A Straight Path Towards 5G

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1 EXECUTIVE SUMMARY

In this white paper, we present Straight Path's 5G vision – Gbps Mobility.

We begin with our observations of macro information and communications technology (ICT) trends that are relevant to 5G, namely, the convergence of the information technology industry and the communications industry, the innovation throughout the economy spurred by the advancement in ICT, and the making of the ubiquitous broadband infrastructure. Together with globalization, these macro trends are powerful forces that are reshaping the ICT industry yet again and transforming societies and economies worldwide. Amid these macro trends, we believe the mobile industry can thrive by focusing on the strongest and most distinctive value proposition of 5G – a quantum leap in mobile broadband characterized by 1000x capacity increase over 4G and Gbps user experience in a mobile environment.

Content, commerce, and mobile Internet of Things (IoT) are among the strongest market drivers for 5G mobile broadband. While content drives mobile traffic growth, mobile commerce increases value added. Mobile IoT, with autonomous vehicles in particular, presents the greatest opportunities for 5G to be a strong catalyst of disruption and to foster new "killer applications" beyond the smartphone.

The fundamental technologies that enable 5G include mmWave, massive MIMO, and small cells. MmWave technologies make it possible to utilize the vast amount of mmWave spectrum for mobile communication; massive MIMO extends the range and increases spectral efficiency in these frequencies by employing a large number of antennas; small cell technologies provide the means to deploy a wide area mobile network with a large number of small cells, scalable backhaul, and proper interference coordination. Collectively, these technologies enable 5G mobile broadband in mmWave spectrum with much larger capacity, much higher data rate, and much denser deployment than 4G.

We also discuss the spectrum bands for 5G, taking into consideration the spectrum needs of 5G, and the tradeoff between spectrum availability and technology feasibility. We believe the prime spectrum for 5G is between 24 GHz and 57 GHz from both the regulatory and technological perspectives. We recommend that the industry prioritizes bands in the 25.25 – 29.5 GHz and the 36 – 40.5 GHz frequency blocks as primary targets to secure for 5G in WRC-19.

As in previous generational evolutions of mobile communication, there should be dual tracks of standardization efforts: one for the ongoing evolution of previous generation and the other for the new generation. We recommend that the industry continue the 4G LTE evolution path under 6 GHz in parallel with 5G standardization for mmWave mobile broadband.

The best way to predict the future is to make it happen. Ultimately, 5G is what the industry makes it to be. 5G represents the best opportunity in the next decade for the mobile communication industry to succeed and contribute to the continuing ICT revolution that will touch every human life and transform the world. Along with industry partners and regulatory bodies, Straight Path looks forward to contributing to the success of 5G with our extensive mmWave spectrum portfolio and strong 5G technical expertise.

2 STRAIGHT PATH 5G VISION

At Straight Path, 5G means Gbps Mobility.

The ICT revolution is at an inflection point where we will see accelerated proliferation of ICT in every part of the economy and the world in the next decade, fostering profound economic and social changes. Several technology and market forces are going to shape the ICT industry, and play an important role in this transformation.

First, the convergence of the information technology industry and the communication industry will accelerate. This trend has been exemplified by the seismic shift of the ICT industry landscape since the advent of the iPhone in 2007, which turned the industry focus to mobile computing and reshuffled the entire lineup of mobile device manufacturers. As we move beyond 4G, mobile computing will continue to be one of the major growth drivers in ICT. Demand for larger capacity and a better user experience in mobile broadband will continue to grow, indicating opportunities for significant value creation by enhancing mobile broadband in 5G. This trend has been observed by many industry experts, leading to aggressive 5G performance targets including 1000x capacity increase over 4G and Gbps user experience.

Second, advancement in ICT will spur innovation in the rest of the economy. ICT is a general-purpose technology[1] that improves productivity across the entire economy. Its impact can be seen by the proliferation of applications and services built on the ICT platform, such as Google (advertising), Amazon (retail), PayPal (payment), Priceline (travel), Airbnb (hospitality), Uber (taxi), etc. Despite the remarkable innovation and growth in recent decades, the ICT industry only accounts for less than 5% of GDP in most parts of the world. As the advancement in ICT is leveraged by the other 95% of the economy, we expect to see further disruptions and significant value creation (and destruction) in multiple industries. This trend can also be seen in the so-called Internet of Things, in which computing and communication are enabled in more devices and machines due to the continuous increase in capability coupled with the decline in cost, size, and power consumption of ICT technologies. This proliferation of ICT technologies will in turn provide virtuous feedback for further technology advancement in ICT as more markets provide more revenue, and new applications require different performance metrics.

Last but not least, broadband will become one of society's most fundamental infrastructures. The world has developed an insatiable appetite for connectedness due to the success of Internet, World Wide Web, and mobile Internet. A variety of communication, networking, and connectivity technologies have been developed to meet these demands. These include wired communication and networking technologies that provide the optical fiber and routers for the Internet's backbone, fiber and cable connections for fixed broadband access, and Ethernet cables for local area networks in buildings, offices, and homes. These also include a suite of wireless technologies such as 3G and 4G cellular technologies for wide area mobile broadband, Wi-Fi technologies for indoor and hotspot connectivity, Bluetooth for low power, short range connectivity, etc. More devices will have built-in connectivity in the coming decades as ICT technologies continue to improve and proliferate. Most of these devices will ultimately be connected to a single converged, interconnected, and yet heterogeneous broadband infrastructure. This broadband infrastructure will be ubiquitous in nature as broadband becomes a necessity in life upon which many of the social and economic activities rely. Just like the power grid has high-voltage and low-voltage transmission lines, and the transportation system has highways and local streets, the broadband infrastructure will also be heterogeneous in nature as devices choose the connectivity technology that best suits their applications.

[1] Richard G. Lipsey, Kenneth I. Carlaw, and Clifford T, Bekar, "Economic Transformations: General Purpose Technologies and Long Term Economic Growth," Oxford University Press, 2006

Although we envision a single broadband infrastructure that connects everything (or most things), we do not believe a single communication technology can (or should) satisfy the communication need of every device – not even 5G. In fact, many envisioned IoT applications derive the bulk of their value through innovative system integration and business models. The existing wired communication infrastructure and wireless communication technologies, with ingenious network architecture, and power and form factor optimization, can already satisfy much of the communication needs of many IoT applications.

The success of ICT has also become the catalyst for another important trend of our time – globalization. As the world becomes increasingly connected, social and business interactions with customers and business partners across the globe can be almost as interactive and rich as face-to-face meetings. The value created by this global connectivity is enormous and has thus enabled many new businesses that in the past would not have been possible. Globalization also creates many opportunities and challenges for existing businesses as it brings players from the whole world into the same arena. On one hand the global market is now within reach, and on the other hand a company's local market stronghold is now exposed to numerous competitors from all across the globe. This duality of market globalization alone has caused significant changes to the business landscape in the global economy.

Although Straight Path would like 5G to be as successful as possible, we caution against the vision that predicts 5G to be the "be all and end all" solution to every business opportunity in the ICT industry for next decade. This vision distorts what 5G really is and distracts the industry from focusing on the key challenges of 5G. Instead of throwing everything onto the 5G bandwagon, we would like to clearly define 5G as the next generation mobile broadband beyond 4G, which we believe is the most value added part of the broadband infrastructure for the increasingly connected world in the next decade. It is apparent that plenty of business opportunities exist outside this narrow definition of 5G. For example, a network infrastructure vendor may expand horizontally by developing new equipment, software, and systems that support a variety of IoT applications. It may expand vertically into managing and operating part of the broadband infrastructure. It may provide solutions or even run services for certain verticals such as monitoring oil fields, refineries, railways, etc. However, we believe these efforts deserve their own buzzwords. Putting them under the umbrella of 5G will not do them justice, and will dilute the meaningful discussion for both 5G and these business opportunities. By focusing on the mobile broadband positioning for 5G, we believe the wireless industry will be able to create the greatest value in its 5G endeavors, making mobile broadband better, stronger, and more pervasive, and potentially enabling new disruptions that can transform the world.

3 MARKET DRIVERS FOR 5G

The ICT industry has been one of the main drivers for productivity and GDP growth in the past three decades. The advances in ICT have fundamentally changed how humans generate, communicate, access, analyze, and utilize information. Studies have shown that a flourishing ICT industry and a solid information technology infrastructure not only benefit the ICT industry and stimulate growth within the industry, but also benefit the entire economy. According to the European Commission's annual report on digital economy in 2007[2], "ICT contributed nearly 50% of EU productivity growth between 2000 and 2004". Mobile communication, in particular, has been a strong driver of worldwide economic development.

