Bits to Beams – RF Technology Evolution for 5G mmwave Radios

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Introduction

When the wireless industry embarked on the creation of 5G, 2020 used to seem so far away. Now we are quickly closing in on 2020 and this will most certainly be the 5G decade. Every day there are announcements in the press of new field trials and upcoming commercial 5G rollouts. It's a very exciting time for the wireless industry. Currently, much of the industry 5G focus is on enhanced mobile broad band, driving toward higher and higher network capacity and throughput utilizing beamforming techniques in mid-band and high-band spectrum. We are also beginning to see use cases emerge such as industrial automation that leverage the low latency features of the 5G network architecture.

It was only a few years ago that the industry was debating the feasibility of using mmwave spectrum for mobile communications and framing the challenges that lay ahead for the radio designer [1]. Much has transpired in short time and the industry has progressed rapidly from initial prototypes to successful field trials and now we on the verge of the first commercial 5G mmwave deployments. Many of the initial deployments will be for fixed or nomadic wireless applications, but we will also see truly mobile connectivity at mmwave frequencies in the not so distant future. The first standards are in place, technology is quickly evolving, and much learning has transpired around the deployment of mmwave systems. While we have made much progress, there remain many challenges ahead for the radio designer. Let's examine some of these challenges for the RF designer in the remainder of this article.

This article is organized into 3 major topics. In the first section, we will discuss some of the leading use cases for mmwave communications and set the stage for the analysis that follows. In the second and third sections we will delve into the architectures and technology for the mmwave basestation systems. In section 2 we will discuss technology for the beamformers and how the required transmit power influences the choice of technology for the system front-end. While the beamformer gets much of the spotlight in the press, there is equally important section of the radio that performs the conversion from bits to mmwave frequency. We will present an example signal chain for this section of the system and suggest some leading-edge components from Analog Devices for radio designers consideration.

Deployment Scenarios and Propagation Considerations

When we are developing technology, it's critical to understand how the technology will ultimately be deployed. In all engineering exercises, there are tradeoffs to be made, and with additional insight creative innovations may emerge. In Figure 1 below, we highlight two of the common scenarios being explored today in the 28 GHz and 39GHz spectrum.
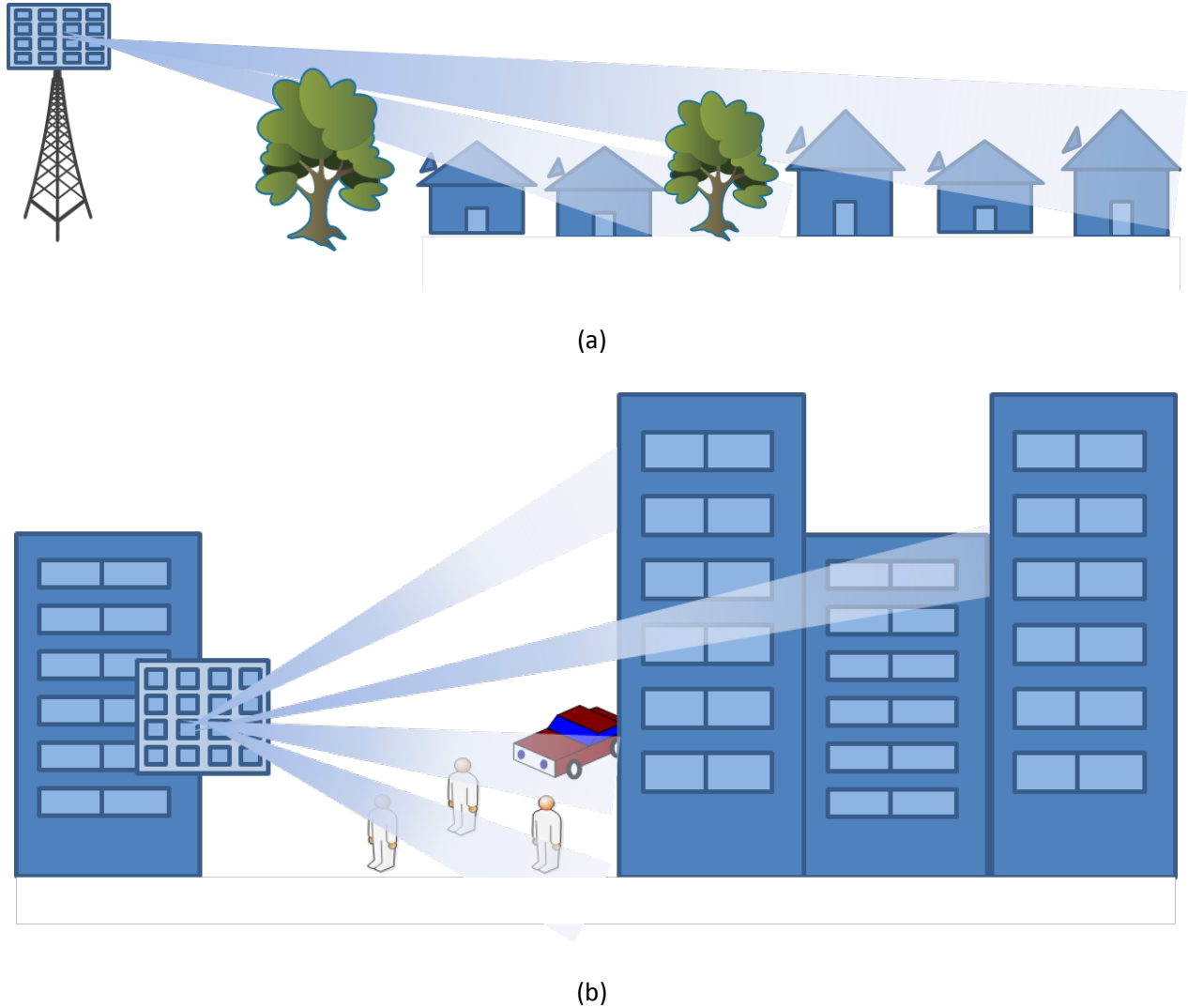
(a)

