A Circuit Designer's Guide to 5G mm-Wave

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***Abstract*—The fourth generation mobile phone standards (4G) in widespread use include Long Term Evolution (LTE) and LTE-A (Advanced), which support up to 44 bands internationally, or an aggregate bandwidth of about 1 GHz in TDD and FDD modes. Techniques such as carrier aggregation allow the mobile operator to maximize bandwidth and deliver high data rate to users. As demand for wireless connectivity continues to grow exponentially, a fifth generation (5G) standard is envisioned, with the requirement to deliver higher throughputs, more spectrum –particularly in the mm-wave bands–higher capacity through spatial diversity, and lower latency. The projected deployment date of 5G is in 2019, and various proposals are under consideration. This paper will highlight important implications for the design of transceivers for 5G, particularly those targeting the mm-wave bands.**

***Index Terms*—5G, mm-waves, mm-wave mobile.**

I. Introduction

The wireless revolution has completely transformed several industries by allowing virtually universal connectivity between people and the Internet. Managed cellular (mobile) communication (2G, 3G, and 4G) in licensed bands by wireless operators along with unmanaged wireless access points (WiFi) have played complementary roles in enabling this vision. Today 4G networks such as LTE and LTE-A offer high download speeds and support high throughput applications such as audio and video streaming. With 44 frequency bands worldwide, it may seems that LTE technology is sufficient to meet our bandwidth needs for a while? LTE technology operates in the highly valuable spectrum from 462.5 MHz – 3800 MHz. Due to the high value of this frequency spectrum, each FDD band has a variable bandwidth from 5 MHz to 80 MHz, with TDD bands ranging from 15 MHz to 200 MHz. The total bandwidth amounts to nearly 1 GHz in the FDD bands and 1 GHz in the TDD bands (or about half the capacity).

While this is a great amount of bandwidth, it should be noted that this bandwidth is fragmented into 44 non-contiguous chunks, and not all of these bands are available in one geographic location, varying from country to country or by continent. Moreover, today no handheld device can tap into all of these bands due to practical area limitations posed by the front-end modules (duplexers / filters) rather than any limit imposed by the electronics. Duplex spacing as low as 10 MHz with typical values of 45 MHz requires bulky FBAR or SAW filters in front of the FDD transceivers. TDD systems also need switches and interference rejection filters since a wideband receiver operating from 450 MHz to 3700 MHz would require extremely aggressive linearity requirements as transmitters in these bands can reach peak powers of 27 dBm and isolation between two devices (antenna to antenna coupling, or board coupling) could amount to 0–10 dBm of interference power.

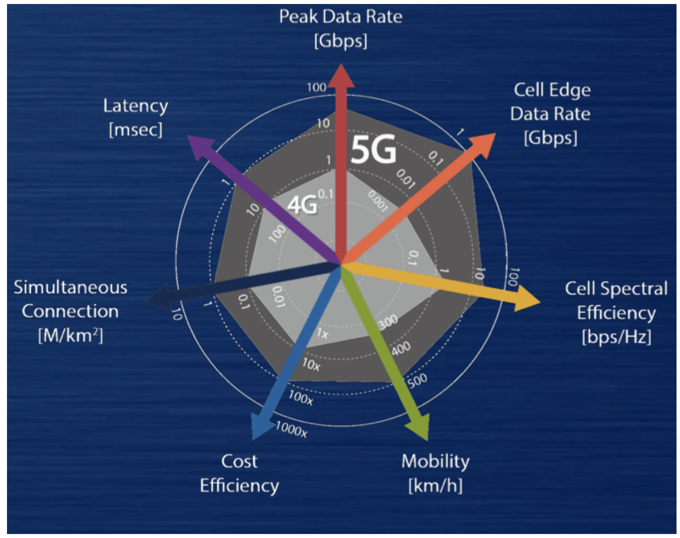

Fig. 1. The 5G Rainbow of Requirements.

The other problems with LTE include incompatibility with WiFi technology, which has the potential to relax the bandwidth requirements on mobile operators, and poor energy efficiency in low power / short range communication, a space today occupied by Bluetooth / BTLE and ZigBee. With the Internet of Things (IoT) revolution putting more wireless connectivity into devices, we see adoption of WiFi and Bluetooth or ZigBee and not LTE.

As we see, LTE is a beautiful technology that has served us well up to now, but with exponentially increasing mobile traffic and Internet access, LTE cannot scale to meet the demands of the future. LTE was also not designed for co-operation in unlicensed bands or for new emerging applications such as IoT or for control over wireless, which requires much lower latency ($\sim$ 1ms) than available today.

A. The 5G Promise

5G technology is positioned to address all of the aforementioned shortcomings of 4G technology. In particular, people envision "everything in the cloud" which can offer a desktop-like experience on the go, immersive experiences (lifelike media everywhere), ubiquitous connectivity (intelligent web of connected things), and telepresence (real-time remote control of machines) [1].

To address these new application scenarios from a mobile device, the following "rainbow of requirements" have been defined: (1) Peak Data Rates up to 10 Gbps, (2) Cell Edge Data Rate approaching 1 Gbps, (3) Cell Spectral Efficiency close to 10 bps/Hz, (4) Mobility up to 500 km/h, (5) Cost Efficiency that is 10-100X lower than 4G, and (6) over 1M simultaneous connections per km^2, and finally, and perhaps most importantly, (7) a latency of 1 ms (see Fig. 1 for a comparison to 4G [2][1]).

