Holographic Beam Forming and Phased Arrays

By Pivotal Staff

Many in the telecom industry have debated whether millimeter wave spectrum could be effectively commercialized. But recent advances in beamforming antennas and generous spectrum allocations have positioned it as a gateway to 5G's most bandwidth-hungry and exciting applications, such as immersive telepresence, VR/AR and remote operations. mmWave is also expected to rescue mobile operators in the US, South Korea and Japan as they run out of 5G mid-band capacity in 2021 or 2022 due to ever-increasing mobile data usage[1].

This paper explores the most important commercial enabler of mmWave, analog beamforming, by comparing two leading technologies: active phased arrays (APAs) and Holographic Beam Forming® (HBF). Digital beamforming, i.e., Massive MIMO, will not be discussed here because exorbitant power requirements and component costs associated with high sampling rates preclude it from practical usability at mmWave frequencies.

Beamforming

While mmWave spectrum delivers more capacity than lower frequency 5G bands, it's also more prone to propagation and penetration losses. To overcome signal losses, beamforming antenna arrays are employed for more signal gain, which for most practical applications at 28 GHz results in a physical antenna area of roughly nine square inches. By enlarging the array to achieve higher gain, the beamwidth narrows. This narrowing has been acceptable for traditional fixed links but won't do for coverage applications targeting mobile 5G users. That is why a 5G beamformer must scan, i.e., move around, to cover multiple users, and perform at electronic speeds unnoticeable to the end users. Electronically scanned, high gain antenna arrays are thus required for mmWave 5G communications. The defense industry has been using APAs for decades at very high cost, size, weight and power consumption, although recent advancements in highly integrated semiconductors have brought APAs closer to commercially viability. By contrast, HBF constitutes a breakthrough in electromagnetic physics with much lower C-SWaP (cost, size, weight and power consumption) than APA.

Beamforming Architectures

Figure 1 compares HBF and APA antenna architectures suitable for 5G applications. In both cases the beam is formed and steered by radiating (or receiving) the RF signal from many radiating elements, but there are two key differences: 1) the method used to steer the signal, and 2) the location of amplification.

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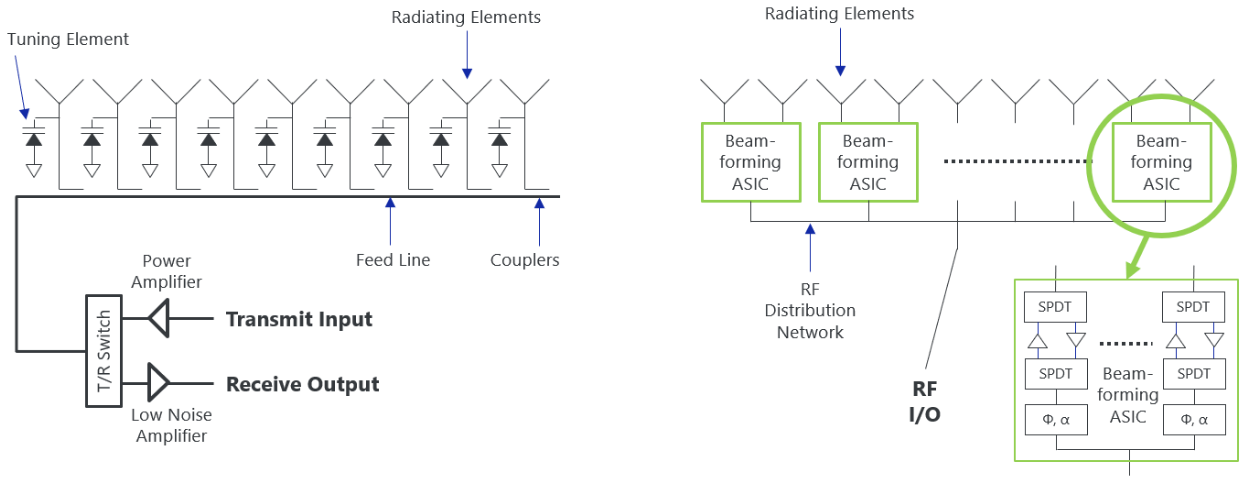
[1] "5G Millimeter Wave 2019: Radio Architecture and Outlook," by Joe Madden, March 2019.



a) Holographic Beamforming Antenna Block Diagram (including external amplifiers and T/R switch)