(b)

Figure 1: *5G mmwave deployment scenarios: (a) fixed wireless access in suburban environment; (b) fixed and mobile deployment in dense urban environment*

Figure 1(a) illustrates a fixed wireless access (FWA) use case, where we are trying to deliver high bandwidth data to homes in a suburban environment. In such a case the basestation will be on a utility pole or tower and is required to cover a large area to produce a positive business case. In the initial deployments, we assume that the coverage is outdoor to outdoor, whereby the customer premises equipment (CPE) is mounted outdoors and the link may be engineered to ensure the best over the air connection. Given that the antenna is pointing down and users are fixed, we may not require a large amount of vertical steering range, but the transmitted power may be quite high, in excess of 65dBm EIRP to maximize the coverage and leverage existing infrastructure.

In Figure 1(b) we illustrate a dense urban scenario, where the basestation will be mounted lower to the ground on a building rooftop or façade, possibly evolving to streetlight or other street level mounting in

the future. In any case this type of basestation will require vertical scanning ability to deliver signals across the entire building elevation and eventually to mobile or nomadic users on the ground (pedestrians and vehicles) as mobile devices emerge. In this case the transmitted power may not need to be so high as in the suburban case, although low E glass has proven to be a problem for outdoor to indoor penetration. As shown we will need more flexibility in the beam scanning range, in both horizontal and vertical axis. The major takeaway here, is that there is not a-one-size fits all solution. Deployment scenario will determine beamforming architecture and architecture will influence the choice of RF technology.

Now let's consider a practical example and derive a simple link budget to illustrate the transmit power requirements for a mmwave basestation as compiled in Table 1. The additional path loss compared to that at cellular frequencies is a major hurdle to overcome at mmwave frequencies but also blockage (buildings, foliage, people, etc.) is a major factor to consider. There is a plethora of work reported in recent years on propagation at mmwave frequencies, with an excellent overview compiled by Rappaport et all in [2]. Several models are discussed and compared, illustrating the dependence of path loss on the environment, and a comparison of line-of-sight(LOS) scenarios versus non-line-of-sight (NLOS). Without going into detail here, we can say that in general an NLOS scenario should be considered for fixed wireless deployment given the desired reach and terrain being considered. In our example, we consider a basestation with 200m reach in a suburban deployment. Here we have assumed a path loss of 135 dB based on an NLOS outdoor to outdoor link. If we were trying to penetrate from outdoors to indoors then the path loss may be as much as 30 dB higher. Conversely if we assume a LOS model then path loss may be on the order of 110dB.

