is worth noting that MIMO is not required to achieve this capacity doubling.

SU-MIMO is also commonly encountered in home wireless routers with multiple (commonly three) antennas. One would hope that MIMO would achieve 3x capacity in such a slow-moving, "rich scattering environment" as the home. These systems rarely even achieve 2x as few end users bother to make sure the three antennas are configured orthogonally. In-the-home multipath scattering alone is apparently not rich enough.

4x4 SU-MIMO is currently seeing early deployment in 4G systems but the results have been disappointing. One expects another doubling in capacity for a 4x4 system over a 2x2 system but most reports show only 50% extra capacity. This is exactly in line with a non-MIMO dual polarized antenna array that just doubled its gain on both ends of the link (and thus could employ a denser coding rate).

Many far-field experiments have shown that SU-MIMO slips into a transmission mode referred to as 'max eigenmode transmission' under most practical scenarios. In this mode, all power is dedicated to the primary channel (or first two channels in a dual polarized system) that correspond to line-of-sight between the two antenna platforms. This mode is the mathematically equivalent of classic RF analog beamforming with the capacity scaling logarithmically with antenna gain. Without an engineered scattering environment, far field SU-MIMO does not appear to have any advantage over conventional, i.e., phased array, beamforming.

However, in the near-field the situation changes dramatically. As of 2017, the world spectral efficiency record is currently held by a near-field experiment conducted at the University of Bristol where the base station and UE are within the a few feet of each another (Figure 4). Both antenna arrays are colossal relative to their separation. In the near-field, beam focusing is possible and the coding mechanisms in MIMO can fully exploit this situation resulting in measured spectral efficiencies greater than 130 bps/Hz. While this result is very exciting, the lack of applicability to far field systems such as cellular suggest SU-MIMO has maxed out.

*Figure 4: University of Bristol MIMO testbed*

### *MU-MIMO*

MU-MIMO systems are sometimes referred to as “Massive MIMO” but this is a misnomer as SU-MIMO may also use large numbers of elements. The key distinction between SU and MU-MIMO is that MU-MIMO generates unique beams simultaneously to multiple, widely separated users. One beam is dedicated to each user device and receives unique data. This technique allows the MU-MIMO system to scale its capacity up to N users provided that the users are sufficiently separated in the angular domain.

MU-MIMO is not without challenges. One issue is that the sidelobes of one data beam become interference to other data beams. A technique called ‘zero-forcing’ has emerged that attempts to mitigate this issue by forcing a radiation null for all beams (other than the desired one) in the direction of other users. This technique is mathematically similar to adaptive nulling strategies used in phased array systems for interference suppression. Just as with adaptive nulling, finer control is needed as the number of nulling targets increases to maintain high suppression ratios.

Practical MU-MIMO demos have shown that it is difficult to achieve linear capacity gain with the number of antenna/radio pairs used. In practice, the observed capacity gains have been more like 1/10$^{th}$ the number of radio/antenna pairs. The reason for this is obvious. Users are rarely spaced on an angularly uniform grid so using so many radios is always overkill. Reducing the radio/antenna count does not help as the beams widen, exacerbating the problem. While this is still a 10x improvement over LTE, for 128 radio backed elements this is a 10x improvement over 4G LTE!

More recently, attention has been drawn to MU-MIMO power consumption in cellular bands. Several researchers have pointed out that a multi-GHz clockrate 8-bit ADCs require 4 Watts of power. For a 128 element MU-MIMO array this implies at least half a kilowatt of power needed just for the ADC components. The dissipated thermal load is substantial which in turn drives cooling requirements, resulting in a heavy, bulky, power hungry and costly system for MU-MIMO. It remains an open question if the cost of 128 radio chains is justifiable for 10x improvement. This situation does not get better at mmW bands where even larger arrays are needed for sufficient antenna gain while power amplifier efficiencies plummet to under 5% at 60 GHz.

Research into MU-MIMO is ongoing and has recently focused on “Hybrid MIMO”. Hybrid MIMO uses fewer DSP radios than the number of elements. The additional elements use more conventional beamforming schemes to augment MIMO. For example, elevation beamsteering might be phased array based while azimuth steering might be MIMO based. This has the potential to reduce cost, size weight and power consumption of MU-MIMO systems. However, the obvious penalty is the increasing complexity of such “hybrids”. Simple, cost effective methods of beamforming are desperately needed for hybrid MIMO schema to be viable. They become even more critical at mmW where DSP radios have difficulty with direct waveform synthesis and MIMO is not an option at all.