Interestingly, at this point 5G is mostly in the discussion phase and there are many elements of 5G which are still in flux. In particular, the frequency band allocation, the modulation schemes and waveforms, the power levels, and many other important factors, are still in debate. Nevertheless, the vision for 5G is very clear and to date several key new ideas are proposed to address these requirements.

B. Tapping into Spatial Capacity

One of the key requirements for 5G is higher spectral efficiency and capacity, allowing more devices to connect at faster speeds, at much lower latencies. Traditionally more users are accommodated in a network through adding more frequency bands, through spatial re-use of frequency bands, or by increasing the spectral efficiency of modulation, for instance using MIMO techniques. In theory, by building smaller cells and limiting transmit power, the number of users can be increased, but in practice interference between cells is a major hurdle. MIMO techniques can increase capacity by utilizing multiple antennas to tap into independent wireless channels created by multi-path propagation. The increase in channel capacity is not dictated by the number of antennas, but rather by the channel multi-path propagation environment. While WiFi technology has benefited greatly from MIMO due to the rich multi path indoor channel, outdoor signal propagation is typically dominated by a few paths which leads to smaller gains using traditional MIMO.

On the other hand, if multiple antennas are used to beamform multiple independent data streams in different directions, a multi-user scenario, then capacity gains are possible due to the fact that beams have minimal interference. The key concept is that Maxwells equations are linear and that electromagnetic waves just pass through each other. Harmful interference really happens because of the receiver's non-linearity when two or more signals are picked up by the antenna and they intermodulate and produce intereference at new frequency bands. Even a single strong interferer "blocks" the receiver and decreases the sensitivity. Most radios today spray energy in all possible directions, which is not only a waste of power, but it causes more interference. The real solution is to utilize the spatial selectivity and directivity of an antenna array to avoid interference (sharp transmit beams) and to suppress interference at the receiver by beam forming and possibly beam nulling in the receiver.

Beam forming is a strong function of the number of antennas, and larger arrays are easier to build at higher frequencies. Moreover, there's 10's of GHz of spectrum that is virtually untapped today, lying $>$ 10 GHz, in both unlicensed bands

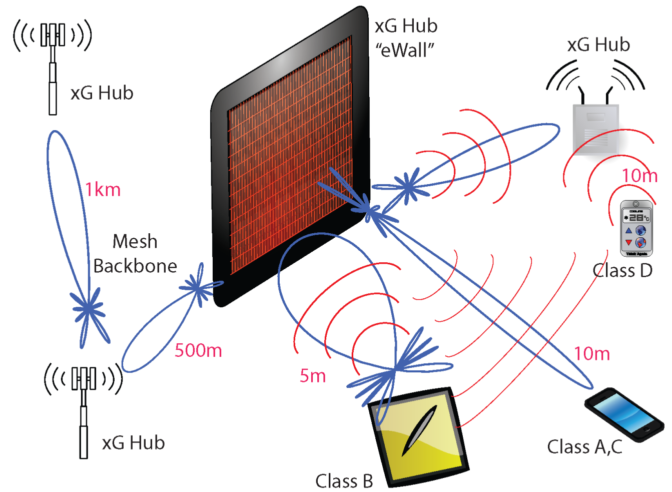

Fig. 2. The BWRC xG ($x \geq 5$) vision for the Next Generation Wireless Standard.

such as 60 GHz, and also licensed bands around 30 GHz, 70 GHz, 80 GHz, and 90 GHz. One of the most exciting aspects of 5G is that the community is embracing the possibility of using mm-wave bands to increase capacity, necessitating completely new ways of building RF transceivers and base stations.

C. The BWRC xG Vision

At the Berkeley Wireless Research Center (BWRC), our vision for the next generation (xG) wireless network is captured in Fig. 2. There are several important concepts highlighted in this figure. First and foremost we have a large aperture Access Point or xG Hub, comprising hundreds to possibly thousands of antennas and radios, serving indoor connections to a plethora of devices using highly direction beams. Beamforming allows spectrum re-use as interference is avoided through spatial selectivity. Note that this hub is beam forming with various devices simultaneously, a concept sometimes referred to as multi-user MIMO (MU-MIMO), but as we shall see, the beam forming can be realized with arrays of sub-arrays of beam formers or by time multiplexing the beams.

Another important concept to highlight from the figure is that the xG Hub need not have a wired connection to the backbone. Due to the large aperture, it can form extremely narrow and directive beams, capable of communication over a large distance (100's of meters to kilometers). The xG hub can be connected to another xG hub in a mesh network, obviating the need for a wired back-haul completely.

In today's wireless systems, different radio standards would address these various devices, including LTE, WiFi, Bluetooth, BluetoothLE, ZigBee, as well as custom radios. We believe that these various devices should have a common radio interface that can encompass devices over the entire range of data rates, communication distance, bandwidth, transmit power, sensitivity, and energy requirements. One would not expect a small energy starved device such as a sensor to communicate as fast as a tablet, but nevertheless there should be a common lower speed radio interface that allows device to device communication. One can envision a fall back mode that is available to all radios, or the xG hub can act as a universal translator to allow indirect device to device communication.

The xG vision and 5G vision overlap in many ways, particularly in the air interface incorporating massive MIMO below 10 GHz and mm-wave beamforming above 10 GHz.