TABLE 1		
Link Budget 200m link @ 28GHz 800 MHz Bandwidth	**Downlink (Basestation)**	**Uplink (CPE)**
Antenna Element Count	256	64
Total Conducted PA power	+33dBm	+19 dBm
Antenna Gain	27 dB	21
TX EIRP	60 dBm	40dBm
Path Loss	135dB	135 dB
Received Power	-75dBm	-95 dBm
Thermal noise floor	-85 dBm	-85dBm
RX Noise Figure	5dB	5dB
SNR per RX element	5dB	-15dB
RX Antenna Gain	21dB	27dB
RX SNR after beamforming	+26dB	+12dB

In this case we assume 256 elements in the basestation and 64 elements in the CPE. In both cases the output power can be satisfied with silicon implementation. The link is assumed to be asymmetric, which provides some relief in uplink budget. In this case the average link quality should allow for 64 QAM operation in the downlink and 16 QAM in the uplink. The uplink can be improved by increasing the transmit power of the CPE if required, up to the legislated regional limits. If one were to stretch the link reach to 500 m, the path loss will increase to approximately 150dB. This is doable but makes the radios on both uplink and downlink more complex and power consumption increases dramatically.
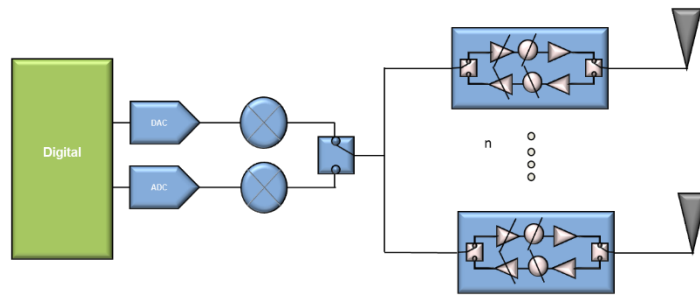
mmwave Beamforming

Now let's consider the various approaches to beamforming; analog, digital and hybrid as shown below in Figure 2. I'm sure we are all familiar with the concept of analog beamforming as this topic has been quite popular in the literature in recent years. Here we have data converters translating the digital signals to and from broadband baseband or IF signals, connecting a radio transceiver performing the up and down conversion processes. At RF (example 28 GHz) we split the RF single into several paths where we perform the beamforming, by controlling the phase of each path so that a beam is formed in the far field in the direction of the intended user. This enables a single beam to be steered per data path, so in theory we can serve one user at time with this architecture.

The digital beamformer is exactly what it sounds like. The phase shift is purely implemented in the digital circuitry and then fed to the antenna array through an array of transceivers. Simply speaking, each radio transceiver is connected to a single antenna element, but in practice there could be several antenna elements per radio depending on the desired sector shape. The digital approach enables highest capacity and flexibility and enables the roadmap to multi-user MIMO at mmwave frequency, similar to mid-band systems. It is highly complex and given currently available technology will consume an excessive amount of DC power both in RF and digital circuits, however as technology evolves in the future, digital beamforming will emerge for the mmwave radios.

The most practical and effective beamforming approach in the near term is the hybrid digital-analog beam former which essentially combines digital pre-coding and analog beamforming to create several beams simultaneously in space (spatial multiplexing). By directing power toward the intended users with narrow beams, the basestation can re-use the same spectrum to simultaneously serve more than user in a given timeslot. While there are a few different approaches to the hybrid beamformer reported in the literature, the sub-array approach shown here is most practically implemented and is essentially a step and repeat of analog beamformers. Currently reported systems support from 2 up to 8 digital streams in practice, which can be utilized to simultaneously support individual users, or alternatively provide 2 or more layers of MIMO to a lesser number of users.

