5G base station architecture: The potential semiconductor solutions

Steve Taranovich - July 17, 2015

For many, 5G is too far away to think about right now; to others 5G is too complex or too aggressive in its goals. Be sure, my friends, that 5G will be upon us like a pouncing tiger, sooner than you think.

I have spoken to many of the key semiconductor companies that I felt had the best potential to create 5G solutions based upon their present architectures and future evolution and advancements in their technology, processes and architectures. I present the following as a discussion as well as an informative view of what may be to come on the road to 5G development. Of course, these companies want to keep their roadmaps close to the vest, but there are some good insights in what they expressed to me below.

I will start with discrete semiconductor solutions, then I will discuss my predictions for architectures, interfaces, and processes and finally provide feedback from the semiconductor leaders in this industry with IC solution possibilities and challenges, working my way up to more complex IC solutions, and finishing with clocking.

Efficient Power Conversion

I discussed 5G with Alex Lidow, CEO and co-founder of Efficient Power Conversion, who said:

As the consumer demands more data wirelessly, the industry needs to move for a 4G to a 5G transmission technology. Unfortunately, as we go to higher data transmission rates there is an exponential and unacceptable decrease in the efficiency of the transmitter. This decrease can be fixed using a technology called envelope tracking, which has already been adopted in newer 4G/LTE base stations as well as cellular phones. Envelope tracking in base stations requires the high speed, high power, and high voltages that are only available using GaN technology. Today this is one of the largest markets for GaN transistors, and will hold that position for the next several years.

I fully expect that eGaN technology will be one of the most important solutions to power efficiency in base station infrastructure for 5G; the peak-to-average ratios will be worse in 5G. Envelope tracking is obvious right now as one way eGaN power transistors will do this, but over the next 3 to 5 years more applications will emerge as eGaN technology progresses.
Lidow says:

Electrons can move more efficiently in GaN and that, along with the small structure size, helps with the speed of the devices (electrons don’t have to travel as far as in they do Silicon devices).

Right now in 4G cell phones the 2.61 GHz frequencies are well handled in CMOS. For 5G and beyond, we expect frequencies above 3.8 GHz and as high as 13 GHz. These frequencies will require alternate materials for the Power Amplifier (PA) in the base stations as well as in the cell phones.

GaN Systems

GaN Systems has a really neat Island Technology. Their island structure is the core GaN Systems IP. It has the dual advantage of a reduction in the size and cost of gallium nitride devices, while transferring substantial current from the on-chip metal to a separate carrier. GaN Systems’ goal is the easy adoption of gallium nitride by designers and systems engineers and I think it will be important for more efficient 5G thermal solutions. See the video below (Courtesy of GaN Systems).
Data Centers: Constantly looking to fit more power in the same rack with the same cooling --> higher density, higher efficiency

Data Centers and Base Stations: Total Cost of ownership --> reduced electricity costs --> higher efficiency at all loads

Base Stations: Cramming more capacity/more channels in a fixed power infrastructure --> higher efficiency, higher density, and envelope tracking

5G goals:

- 1,000 X in mobile data volume per geographical area reaching a target = 10 Tb/s/km²
- 1,000 X in number of connected devices reaching a density = 1M terminals/km²
- 100 X in user data rate reaching a peak terminal data rate = 10Gb/s
- 1/10 X in energy consumption compared to 2010
- 1/5 X in end-to-end latency reaching 5 ms for e.g. tactile Internet and radio link latency reaching a target = 1 ms for e.g. Vehicle to Vehicle communication
- 1/5 X in network management OPEX
- 1/1,000 X in service deployment time reaching a complete deployment in = 90 minutes

It is hard (I would say impossible) to imagine that these goals can be met without an absolute revolutionary change to power management. Wide bandgap, and in particular GaN-on-Silicon (because we’re talking about voltages between 12V to off-line voltages) is being looked at by most of the major segment leaders as a way to realize immense power management improvements.