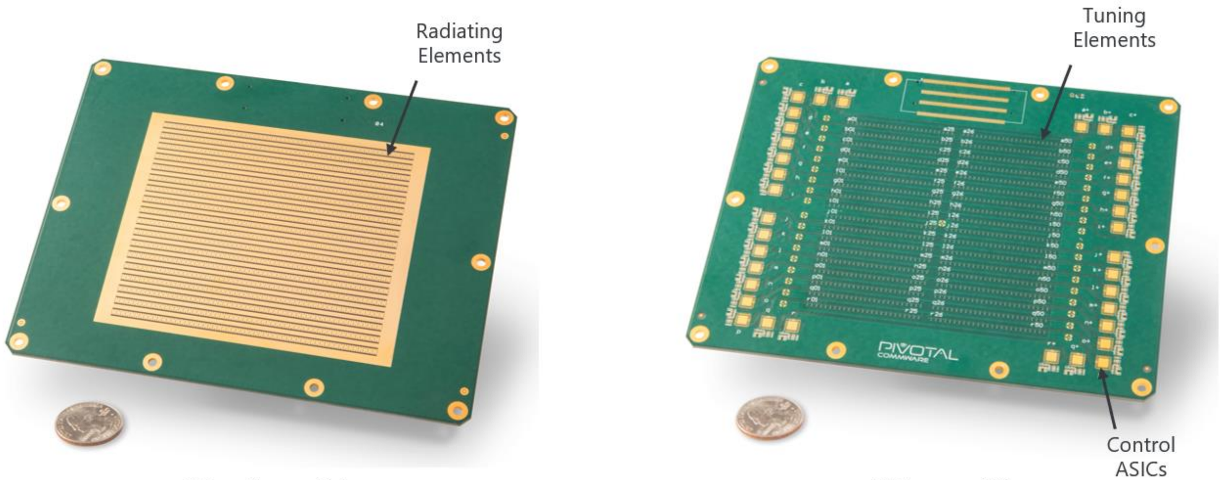
b) Active Phased Array Antenna Block Diagram

Figure 1: Simplified HBF and APA antenna block diagrams

The APA antenna has phase shifters at every radiating element, which are commanded to set the desired phase of the signal at each antenna element, thus steering the beam. APAs also have amplifiers at every radiating element to offset RF losses. Most APAs also have RF gain control elements (either attenuators or variable gain amplifiers) at every element. These devices are used to correct for amplitude errors associated with other circuit elements and they are typically also used to control the RF signal amplitude at each radiating element thus controlling the beam sidelobe levels.

In order to reduce cost and ease packaging challenges, it is common for these RF components to be realized within a beamforming ASIC (Application-Specific Integrated Circuit) which supports multiple radiating elements. Many commercially available ASICs support half duplex communications by including both transmit and receive components for each radiating element. Transmit/receive switches are commonly used to connect the appropriate RF path within the ASIC to the antenna radiating elements. A typical APA tiles several beamforming ASICs on a printed circuit board (PCB) to realize the required aperture size. In order to support large scan angles with good beam quality the radiating elements are typically placed on a roughly half wavelength grid.

The HBF antenna has a feed line coupled to each radiating element within a row of radiating elements. There is a tuning element associated with each radiating element. The tuning elements provide a controllable capacitance which is set to modulate the propagation of the RF signal along the feed line and to modulate the coupling to each radiating element. This manipulates the amplitude and phase of the signal at each radiating element, thus forming and steering the beam in two dimensions. The details of the beamforming process are like forming a hologram, hence the term “Holographic Beam Forming”.



a) Free Space Side

b) Reverse Side

Figure 2: HBF Antenna

Figure 2 shows an HBF antenna. HBF antennas are passive because they use no active amplification. That makes them fully reciprocal, forming the same beam pattern in both transmit and receive operation. External amplifiers set the power level of the transmit signal and/or provide low noise amplification of a received signal.

Owing to the difference in array grids an HBF antenna typically has about 2.5 times as many radiating elements as an APA antenna with the same antenna directivity. However, the HBF antenna has only one low cost, discrete RF component at each radiating element whereas the APA has many RF components associated with each radiating element. Therefore, HBF is significantly less costly and power hungry than APA.

Performance Comparison

To a first order comparison, both antenna types can provide the same performance. Both can meet typical transmit (EIRP) and receive (G/T) performance requirements associated with 5G communications applications. Both can be implemented at the primary frequency bands of interest to the mmWave 5G market (24, 28, 39 GHz) and both can support the required bandwidths associated with each of these frequency bands. Furthermore, both antenna types can support rapid beam hopping and rapid switching between transmit and receive operation as required for 5G communications.