Let's dive a little deeper into the technology choices for the analog beamformer, the building block upon which the hybrid beamformer is constructed as shown in Figure 3. For the treatment here, we have segmented the analog beamforming system into 3 blocks, digital, bits-to-mmwave and beamformer. This is not the way a practical system will be partitioned as one would place all mmwave components in close proximity to mitigate losses, but this division becomes obvious shortly.
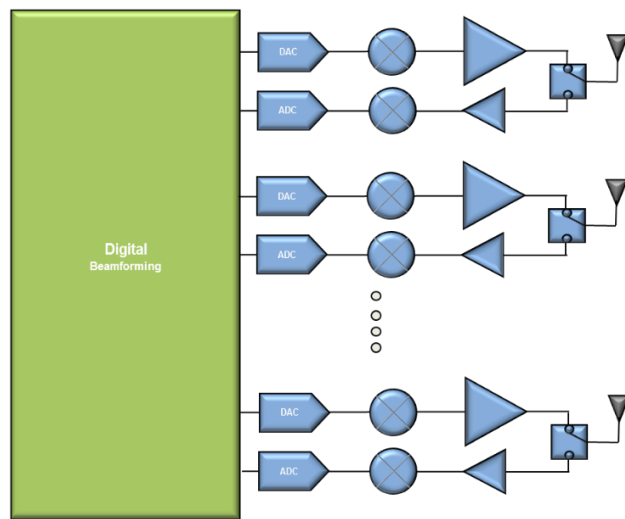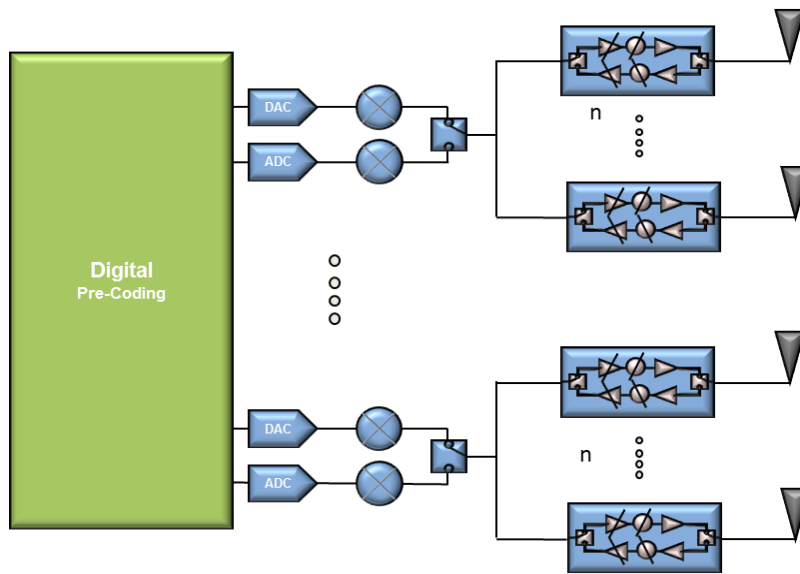
Figure 2: (a) Analog beamforming; (b) Digital beamforming; (c) Hybrid Digital-Analog Beamforming

The beamformer function is driven by many factors including segment shape and reach, power levels, path loss, thermal constraints etc., and is the section of the mmwave systems that requires some flexibility as the industry learns and matures. Even then, there will continue to be a variety of transmit power levels required to address deployment scenarios ranging from small cell to macro. On the other hand, the bits to mmwave radio for a basestation requires much less flexibility and can largely be derived from the current Release 15 specification [3]. In other words, a designer can re-use the same radio in conjunction with several beamformer configurations. This is not unlike current cellular radio systems where the small signal section is common across platforms and the front-end is more tailored per use case.

We have mapped the progression of possible technologies for the signal chain as we move from digital toward the antenna. Certainly, the digital and mixed signal are produced in fine line bulk CMOS processes. Depending on the requirements of the basestation the entire signal chain may be developed in CMOS or more likely in a mix of technologies to provide the optimum performance for the chain. For example, a common configuration is to use CMOS data converters with a high performance SiGe BiCMOS IF-to-mmwave conversion. The beamformer may be implemented in several technologies as shown, depending on the system requirements as we will discuss next. Depending on the choice of antenna size and transmit power requirements it may be possible to implement a highly integrated silicon approach, or it may be a combination of silicon beamformer with discrete PA and LNA.
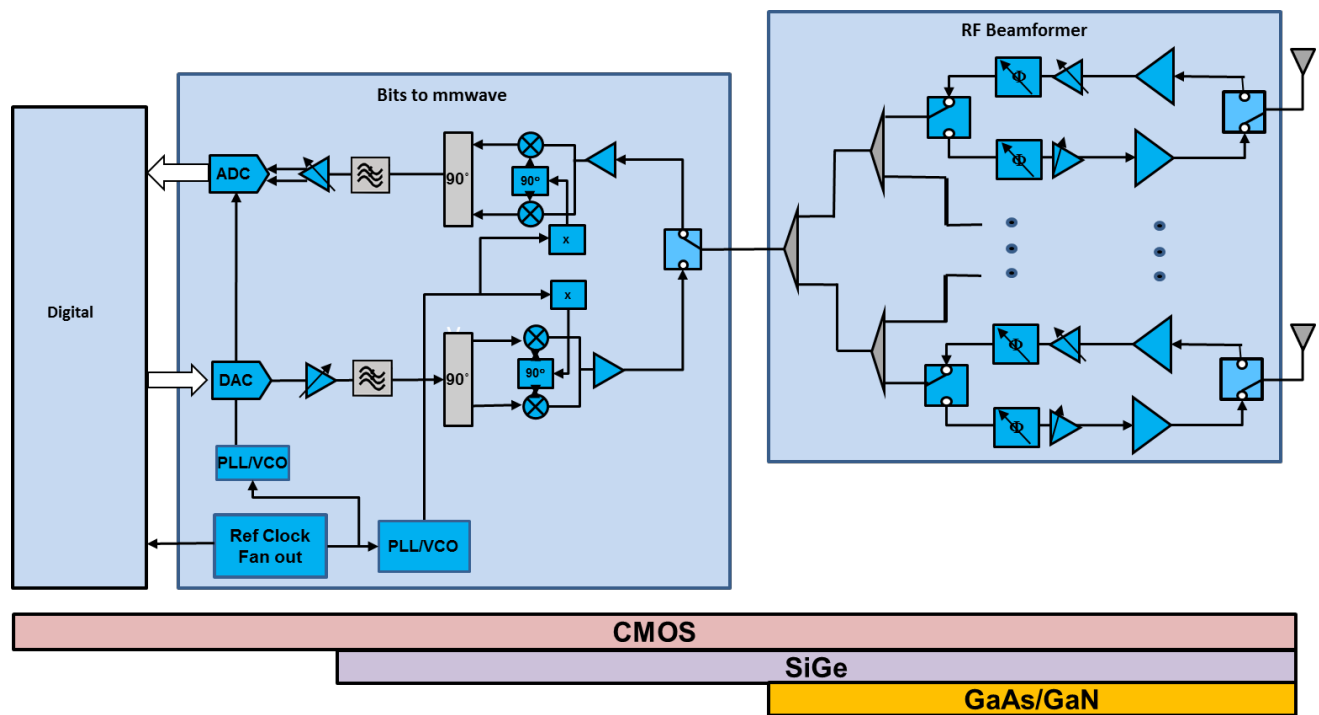