Let’s look at each one:

1) 1,000 X in mobile data volume per geographical area reaching a target = 10 Tb/s/km²

- More data = More data centers = More servers = more power » driving need for efficiency and power savings even higher
- More data = millions of "pico stations" deployed in stadiums, malls, streets, and homes. Each one will be low power but will require offline efficiency, 100% uptime in many cases

2) 1,000 X in number of connected devices reaching a density = 1M terminals/km²

- Imagine 1 million devices in a square kilometer. Imagine (as 5G projects) sensors ever few meters of every road in every country as well as every consumer product in existence being connected to the internet. There’s a huge need for very small, very efficient power conversion to allow sensors to have many years battery life and to be ultra-small, where GaN allows very high frequency switching (we’ve had one of our customers test our devices to 70MHz)

3) 100 X in user data rate reaching a peak terminal data rate = 10Gb/s

- Power amplifiers are going to have to process higher data » more power » more channels, so extreme efficiency including Envelope tracking will be required.
4) 1/10 X in energy consumption compared to 2010

- This one says it all. How can everything else go UP by 100's or 1000's and power consumption go down 90% without every aspect of deployment focusing on how and where power can be reduced? Most reports show that this goal is near impossible and will require immense efforts. I can't imagine that GaN (and GaN Systems) won't be a big part of this.

5-7 have effects on power that are less extreme.

**What's GaN Systems doing?**

1) We make the easiest to drive, highest Figure of Merit \((R_{dson} * Q_g)\) power transistors in history. 13X better than the best silicon.
   a) FOM is important to make the systems the smallest, lightest, most efficient, lowest cost
   b) easiest to drive is important to make the engineer's job quick and simple – same thing they've always done
2) We make 100V (for 48V systems) and 650V (for off-line systems)
3) We make high current devices (unique to GaN market) to allow increased efficiency in large data center infrastructure equipment such as UPS's in the 100's of kW
4) We have a roadmap down to 40V to allow extremely high frequencies and cost structure in the DC/DC arena, which will be a big part of the overall deployment. **5G evolution in semiconductors**

**Architecture**

One of the first promising areas in evolving 5G architecture would be the move towards a fully digital radio (Or at least as close as we can get to fully digital). In this type of design a GaN Voltage mode Class S Power Amplifier (VMCS-PA) has also been implemented to enhance overall power efficiency.

![Figure 2:](image)

Enhanced digital processing by the use of CMOS shrinking geometries can also greatly improve performance in RF sampling ADCs.

Next up would be the possible extrapolations of the single-bit sigma delta architecture towards 5G speeds with lower power dissipation. It has been shown that a single-bit digital transmitter, having the RF digital stream in conjunction with the wireless signal, can be amplified and filtered and subsequently generated and sent out of the PA onto the transmitting antenna. Using a switching PA will greatly enhance the efficiency even further (See above regarding a GaN Voltage mode Class S...
Continuous-time delta-sigma (CTDS) ADCs used in handsets in the past might find their way into cellular infrastructure systems in the future.

Advances in analog to digital converter interleaving may also be a possible help with the ability to increase sample rates.

Interface

One of the relatively new high speed interfaces for high speed data converters is the JESD204B. With data converters now operating in the Giga-sample-per-second (Gsps) speeds, an evolution of the JESD204B standard or some other new standard and/or interface architecture will have to be adopted.

Process

CMOS can be a promising process with an evolution towards lower power dissipation and higher speeds in data converters.

GaN transistors for RF might get an assist with GaN-on-diamond technology.

What the industry leaders think

Analog Devices

Thomas Cameron, CTO, Communications Infrastructure at Analog Devices, gave me his input regarding the coming of 5G. He stated that right now LTE-A is a prelude to 5G and will evolve toward 5G. There will be higher frequencies ranging from 6 GHz to 100 GHz emerging to support the bandwidth needed for 5G. In 2019 the ITU will ratify frequency bands at higher frequencies. The 3.8GHz to 4.2 GHz bands should re-allocate this year as at WRC-15 providing much needed spectrum for pre-5G deployments.

