I thought that now would be a good time to review, with you the EDN design audience readership, where we are at technically with the formation of 5G technology in light of the recent Brooklyn 5G Summit that took place on April 8-10, 2015 jointly organized by Nokia Networks and the NYU Wireless research Center at Polytechnic School of Engineering at New York University. (A few days after this Summit, Nokia agreed to buy Alcatel-Lucent which will strengthen their base station infrastructure as well as to get Nokia into the $13B router market where Alcatel-Lucent is strong. Reuters reported that: Carriers will judge suppliers for 5G technology by their ability to present a single product roadmap by late 2017. Surely the joining of these companies will help assure that Nokia become more cost-effective and their technology more advanced.)

The other recent big 5G meeting took place shortly thereafter on April 14-15 in Palo Alto, CA. This was called the 5G Forum USA launched by the LTE World Series and brought together senior executives and key decision makers from the 5G ecosystem to discuss the 5G future.

In this multi-part article, I will examine the view and challenges of the big players in this market from semiconductor suppliers, to Test & Measurement developers as well as university and telecom carriers. Part one will examine the 5G concept as it exists today as well as some early development ideas and hardware/software developments. We will also discuss the need for Test & Measurement to step up and get design tools ready quickly for developers to test their ideas and designs. Finally, we will discuss the first area in 5G that needs to be investigated: The channel.

In Part two we will reveal the challenges and development ideas of the semiconductor IC suppliers in our industry for 5G solutions.

What is 5G?

Next Generation Mobile Networks (NGMN) says:
5G is an end-to-end ecosystem to enable a fully mobile and connected society. It empowers value creation toward customers and partners, through existing and emerging use cases delivered with consistent experience and enabled by sustainable business models.

Tom Keathley, SVP, Wireless Network Architecture & Design for AT&T says that 5G is expected to appear as enhanced capabilities of LTE-Advanced (LTE-A). So 4.5G will emerge on the way to 5G as LTE-A evolves. Right now 4G is still being deployed, but early designs have started on its replacement: 5G.

**LTE-Advanced**

Essentially Qualcomm states that LTE Advanced is evolving to include carrier aggregation, enable hyper-dense Heterogeneous Networks (HetNet) with enhanced receivers. HetNets or Heterogeneous cellular networks (HCN) introduce small cells within the transmission range of a macrocell. For proper operation the high power macrocell will need to shut down its transmissions for a period of time to enable the smaller cells to transmit. This can be achieved by Time-Domain Resource Partitioning (TDRP)\(^2\). See Figure 1.

![Diagram of an HCN](Image)

**Figure 1:** An example of an HCN made up of a single macro base station and several pico and femto base stations. Each base station can, for example, stream videos to a subset of users\(^2\). (Image courtesy of Reference 2)
Extension of LTE into the unlicensed spectrum and moves LTE towards such things as device-to-device functionality, broadcast TV and higher bands.

**Carrier Aggregation**

LTE-A will promote wider bandwidths towards 100 MHz via carrier aggregation which means higher data rates (bps) to enhance the user experience. See Figure 2.

![Carrier Aggregation Diagram](image)

**Figure 2**: In applications such as web browsing, with its bursty nature, aggregated carriers will be able to support more users at the same response (user experience) as compared to two individual carriers. 5G will have higher peak data rates, enable higher user data rates and lower latencies and will leverage all spectrum assets. (Image courtesy of Qualcomm)

It will use more antennas with MIMO for higher spectral efficiency (bps/Hz). And it will employ HetNets with advanced interference management via small cell range expansion which leads to higher spectral efficiency per coverage area (bps/Hz/km²)

**More antennas with MIMO**

More antennas will be deployed to achieve large gain from receive diversity and MIMO. See Figure 3.
Figure 3: LTE-A R10 and beyond will require 8x8 Downlink MIMO, enhanced Multi-User MIMO (MU-MIMO) and uplink MIMO up to 4x4. (Image courtesy of Qualcomm)

**Backhaul**

The system will need to leverage fiber backhaul infrastructure and use Coordinated Multipoint (CoMP) to increase capacity and improve the user experience. The CoMP technique mitigates inter-cell interference (ICI) and enhances the performance of cell edge users. Groups of Remote Radio Equipment (RRE) are connected to the central Base Station (eNode B) via optical fiber. See Figure 4.