Figure 3: *Analog Beamforming System Block Diagram*

An analysis of the relationship between transmitter power and the choice of technology has been presented in [4] and [5], so will not be repeated in depth here. However, just to summarize that analysis, we have included the graph in Figure 4. The selection of power amplifier technology is based on combined consideration of required transmitter power, the gain of the antenna (number of elements)

and the RF power generating capability of the selected technology. As shown in the graph, the desired EIRP may be accomplished with fewer antenna elements using II-V technologies in the front end (low integration approach) or using a silicon based high integration approach. Each approach has advantages and disadvantages and practical implementation comes down to engineering tradeoffs of size, weight, DC power consumption and cost. To generate an EIRP of 60 dBm for case derived in Table 1, the analysis [5] concluded that the optimum antenna size is between 128 and 256 elements, the lower count enabled by GaAs power amplifiers, while the larger one is achievable in all-silicon beamformer RFIC based technology.
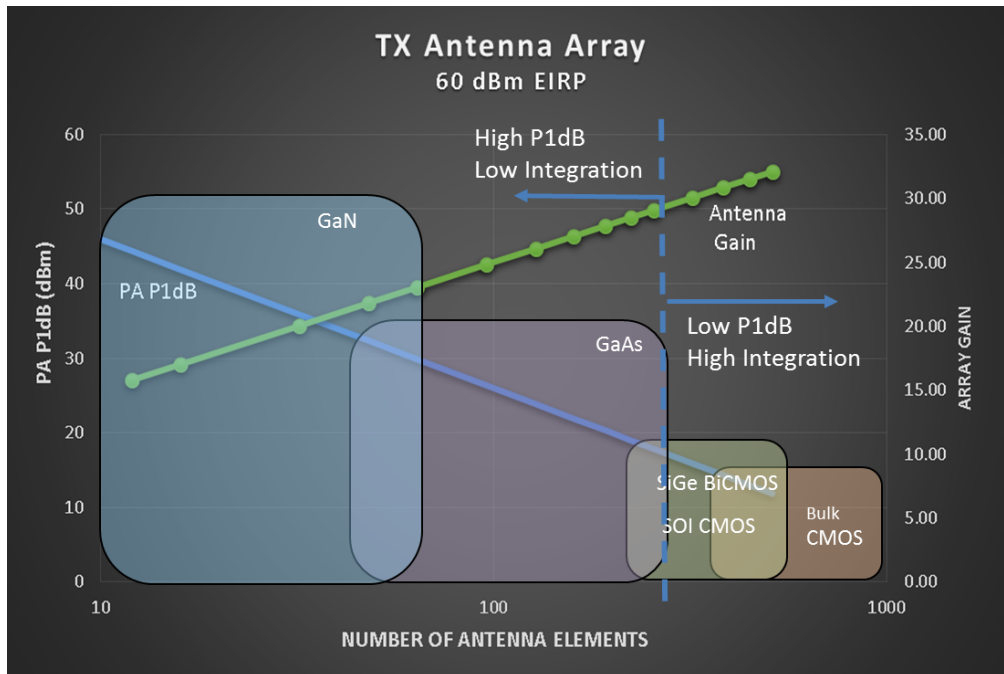