There are some meaningful differences between the two antenna types. For example, in the azimuth plane HBF antennas can support higher scan angles (up to about ± 80°) than is possible with APAs, which are typically limited to around ± 60° scan. This higher scan capability results from the size of each HBF radiating element being smaller than the half a wavelength associated with APA. For HBF, this size difference creates a wider beam pattern for each radiating element than is created by APA. HBF's higher scan angle allows mobile network operators to reduce basestation sectors from three to two.

Also, HBF antennas use external amplifiers to set the transmit power and the receive sensitivity. Typically, only one transmit amplifier and one receive amplifier are used per HBF. This permits the use of digital pre-distortion on transmit. Digital pre-distortion corrects for signal distortions created by operating power amplifiers close to their maximum output power. If it is not possible to correct for these distortions it is necessary to oversize the power amplifiers so that the operating point is considerably below the maximum possible output power. This increases the cost, power consumption and heat generation of the power amplifiers. It is not practical to implement this technique with APAs, because APAs have one transmit amplifier at every radiating element.

As noted above, APAs require commandable attenuators or variable gain amplifiers at every element. These components may be used to adjust the beam sidelobe levels during operation. HBF also adjusts sidelobe levels but uses the existing control elements to lower sidelobes. No additional hardware is needed. In locations with severe multi-path challenges it is attractive to operate with reduced sidelobes to harden the channel even though this degrades both transmit power and receive sensitivity.

C-SWaP Comparison

As mentioned, C-SWaP stands for Cost, Size, Weight and Power consumption. 65%-70% of the total cost of ownership of a network is in the RAN (Radio Access Network)[2]. As the RAN densifies in 5G, beamformers will dominate RAN costs, so lowering beamformer costs will be critical to operators. Hardware cost depends on many assumptions, but the fairest comparison places HBF at about half the cost APA due to the cost of relatively high-priced components, mainly ASICs. APA has many RF ASICs, per Figure 1(b). HBF typically has one digital control ASIC per 25 tuning elements. This very simple ASIC sets the control voltage applied to each tuning element thus steering the beam. Other costs include phase shifters and amplifiers. HBF uses no phase shifters, one amplifier for transmit and one amplifier for receive. APA requires many of both. The only part used in quantity on an HBF is a sub-dollar tuning element found in smartphones. Indeed, the simple parts needed for an HBF (tuning elements, PCB, DC control circuitry, a single PA/LNA) result in not only lower cost, but also smaller size, weight and less power consumption. Even comparing the most optimistic scaling scenarios for APAs against the most pessimistic HBF scaling shows APAs being double the price of HBF. With more realistic assumptions that compare todays pricing and similar scaling, HBF has a dominating cost advantage of 1/10th the price of an APA.

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[2] "O-RAN: Towards an Open and Smart RAN," O-RAN Alliance White Paper, October 2018.

Power Consumption

Let's not forget ongoing operating costs. Multiple ASICs, phase shifters and amplifiers mean that APA consumes a lot more power than HBF. Figure 3 compares HBF to a typical APA[3]. The difference in power consumption is striking.

	Phased Array	HBF	Unit
Number of Unit Cells	256	640	#
Antenna Gain	28	26	dB
Number of RF chains	256	1	#
Transmit Power per chain	6.2	2512	mW
Total RF Transmit Power	1.58	2.51	W
Power Added Efficiency	4.0%	25.0%	%
DC Draw for RF	39.6	10.0	W
HBF Controller	0	2.9	W
Total DC Power	**39.6**	**12.9**	**W**

Figure 3: Difference between HBF and Active Phased Array power consumption

In the context of dense mmWave deployments, even small differences in power consumption can add up to significant OPEX for operators and APA vendors are aware of this problem.[4]

While it's true that individual gNBs will consume less power than their 4G brethren, there will be orders of magnitude more of gNBs due to more limited mmWave propagation. This is one reason why 5G is expected to drive electricity costs even higher in the coming years[5] (Figure 4). This is significant considering that today, powering cell sites accounts for roughly 70% of operator OPEX[6].

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[3] "5G Millimeter Wave Frequencies and Mobile Networks," International Wireless Industry Consortium, June 14, 2019.

[4] "What is new at Anokiwave – 20 Years Celebration and mmWave 5G is now a Commercial Reality," Anokiwave website, by Alastair Upton, May 23, 2019.