Figure 4: Radio network structure for fast inter-cell radio resource management using (RRE) deployment to achieve CoMP transmission and reception among different cell sites for LTE-A (Image courtesy of Reference 1)

First up: Test & Measurement
Test & Measurement (T&M) must be one of the first areas to align test tool solutions quickly so that 5G developers can accurately verify their prototype design performance both in hardware and in software.

**National Instruments: “Tools are enzymes”**

“Tools are enzymes” says Dr. James Truchard, President, CEO and co-Founder of National Instruments (NI) at the Brooklyn 5G Summit. We will need next generation tools for next-generation 5G research (See [NI 5G wireless portfolio](#)). Platforms drive innovation. Communications Systems Platform-Based Design is shown in Figure 5.

![Figure 5: A communications System Platform-based Design](Image)

NI takes the approach to Platform Design with LabVIEW®. See Figure 6.
Truchard said that there are four vectors in 5G: Massive MIMO, Ultra-Dense Networks, 5G Waveforms and mmWave. See Figure 7.

**Technologies Under Investigation**
The 4 Vectors of 5G

- **Massive MIMO**
  - Dramatically increased number of antenna elements on base station.

- **Ultra-Dense Networks**
  - Substantially reduced cell sizes to handle more users.

- **5G Waveforms**
  - Improve bandwidth utilization through signal structure improvements such as NOMA, GFDM, FBMC, & UFMC.

- **mmWave**
  - Utilize potential of extremely wide bandwidths at frequency ranges once thought impractical for commercial wireless.

Figure 7: 5G consists of four critical vectors. (Image courtesy of NI)
From the NSF Workshops on Future Wireless Communication Research we know that testbeds are a very important tool used in evaluation under realistic operating conditions. The testbed takes radical ideas and tests them in a complete, working system environment. Algorithms cannot be researched and created without running it in a realistic prototyping system. The Platform Enabled design flow goes from Algorithm Development to System Mapping to System Implementation with the algorithm ultimately running on a prototype. Unlike conventional separate teams at each juncture, a collaborative design team (Maybe even a single design team) works across all design flow steps with a single, cohesive toolchain.

NI’s LabVIEW® enables rapid prototyping. An example is a customer doing mmWave, also known as Extremely High Frequency (EHF), prototyping in one calendar year---this was less than half the time normally taken with other tools, stated Dr. Amitava Ghosh, Head of Broadband Wireless Innovation, Nokia Networks.

NI has configured a platform, PXI Express, to perform all the signal processing, synchronization, control functionality, and I/O needed by developers to implement wireless protocols to meet the multi Gbps needs for 5G infrastructure. See Figure 8.

<table>
<thead>
<tr>
<th>mmWave Cellular</th>
<th>Platform Capability</th>
<th>Implemented today</th>
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<tbody>
<tr>
<td>dōcomo</td>
<td>Up to 2 Antennas</td>
<td>Up to 2 Antennas</td>
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<tr>
<td></td>
<td>2 GHz BW</td>
<td>2 GHz BW</td>
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<tr>
<td></td>
<td>Up to 110 GHz Frequency</td>
<td>72 GHz Frequency</td>
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<tr>
<td></td>
<td>&gt;10 Gbps Throughput</td>
<td>10 Gbps Throughput</td>
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<table>
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<tr>
<th>Massive MIMO</th>
<th>Platform Capability</th>
<th>Implemented today</th>
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<tbody>
<tr>
<td></td>
<td>Up to 256 Antennas</td>
<td>100 Antennas</td>
</tr>
<tr>
<td></td>
<td>Up to 100 MHz BW</td>
<td>20 MHz BW</td>
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<tr>
<td></td>
<td>Up to 6GHz Frequency</td>
<td>Up to 6GHz Frequency</td>
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<tr>
<td></td>
<td>&gt;10 Gbps Aggregate Throughput</td>
<td>1 Gbps Aggregate Throughput</td>
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<table>
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<tr>
<th>Dense Networks/ New Waveforms</th>
<th>Platform Capability</th>
<th>Implemented today</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Up to 2 Antennas</td>
<td>2 Antennas</td>
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<tr>
<td></td>
<td>Up to 160 MHz BW</td>
<td>20 MHz BW</td>
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<td>Up to 6GHz Frequency</td>
<td>Up to 6GHz Frequency</td>
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<tr>
<td></td>
<td>&gt;1 Gbps Throughput</td>
<td>&gt;1 Gbps Throughput</td>
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</table>

**Figure 8:** NI is providing tools and technology for prototyping and helping to define this new 5G frontier for wireless communications (Image courtesy of NI)

NI’s acquisition of BEEcube in March 2015 will be a strong asset in 5G T&M. Their platforms give real time development with combined ADC and DAC modules and the latest Xilinx FPGAs. The simultaneous capture of analog output signals is presented directly to the designer via algorithm display tools like Matlab in real time. Their ADC reference design is capable of sampling at rates up to 5 GHz for direct RF sampling capability.
Finally, NI and NYU Polytech (Professor Ted Rappaport) are working together on 5G wireless development with channel sounding at 28, 38 and 72 GHz. The prototype system uses NI FlexRIO and NI LabVIEW.