There will be a massive number of antennas with beam-steering and Massive MIMO in 5G. There will be need for RF and Analog to operate at higher frequency and bandwidth in conjunction with these antenna arrays.

I strongly believe that Analog Device’s role in 5G is greatly strengthened by their strategic acquisition of Hittite Microwave in 2014.
Figure 3: Analog Devices broad portfolio includes the Hittite acquisition for RF as well as its high speed amplifiers and data converters, demodulators, and not-to-be-forgotten power supply solutions (Image courtesy of Analog Devices).

Cameron says that size, power, lower operating cost per bit, and improved spectral efficiency while maintaining energy efficiency will be the main focus of 5G radio development. We must drive integration which will help improve size and power.

Mobility has enabled all of this effort; the big driver being the mobile internet—apps are enabled and this will enable the use case. 5G will enable new applications in vertical markets. The best publicized application is IoT, requiring massive connectivity (millions of devices per sq km). Another emerging 5G application is high reliability, low latency communications for mission critical industrial control. While very different, both of these applications will be enabled by the capabilities of 5G technology.

We must start with channel models first to characterize the propagation channels at cm and mm wave frequencies. There is a large body of work being done in universities like NYU/Brooklyn Poly. So far results have been positive but beam-forming is required to overcome the propagation loss. Next to emerge will be new waveform proposals and system test beds in preparation of the standards discussions. The standards process will take some years to complete but the IMT2020 initial standard specifications are expected to be complete in 2020.

At cm and mm wave frequencies, beam-steering element antenna arrays with greater than 100 elements will be small. The big challenge will be developing the electronics behind it.

Algorithms and design techniques in 5G will advance development, as cell phone technology did to drive longer battery life and smaller size in handsets. In 5G we will need to be clever to enable very high frequency operation in a workable manner. We need to employ the integration techniques that we have developed for cellular base station radios to cm and mm wave radios.

Browsing through the IMS2015 technical program I am encouraged to see many papers directed at cm and mm wave advancements, from basic circuit techniques, process technologies, system
architectures, antenna design, and packaging technology, to name a few. All of these areas must move forward together to enable practical 5G beam-forming systems.

It took 10 years to go from one generation to the next in wireless architecture. The industry is few years into 5G research but we have a long way to go. I am personally excited about the role Analog Devices will play in enabling 5G with our future analog and RF technologies.

**Linear Technology**

I recently spoke to James Wong, Product Marketing Manager for Linear Technology High Frequency products, about 5G. Wong said that for carrier aggregation to work, radios need very wide bandwidths to cover 800 MHz, 2.4GHz, and 5.8 GHz, so radios can operate simultaneously on all bands.

Linear Technology has technology for mixers and radios at 450 MHz, 700 MHz, and 850 MHz, as well as 1.9 GHz and 3.6 GHz ranges. For one device to handle all frequencies is a challenge and few, if any, RF ICs can do this right now. The ones that say they can handle all frequencies in one IC need to re-tune each channel.

Linear Technology’s approach to build a simultaneous receiver without re-tuning is tough to do but they did it. Their LTC5577 down-converting mixer handles frequencies from 300 MHz to 6 GHz. In multiband 5G there is another big issue which is prevalent in LTE-A and higher frequency bands—that is, more potential interferers and blockers like those from police and fire broadcast radios.

Linear Technology’s mixers and modulators have the high dynamic range inputs which will be needed in 5G radios. They have 100 MHz to 1 GHz bandwidths right now and will improve in the future.

Wong says that a major challenge in 5G radios will be power consumption and thermal issues. Power Amplifiers (PAs) on the transmit side have efficiency boosts with Digital Pre-Distortion (DPD) techniques. Linear Technology has RF detectors at 100 MHz that can track 5G envelopes for PA efficiency improvement—this technique called Envelope Tracking coupled with DPD is a help in improving power efficiency in the PA.