[2] http://europa.eu/rapid/press-release_IP-07-453_en.htm?locale=en

According to GSMA[3], "the mobile industry (both directly and indirectly) contributed around 3.6% of global gross domestic product (GDP) in 2013, equivalent to over $2.4 trillion. This figure is expected to increase to 5.1% of global GDP by 2020."

Going forward, mobile computing will continue to be a strong market driver for 5G. As mobile computing continues to grow in market penetration and the applications and services it can provide, there will be greater demand for better, faster, and more pervasive mobile broadband. Numerous studies have predicted the explosive growth of mobile traffic (*e.g.*, Cisco Visual Network Index[4] and Ericsson Mobility Report[5]). For mobile broadband as a business, however, the most relevant question is not the growth in traffic, but the growth in revenue. The value proposition of mobile broadband can be expanded in the following two ways: creating more value in existing markets, and serving new markets.

Existing Markets for Mobile Broadband

Among existing markets for mobile broadband, multimedia content is one of the strongest growth drivers in the largest existing market – smartphones. A variety of applications and services have been created to enable smartphone users to better create and consume music, radio, photo, and video content. Online streaming services such as Netflix and Pandora are aggressively expanding their offering onto smartphones. New services such as Snapchat and Instagram are inherently mobile centric. New types of content including 4K/8K video, 360º video, and Virtual Reality are emerging. These new types of content often provide a better and more immersive user experience, but require higher bandwidth than traditional multimedia. Moreover, as mobile broadband becomes readily available, more services start to embed rich content. The traffic growth due to multimedia content increases the value of mobile broadband to end users, but also demands larger capacity and higher data rates to ensure good user experiences. In the end, this translates into demand for a 5G mobile broadband network with significantly improved performance metrics: larger capacity, higher data rates, and better coverage.

Mobile commerce is another market driver that adds significant value to mobile broadband. The growth of mobile commerce comes from both the expansion of existing e-Commerce business models onto mobile platforms, and from the creation of new business models enabled by mobile broadband. Examples of the former are Internet companies (Google, Amazon, etc.), which expand from online shopping to mobile shopping and from online advertising to mobile advertising. Examples of the latter include new business models such as Uber and Lyft, which rely on the exchange of customers' and drivers' location information in real time via mobile broadband. The growth of mobile commerce correlates with the growing impact of ICT on other industries, and the emergence of broadband as a fundamental infrastructure for social and economic activities. As more commerce becomes conducted online via mobile broadband connections, the value of 5G mobile broadband increases. Note that many mobile commerce applications and services may have different requirements in terms of mobile broadband provision. For example, mobile banking services may have stringent requirements on security, while video streaming services require a lot of bandwidth. It is crucial that the broadband infrastructure, including 5G mobile broadband, should be architected with scalability and flexibility so that applications and services with different capacity, data rate, coverage, reliability, and security requirements can be supported without overbearing complexity and cost.

In short, in the existing market of mobile broadband for smartphone users, content drives traffic growth while commerce increases value added. Both increase the value of a faster and more robust mobile

[3] GSMA, "The Mobile Economy 2014," http://www.gsmamobileeconomy.com/
[4] Cisco Visual Network Index, available at http://www.cisco.com/c/en/us/solutions/service-provider/visual-networking-index-vni/index.html
[5] Ericsson Mobility Report, available at http://www.ericsson.com/mobility-report

broadband network with larger capacity. Some over the top (OTT) applications and services may be able to create value disproportional to the required bandwidth, *e.g.*, messaging services (WeChat, WhatsApp, etc.). The bulk of the value created by these services will be accrued mostly to the services themselves and less so to the network providers. In certain cases, some of the OTT services may even compete with the legacy businesses of network providers. For example, many popular messaging services support voice chat features, which reduce the value of voice services from network operators. This, in our view, is yet another reason why network operators need to aggressively grow the mobile broadband value proposition before the revenue stream from legacy services becomes irrelevant.

New Markets for Mobile Broadband

Among potential new markets, mobile IoT presents the most promising opportunities to create value for 5G mobile broadband. Many of the IoT opportunities that require fixed wireless access can already be addressed by today's technology with minor enhancements. What's more, the value proposition in these opportunities often lies in design innovation, system integration, and industry-specific expertise, not so much on the broadband access. Therefore, although these IoT business opportunities may be great for entrepreneurs, system integrators, and niche market players with specific industry expertise, we do not believe these opportunities can create significant economic benefits for mobile broadband providers.

The core value proposition of mobile broadband lies in its namesake, *i.e.*, the ability to provide broadband connectivity in mobility environments, as exemplified by the phenomenal success of smartphones. Going forward into the next decade, we believe autonomous mobile devices – especially autonomous vehicles – represent the single largest opportunity in mobile IoT that can fundamentally change how we live our lives. Driving a car requires significant commitment from humans, and comes with the high cost of inevitable human error. Self-driving and/or remotely controlled cars can save people hours of commute time every day. Autonomous vehicles can also liberate people (*e.g.*, kids or seniors) with no or limited driving capabilities from confinement or dependency. As world population ages, this value proposition will become particularly attractive to a growing customer base. Moreover, autonomous vehicles should not be limited to transporting people. For example, trucking and delivery are big businesses that could potentially be transformed by autonomous vehicles. In addition, a long list of retail and service businesses can benefit from a low-cost unmanned pickup and delivery service, such as grocery, food, pharmacy, dry cleaning, waste management, etc. Delivery by autonomous vehicles may disrupt the retail industry yet again as it can enable traditional retail companies to leverage their large presence of brick and mortar stores for quick fulfillment, an advantage that cannot be matched by pure online retail operations. 5G mobile broadband is a key enabler of autonomous vehicles. By enabling 5G mobile broadband to and from millions of autonomous vehicles, these vehicles are constantly updated with the latest traffic, route, and task information. An autonomous vehicle can inform the controller (possibly a cloud server, or a remote driver, or both) of the vehicle's status and driving condition in real time. Some information exchanges between the autonomous vehicle and its controller are so critical that they require both high reliability and low latency (e.g., driving directions from controller to vehicle), while others may require a significant amount of bandwidth (e.g., video feed from vehicle to controller). A 5G system that can provide high-speed low-latency mobile broadband connections can add significant value to autonomous transportation, and will be a key enabler for the mass adoption of autonomous vehicles.

Technology trends and market forces will not only drive the demand for 5G mobile broadband, but also reshape the industry landscape. As the industry matures, specialization and horizontalization[6] will be

[6] Christensen, Clayton M., and Michael E. Raynor, "The Innovator's Solution: Creating and Sustaining Successful Growth," Harvard Business School Press, 2003

the main theme in the ICT ecosystem dynamics. However, opportunities also exist for vertical integration, especially in emerging IoT businesses. On one hand, technology trends and market forces provide ample opportunities for ICT companies to grow and compete regardless of their current position in the ecosystem. For example, network operators, infrastructure vendors, and service providers may find themselves well positioned to not only provide access, equipment, or services, but also to provide the entire solution in certain vertical markets. This allows these players to enter different parts of the ecosystem if they find opportunities aligned with their overall business strategy. On the other hand, the fast pace of innovation and rapidly changing industry dynamics constantly challenge conventional wisdom and threaten the very existence of many traditional businesses (*e.g.*, voice services). While the overall value of mobile broadband will grow, the changes in industry landscape will inevitably create winners and losers. The best winning strategy for individual companies is to innovate and compete, which collectively brings the best out of the whole industry by creating a 5G ecosystem that achieves the greatest technology advancement, business success, and economic and social impact.

4 TECHNOLOGY ENABLERS FOR 5G

The industry has rightly set aggressive targets for 5G – Gbps mobility and 1000x capacity increase over 4G – because any incremental improvement over 4G would not justify the significant capital expenditures needed to overhaul the existing mobile broadband network, nor would it be able to meet the mobile traffic growth or create new business possibilities to expand the ecosystem.

As the lower frequency bands become congested, it is very difficult to secure the amount of spectrum needed for 5G in these bands to meet the capacity and data rate targets. Even if a limited amount of spectrum can be made available at these frequencies, the cost of the spectrum is going to be so prohibitively high that it will hinder the economics of a successful mass market adoption of 5G. For example, in the recent AWS-3 spectrum auction in the U.S., operators paid nearly $45 billion for 65 MHz of spectrum around 1.7/2.1 GHz.[7] In contrast, millimeter wave bands are much less congested and can potentially provide the multi-gigahertz spectrum required by 5G at a much lower cost. In recent years, there have been promising developments of 5G technologies, including Millimeter-wave Mobile Broadband[8], massive MIMO[9], and small cell technologies[10]. Millimeter-wave Mobile Broadband makes it possible to utilize the vast amount of millimeter-wave spectrum for mobile communication; massive MIMO technologies extend the range and increase spectral efficiency in these frequencies by employing a large number of antennas; small cell technologies provide means to deploy a wide area mobile network with a large number of small cells that can provide good coverage with scalable backhaul and proper interference coordination. Collectively, these technologies enable 5G mobile broadband in millimeter-wave spectrum with much larger capacity, much higher data rates, and much denser deployment than 4G.