[5] "Energy Efficiency and Coverage Trade-Off in 5G for Eco-Friendly and Sustainable Cellular Networks," by Alsharif, Kelechi, Kim and Kim, Symmetry by MDPI, March 20, 2019.

[6] "What 5G Means for Energy," by Amy Myers Jaffe, Council on Foreign Relations, Energy Realpolitik, May 31, 2019.

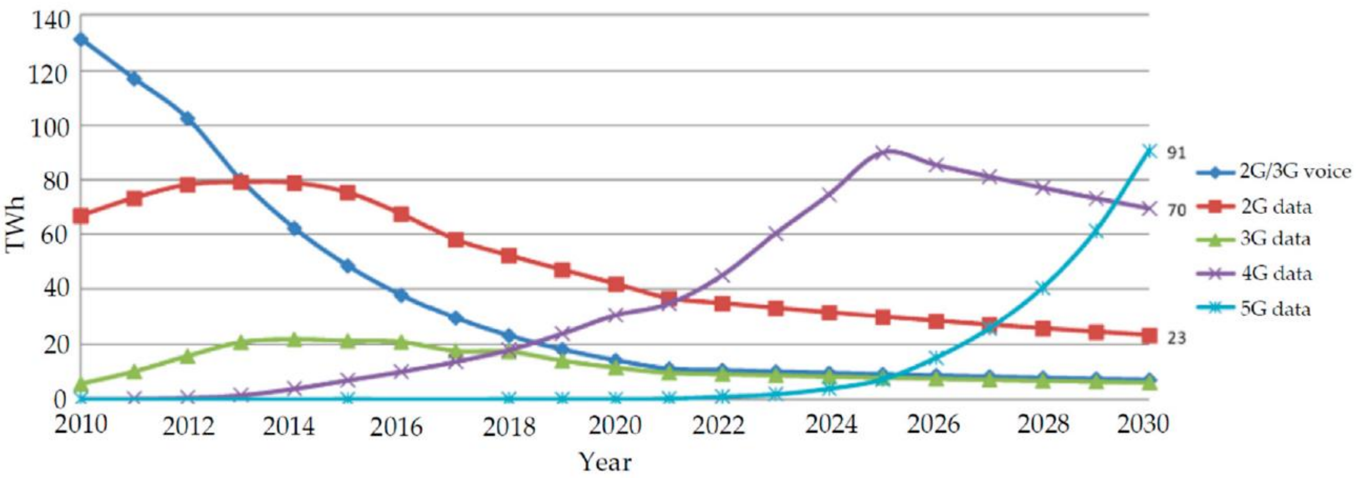

Figure 4: Expected electricity usage of wireless access networks

Size and Weight

To the extent higher power consumption generates heat, APAs require more surface area to dissipate it. This means that the APA-based products, driven by thermal design considerations, will be significantly larger than HBF-based products, which means they will be heavier, too. Unlike 4G nodes, 5G nodes will be frequently placed on public property or in local public rights-of-way where people can see them. They can't be disguised as trees, and unlike cell towers, they'll need to be placed in residential areas. In this new paradigm of public visibility, the size and aesthetic appeal of telecom equipment will influence the speed of 5G deployment.

Pivotal Commware's Echo 5G Subscriber repeater, designed to facilitate in-building penetration of mmWave signals, reflects the 5G hardware size and weight that municipalities and end-users will prefer (Figure 5). The window-attached unit, which contains the beamformer, measures 7" (h) x 7" (w) x 1.5" (d) and is lightweight enough to attach to window glass as shown. What's more, the outdoor unit requires so little power that, uniquely, it can be operated inductively from the inside unit, through the glass. The Echo 5G in Figure 5 is not a network node, but it's indicative of emerging mmWave products such as repeaters that will appear not only outdoors but also indoors, where low C-SWaP will be an important consideration.

Figure 5: Echo 5G Subscriber

Summary

This paper compared two beamforming technologies uniquely suited to mmWave frequencies used for 5G communication: active phased array (APA) and Holographic Beam Forming (HBF). HBF is a newer, simpler architecture that uses low-complexity, low-cost components. APAs, because of their more complex architecture, use multiples of more expensive components like ASICs, phase shifters and amplifiers. Consequently, APAs cost considerably more than HBFs and consume significantly more power, which, in turn, generates more heat and the need to dissipate that heat with more and therefore heavier surface areas. HBF's relatively lower C-SWaP (cost, size, weight and power consumption) reduces operator CAPEX and OPEX, as well as municipal resistance to 5G equipment occupying public property or in local public rights-of-way where people can see them.