NI and TU Dresden (Dr. Gerhard Fettweis) are working together on a 5G testbed, 5G PHY exploration and prototype using LabVIEW system design software. Dr. Fettweis also presented “Designing a Possible 5G PHY With GFDM” at Globecom 2014. Generalized Frequency Division Multiplexing is a digital multi-carrier transceiver concept. GFDM has lower Peak-to-Average Power Ratio (PAPR) as compared to Orthogonal Frequency Division Multiplexing (OFDM), an ultra-low out-of-band radiation due to adjustable TX filtering and is very effective in heavily fragmented spectrum areas. LabVIEW Communications has a 2x2 GFDM prototype which was demonstrated at CEBIT in March 2015.

NI and Lund are working towards building a massive MIMO prototype 100x100 antenna system with real-time processing. We describe the Lund University Massive MIMO testbed – LuMaMi as a flexible testbed where the base station operates with up to 100 coherent radio-frequency transceiver chains based on software radio technology. Orthogonal Frequency Division Multiplex (OFDM) based signaling is used for each of the 10 simultaneous users served in the 20 MHz bandwidth. Real time MIMO precoding and decoding is distributed across 50 Xilinx Kintex-7 FPGAs with PCI-Express interconnects. The unique features of this system are: (i) high throughput processing of 384 Gbps of real time baseband data in both the transmit and receive directions, (ii) low-latency architecture with channel estimate to precoder turnaround of less than 500 micro seconds, and (iii) a flexible extension up to 128 antennas. See Figures 9 and 10.
Figure 9: A hierarchical overview of the 100x100 antenna base station (Image courtesy of Reference 3)
Figure 10: On the left are the main blocks of a typical MIMO OFDM transceiver. On the right is a Base Station subsystem for partitioned baseband processing (Image courtesy of Reference 3)

Another key area that NI is developing is Digital Predistortion (DPD) in the very inefficient Power Amplifier (PA) in the base station transmitter. Their LabVIEW/AWR VSS Based system will simulate the RF amplifier with AWR and take measurements in one system. They have the freedom of placing the DPD algorithm in software of a real-time FPGA. This is a vital area of development that can significantly lower wasted energy in the PA.

**Keysight**

I interviewed Roger Nichols, Keysight 5G Program manager to get his perspective of test challenges that 5G designers will need and how Keysight will support them.

Nichols is the 5G Program Manager for Keysight Technologies. His 30 years of engineering and management experience in wireless test and measurement at Hewlett-Packard, Agilent Technologies, and Keysight spans roles in manufacturing, R&D, and marketing, and crosses the evolution from analog cellular radio through LTE and beyond. He spent seven years as the Marketing Director for Keysight’s (Agilent’s) Mobile Broadband Operation responsible for the wireless test-sets and systems that are used in all major design and certification labs as well as manufacturing facilities worldwide. Nichols holds a BSEE from the University of Colorado, Boulder.

Nichols told me that he will be giving an IMS Keynote address on 5G this May 19 in Phoenix entitled “5G Wireless: A Measurement and Metrology Perspective” in the MicroApps Pavilion.
Nichols said that for the first time Next-generation wireless is being much more viewed from a user perspective and more user technologies will come from that.

5G will involve significant changes to radio systems under 6GHz but will also add access technologies above 6 GHz both of which will drive significant infrastructure challenges. Fiber-optic and other backhaul need to be faster with lower latency as well.

From a Test & Measurement point of view a broad range of technologies will be covered. Most of Keysight’s product lines and software will have opportunities across the board in photonics, millimeter wave, and MIMO test; plus digital busses will need to be significantly faster.