II. mm-Wave Signal Propagation

Today most mm-wave links are point-to-point, and there is considerable interest in building short-range wireless networks for video and high speed local area networks in the 60 GHz band. Several standards exists for wireless HD video transmission (Wireless HD) and data / docking (WiGig, 802.11ad) with data rates approaching 10 Gpbs.

A common conception is that signal propagation at mm-wave carrier is worse than at lower frequencies. From Friis equation, one would conclude that the propagation loss is $100\times$ worse at 60 GHz compared to say 6 GHz. But conservation of energy tells us that in absence of absorbing media, the energy density of an isotropically transmitted waveform is the same at a given distance from the source no matter what the frequency. The reason for this error is that in interpreting Friis equation, we inherently assumed that the gain of the antennas at 6 GHz and 60 GHz were comparable. But in fact for the same antenna aperture, the gain of a 60 GHz antenna is larger than 6 GHz antenna by exactly the same factor, which means the energy received for a fixed aperture is identical. So the correct way to look at the Friis equation is to say that the size of our antennas are constrained by the dimensions of mobile phones and other devices, which in turn determines the antenna gain.

What about absorption by the media such as air? It is well known that the 60 GHz band is the "Oxygen Absorption Band" and the media is not lossless. But to get a sense for this loss, take into account that even at 60 GHz, which lies at the peak absorption frequency, the loss is below 10 dB/km in normal conditions[1] These losses really add up for a very long range link, but for a link < 1 km, the extra losses can be easily absorbed into the link budget.

One big difference between a low GHz and a mm-wave antenna is that for a fixed aperture on the order of a few centimeters square, the mm-wave antenna is much larger than the wavelength squared, and so it has very high gain. The lower frequency antenna, though, is about the same order as the wavelength, and so it has lower gain. This large gain means the mm-wave antenna is also highly directive, both a desirable and undesirable property. Directivity means that the antenna has to be pointing in the right direction for it to work properly, an undesired property. At the same time, a directive antenna makes the system more robust against multipath propagation and interference, since the antenna can spatially filter out these unwanted signals. The directivity can be harnessed with a phased array, where the large aperture is made up of an array of antennas, electronically steerable by controlling the phase (and possibly the amplitude) of each element.

When signals bounce off of walls or windows, we find that the reflections are more specular at mm-wave frequencies. We also find that materials tend to absorb more energy so after a few reflections the mm-wave signal dies off faster. This means that the best way to communicate in the mm-wave bands is through a direct line of sight, or perhaps through a few reflections. In contrast, at lower frequencies the signal reflections are more diffuse and there are many paths from source to destination, leading to a complex time-varying channel which is best modeled in a statistical manner.

We see that mm-wave signal propagation for a fixed aperture has comparable propagation loss, but due to the directivity of the antennas, point-to-point links or communication with only a few reflections are preferred. Otherwise there is no inherent disadvantage to moving to a higher carrier frequency. In fact, quite the opposite is true, as moving to higher frequency avails us of more bandwidth for communication, more secure channels (due to the directivity), and also more degrees of freedom to share bandwidth through spatial diversity (in addition to time, frequency, and code).

A. mm-Wave Link Budget

TABLE I
LINK BUDGET FOR A MM-WAVE DOWN-LINK (BASESTATION TO MOBILE) AND UP-LINK (MOBILE TO BASESTATION).

Link Budget Analysis	**Downlink**		**Uplink**	
Distance (km)	0.25	0.50	0.25	0.50
Transmiter power (dBm)	40	40	23	23
Transmit antenna gain (dBi)	25	25	12	12
Carrier frequency (GHz)	30	30	60	60
Free space prop. Loss (dB)	-110	-116	-116	-122
Other losses (shadowing, fading)	20	20	20	20
Receive antenna gain (dB)	12	12	35	35
Received power (dBm)	-53	-59	-66	-72
Bandwidth (GHz)	0.5	0.5	0.5	0.5
Thermal noise PSD (dBm/Hz)	-174	-174	-174	-174
Noise figure	7	7	5	5
Thermal noise (dBm)	-80	-80	-82	-82
SNR (dB)	27	21	16	10
Implementation loss	3	3	3	3
Shannon spectral eff.	8.0	6.0	4.4	2.6
Data rate (Gbps)	**4.0**	**3.0**	**2.2**	**1.3**

The link budget for a mm-wave system is shown in Table I[1]. Both the downlink (basestation to mobile) and uplink for a range of 0.25 - 0.5 km and a 500 MHz bandwidth signal on a 30/60 GHz carrier are considered. Achievable downlink datarates in excess of 4 Gbps are possible if we can realize sufficient antenna gain. The Tx power and gain of the basestation is fairly high at 40 dBm and 25 dBi, but as we shall see later, it is actually more efficient to realize the total required EIRP of 65 dBm using a larger array of low power transmitters. On the receiver the required power and gain is more modest (23 dBm, 12 dBi), since mobile devices are smaller in size, have smaller energy sources, and much more likely oriented in unfavorable

[1]Rain is an important loss mechanism that needs to be taken into account in the mm-wave link budget, adding an addition 10-30 dB of loss depending on the range and frequency.

directions of transmission, such as end-fire. Based on todays CMOS technology, appropriate for the handset, 39 dBm EIRP has been demonstrated using phased arrays [3] in the 60 GHz band, and it is not unreasonable to assume that we can reach these targets. In a like manner, advances in GaN technology enable high voltage and high frequency operation, and the EIRP numbers for the basestation are also quite reasonable.