## Holographic Beam Forming

Holographic Beam Forming™ is a new beamforming technique using Software Defined Antennas (SDAs) that employs the lowest C-SWaP (Cost, Size, Weight, and Power) dynamic beamforming architecture available. It is substantially different than conventional phased arrays or MIMO systems.

HBFs are passive electronically steered antennas (PESAs) that use no active amplification internally. This leads to symmetric transmit and receive characteristics for HBF antennas. However, HBFs are distinct from Phased Array type PESAs. HBFs do not use discrete phase shifters to accomplish beam steering by the antenna. Instead, beamforming is accomplished using a hologram. This is a very different operating mode than a traditional phased array and warrants some explanation.

A typical HBF is shown in Figure 5a. This device is a Ku band aperture with two-dimensional beam steering in azimuth and elevation and is approximately 10” X 10” X 1/8” in size. It is constructed as a multilayer printed circuit board.

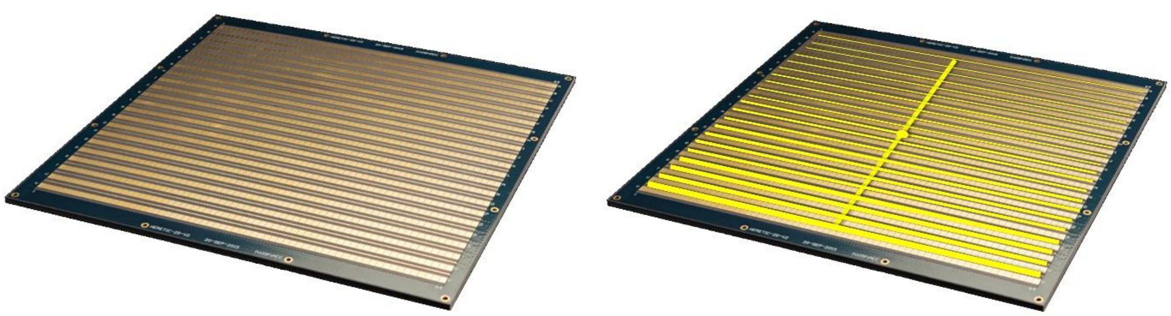


*Figure 5a: A Ku band HBF. 5b: The same HBF with the internal Reference Wave distribution network overlaid as yellow lines.*

The HBF has a single RF input port on the backside center of the antenna which is directly connected to an RF distribution network on the inner layers of the HBF. A travelling RF wave propagates from the input connector through the distribution network and is depicted as yellow lines fanning out from the central feed point in Figure 5b. In optical holography, this travelling wave is referred to as the 'Reference Wave' and it is this wave we wish to transform into a desired beam. The desired beam shape is referred to as the 'Object Wave' in optical parlance. The 'Hologram' is then the structure that will transfer energy from the Reference Wave into the Object Wave.

Adjacent to the distribution network is a carefully designed set of radiating antenna sub-elements. The coupling between the Reference Wave and these elements (and thus the Object Wave) is varied by use of a single varactor per antenna sub-element. The varactors are also located on the backside of the array with control and interface electronics. Careful DC bias of the varactor changes the impedance seen by the reference wave at each element. This impedance pattern is the Hologram and can be calculated directly with knowledge of the provided Reference Wave and the desired Object Wave. Figures 6a and 6b show two different digital overlays on the HBF representing the bias states of the varactors (The Hologram). The Hologram in 6a steers an RF beam in one direction while the Hologram in 6b steers the beam to broadside.