Figure 4: *Relationship between required transmitter power, size of antenna and choice of semiconductor technology for antenna with 60dBm of EIRP [5]*

Now let's examine the problem from a different perspective. 60 dBm EIRP is a commonly quoted EIRP target for FWA, but the number can be higher or lower depending on the desired reach of the basestation and the surrounding environment. Given the high variation in deployment scenarios, whether the area is highly treed, or composed of street canyons, or wide-open spaces, there will be a large range of path loss to contend with on a case by case basis. For example, in a dense urban deployment where LOS is assumed, the EIRP target may be as low as 50dBm.

There are definition and published specifications as well as transmit power limits from the FCC by equipment class [3, 6], and here we follow the 3GPP terminology for basestations [3]. As illustrated in Figure 5, the class of equipment more or less defines the choice of technology for the power amplifier. While not an exact science, we can see that clearly the mobile user equipment (handset) is well suited for CMOS technology and a relatively low antenna count can achieve the required transmitter power. This type of radio will very highly integrated and power efficient to meet the needs of portable equipment. The local area basestation (small cell) and consumer premise equipment (transportable power) share similar requirements and span a range of technologies from CMOS on the low end of TX

power requirements to SiGe BiCMOS for the higher end. The medium range basestations are ideally suited for SiGe BiCMOS technology to achieve a compact form factor. At the high end, for wide area basestation there is a range of technology that may be applied, and it comes down to the tradeoffs of antenna size and technology cost. While SiGe BiCMOS can be applied in the 60dBm EIRP range, GaAs or GaN power amplifiers are more practical for higher power.
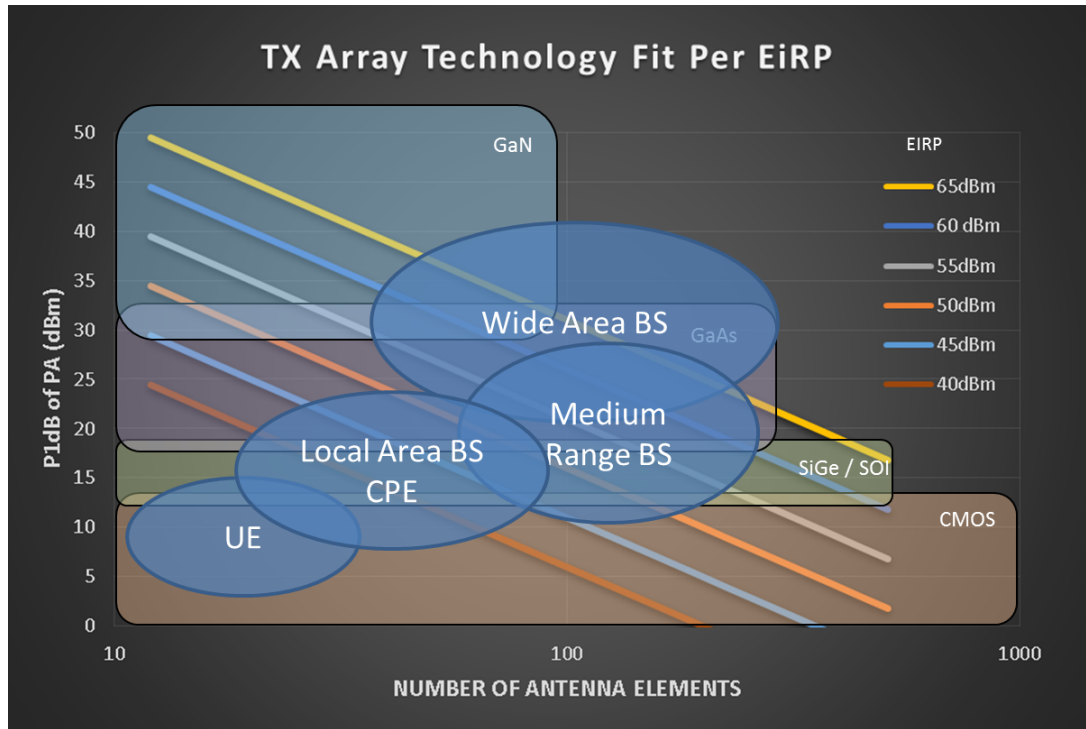

Figure 5: *Technology fit for various mmwave radio form factors based on transmitter power [5].*

The above is snapshot of current technology, but much progress is being made in the industry and technology continues to improve. As mentioned in [5], one of the key challenges for the designer is to improve the DC power efficiency for mmwave power amplifiers. As new technologies and PA architectures emerge, the curves above will shift, and more highly integrated structures will be available for the high power basestations. A good overview of advancements in PA technology is presented in [7].