III. CMOS Technology Trends

In the past decade, technology scaling from 90nm to 28nm has continued to produce faster transistors, as seen by the increase in device f_T (Fig. 3), whereas the maximum frequency of oscillation (or equivalently activity) f_{max} has not kept pace, and seems to be saturating at 250 GHz. This plot is for a real device rather than an intrinsic device, and as such it contains metal parasitics required to access a device, so the results are more realistic than some previously published results.

This trend is bad news for mm-wave electronics since it does set an upper frequency limit that one can realize useful building blocks such as amplifiers and oscillators. The RF gain is approximately f_{max}/f, which means that one can build reasonable amplifiers up to about 100 GHz. So is technology scaling helpful at all? Traditional scaling causes $g_m r_o$ (instrinsic gain) to decrease, however processing innovations have allowed an increase in $g_m r_o$ in recent technologies, such as the use of high-k gate dielectric for improved the control of the channel causing (28nm bulk), and further 3D device structure innovations such as FinFET technology provides even better channel control [4]. Another direct benefit of scaling is the ability to realize gain at lower current drive. In other words, one can back-off from the peak f_T/f_{max} points and save a considerable amount of power, as born out in mm-wave amplifiers designed in various technology nodes.

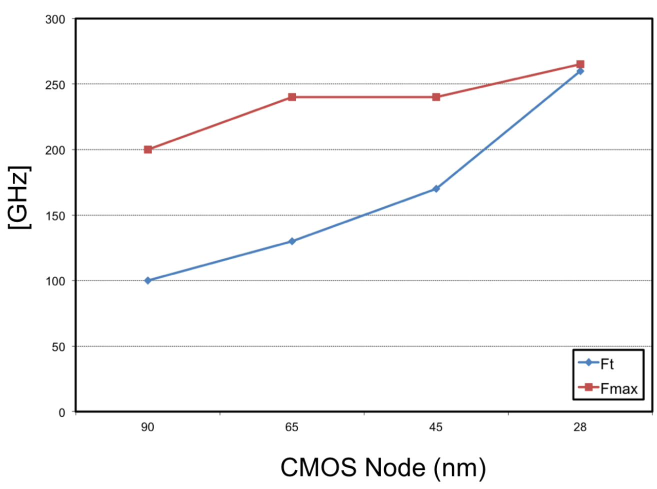

Fig. 3. CMOS technology scaling trends for f_T and f_{max}.

Plots of Unilateral Gain (U) versus gate bias voltage are shown in Fig. 4. As evident from the figure, a single device can deliver between 7-12 dB of gain from 60 - 100 GHz at the peak overdrive voltage of 0.7V. However, high gain is

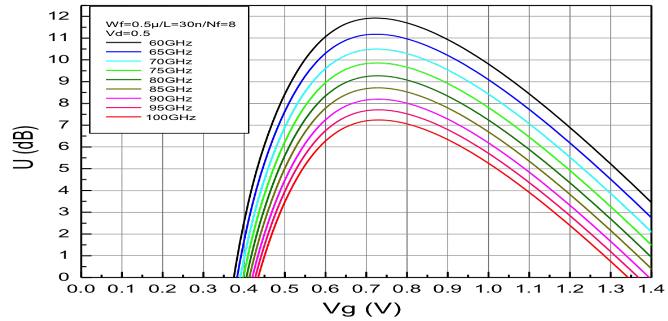

Fig. 4. The simulated maximum unilateral gain (U) in 28nm bulk CMOS.

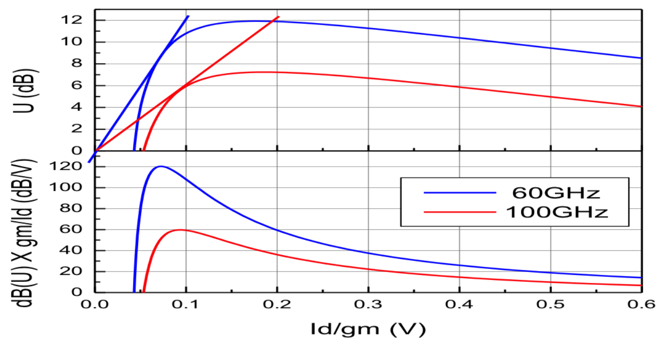

Fig. 5. A power aware power gain figure of merit for CMOS.

achievable with relatively high power gate bias, or high power consumption. In other words, the peak gain point is a very low point in the g_m/I curve, indicating poor transconductance efficiency. A newly proposed power aware gain metric takes the product of U and the transconductance efficiency g_m/I, in order to find the optimal trade-off between gain and power consumption (Fig. 5). Operation at the peak point of this metric (550mV) results in more power efficiencient designs albeit at lower gain. In practice, operating with more cascade stages at lower overdrive voltage therefore results in overall lower power and comparable gain.

The minimum achievable noise figure of a MOSFET device can be shown to be related to the device f_T, not the f_{max}, so that the sensitivity of receivers continues to improve, as shown in Fig. 6. In this calculation, we take the absolute lower limit of F_{min} by assuming that only channel resistance contributes to gate induced noise and the gates are either made of metals or are realized with many short fingers to render this term negligible. In practice, a receiver may have 2-3 dB higher noise than the F_{min} of the technology, which means even at 100 GHz, sub 5 dB noise figure receivers are possible.