PAs generate second and third order harmonics and can fail ACPR requirements. This is also improved by implementing DPD with high speed ADCs feeding back a portion of the PA’s output signal for further signal processing through an FFT which will capture harmonic content and then create a negative component of that FFT that sums back into the signal to pre-distort the transmitted output from the PA.

Linear Technology focuses on using less energy and improved thermals in their designs. Wong tells me that soon there will be a design of an integrated DPD receiver coming from his group.

Regarding Massive MIMO, there will be considerable deployment costs for carriers. For example a large antenna with 100 patches is costly due to physical size. They will pay for these large antennas as part of the cost of ownership. Instead Linear Technology will focus on achieving optimum power consumption vs. performance balance to help alleviate this cost dilemma.

Wong believes in MIMO but it must be done in an intelligent way. As many functions as possible need to be integrated, but intelligently—they must be functional and cost-effective. His team makes a
dual mixer right now for standard MIMO, the LTC5569. Octals and quads can be done for the future of 5G. Also they have written a white paper entitled “Making MIMO receivers smaller,” which addresses size and power consumption—this effort will carry forward to Massive MIMO, as well.

![Figure 4: Linear Technology’s Diversity Receiver with 190 MHz Bandpass IF matching is a good example of their high speed and RF portfolio capabilities. (Image courtesy of Linear Technology)](image)

5G will need bandwidths in excess of 1 GHz and this means ADC speeds must go up along with radio and RF bandwidth. The noise band will increase since noise will be wideband in 5G.

Semiconductor processes also need to be addressed for optimum solutions to be created. Linear Technology works with all the base station manufacturers and will be developing 5G solutions as we move forward toward deployment in 2020.

**Maxim Integrated**

Rajeev Krishnamoorthy, Executive Director at Maxim Integrated, told me that his company looks at more than just component solutions, but customer end-to-end system needs and where they can best enhance those systems with their solutions.

As 5G changes the architecture of a base station, the RF and baseband front-end split will be affected.
As a part of 5G he sees Cloud-empowered radio access networks (C-RAN), with the baseband and processing centrally located, and high speed fiber to the radio front ends. Maxim aims to make the front end modules more effective with their evolving high speed ADC and DACs that will be operating at several Gsps (Giga samples per second) for mobile broadband.

Efficient power and dynamic spectrum will need to be addressed, since these are two challenges to the industry for 5G implementation. The 5G evolution has started with Massive MIMO beginning at 64 to 128 antennas in beam-forming designs being tested now. Already, TD-LTE is using 8 antennas (8 transmit and 8 receive) for over half of its macro-base stations, and higher numbers of antennas are already being deployed in commercial systems.

The amount of data in the baseband is rapidly changing because:

1. The communication to the baseband radio is running at high capacity
2. Baseband to RF front-end digital data will have so many more lanes that will burn a great deal of power. The large number of proposed multiple antennas on the front end will highly contribute to great power increases as well.

Maxim wants to enable efficient front ends as the DPD moves from the baseband into the front-end.

The PA is a big contributor to poor power efficiency, especially as waveform complexity increases like in multicarrier modulation signals (MCM) with high peak-to-average power ratios (PAPR). Maxim’s linearization technology in order to increase the efficiencies of broadband power amplifiers can address this.

Power amplifier partners are working on 10 to 90 W designs which are about 50% efficient. 5W systems and going as low as 100 mW are Class AB and are 5 to 20% efficient. Recent efforts by power amplifier companies to increase the efficiencies of low-power (100 mW - 5W) power amplifiers
are now coming to fruition, although they all need linearization in order to achieve high efficiencies. This is needed in order to make the RF front-ends consume less power.