[7] http://www.fiercewireless.com/story/its-over-fccs-aws-3-spectrum-auction-ends-record-449b-bids/2015-01-29
[8] Zhouyue Pi; Khan, F., "An introduction to millimeter-wave mobile broadband systems," Communications Magazine, IEEE , vol.49, no.6, pp.101 – 107, June 2011
[9] Marzetta, T.L., "Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas," Wireless Communications, IEEE Transactions on , vol.9, no.11, pp.3590 – 3600, November 2010
[10] Bhushan, N.; Junyi Li; Malladi, D.; Gilmore, R.; Brenner, D.; Damnjanovic, A.; Sukhavasi, R.; Patel, C.; Geirhofer, S., "Network densification: the dominant theme for wireless evolution into 5G," Communications Magazine, IEEE , vol.52, no.2, pp.82 – 89, February 2014

There are three primary factors that have made millimeter wave bands attractive for 5G.

First, the sophisticated antenna arrays required for 5G are best employed in higher bands. In 2011, a Millimeter-wave Mobile Broadband (MMB) system was shown to achieve a link budget sufficient for 1-km distance in a mobile environment at 28 GHz and 72 GHz by utilizing large number of antennas.[11] Practical designs of antenna arrays with compact form factor for MMB were also demonstrated.[12] The same results could not be achieved in lower bands because the larger antennas required in lower bands would make the use of antenna arrays with hundreds of antenna elements infeasible. In 2012 – 2014, a series of channel measurement campaigns were conducted for millimeter wave frequencies in outdoor cellular environments for 28 GHz, 38 GHz[13], 60 GHz, and 73 GHz[14]. In these papers, the authors found that with transmitter and receiver antenna beamforming, less than 20% of the transmitter-receiver links within 200 meters are in outage, and the outage locations can be easily predicted by site-specific planning. Around the same timeframe, many papers were also published to address signal processing and system aspects of a mmWave massive MIMO system with practical system designs and transceiver algorithms that can efficiently utilize the transmitter and receiver antenna arrays to significantly improve signal noise ratio (SNR) and throughput. These activities have laid a strong foundation for millimeter wave 5G from both communication theory and system research perspective.

Second, device technology has progressed sufficiently to support the commercial production of base stations and mobile devices in mmWave bands. In the past, the available devices in mmWave frequencies were either too bulky, too expensive, or too inefficient to be used for commercial base stations or mobile devices. The advances of Gallium Arsenide (GaAs) and Indium Phosphide (InP) High-electron-mobility Transistor (HEMT) and Heterojunction Bipolar Transistor (HBT) devices made it possible for solid state power amplifiers to transmit a few Watts of power with power added efficiency around 20% at mmWave frequencies[15]. These devices are monolithic and can be assembled in multi-chip modules and surface mount packages, which allows the whole mmWave transceiver to be integrated on a single printed circuit board, enabling mmWave base station and mobile station transceivers to be mass-produced at low cost. The recent interest in 60 GHz further accelerated the development of highly-integrated low-cost mmWave circuits. Standard-compliant WiGig/11ad transceivers at 60 GHz are already fully integrated into a single CMOS radio frequency integrated circuit (RFIC)[16]. Phased array RFICs for up to 16 channels have

[11] Zhouyue Pi; Khan, F., "An introduction to millimeter-wave mobile broadband systems," Communications Magazine, IEEE , vol.49, no.6, pp.101 – 107, June 2011

[12] Rajagopal, S.; Abu-Surra, S.; Zhouyue Pi; Khan, F., "Antenna Array Design for Multi-Gbps mmWave Mobile Broadband Communication," Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE , 5-9 Dec. 2011

[13] Rappaport, T.S.; Ben-Dor, E.; Murdock, J.N.; Yijun Qiao, "38 GHz and 60 GHz angle-dependent propagation for cellular & peer-to-peer wireless communications," Communications (ICC), 2012 IEEE International Conference on , vol., no., pp.4568,4573, 10-15 June 2012

[14] Nie, Shuai; MacCartney, George R.; Sun, Shu; Rappaport, Theodore S., "28 GHz and 73 GHz signal outage study for millimeter wave cellular and backhaul communications," Communications (ICC), 2014 IEEE International Conference on , pp.4856,4861, 10-14 June 2014

[15] Hadziabdic, Dzenan; Krozer, Viktor, "Power Amplifier Technology at Microwave and Millimeter-Wave Frequencies: an Overview," Microwave Conference (GeMIC), 2008 German , pp.1,8, 10-12 March 2008

[16] Tsukizawa, T.; Shirakata, N.; Morita, T.; Tanaka, K.; Sato, J.; Morishita, Y.; Kanemaru, M.; Kitamura, R.; Shima, T.; Nakatani, T.; Miyanaga, K.; Urushihara, T.; Yoshikawa, H.; Sakamoto, T.; Motozuka, H.; Shirakawa, Y.; Yosoku, N.; Yamamoto, A; Shiozaki, R.; Saito, N., "A fully integrated 60GHz CMOS transceiver chipset based on WiGig/IEEE802.11ad with built-in self calibration for mobile applications," Solid-State Circuits Conference Digest of Technical Papers (ISSCC), 2013 IEEE International , pp.230,231, 17-21 Feb. 2013

also been successfully implemented in CMOS and SiGe processes for transmitters[17] and receivers[18] for a wide range of mmWave frequencies. These circuit technology advances allow miniature devices to drive sophisticated antenna arrays with a large number of antenna elements and RF transceiver chains, enabling massive MIMO transmission and reception at both the base station and mobile station.

Third, Analog to Digital Converters (ADCs) have been developed in a manner that will now support Gbps mobile communication. To deliver a multi-Gbps experience in 5G, multiple channels of Analog-to-Digital Converters (ADCs) with a sampling rate of a few hundred MHz to a few GHz are needed. Just a few years ago, these ADCs would consume a few Watts of power, making Gbps communication impractical for mobile devices. The state-of-the-art ADCs today with GHz sampling rates and up to 8-bit resolution can be achieved with a few milliwatts[19] of power consumption. On the digital circuits, the latest mobile application processors integrate multiple cores and cellular & Wi-Fi modems on a single chip with more than 1 billion transistors, achieving the same level of complexity as the most advanced personal computer CPUs just a few years ago, but with a size and power budget manageable on a smartphone. With the ever increasing demand of higher speed and wider bandwidth for mobile communication, we envision the performance of these circuits will be at least another order of magnitude better when 5G hits the market.

Since Millimeter-wave Mobile Broadband[20] was proposed in 2011, many major industry players have announced progress in millimeter wave technologies for 5G. In March 2013, DoCoMo announced 10 Gbps uplink transmission in the 11 GHz band[21]; in May 2013, Samsung announced 1 Gbps downlink transmission in the 28 GHz band[22]; in July 2014, Ericsson announced demonstration of 5 Gbps transmission in the 15 GHz band[23]; in October 2014, Samsung again demonstrated in the 28 GHz band, with 7.5 Gbps transmission in a stationary environment and 1.2 Gbps transmission with a vehicle traveling at over 100 kmph.[24] In the meantime, leading researchers in the industry and academia are also pushing the technology envelope by developing fundamental technologies and engineering know-hows crucial to the success of mmWave 5G systems.

In the rest of this section, we share some insight into three fundamental technologies that help enable 5G mobile broadband in mmWave spectrum, namely, mmWave mobile broadband transceivers, mmWave massive MIMO, and small cells.