Challenges for 5G will be:

1. Millimeter wave: This used to be primarily in the aerospace and military/defense arenas. Now this technology will go commercial in 5G so Keysight solutions will be there for these customers to test their system designs.
2. MIMO: As we approach higher order MIMO traditional approaches could increase costs in Test & Measurement equipment for commercial customers. Keysight is working on ways to streamline testing of these “massive MIMO” techniques for the commercial wireless industry.
3. Radio measurements: Test equipment connection to the Device Under Test (DUT) can be done with cables of transmission lines, but in millimeter wave, antennas are likely to be connected directly to the IC and measurements will be challenging. Even under 6 GHz the antenna connections could be eliminated a base station. How can we make calibrated measurements? Today’s methods are complex and expensive and Keysight is working on the challenge to simplify but retain confidence in the metrology.

Keysight works very closely with developers in the commercial and academic research space to evolve their Test & Measurement capabilities.

I asked Nichols if Keysight could somehow modify their existing solutions to bridge the gap to 5G test technology as designs develop. Nichols stated that almost all 5G work to date is research and tools like MATLAB are widely used by their customers (Keysight uses these as well). Given this, simulations will be the first line of verification of new design architectures and that will have to develop along with 5G progress first. But Keysight has gone a step further with the 5G Baseband Exploration Library in SystemVue. See Figure 11.
Figure 11: The W1906BEL 5G Baseband Exploration Library gives designers ready-to-use reference signal processing IPs for 5G technology research in C++ format (Image courtesy of Keysight)

This Library, **W1906BEL**, is used to explore baseband technologies for 5G. Couple this with Keysight hardware and this is a start to the road to 5G development that will surely evolve as we proceed forward.

There will be ambitious claims in components that Test & Measurement will have to prove.

One challenging area will be at 60 GHz using Wideband Modulation. Keysight has created a flexible solution for WiGig Testing. Wireless Gigabit (WiGig) is expected to enable wireless connectivity of up to 7 Gb/s in data, display and audio applications. IEEE 802.11ad is the industry standard for this development.

Nichols’ favorite quote is from a China Mobile paper which stated that with current architectures 1.1 Million base stations consumed 67% of the network’s 14 Billion KWH power consumption in 2012. Power consumption is dominated by RF power-amplifiers and the air conditioning that is needed to keep the temperatures reasonable for operating purposes and reliability. By late 2014 they had built an additional 720,000 4G base stations which no doubt puts a further strain on the power budget.

There is continuous work to make RF PAs more energy-efficient with signal processing techniques. Would a more digital-oriented process make for better efficiency? That remains to be seen but research and design groups around the world are hot on this trail.

**First challenge to tackle: Channel Modeling**

**First challenge to tackle: Channel Modeling**
At the Brooklyn 5G Summit Dr. Timothy Thomas and Dr. Amitabha Ghosh from Nokia presented their views of critical modeling aspects and their effect on system design and performance.

LTE-A is an essential foundation of the integrated 5G system below 6 GHz and must evolve in parallel to 5G. The frequencies from 6 GHz to 100 GHz is expected to be within the scope of World Radio Conference 2019 (WRC2019). 5G will enable above 6 GHz access and optimize below 6 GHz access. See Figure 12.

Figure 12: 5G will expand spectrum assets and must deliver capacity and experience to users. There are challenges here that must be resolved over the coming years. There is plenty of spectrum to exploit below 100 GHz, so we do not need to go beyond that limit since technology will be easier here plus measurements are available in this region according to Nokia. (Image courtesy of Nokia)

6 to 100 GHz makes sense because channel models exist below 6 GHz but the question remains whether those models will be consistent with channel models from 6-100 GHz. We need to see if it is reasonable to make a comparison between three simulated systems: one at 2.6 GHz, one at 10 GHz, and one at 72 GHz.

The 6-100 GHz channels will need to cover a wide variety of outdoor environments. There is the Urban Micro mix of street canyons, open squares, cell radii is mostly less than 100m and access
points are below rooftops. Then there is also Urban Macro with access points on rooftops with cell radii >200m and 5G will need to overlay to the small cells as well. Finally, there will be stadiums, festivals and train stations to name a few areas of access coverage that will be needed.

Then there will be the Indoor Challenge. Areas include the indoor office with desks, cubicles and offices; shopping malls (Single vs. Multi-level) and inside vs. outside shops.

Then the potential of a high density of people needing access at stadiums and train stations and don’t forget about home access.

Modeling needs to be done to ensure consistency across frequency, consistency in space (MU-MIMO/Massive MIMO needs to capture spatial correlation of channel), Diffraction and diffuse scattering (There will be a decrease in diffraction as frequency increases and diffuse scattering will be much more prevalent at higher frequencies.) and then there will be penetration losses which will be material dependent like cement, steel, etc. This loss usually will increase with higher frequencies. See Figure 13.