Another noise related metric is the phase noise of mm-wave oscillators. A plot of the most widely used VCO FOM from published literature is presented in Fig. 7. As evident from the graph, mm-wave VCO's operating above 10 GHz suffer about 5 dB lower FOM compared to their lower frequency counterparts, both the peak FOM and the average. For most modulation schemes of interest, including OFDM, system simulations show that the transmitter EVM and receiver sensitivity is not significantly impacted by the VCO phase noise if levels of -85 to -90 dBc/Hz at 1 MHz offset, which is clearly achievable with reasonable power consumption. In practice the frequency of the LO may be considerably higher than the VCO frequency if multipliers are used, which can alleviate concerns with phase noise, and more importantly tuning range (which is not covered in the plotted FOM). Due to lower varactor quality factor in the mm-wave bands, tuning range is often a primary concern.

Another area of concern is that with technology scaling, $1/f$ noise is considerably higher for minimum channel length devices, typically required by mm-wave oscillators, which results in high sideband phase noise. Using a physically larger device helps, at the cost of power consumption, and various techniques to suppress flicker noise in oscillators has been investigated [5]. More importantly, due to the application of wideband modulation (approaching 500 MHz or 1 GHz), flicker noise is less of a concern for such mm-wave systems.

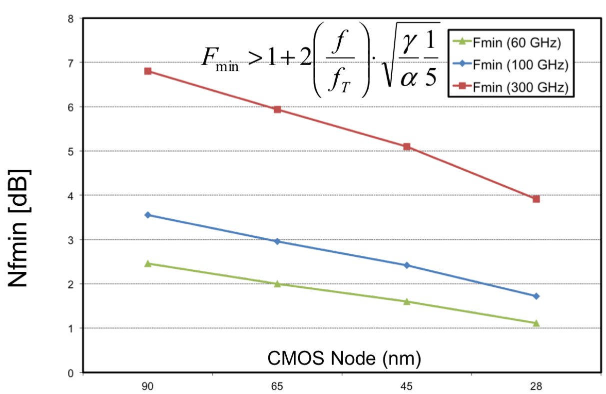

Fig. 6. CMOS technology scaling trends for theoretically minimum achievable noise figure.

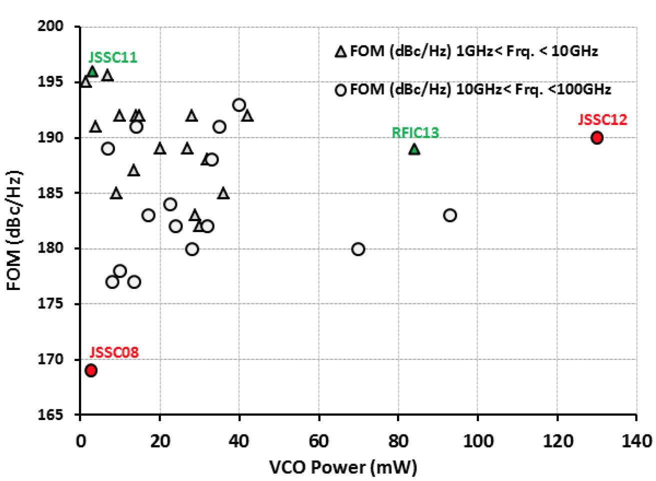

Fig. 7. VCO FOM for recent publications below and above 10 GHz.

ADC effective number of bits (ENOB) and power consumption are two other issues that limit the maximum bandwidth that we can process with a receiver. In mm-wave solutions we prefer to use as large of a bandwidth as possible to maximize data rates, but as shown in Fig. 8, the maximum ENOB drops at higher sampling rates, partially set by the aperture jitter of the sampling clock. To realize 8-10 bits of ENOB limits using a reasonable clock source of say 0.5 ps of jitter dictates limiting the BW to about 2 GHz. Power consumption is the other major hurdle (Fig. 9), and for high speed converters it's increasingly difficult to maintain a low energy per bit FOM. Taking a relatively conservative value of 100fJ/conv leads to 50mW of power consumption for the ADC. Even though better FOMs have appeared in the literature, once we include clock power, reference buffers, and buffers driving the ADC, the FOM degrades.

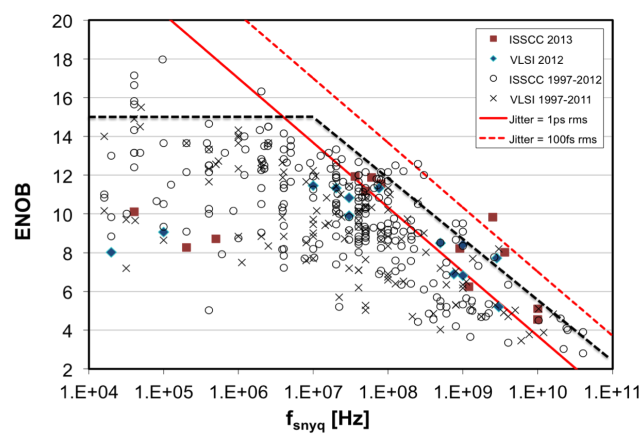

Fig. 8. Published ADCs ENOB from literature as a function of sampling frequency [6].