To summarize the beamformer section, let's reiterate the point made above. Currently there is not a one-size-fits all approach and one may need to design a variety of front-end designs to address the various use cases from small cells to macros.

mmwave Radio – From Bits to mmwave and Back

Let's move on now to the bits-to-mmwave radio in more detail and explore the challenges in this section of the system. It's critical to translate the bits to mmwave and back with high fidelity to support high order modulation techniques such as 64QAM and possibly as high as 256 QAM in future systems. One of the main challenges for these new radios is bandwidth. The 5G mmwave radios must nominally process 1GHz of bandwidth or possibly higher depending on how the spectrum is allocated in practice.

While 1GHz of bandwidth at 28Ghz is a low relative (3.5%) bandwidth, that same bandwidth at an IF of say 3GHz is much more challenging to design for and requires some leading-edge technology to achieve a high-performance design.

Figure 6 illustrates an example of block diagram for a high-performance bits-to-mmwave radio based on components form the Analog Devices' broad RF and mixed signal product portfolio. This signal chain has been demonstrated to support contiguous 8X100MHz NR carriers at 28GHz with exceptional error vector magnitude (EVM) performance. More details on this signal chain and its' demonstrated performance can be found at [8].

First, let's consider the data converters. In the example of Figure 6 we show direct high IF TX launch and high IF RX sampling used, whereby the data converters are launching and receiving at the intermediate frequency (IF). The IF needs to be as high as can be reasonably achieved to avoid unwieldly image filtering at RF, driving the IF frequency to 3GHz and above. Fortunately, leading edge data converters are capable of operating at this frequency. The AD9172 [9] is a high performance, dual, 16-bit DAC that supports sample rates to 12.6 GSPS. The device features an 8-lane, 15 Gbps JESD204B data input port, a high performance, on-chip DAC clock multiplier, and digital signal processing capabilities supporting broadband and multiband direct to RF signal generation up to 6GHz. In the receiver we show the AD9208 [10], a dual, 14-bit, 3 GSPS ADC. The device has an on-chip buffer and a sample-and hold circuit designed for low power, small size, and ease of use. This product is designed to support communications applications capable of direct sampling wide bandwidth analog signals of up to 5 GHz.

In both the transmit and receive IF stages we suggest digital gain amplifiers that convert from single to balanced and vice versa to avoid the use of baluns. Here we show the ADL5335 in the transmit chain and the ADL5569 in the receive chain as examples of high performance broadband amplifiers.

 For the up and down conversion between IF and mmwave, we have recently introduced both a silicon based broadband upconverter the ADMV103 and a downconverter, the ADMV1014. These frequency conversion devices enable the designer to cover the most of the FR2 NR (3GPP frequency range 2 new radio) bands (bands n257, n258, n260 and n261) [3] using a single device with RF coverage ranging from 24.5 to 43.5GHz. Both support an IF interface up to 6GHz and two frequency conversion modes. As shown in Figure 6 both devices include an on-chip 4X local oscillator (LO) multiplier with LO input ranging from 5.4 to 11.75 GHz. The ADMV103 supports both direct conversion from baseband I/Q to RF and single sideband up conversion from IF. It provides 14 dB of conversion gain at a high output IP3 of 24dBm. If implemented in single sideband conversion as illustrated in Figure 6 the device provides 25 dB of sideband suppression. The ADMV1014 supports both direct conversion from RF to baseband I/Q and image-reject down-conversion to IF. It provides conversion gain of 20 dB with a noise figure of 3.5dB and input IP3 of -4dBm. Sideband suppression in image-reject mode is 28dB.

The final component in the RF chain is the ADRF5020 Broadband Silicon SPDT Switch. The ADRF provides both low insertion loss of 2dB and high isolation of 60 dB at 30GHz.