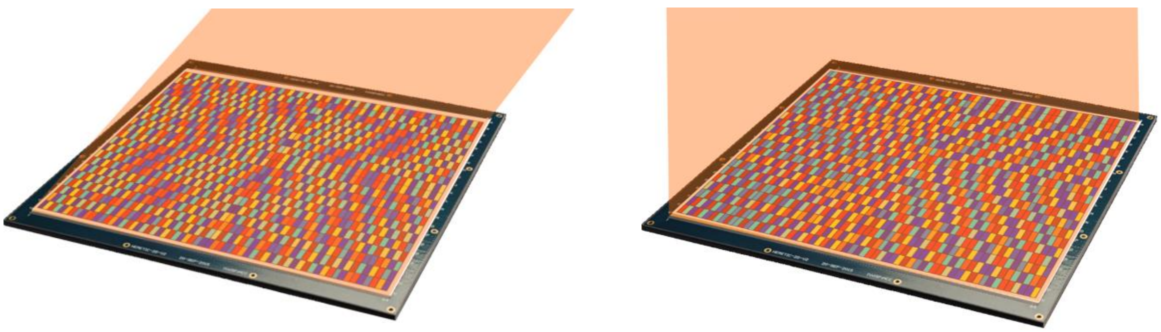


*Figure 6a: HBF with color overlay of the hologram used to steer the beam off broadside. 6b: HBF with color overlay of the hologram used to steer the beam to broadside.*

All components used in the construction of HBF antennas are high volume commercial off the shelf (COTS) parts. These incredibly low-cost control components take advantage of their widespread use in handsets, leading to economies of scale that bespoke silicon implementations can only dream of. Equally important, the beam pointing function is accomplished using a large array of reverse biased varactor diodes. This leads to a nearly negligible power draw by the antenna's pointing operations. Most HBFs need only USB or PoE levels of power to operate. This then eliminates the need for active or passive cooling solutions and drives a significant size and weight reduction.

As mentioned, MIMO uses antenna/radio pairs to achieve beamforming with a very complex baseband unit coordinating the system. Phased arrays are simpler in that only a phase shifter and amplifier(s) are needed for each antenna element. Control is relatively straightforward for phased arrays. Holographic beamformers have similarly simple control and use more densely packed antenna arrays. Roughly 2.5-3x as many elements are used by HBF systems. Fortunately for HBF, the control elements needed are trivially priced. These differences are summarized in Figure 7.

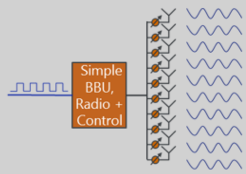
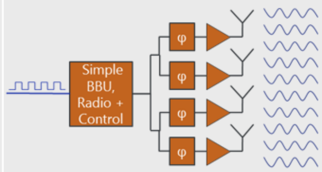
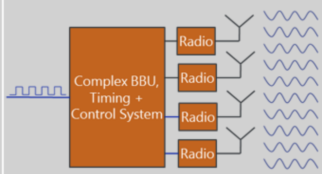
| Architecture | Block Diagram | Cost | Size | Challenges |
|---|---|---|---|---|
| Holographic Beam Former |  | Super-sampled COTS design enables low price | Thin, Conformable | Single beam per polarization per sub-aperture. |
| Phased Array |  | Distributed phase shifters and amplifiers pushes moderate price | Trades cost for thickness. Thin is very expensive | Thermal challenges difficult due to distributed amplification.<br><br>Multi-beam significantly increases cost (more phase shifters, distribution layers) |
| MIMO |  | Radios behind every element and complex BBU drives high price and power consumption | Usually thick but antenna thickness can be reduced by hiding BBU in baseband cabinet | No FDD<br><br>Unworkable at mmW<br><br>Spectral Efficiency vs. cost scales poorly |

*Figure 7: Summary of key differences among holographic, phased array and MIMO beamformers*

MIMO has fewest elements, but the highest overall cost due to relatively expensive components behind each element, not to mention a complex and costly BBU. Phased arrays place second in overall cost because they have same number of elements as MIMO but less expensive components behind each one. HBF offers the least overall cost because, while it has the most elements, each one is backed by the fewest and least costly components.

## Summary

This paper has introduced readers to a new dimension, space, for increasing capacity and performance in 4G and 5G networks with SDMA, or beamforming. Besides these benefits, beamforming, combined with sub-microsecond beamsteering, can a) accelerate small cell deployments by reducing installation and alignment expenses and overcoming aesthetic objections by blending antennas into building facades or around light poles, b) introduce real SON by obviating truck rolls, and, c) for 5G, provide personal cell coverage. But none of these benefits will materialize in the commercial market without the low C-SWaP architecture that only HBF provides. MIMO's C-SWaP is exorbitantly high, followed by phased arrays that, while field-proven in military applications for decades, cannot reduce their C-SWaP profile enough to satisfy commercial market requirements, despite the best R&D that the defense industry, who coined the term C-SWaP, can buy. HBF represents breakthrough beamforming technology that finally provides a viable C-SWaP profile for commercial 4G and 5G networks.

The next paper will introduce several use cases utilizing HBF as a cost-effective beamformer.