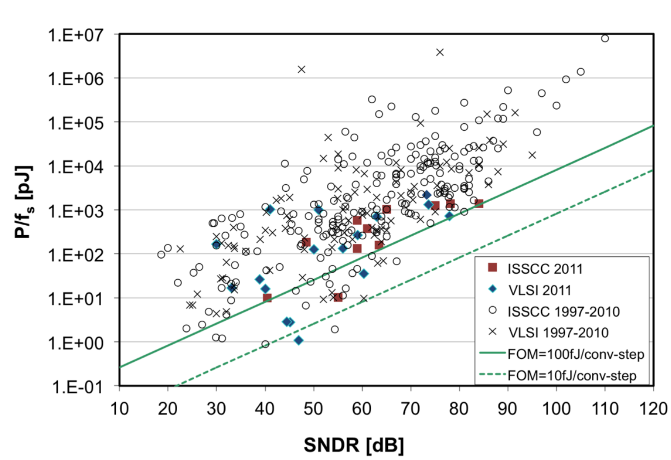

Fig. 9. Energy per conversion figure of merit versus SNR [6].

As we have seen, CMOS technology can operate up to 100 GHz with reasonable sensitivity and analog DACs and ADCs can easily digitize several gigahertz of bandwidth. But one area that CMOS has always struggled with is transmit power, and mm-waves power is even harder due to the requirement to scale the device size to limit parasitics and the dropping supply voltage of deeply scaled CMOS. These trends are evident in Fig. 10, showing that mm-wave output power capability and raw power drops. In our research, several power combining techniques have been used to boost the output power for a Class A PA to around 17 dBm for a single PA [7]. But the issue with these power amplifiers is the efficiency drop with power back-off. When high PAR signals such as OFDM are required, one must back-off 6-dB or more from the carrier, reducing the efficiency from a peak value of 19% down to 2%. Fortunately, a large array does not require high power amplifiers, as spatial combining is used to realize the EIRP. This relaxes the requirements on CMOS, but nevertheless the poor efficiency, especially for high PAR signals, is of concern for handsets that have a more limited aperture.

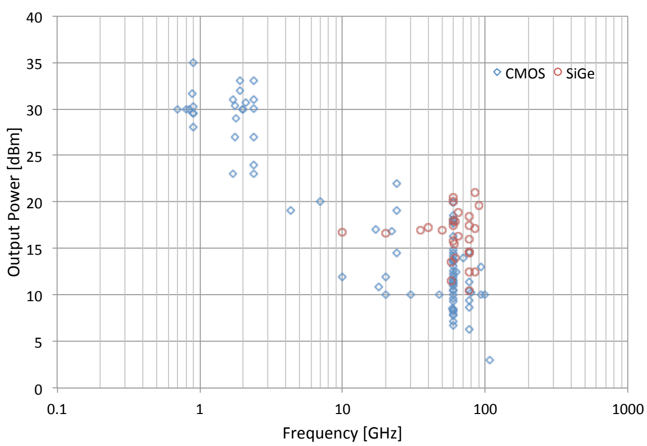

Fig. 10. Published CMOS and SiGe PA output power versus frequency [8].

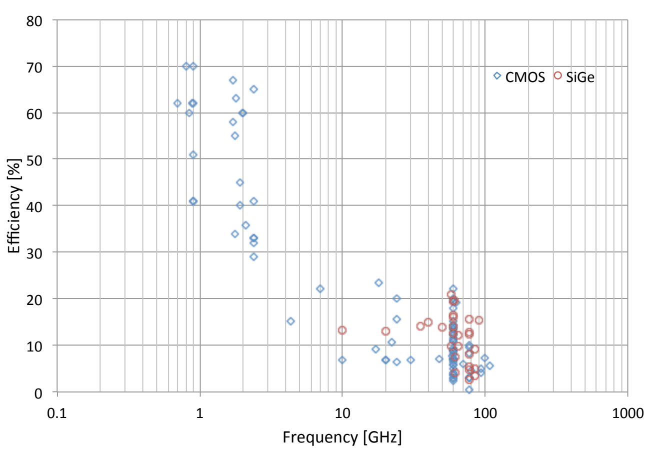

Fig. 11. Published CMOS and SiGe PA efficiency versus frequency [8].

IV. Antennas, Packaging, and Testing

At RF frequencies it's easy to separate the antenna design from the transceiver, although package parasitics must be carefully accounted for. In mm-wave systems, this remains the case, but since the performance of the transceiver is a strong function of the number of antennas in the array, a "free" parameter, one cannot design a transceiver in isolation from the antenna system specifications. More antennas N_t for example, boosts the EIRP by N_t^2 (due to coherent combining), and receiver noise figure can be relaxed by the number of receive antennas.

As in RF frequencies, in mm-wave transceivers packaging parasitics must be taken into account at the design stage for key blocks such as the LNAs and PAs, often requiring flip-chip micro bumps to minimize package inductance and capacitance. Transmission line loss increases with frequency, and PCB materials such as FR4 may be prohibitively lossy, favoring LTCC, HTCC, or Rogers to realize a module with integrated antennas.