Finally, let's discuss the frequency sources. Given that the local oscillator may big a large contributor to the EVM budget it's important to use a source with very low phase noise for the mmwave LO generation.
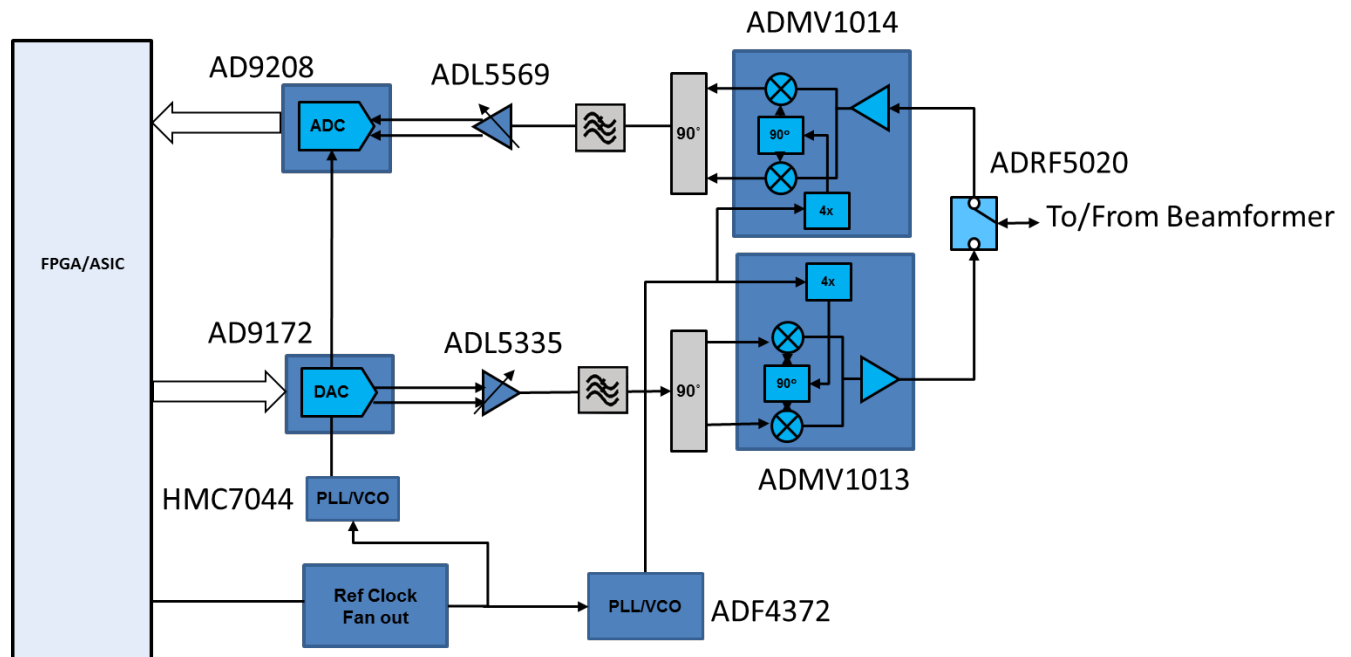
Figure 6: *Block diagram for broadband bits to mmwave radio*

The ADF4372 is wideband microwave synthesizer with an industry leading integrated PLL and ultra-low phase noise VCO with output capable of 62.5MHz to 16GHz. It allows implementation of fractional-N or integer-N phase-locked loop (PLL) frequency synthesizers when used with an external loop filter and an external reference frequency.   access to the VCO Output. VCO phase noise at 8GHz is an impressive -111dBc/Hz for 100kHz offset and -134dBc/Hz at 1MHz offset.

The block diagram of figure 6 is a good starting point for any designer considering a mmwave design in the 28 and 39 GHz bands and suitable for use with a variety of beamforming front-ends requiring a high performance broadband radio. There are also many components listed in [11] that may be of interest to the designer for other signal chain architectures or for similar high frequency applications.

Summary

mmwave radios have seen great progress in recent years, moving out of the lab to field trials with commercial deployments launching is the coming months. The evolving ecosystem and emerging use cases require some flexibility in the beamforming front end, but as discussed there are suitable technologies and approaches to choose from for the near antenna designs. The broadband nature of the radio (bits to mmwave) demands leading edge technology, but silicon-based technology is quickly evolving to meet the requirements in mixed and small signal domain. A high-performance radio design example has been presented based on currently available components.

As the 5G ecosystem continues to evolve, Analog Devices will continue to bring to bear our leading-edge technologies and signal chain solutions to enable our customers to develop differentiated systems for the emerging 5G mmwave market.

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