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[17] Kwang-Jin Koh; May, J.W.; Rebeiz, G.M., "A Millimeter-Wave (40–45 GHz) 16-Element Phased-Array Transmitter in 0.18- µm SiGe BiCMOS Technology," Solid-State Circuits, IEEE Journal of , vol.44, no.5, pp.1498,1509, May 2009

[18] Natarajan, A; Reynolds, S.K.; Ming-Da Tsai; Nicolson, S.T.; Zhan, J.-H.C.; Dong Gun Kam; Duixian Liu; Huang, Y.-L.O.; Valdes-Garcia, A; Floyd, B.A, "A Fully-Integrated 16-Element Phased-Array Receiver in SiGe BiCMOS for 60-GHz Communications," Solid-State Circuits, IEEE Journal of , vol.46, no.5, pp.1059,1075, May 2011

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[20] Zhouyue Pi; Khan, F., "An introduction to millimeter-wave mobile broadband systems," Communications Magazine, IEEE , vol.49, no.6, pp.101,107, June 2011

[21] http://www.engadget.com/2013/02/27/ntt-docomo-confirms-successful-10gbps-wireless-test/

[22] http://spectrum.ieee.org/telecom/wireless/millimeter-waves-may-be-the-future-of-5g-phones

[23] http://www.ericsson.com/news/1810070

[24] http://www.zdnet.com/article/samsung-boasts-7-5gbps-mobile-speed-record-in-5g-trial/

4.1 MMWAVE MOBILE BROADBAND TRANSCEIVERS

Just like it took a superheterodyne transceiver to make FM radio a reality[25], it takes an innovative mmWave transceiver to accomplish the quantum leap from sub-3 GHz for 1/2/3/4 G to mmWave frequencies for 5G. The mmWave transceiver for 5G includes a few key components: antenna array, printed circuit board (PCB), mmWave front end (MFE) and RFIC. The antenna array is the device that can radiate and capture mmWave signals over the air. By judiciously setting the amplitude and phase of the signals among antenna elements, the antenna array can selectively amplify mmWave signals in certain spatial directions while suppressing them in others. The MFE includes the power amplifier (PA) for transmitting mmWave signals, the low noise amplifier (LNA) for receiving mmWave signals, and the transmitter receiver switch (T/R switch) that connects the antenna array with the PA (or the LNA) in transmitting (or receiving) time slots. Note that we assume a TDD system for 5G for a number of reasons that we have explained in our comment[26] to the 5G NOI by the FCC. The RFIC is the device that converts the signals from mmWave frequencies to baseband and vice versa. In 5G transceivers where RFICs need to drive antenna arrays, the RFIC has an additional function of beamforming. In other words, the RFIC is the device that sets the amplitude and phase of signals among antenna elements, thereby achieving beamforming towards certain spatial directions.

4.1.1 Antenna Array

The current applications of mmWave frequencies include point-to-point, point-to-multi-point, and satellite communications. These systems all use some form of high-gain antennas to overcome the limited PA output power in these frequencies. For example, the point-to-point microwave and mmWave links often use a dish antenna with gain up to 40 – 50 dB. These dish antennas are large and heavy, making it impossible to use in mobile devices, especially handsets. For successful commercialization of 5G, the antenna array for both base stations and mobile stations needs to be low-cost, low-profile, and highly efficient. We discuss a few popular choices of mmWave antenna designs as follows:

- Horn antenna – This is a choice under consideration because horn antennas have been used in past systems at mmWave frequencies (*e.g.*, point-to-multi-point systems in LMDS). However, we do not favor horn antennas for a few reasons. First, they are expensive to manufacture. The complicated waveguide structure often requires precision molding and milling, which cannot be manufactured cheaply and has limited scalability to mass production. Secondly, the launch or feed network to these arrays needs an array of waveguide connectors, which are also expensive and bulky. While performance of these arrays could be good, we expect these arrays to be orders of magnitude more expensive than other solutions. Lastly, in order to achieve beamforming, an array of horn antennas would be needed, which would likely be too big to be suitable for 5G devices (including base stations).
- Antenna array on printed circuit board (PCB) – This is our current preferred design choice, especially on the base station side. Patch antenna arrays on PCB can be easily manufactured at low cost. They are essentially copper patches on the top metal layer of the PCB. Note that in order for the antenna array and the feed network to have good efficiency, the material and thickness of the

[25] https://en.wikipedia.org/wiki/Edwin_Howard_Armstrong
[26] Straight Path comment to FCC 5G NOI, available at http://apps.fcc.gov/ecfs/document/view?id=60001013744

top metal layer and the substrates underneath need to be carefully chosen[27]. For example, even with the best PCB materials, the loss expected on PCB is about 1 dB per inch for 39 GHz. This limits how long the feed lines can be. Assuming we would like to limit the feed loss to 2 dB from the PA output to the antenna, the feed line can be at most 2 inches long (~5 cm). Assuming around 80% efficiency for the patch antenna element, altogether that is already a 3-dB loss of the PA output power. In other words, only 50% of the output power of the PAs is actually radiated over the air. That's a pretty big loss! Generally, PAs (or front end modules) are placed around the antenna array if they are on the same side of the PCB. The limit on the feed line length will in turn limit the size of the antenna array to around 5 ~ 10 cm in each dimension. This effectively limits the maximum number of elements per array to several hundreds. As a rule of thumb, we recommend the maximum antenna array size to be no more than 256 (16×16) for the antenna array on PCB approach. If larger arrays are needed, we can always tile up multiple antenna arrays in the same sector, and rely on digital MIMO processing to achieve the extra beamforming gain needed.

- Antenna array in package – In this approach, antennas are embedded on the package that encapsulate the MFE chip or multi-chip-module (and possibly the RFIC as well). In order to achieve high efficiency and low loss, the package is typically made of ceramics or liquid crystal polymer (LCP). In order to achieve good interconnection between the MFE/RFIC pinout and the antenna, the MFE/RFIC is often flip-chip attached to the bottom of the package in which the antenna array is integrated[28]. In comparison with patch antenna array on PCB, this design is much more compact and has the potential to significantly reduce the overall form factor of the transceiver. This approach is particularly interesting for 5G mobile stations where real estate is at a premium while output power requirements and thermal challenges are lower than those of 5G base stations. Note this approach requires careful co-design of the MFE/RFIC and the package. Considerations and requirements derived from the overall device design (size, shape, location, orientation, thermal consideration, etc.) should be taken into account as well.
- Antenna array on chip – So far this option does not appear to be a good design choice for 5G due to the poor antenna efficiency on silicon substrate at mmWave frequencies. Because of the low resistivity and high relative permittivity of the silicon substrate, on-chip antennas often result in low efficiency and low gain. We believe the mmWave frequencies most suitable for 5G are below 40 GHz (more on that later). For frequencies <40 GHz, the antenna elements are still fairly sizeable in comparison with the die size. Manufacturing antenna elements on chip would greatly increase the die size and cost, especially for large antenna arrays. Variations of this approach such as antenna arrays in superstrate on top of the die could solve the antenna efficiency issue but may still result in large die size and increase the cost of the chip. Moreover, the benefit of this approach does not seem to be clear in comparison with the antenna array in package approach.

In summary, antenna array on PCB and antenna array in package are two good solutions for 5G antenna arrays, with antenna array on PCB the preferred approach for 5G base stations, and antenna array in package the preferred approach for 5G mobile stations (and possibly low-power 5G base stations).

[27] John Coonrod, "Choosing circuit materials for millimeter wave applications," available at https://www.rogerscorp.com/documents/2610/acm/articles/Choosing-Circuit-Materials-for-Millimeter-Wave-Applications.pdf

[28] Dong Gun Kam; Duixian Liu; Natarajan, A.; Reynolds, S.; Floyd, B.A., "Low-cost antenna-in-package solutions for 60-GHz phased-array systems," Electrical Performance of Electronic Packaging and Systems (EPEPS), 2010 IEEE 19th Conference on, pp.93,96, 25-27 Oct. 2010

4.1.2 Printed Circuit Board

High frequency circuit materials such as RO3000 or RO4000 series should be used as the RF substrate. These materials are ceramic-filled PTFE composites that offer excellent electrical and mechanical properties suitable for multi-layer PCB for high frequency applications. For example, the RO3003 or RO3203 substrate can be used at relatively high frequencies because of its low dielectric loss (dielectric constant around 3.0). With a Coefficient of Thermal Expansion (CTE) matched to that of copper and FR4 in the X-Y plane, RO3000/FR4 hybrid constructions can be fabricated reliably, leading to a low cost construction of PCB that can support frequency up to 50 GHz[29]. The thickness of the top metal layer and the RF substrate should be carefully chosen to optimize the patch antenna array efficiency (assuming patch antenna array on PCB). The routing of high frequency signals should stay on the top metal layer to avoid lossy transition to and from the inner layers. Even so, the loss for the best high frequency material available is still around 1 dB per inch for 39 GHz. This motivates a compact design with small PCB size. In addition, to reduce feed loss, the MFE/RFIC should be placed close to the antenna array. This motivates a right choice of the level of integration for the MFE/RFIC.

4.1.3 MFE and RFIC

There are 3 main functions of the transceiver chain: signal amplification, frequency conversion, and analog beamforming. The signal amplification is done by the PA (on the transmitter side) and the LNA (on the receiver side). The frequency conversion is done by the mixer. For superheterodyne transceivers, the frequency conversion is accomplished in two stages – RF mixing and IF mixing (I/Q modulation & demodulation). In direct conversion transceivers, the frequency conversion and the I/Q modulation is combined into one step, *i.e.*, the signal is converted directly between the RF frequencies and the baseband I/Q signals. Analog beamforming can be done either via RF beamforming, or IF beamforming, or LO beamforming. We will discuss the pros and cons of each scheme later.