V. System Level Considerations

One of the most interesting aspects of 5G is the utilization of a large number of antennas and the move to mm-waves for new spectrum. One important distinction is between a MIMO receiver, where each antenna element has a independent ADC, versus an RF phase shifter shown in Fig. 12. Clearly the MIMO digital architecture has a larger hardware footprint, but it allows us to trade-off spatial diversity of the channel in various ways, including for higher capacity through multiple streams, through beam forming for higher directivity, or through multi-user beam forming (MU-MIMO) to increase capacity, essentially transmitting independent data streams to multiple users. An RF phase shifter, in contrast, can create an arbitrary antenna pattern (if we allow the gain and phase of each element to be controlled) for a single stream, and multiple streams requires duplicating the hardware similar to a digital MIMO.

An appealing architecture for mm-wave bands is a hybrid digital / analog approach where arrays of antennas are controlled using RF phase shifting, and arrays of antennas are used to build independent data streams for MU-MIMO and other scenarios, shown in Fib. 14. These streams can even point in the same direction if polarization diversity is exploited for additional isolation, doubling the data rate. While reflections tend to mix the polarization, mm-wave signals that propagation via LOS or with a limited number of reflections maintain enough polarization diversity.

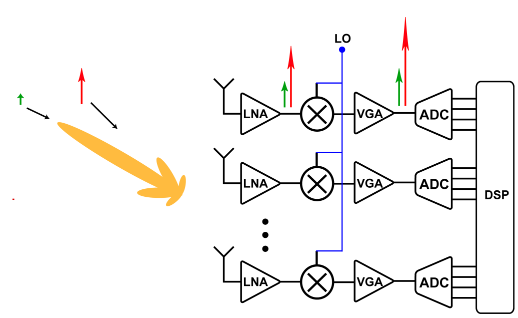

Fig. 12. A fully digital MIMO system.

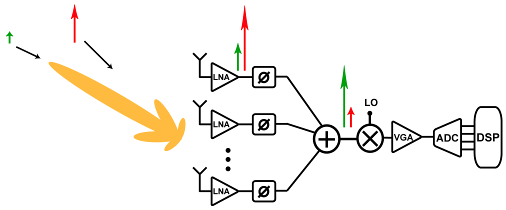

Fig. 13. An RF phase shifting array.

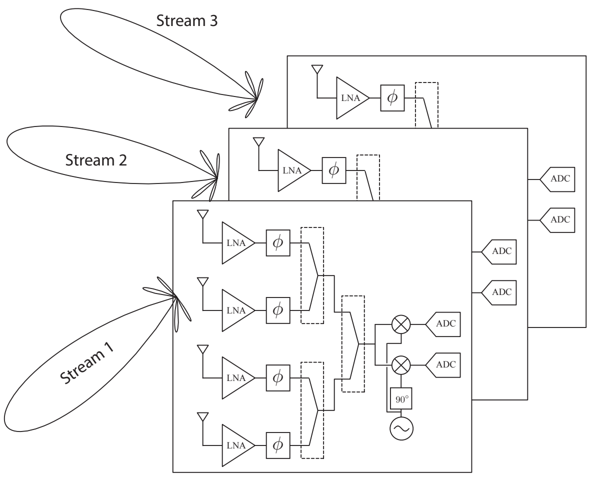

Fig. 14. A hybrid analog/digital array.

A. Interference Mitigation and Spatial Diversity

Arrays of radios are used to minimize interference through transmit and receive beam forming, essentially filtering the signal in the angular domain. The detrimental impact of multi-path propagation is also minimized since multi-path components at most angles of arrival will be filtered by the receiver beam pattern. Moreover, when a receiver link margin is not noise limited but interference limited, some gain can be traded off and a beam null can be intentionally inserted into the pattern in the direction of an interferer (Fig. 15), in theory completely eliminated a narrow undesired beam. In practice, beam nulling requires very high precision in the beam coefficients, and any amplitude error (σ_ϵ) or phase mismatches (σ_δ), arising from quantization noise, phase noise, and other non-idealities, limits the amount of nulling to $10\log(\sigma_\epsilon^2+\sigma_\delta^2)$, which is independent of the number of elements in the array [9].

VI. mm-Wave Design Examples

Given the wider bandwidths of mm-wave communication, and the need to operate in both licensed and unlicensed bands, design techniques require special considerations. Tuned amplifier stages in cascade in many cases may not have sufficient bandwidth to cover even one band, e.g. the unlicensed 60 GHz band is 7 GHz wide.

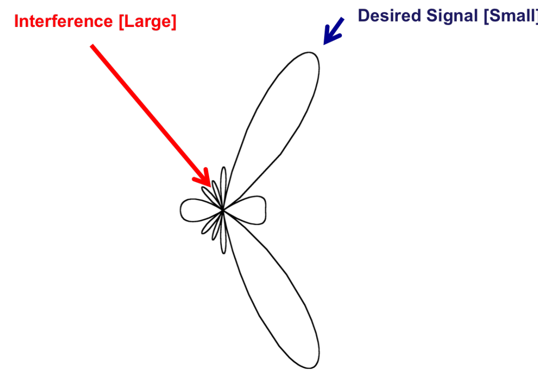

Fig. 15. A receiver that is perform beam forming and nulling to maximize SNDR.

A. Low Coupling Transformer for BW Extension

To extend the bandwidth, loosely coupled (low k) transformers are proposed for amplifier designs. Fig. 16 shows the simplified two port second-order network of a transformer matching network loaded with capacitors on the primary and secondary sides. The physical layout of a single-turn transformer with low k is also shown. The impedance transformation is from 125Ω to 250Ω, and by reducing the coupling k of the transformer from $k = 0.8$ to 0.2, the transformer network doubles the 1dB bandwidth as shown in Fig. 16. Analogous capacitive coupling techniques have also proved useful in this regard [10].