There will probably be a move to higher frequencies, but this comes at a price. The increased path loss at higher frequencies means less coverage. In order to compensate for this, signals will be more directional, so will also need more antennas because of that.

In Enterprise systems, the baseband designs will be powered by Power-over-Ethernet (PoE) and will need ultra-low power consumption here, as well.

Small cells will have to be frequency agile with wider bandwidths in 5G. Maxim has the ADCs and DACs running at multi-GSPS to meet these needs.

I had some concern with the size of the antenna with Massive MIMO, but Krishnamoorthy told me that 128 antenna systems are being deployed in 8x8 arrays without a huge footprint or size. As a matter of fact, TD-LTE in China has 8 transmit and 8 receive antennas in a 64x2 array. Beams are controlled electronically and can be focused where most effective—towards the ground. Antennas can even switch between highway lanes in the morning for rush hour traffic and then re-direct to the opposite direction for the evening rush.

Present antenna arrays can go from 10+ to 100 antennas in the size of 3 to 5 feet x 3 to 5 feet. On top of a tower it might be possible to have 16 or 32 antenna arrays as well. As for space on the top of a tower for this, telecom providers pay for space due to “wind loading.” There are also trade-offs, because at higher frequencies antennas are typically closer.

Note on the previous couple of paragraphs: There is still some concern about the size of the arrays, because 3x5 feet is not tiny! For macro base stations this is not a problem, but for small cells this could be pretty big. Another point to note is that with higher frequencies (above 6 GHz) antennas get smaller—the dimension of the antenna is directly proportional to the wavelength, and so decreases with increasing frequencies. Massive MIMO systems will be increasingly deployed with higher frequency systems in 5G, so this should also help the size issue.

Moving to Millimeter Wave we will need good accuracy and beam-forming. In a place like NYC there are a large number of users per relative location and lots of fiber can be put into NYC infrastructure.

Small cells will work well in those types of cities.

In Tokyo there are base stations every few hundred meters.

Maxim Integrated understands end-to-end systems.

**Microchip**

Trent Butcher, Product Manager for Analog and Interface at Microchip, spoke to me about the company’s ideas regarding 5G. Butcher knows that 5G will push the envelope in speed, bandwidth, and resolution that the industry does not yet have. There are 16 bit 200 Msps ADC solutions now at Microchip, and Butcher is very positive about digital processing in their ICs as their strength, with a fully digital IC process going forward to meet 5G needs.

Microchip’s Intelligent power management solutions are going to play a big role in 5G, as well.
Texas Instruments

TI’s Chuck Sanna discussed 5G with me. Sanna is the Product Line Manager (PLM) for Wireless Infrastructure. He commented that Heterogenous Networks (HetNet) would be important to 5G and discussed a bit about Massive MIMO aspects with regard to steerable antennas in a 128 port array at 2.6 GHz center frequency. A 128 element linear array like this could be 7.3 m long. Big, but doable.

TI has a pretty strong development advantage with its Kilby Labs research and development teams. There are three Kilby Labs locations right now: Dallas, TX; India, and Silicon Valley. Plans are underway to locate more labs around the world in other locations.

Sanna believes that 4G will be handling the communications in a hybrid combination model for high speed for the 5G system, just as 4G uses 3G as its voice communications channel today. TI certainly has a solid high speed converter portfolio for infrastructure today, and will be doing further development in future evolution. Of course, different and disruptive architectures will probably be needed, channel costs will need to be kept low, and optimum controls will need to be implemented in beam-steering antenna arrays.

Sanna said that every company will, of course, want to use their own existing product portfolios or some advanced version thereof. They will take their strengths and build on them to meet 5G needs. 4.5G and 5G will be pillars of TI’s business. 4.5G and 5G do not exist yet. 3G and 4G, along with aerospace, defense, medical, and test and measurement are the foundations of TI’s business. Of course the Test & Measurement guys will be leading the way at the beginning with their solutions and will probably be the first to innovate changes and adapt to 5G needs.