An appropriate integration level should be selected for the MFE and RFIC. On one hand, there are strong reasons why we should integrate as many components into a single MFE IC or RFIC as possible. The cost can be greatly reduced. The PCB can be smaller, more robust, and less prone to manufacturing error. The performance can be improved because integration reduces the interconnection between ICs, which can be lossy for mmWave frequencies. On the other hand, there are reasons why distributing active devices on multiple locations on the PCB also has merits. In order to achieve good coverage, multiple watts of output power is required at 5G base stations, which means a few tens (if not hundreds) of watts of heat that needs to be dissipated. For the same amount of heat, distributed heat sources make thermal design easier, which translates into mechanical design benefits (less heat sink, no fan, smaller and lighter units, etc.). Moreover, to minimize loss of power, the MFE should be placed as close to the antenna elements as possible. If the MFE for all antenna elements were integrated into a single chip, it will result in long feed lines between the MFE IC pinouts and at least some antenna elements, causing loss of output power (on Tx) or degradation of signal quality (on Rx). Another issue of having too much integration in an MFE IC is routing congestion. Since the signals between the MFE IC and the antenna elements are at mmWave frequencies, the interconnection between them must be routed on the top metal layer to avoid vias to and from the inner metal layers that can cause significant loss. Having a large number of input or outputs at mmWave frequencies on a single MFE IC makes the routing and planning of the whole PCB very difficult.

[29] John Coonrod, "Choosing circuit material for millimeter wave applications," available at https://www.rogerscorp.com/documents/2610/acm/articles/Choosing-Circuit-Materials-for-Millimeter-Wave-Applications.pdf

As a rule of thumb for antenna arrays on PCB, the MFE IC should integrate no more than 8 transceiver chains. Note this guideline should be revisited if antenna arrays are either on package or on chip, although the same set of tradeoffs still apply.

There are two parameters defining the level of integration for MFE ICs and RFICs: integration breadth and integration depth. By integration breadth we mean how many parallel channels an MFE IC or RFIC integrates. By integration depth we mean how many steps along the transceiver chain an MFE IC or RFIC integrates. A few guidelines drive our design recommendations. First of all, as we mentioned previously, the MFE ICs should be placed as close to antenna elements as possible. Secondly, we would like to minimize the routes and interconnections that mmWave signals travel. Table 1 shows our recommendation for the integration breadth and depth for typical MFE ICs and RFICs.

Table 1. Recommended integration breadth and depth for MFE IC and RFIC

	MFE IC	RFIC
Integration depth	PA, LNA, TR switch	RF gain blocks, RF phase shifters, RF switch, RF combiner/splitter, RF mixer
Integration breadth	2 – 8 channels	2 – 8 channels

It is certainly possible to integrate the RFIC and the MFE IC. The result will be greater integration depth from the antenna port all the way to IF or baseband. In order to maintain close proximity of the MFE to the antenna elements, the integration breadth must be limited in this case and thus multiple MFE/RFICs are needed to drive the antenna array. The IF/baseband ports of the multiple MFE/RFICs can be connected to another frequency conversion stage or directly to baseband. From baseband modem standpoint, the digital MIMO processing is very much like the 4G LTE system with multiple MIMO channels. The number of parallel IF/baseband channels should be no more than 16. The practical benefit of more than 16 digital streams is limited at best because the number of users requesting simultaneous transmissions tend to be low in small cells, and each user's channel tends to only have a couple of dominant paths for mmWave frequencies.

4.1.4 RF Phase Shifting vs. LO Phase Shifting vs. IF Phase Shifting

The biggest benefit of RF phase shifting is that the RF signals from multiple antenna elements can be combined before going into the RF mixer. This architecture requires a smaller number of RF mixers than the number of RF channels in the front end. For LO phase shifting and IF phase shifting, the number of RF mixers required is the same as the number of RF chains, since the combining can only be done after RF mixing. The benefit of LO phase shifting, however, is the phase shift is frequency agnostic. It is often difficult to build a good phase shifter with flat response across a wide bandwidth in all phase shifting states. LO phase shifting bypasses this problem by applying the phase change to the LO frequency, thereby achieving the same phase for the whole signal bandwidth. For a 5G system with hundreds of megahertz or even gigahertz of bandwidth, the frequency flatness of phase shifting can be better achieved in either RF phase shifting or LO phase shifting, while this is considerably more challenging for IF phase shifting because the percentage bandwidth is so much larger at IF.

If LO or IF phase shifting is used, there needs to be multiple RF mixers for RF channels that will eventually be combined during analog beamforming. Great care must be exercised in the clock generation and distribution for the multiple RF mixers used in the phased array transceiver. In general, a single

reference clock should be used to derive the multiple LO signals for RF mixing. The LO signals for multiple RF channels that are combined into a single IF or baseband stream should be synchronized in phase, and thus should come from a single frequency synthesizer (PLL). Note that the LO output from different frequency synthesizers cannot guarantee phase synchronization, even if these PLLs share the same reference clock. This is because for each phase of the reference clock that is running at a much lower frequency, there can be multiple phases of the VCXO (the part within the PLL that generates the LO signal) that can reach the steady state of the phase lock loop. In other words, multiple PLLs can achieve phase locking to the reference clock at the reference frequency, but the phases of these PLLs can actually be different. Using LO derived from multiple PLLs for mixing multiple RF channels that are combined during analog beamforming leads to unpredictable phase incoherence that destroys the analog beamforming gain and results in random beamforming pattern. This design flaw can be fatal for the phased array receiver as there is no way to recover the beamforming gain once incoherent signals are combined. In other words, any RF channels that are combined in the analog domain must use the same frequency synthesizer to derive their LO for frequency conversion.

However, there are advantages in using multiple frequency synthesizers. For example, it can shorten the routes from a frequency synthesizer to the RF mixers it drives, thus reducing loss and maintaining good phase noise of the LO. It is OK to use different frequency synthesizers for different digital baseband signals as long as proper reference signals are provided. Digital signals that are frequency converted using different frequency synthesizers must use separate reference signals to estimate the channel coefficients, which embed the phases of the frequency synthesizers at both the transmitter and the receiver.

This issue of the PLL phase synchronization also has important implications in RFIC integration. It is often tempting to integrate PLL together with the RF mixer so that only low-frequency reference clock needs to be routed on the board. However, based on the analysis above, this also means that analog beamforming cannot be applied between an RFIC with an integrated PLL and another RFIC with another integrated PLL. This limitation must be carefully evaluated at the system level to make sure this does not fundamentally limit the intended beamforming and MIMO operations. From the mobile station perspective, this limitation may not be an issue as there are relatively fewer antenna elements and RF chains. In order to mitigate antenna blocking/detuning due to human body and to capture dominant paths in a scattered environment, a mobile station should have a few antenna sub-arrays that are distributed within the device, with each antenna sub-array having a small number of antenna elements. For example, one possible configuration is to have 4 antenna sub-arrays with each sub-array consisting of 4 antenna elements. Each antenna sub-array can be driven by a 4-channel RFIC with integrated mixer and PLL. Analog beamforming is achieved within each RFIC while digital MIMO processing can be applied across multiple RFICs. In base stations, however, it is a bit trickier because the antenna arrays are typically larger. So, whether to integrate a PLL in an RFIC depends on whether analog beamforming is desired across multiple RFICs. For an antenna subarray that needs to achieve analog beamforming for all of its antenna elements, a single PLL should be used to derive the LO signal for all the RFICs used to drive the antenna subarray. If multiple RFICs are used, the single PLL is then preferably outside of the RFICs. In the case when a single RFIC is used, the PLL can be integrated into the RFIC.

Note RF phase shifting does not have this PLL phase synchronization issue because analog beamforming is done in RF domain. There is only one RF mixer for the multiple RF channels going through the same analog beamformer. This is yet another advantage of RF phase shifting.

4.2 MMWAVE & MASSIVE MIMO – A MATCH MADE IN HEAVEN

Significant synergies exist between mmWave frequencies and massive MIMO technologies. While mmWave makes massive MIMO practical, massive MIMO makes mmWave viable for mobile broadband.

On one hand, mmWave 5G systems have to rely on antenna arrays and analog beamforming to achieve the desired cell radius of 100 m – 1 km for wide area coverage. The link budget that a 5G system needs to achieve such a cell radius in an urban environment is around 140 – 150 dB. At mmWave frequencies, this can only be achieved with large number of antennas (and massive MIMO processing) on both the base station and the mobile station. On the other hand, massive MIMO needs a large number of antennas to work, which is only feasible in practice when the carrier frequency is high and the antenna elements are small. Going into mmWave frequencies makes it possible to have hundreds of antenna elements at the base station and a few tens of antenna elements at the mobile station within the same or smaller form factor as the base stations and mobile stations we have today. For example, at 39 GHz, a 16×16 patch antenna array will only have dimension around 60 mm × 60 mm, which can be easily accommodated in a base station or access point form factor. In comparison, a 16×16 patch antenna array at 3 GHz would have a size around 800 mm × 800 mm, making the antenna array very difficult to manufacture and install.