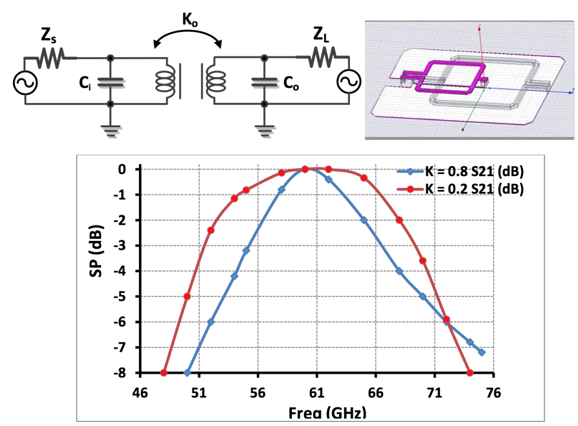

Fig. 16. Transformers with low coupling factor can be double tuned for broadband response.

B. Differential Pair Gate-Drain Neutralization

The gate-drain parasitic capacitances of NMOS transistors lowers the frequency of the operation, and C_{gd} neutralization is used for unilateralization and achieving higher frequency of operation. Fig. 17 shows the schematic of NMOS gate-drain capacitance neutralization for unilateralization. C_{gdn1} and C_{gdn2} are realized with metal parasitic capacitance without adding extra capacitors as shown in Fig. 17. It can be shown that this technique can improve the gain to $2U-1$ under optimal neutralization conditions [11].

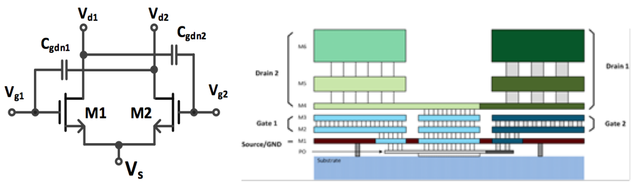

Fig. 17. Gate-drain neutralization can be achieved with the inherent layout parasitics by exploiting a multi-finger differential pair layout and metal overlap.

C. PA Design Examples

Fig. 18 shows complete circuit diagram of the 60GHz power amplifier which consists of three stages in cascade using low coupling coefficient transformer-based matching networks. A transmission line base power combiner sums the power from the preceding interstage and output stage PA units to generate higher output power. Both PA units utilize drain-source neutralized cascode stages to achieve better stability and allow high output voltage swings [12]. The PA was fabricated in 28 nm bulk CMOS process with total area of 0.64 mm^2 and the core area of PA of 0.122 mm^2. The measured performance of the PA is shown in Fig. 19. The PA achieves 24.4dB peak gain with 3 dB BW of 11 GHz from 56 GHz to 67 GHz. The PA achieves P_{sat} of 16.5 dBm with PAE of 12.6 % and P_{-1dB} of 11.7dBm at 62 GHz.

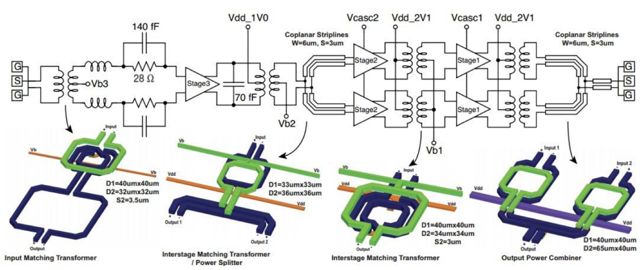

Fig. 18. A three-stage power amplifier design based on low-k coupling matching.

VII. Conclusion

The 5G wireless networks will be revolutionary in utilizing arrays of antennas and new high frequency bands up to 100 GHz, and perhaps beyond. This dictates a completely new perspective on designing RF transceivers for both the handset and the basestation. By exploring the increase in EIRP and spectral diversity offered by large arrays, the performance of the system can be optimized to allow more users and therefore higher capacity. In this paper we have shown that CMOS technology is capable of meeting the challenges posed by 5G requirements, although key areas such as transmitter efficiency for high PAR signals and large array design challenges remain as challenging problems to be solved.

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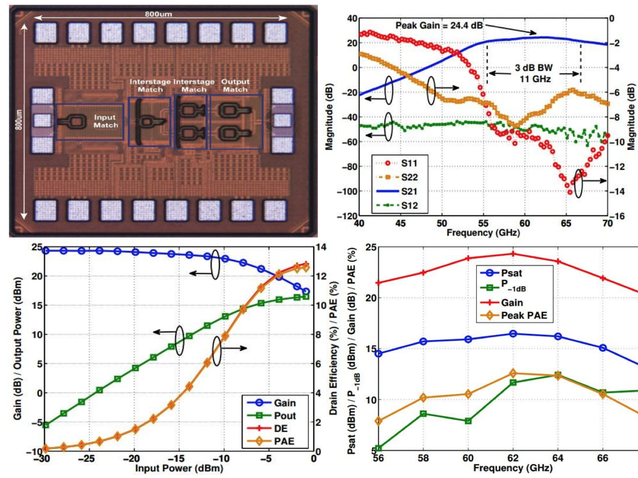

Fig. 19. Measured performance of the three-stage PA in 28nm CMOS.

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