And on to even higher complexity and integration:

imec

I spoke to Wim Van Thilo, program director of perceptive systems at imec, regarding 5G.

Peraso Technologies, a fabless semiconductor, has a 60 GHz WiGig baseband IC, PRS4000 that InterDigital has selected for its backhaul system, in which Interdigital’s software provides self-configuration and data routing for the multi-hop mesh backhaul. This is the first WiGig-based mmWave mesh backhaul solution for small cells. This system includes imec’s 60 GHz PHARA4 radio and phased array antenna with fast electrical beam steering in azimuth and elevation. In the future imec may be able to add 28 and 32 GHz capability.

In the RF arena that might help for 5G development, imec has done some work as follows:

1. A re-configurable radio testbed was developed with Renesas for <6G frequency with cognitive radio and SDR, for WiFi, LTE-A and LTE, and ultimately a good framework for 5G. This research gave good experience for LTE and LTE-A, with so many different bands covered in one IC. Work was done in 45nm and 28nm, in which the inductors do not scale but power does...Power is a critical factor in 5G.
2. In mmWave power imec research includes 60 GHz communications work as well as 79 GHz radar.

Van Thilo said that Massive MIMO is still in early research right now in the industry, but their smaller cells for mmWave have some advantages for 5G:

1. Smaller and medium-sized backhaul systems cannot use fiber, so mmWave is ideal there.
2. In mmWave smaller cells will use backhaul at 28, 32 and 60 GHz—perfect for imec technology.

The main challenges, according to Van Thilo, will be cost and power consumption.

At the Mobile World Congress 2015, imec introduced a stand-alone multiband electrical-balance duplexer in 0.18µm SOI CMOS. This type of duplexer is a potential alternative to the fixed frequency surface-acoustic wave (SAW) filters implemented in mobile phones providing transmit-to-receive (TX-to-RX) isolation.

Regarding high speed ADCs, the latest from imec are two-fold in the wireless reconfigurable radio and millimeter wave arena:

1. Reconfigurable radios: imec has a front end, reconfigurable program in which they feature operation with WLAN, WPAN, broadcast, and positioning standards with frequency ranges from 174 MHz to 6 GHz. The SAR ADCs include an 11 bit, 400 Msps ADC in 28 nm with 2.1 mW of power dissipation and future 28/16 nm higher speed and lower power ADCs coming.

2. Millimeter Wave applications: The latest is an 8-times interleaved hybrid SAR/CABS ADC in 40 nm at 7 bit, 2 Gsps with less than 4 mW power dissipation. The thinking is that at mmWave frequencies the base stations will be much closer together, so 10 to 16 bit dynamic range may not be needed like those in 4G with interferers being less of a problem in 5G mmWave systems.

imec also has the technology in-house for fully integrated systems. This will be needed to make solutions smaller for 5G needs.

Clocking

Timing devices/clocking will have to advance as we approach 5G. Small cells and Heterogeneous Networks (HetNet) will need clocking at high speeds and minimal power consumption.

Clocking wideband ADCs using JESD204B in multiple ADC architectures is a nice technique that can be developed further.

Summary

This article shows some of the potential challenges and possibilities to meet and reach beyond the needs of the coming 5G system in telecom the next few years. As we progress towards 5G, our technology will surely improve as it has over the years because Germanium transistors were used in electronic design. It’s an exciting time to be in electronics and to be an engineer in this second decade of the 21st century.

References:

1. Efficiency optimization in linear-assisted switching power converters for envelope tracking in RF power amplifiers. ISCAS, 2005; V. Yousefzadeh, et. al.


This article is part two in a series on 5G. In Part 1 of this series, we discussed how 5G was evolving at the present time.

Also see:
- 5G base station architecture: Evolution
- The Evolution of the Protocol Stack from 3G to 4G and 5G
- Chasing 5G: Pizzacato, sigma delta and other architectures