Massive antenna arrays provide the ability to exploit the spatial domain in much finer granularity than what's possible in the legacy cellular systems. A few multiple antenna technologies already exist to unleash the power of massive antenna arrays. The first technology is beamforming, by which the transmitter and receiver can find and track the most advantageous spatial directions to transmit and receive signals. One form of this technology has been implemented in the WiGig/11ad standard, which is proven effective in short-range (with footprint similar as or smaller than Wi-Fi hotspots) and low-mobility (stationary to pedestrian speed) environment. However, 5G will require a new design to support beamforming in a mobility environment with much larger coverage. The second technology is MIMO. While beamforming can enable the transmitter and receiver to transmit and receive along the most advantageous path thus increasing signal and reducing interference, MIMO provides the ability to transmit and receive multiple spatial streams, which multiply the throughput (and thus spectral efficiency) delivered in the same piece of spectrum.

MIMO technology has been well researched and deployed in mobile communication systems since its inception.[30] There are two main challenges that makes the extension of MIMO technology to massive antenna arrays not as straightforward as we would like. First, the MIMO technology developed in the past 2 decades for mobile communication largely focused on sophisticated processing of multiple streams of digitized signals. This is manageable for 2, or 4, or 8 streams with each stream only having 20 – 100 megahertz of bandwidth, as in the case of LTE or LTE-Advanced. However, a complete digitization of received signals from all antenna elements for 5G is not practical with the circuit technology today. As an example, for a moderate base station configuration of 64 antenna elements, converting all received signals to baseband would require 64 complete transceiver chains from mmWave frequencies to baseband. Secondly, to digitize all received signals, 64 ADC would be required. Since we envision 5G system bandwidth will be around 100 megahertz to 1 gigahertz, each ADC would need to operate at multi-gigahertz sampling rate. Therefore, a brute-force implementation of an all-digital transceiver would have 64 complete mmWave transceiver chains, and 64 ADCs operating at multi-gigahertz sampling rate. This design, while

[30] Gerard. J. Foschini and Michael. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," Wireless Personal Communications, vol. 6, no. 3, pp. 311–335, 1998

not technologically impossible, would push the complexity and cost of devices so high that will severely limit the market and commercial success of 5G.

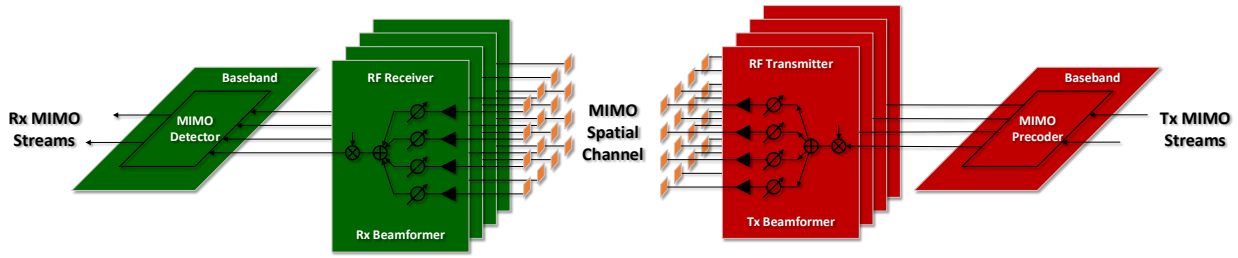

Figure 1. Analog & Digital Array Processing Technique (ADAPT)

The solution to this problem lies in the harmonious combination of digital MIMO processing with analog beamforming, which we call Analog & Digital Array Processing Technique (ADAPT). This is achieved by partitioning the antenna array into multiple subarrays, with analog beamforming within each subarray, and digital MIMO processing across subarrays, as illustrated in Figure 1. The analog beamforming stage can be used to align the transmitter and receiver beams towards the dominant spatial paths, while the digital MIMO processing can further resolve the channel and optimize the transmission and receiving MIMO strategy based on the effective MIMO channel as a result of the spatial channel and the analog beamforming. Some of the early work has shown the asymptotic optimality of this approach as the number of antenna elements approach infinity.[31] Nevertheless, the ADAPT approach loses some flexibility in MIMO processing compared with the all-digital MIMO processing. Within each antenna subarray, there is no flexibility in applying different beamforming to different frequencies within the system bandwidth. On the other hand, the benefit of analog beamforming is that the received signal from multiple antennas are combined into one in the analog beamforming process, reducing the number of streams to be digitized and processed in the baseband. In addition, analog beamforming also reduces the reference signal overhead by reducing the number of digital MIMO streams because each digital MIMO stream requires its own reference signals for the receiver to estimate the channel.

In a typical cellular system, radio waves travel along a few dominant spatial directions between the transmitter and the receiver. This is particularly the case for mmWaves, whose propagation characteristics is more specular than lower frequencies. In 5G systems, base stations are typically installed on locations with good clearance to achieve good coverage. As a result, the base station can concentrate transmission power to a specific direction when transmitting to a mobile station. However, this is often not the case at the mobile station. Mobile stations are often surrounded by many objects, such as buildings, walls, trees, pedestrians, vehicles, etc. The radio waves to and from these mobile stations are often dispersed and exhibit much weaker spatial concentration than that at the proximity of base stations. As a result, there is less spatial gain to be had at mobile stations. This observation suggests that we should have higher gain (and thus larger) antenna arrays at the base station than those at the mobile station, which works out nicely for 5G as it matches with the fact that in general there is space for more antenna elements at the base station than that at the mobile station.

The spatial characteristics of a channel, such as angles of arrival (AoAs) and angles of departure (AoDs), typically are dictated by the surrounding environment that changes slowly (on the order of 10 ~ 100ms). For example, a vehicle moving at 120 kmph (75 mph) will take 30 ms to move about 1 meter, at

[31] El Ayach, O.; Rajagopal, S.; Abu-Surra, S.; Zhouyue Pi; Heath, R.W., "Spatially Sparse Precoding in Millimeter Wave MIMO Systems," Wireless Communications, IEEE Transactions on , vol.13, no.3, pp.1499-1513, March 2014

which point a change of long-term channel characteristics might occur, *e.g.*, the vehicle may move into the shadow of a building. This kind of long-term fading can be well tracked and adapted using analog-beamforming. The short-term fading of the channel occurs much faster, typically on the order of half of the wavelength of the carrier frequency. For a 39 GHz system, the channel can experience significant variation of channel coefficients if the vehicle moves half of the wavelength, which is about 3.75 mm. For a vehicle moving at 120 kmph, that only takes about 100 us. Fortunately, we can design the 5G system to adapt digital MIMO processing at that rate. Note this is also why the time slot duration in mmWave 5G systems needs to be around 100 us. With adaptation at this rate, and the flexibility of digital processing, channel sensitive scheduling and MIMO adaptation can be achieved to exploit the channel fading in time, frequency, and space.

Coincidentally, the 2-stage ADAPT with analog beamforming and digital MIMO processing matches very well with the long-term fading and short-term fading nature of the spatial channel. The analog beamformers can be used to track the long-term fading in AoDs and AoAs. Since these changes are slow, the analog beamformers for a mobile station only changes on the order of 10 ~ 100 ms. From 5G system perspective, the adaptation of analog beamformers should preferably be implemented via mobility management mechanisms to ensure reliability. The digital MIMO processing can be used to maximize spectral efficiency by transmitting and receiving multiple MIMO streams on the effective spatial channel formed by analog beamforming. Note the channel coefficients changes due to short-term fading can be fast (with a time constant on the order of 100 us). The transmitter needs to transmit sufficient demodulation reference signals to aid the receiver in detecting the digital MIMO streams. Table 2 summarizes our recommendations on how to utilize ADAPT most effectively to track and resolve the large-dimensional spatial channel with massive transmitter and receiver antenna arrays.