Figure 13: Users 1 and 2 will likely see the same clusters and similar blockage. Different frequencies will see many common reflectors, but blockage could be different (Image courtesy of Nokia)

Diffraction
Diffraction is an important modeling aspect. Diffraction is described as the amount of power that bends around objects such as building corners/rooftops. Note that at frequencies below 6 GHz diffraction over a rooftop is an important propagation mechanism in non-Line-of-Sight (NLOS).

Diffraction will decrease with carrier frequency. In Figure 14, the object is a truck 3.7 m high (Other objects such as buildings are not shown in this example)

Figure 14: There are many scenarios in modeling Diffraction correctly in a real environment. (Image courtesy of Nokia)

Diffraction is a dominant mechanism for all frequencies when Building 2 is not present in Figure 14, but there will be significant power loss as frequency increases. Reflection is a dominant mechanism for 10 GHz and 73.5 GHz with blockage and building 2 present in Figure 14. See Figure 15 for the power of the strongest path relative to unobstructed LOS path.
Penetration

Penetration must also be modeled under different conditions. Outdoor to indoor penetration loss usually will increase with frequency. A good example is a concrete/brick exterior wall. See Figure 16.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Blockage w/building 2</th>
<th>Blockage w/o building 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.6</td>
<td>-22.8 dB (diffraction)</td>
<td>-22.8 dB (diffraction)</td>
</tr>
<tr>
<td>10</td>
<td>-23.3 dB (reflection)</td>
<td>-25.7 dB (diffraction)</td>
</tr>
<tr>
<td>73.5</td>
<td>-23.1 dB (reflection)</td>
<td>-33.9 dB (diffraction)</td>
</tr>
</tbody>
</table>

**Figure 15:** This chart shows the power of the strongest path relative to unobstructed LOS path. (Image courtesy of Nokia)

**Figure 16:** The graph shows that outdoor to indoor penetration loss greatly increases with frequency through a wall made of reinforced concrete and brick. (Image courtesy of Nokia)

This phenomenon must be studied and tested extensively in order to see if this 6 GHz to 100 GHz
frequency range will be practical in outdoor-to-indoor coverage.

**Distance dependence**

At last year’s summit, Nokia demonstrated that elevation parameters are distant dependent in all environments. The elevation angle will spread and bias the signal. Going forward at frequencies above 6 GHz we must do further extensive testing regarding distance dependence.

The Rician K factor, according to Nokia estimates and tests, has some sort of distance dependence especially in street canyons which act as a sort of waveguide effect. Reference 4 describes a patent application for a Physics-based statistical model and simulation method of RF propagation in urban environments with the canyon waveguide effect.

**Antenna arrays**

There will need to be studies done to model antenna arrays for high bandwidth needs of 5G. At the higher bandwidths, delays will need to be simulated and evaluated in RF antenna arrays.

**Polarization**

We will also need to carefully and extensively model antenna polarization. Some measurements have been made showing that at 72 GHz polarization is retained with reflections. More studies are warranted in looking at spread in the channel due to polarization.

*Channel modeling at mmWave frequencies*

At the Brooklyn 5G Summit, Theodore Rappaport and George R. McCartney, Jr. from NYU Wireless, addressed mmWave Channel models. NYU Wireless in conjunction with its Polytechnic School of Engineering (Both are my alma maters!) has adopted a 1 meter close-in reference distance model for both LOS and Non-Line-of-Sight (NLOS) environments.

Their models are using Free Space Reference Distance and Path Loss. Studies were done at 28 GHz and 73 GHz for Path Loss. They have found that it would be recommended that all testing and modeling be done at $d_0 = 1\text{m}$ for mmWave for many practical reasons including simpler math, easier
comparison of results between different groups with different frequencies, locations and separation distances.

In Part two of this article we will investigate the semiconductor market and their thoughts and ideas regarding their challenges and vision for the 5G architectures.

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3. A flexible 100-antenna testbed for Massive MIMO, Joao Vieira, Steffen Malkowsky, Karl Nieman, Zachary Miers, Nikhil Kundargi, Liang Liu, Ian Wong, Viktor Owall, Ove Edfors, and Fredrik Tufvesson; 1 Dept. of Electrical and Information Technology, Lund University, Sweden, 2 National Instruments, Austin, Texas, USA

Also see:

- 5G base station architecture: The potential semiconductor solutions
- 5G to disrupt the test equipment market
- 5G: What to expect
- Chasing 5G: Pizzacato, sigma delta and other architectures