Table 2. Design guidelines for using ADAPT to track spatial channel for massive antenna arrays

ADAPT Stage	Channel State Information resolved	Time constant	Potential 5G Spec Impact	Reference Signal needed
Analog beamforming	Long-term / slow fading	10 ~ 100 ms	MAC Mobility Management & PHY Control Channel Signaling	Common reference signal
Digital MIMO processing	Short-term / fast fading	100 us ~ 1 ms	PHY Control Channel Signaling	Demodulation reference signal

4.3 SMALL CELLS – SMALL BASE STATIONS, NOT SO SMALL FOOTPRINT

As the link budget analysis[32] shows, the mmWave 5G cells are going to be small with cell radius ranging between 100 m and 1 km. However, these small cells are not to be confused with the notion of femto cells, which has about the same footprint as a Wi-Fi access point and are typically used in indoor environment. The 5G small cells need to be big enough to provide good coverage in metropolitan areas and sub-urban areas. In rural areas where the weather is dry and there is no heavy foliage, 5G small cells can achieve cell radius well beyond 1 km and can be economically viable for areas with low population density. The distinctive technical merit and competitive advantage of 5G is the ability to provide *wide-area* Gbps mobility. This is a crucial point that the mobile industry should keep in mind in researching and developing standards and products, deploying networks, and marketing and providing services to customers.

[32] *See* Appendix A, "Examples of 39 GHz mobile network link budget"

First of all, a bit delivered in an outdoor mobile environment is more valuable than a bit delivered indoor or in short range. The value of wireless connectivity indoor is the freedom for the users not to be tethered to a fixed station to communicate or consume information. This value proposition, however, has been excelled by an alternative technology – Wi-Fi. Focusing on that value proposition means pitching 5G against Wi-Fi in Wi-Fi's stronghold, which is neither smart nor productive. That is not to say there is no place for indoor 5G deployment, or indoor cellular deployment in general. However, the mobile industry should not expect that – *i.e.*, indoor or hotspot Gbps connectivity – to be the main value (or revenue) driver for 5G. Operator's preference in deploying 5G (or other licensed technology) or Wi-Fi (or other unlicensed technology) should solely be based on which technology is superior in providing the desired user experience with lower CAPEX and OPEX. From cost perspective, Wi-Fi has a strong advantage because of the cost of equipment is low, and spectrum is free.

Cellular (including 5G) excels where Wi-Fi fails. Let's take the Dallas Fort Worth Metroplex as an example. The Metroplex encompasses 9,286 square miles (24,100 km^2) and has an estimated population of 6.9 million (2014 U.S. Census)[33]. In order to provide 5G coverage in the city, about 9,000 5G cells would be required (assuming 1-km cell radius). Try that with Wi-Fi. Assume 50 meter coverage for each Wi-Fi hotspot (which is already a very generous assumption). It will take about 3.6 million Wi-Fi hot spots. Basically, you have to install one Wi-Fi access point for every two "potential" customer, which is clearly not an economically viable solution.

The moral of the story is that cellular and Wi-Fi each has its strength, and its place in providing the next generation broadband experience. Understanding what 5G should be, in consideration of the strength and weakness of Wi-Fi technologies and other communication technologies and systems (Bluetooth, Bluetooth low power, GSS satellite communication, LEO satellite communication, balloons, etc.), is crucial in maximizing the commercial success and return on investment for 5G. It is unlikely for Wi-Fi, or any unlicensed technology for that matter (*e.g.*, LTE-U), to provide the meaningful user experience upgrade in a wide area mobility environment that can justify a generational upgrade of a mobile broadband operator's network. Wi-Fi and other unlicensed technology, however, can be useful complements in filling coverage holes or providing extra capacity in hot spots.

The core value of 5G is the quantum leap of user experience in wide area mobility environment. This value proposition can only be realized by a significant increase of guaranteed, typical, and peak data rate that a user can enjoy, and a significant increase in capacity. This point has been well recognized in the industry. Hence the discussion in the industry about 1000x capacity improvement for 5G. However, there is still plenty of work in 4G evolution that is continuously improving the capabilities and features of LTE based systems. This situation is no different than what has happened in the past generations. When 3G (WCDMA) was under development, 2G continued its evolution with GPRS, EDGE, and EDGE+. When 4G (LTE) was under development, 3G continued its evolution with HSPA+. We expect 4G will continue to evolve below 6 GHz, with enhanced capabilities and features. However, we expect these enhancement to be rather limited in comparison with existing 4G systems (LTE or LTE-Advanced). For example, it is expected FD-MIMO, a key technology for further evolution below 6 GHz, to be able to provide up to 2x spectral efficiency improvement over LTE. With limited spectrum available below 6 GHz, this cannot achieve the 1000x capacity improvement and Gbps user experience we expect from 5G. Moreover, the spectrum below 6 GHz has become exceedingly expensive. For instance, operators in the US spent $45 billion on 65 MHz of spectrum in the AWS-3 band, averaging more than $2 per MHz-POP. In order to deliver Gbps user experience, a few hundred megahertz of spectrum would be needed. In the US with more

[33] https://en.wikipedia.org/wiki/Dallas%E2%80%93Fort_Worth_metroplex

than 300 million population, the cost of spectrum would be a few hundred billion dollars for such a system. In other words, the spectrum cost alone, for Gbps mobile broadband system below 6 GHz, would likely make the system economically unviable. So, let's make it clear. Sub-6 GHz is great for providing mobile broadband coverage on the order of 10 Mbps – 100 Mbps. But for Gbps mobile broadband experience, mmWave is the solution.

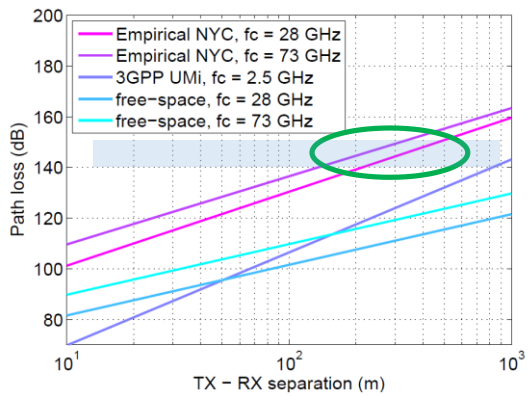

Figure 2. Path loss of mmWave in urban areas[34]

In rural areas where there is no frequent heavy rain fall or heavy foliage, 5G small cells can achieve a cell radius well beyond 1 km and can be economically viable for areas with low population density. As shown in Figure 3, much of the world land mass falls under rain regions A – M, which experience rainfall intensity greater than 22 mm/hr less than 0.1% of the time. For 5G communication at 39 GHz, 22 mm/hr translates into around 6 dB/km rain loss. In rural areas where line of sight or near line of sight can often be established, a 5G system with 150 dB link budget can achieve cell radius of 3 km (~25 km^2 area coverage). As an example, assume annual ARPU of $500, and annualized CAPEX + OPEX of $25k per cell, an operator would need on average of 50 subscribers per cell to break even. Assuming 20% market penetration, an operator will need 250 *potential* subscribers within each cell to break even, which translates into a population density of 10 person / km^2. Luckily, the vast majority of population in the United States and the rest of the world live in areas with population density higher than that. Note that with the 5G system configuration as shown in the link budget analysis[35], 300 Mbps can be achieved with 150 dB link budget. The system coverage can be further extended, albeit with reduced level of services or level of availability.

[34] Akdeniz, M.R.; Yuanpeng Liu; Samimi, M.K.; Shu Sun; Rangan, S.; Rappaport, T.S.; Erkip, E., "Millimeter Wave Channel Modeling and Cellular Capacity Evaluation," Selected Areas in Communications, IEEE Journal on , vol.32, no.6, pp.1164,1179, June 2014

[35] *See* Appendix A, "Examples of 39 GHz mobile network link budget"

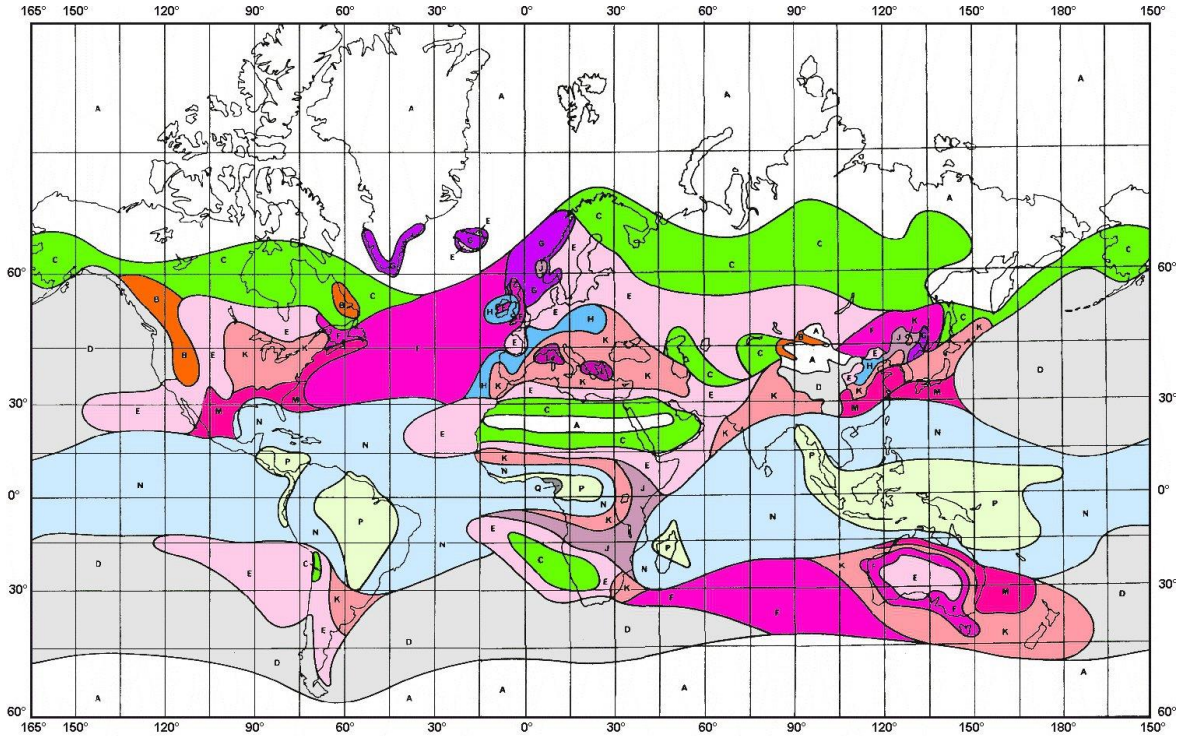

Figure 3. ITU rain statistics[36]

In summary, it is utterly important for the industry to recognize that mmWave 5G is a wide area mobility solution, *not* a femto cell or hot spot technology. It is on the value proposition of wide area mobile broadband that 5G has the greatest competitive advantage in performance and cost against other alternatives. It is also on this value proposition that 3G and 4G mobile broadband have achieved great commercial success, which 5G must continue to focus and excel.

5 5G SPECTRUM

Which spectrum to focus on heavily depends on the value 5G to add to the ICT ecosystem. As discussed above, the distinct value proposition of 5G is Gbps mobility. The key metrics are 1000x capacity increase over 4G, and Gbps user experience in mobile environment. These metrics can only be achieved with a large amount of spectrum on the order of 100 megahertz – 1 gigahertz per system. With multiple operators, we expect at least 2 – 3 gigahertz of spectrum will be needed even in the initial phase of 5G deployment. The 5G NOI proceeding from the FCC[37] and the 5G CFI from the Ofcom[38] demonstrate that it is extremely difficult, if not impossible, to obtain that amount of spectrum below 24 GHz.

[36] http://leleivre.com/rf_mmwavelink.html

[37] *Use of Spectrum Bands Above 24 GHz For Mobile Radio Services, et al.*, Notice of Inquiry, 29 FCC Rcd. 13020 (2014) ("*5G NOI*"), available at https://apps.fcc.gov/edocs_public/attachmatch/FCC-14-154A1.pdf

[38] "Laying the foundations for next generation mobile services: Update on bands above 6 GHz", available at http://stakeholders.ofcom.org.uk/binaries/consultations/above-6ghz/5G_CFI_Update_and_Next_Steps.pdf

In order for 5G to be competitive as a mobile broadband technology, 5G cells need to have large coverage. We recommend the footprint of 5G cells to be at least 2 orders of magnitude larger than Wi-Fi hotspots. In other words, for the same coverage area that needs a few hundred Wi-Fi access points, a single 5G cell should suffice. This positioning provides a non-overlapping value proposition between cellular and Wi-Fi, and collectively creates the largest possible value for the wireless industry. This also means the solid state electronics in 5G frequency need to deliver a few watts of power and a similar level of EIRP (~60 dBm) as cellular systems.[39] In addition, the transceiver needs to be efficient enough that the heat generated per base station is less than 100 Watts in order to allow compact form factors for 5G base stations to facilitate successful deployment of a large number of 5G small cells. In other words, the power amplifier efficiency needs to be on the order of 10 – 20% when operating in the linear region (with improvement to 20 – 40% efficiency in future iterations). All these requirements collectively mean that it will be extremely difficult to make 5G technically viable in bands beyond the 60 GHz band (starting from 57 GHz beyond which the oxygen absorption exceeds 10 dB/km). The power amplifiers above 60 GHz can rarely deliver more than 1 Watt of power, with linear efficiency on the order of a few percent. The additional losses in the system (feed lines, interconnects, package, etc.) are also noticeably larger. Given the state of the art of solid state electronics technology today, we believe 60 GHz and above can be better utilized for unlicensed technologies and point-to-point microwave communication.

Therefore, we believe the prime spectrum for 5G is between 24 GHz and 57 GHz from both the regulation and technology perspective. While this range is already much narrower than the 3 – 300 GHz range that was originally proposed for millimeter-wave mobile broadband,[40] we still need to identify actual frequency bands that can be made available for 5G within this range. From the ITU perspective, about 21 gigahertz of spectrum in the 24 – 57 GHz range has primary mobile allocation across all 3 ITU regions (See Figure 4). However, many other services (FSS, MSS, terrestrial fixed services, radio astronomy, etc.) also have primary allocation in these bands. This often leads to different regulation in different countries, complicating the global harmonization of 5G spectrum.

[39] *See* Appendix A, "Examples of 39 GHz mobile network link budget"

[40] Zhouyue Pi; Khan, F., "An introduction to millimeter-wave mobile broadband systems," Communications Magazine, IEEE , vol.49, no.6, pp. 101 – 107, June 2011

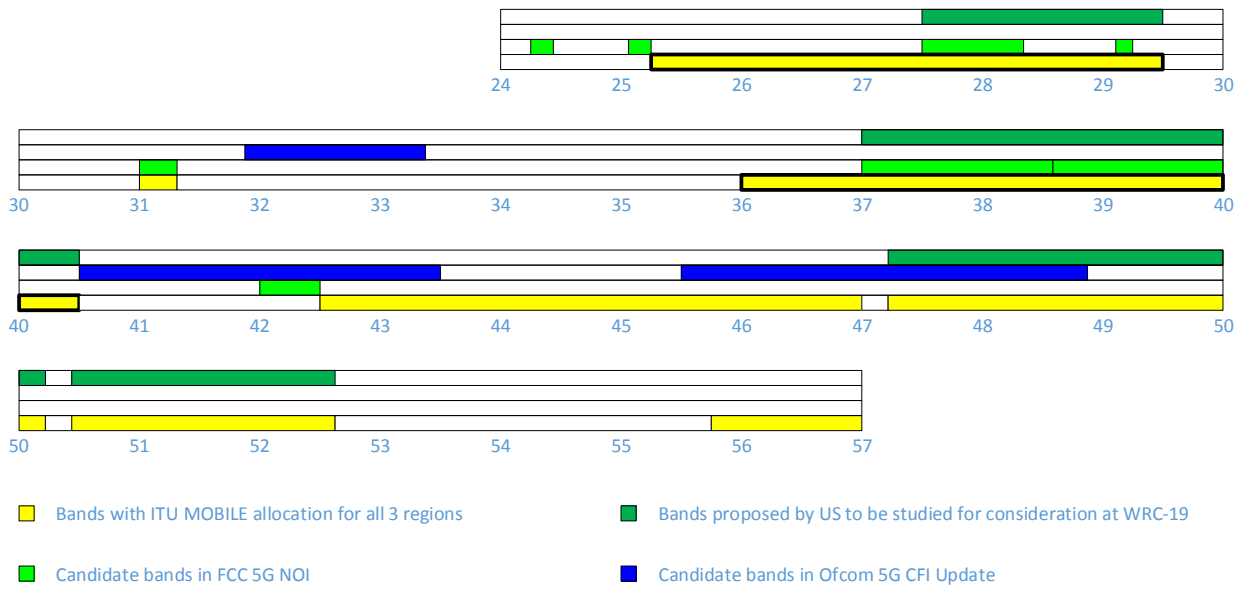

Figure 4. Candidate bands for mmWave 5G

It will be of great value to the industry if at least some bands can be made (mostly) globally available for 5G. For example, the 900/1800 MHz band for GSM in EMEA (ITU Region 1) and APAC (ITU Region 3) and the 850/1900 MHz for GSM in Americas (ITU Region 2) have greatly contributed to the commercial success of GSM. To this end, the bands within 24 – 57 GHz range in which mobile services are primary across all 3 ITU regions are a good starting point. These bands give the highest chance of success in global harmonization. So far both FCC and Ofcom have proposed bands between 24 and 57 GHz to be considered for 5G mobile broadband. The FCC proposal in its initial 5G NOI included 27.5 – 28.35, 29.1 – 29.25, 31 – 31.3, 37 – 40, and 42 – 42.5 GHz within the 24 – 57 GHz range. The Ofcom proposal in its updated 5G CFI included 31.8 – 33.4, 40.5 – 43.5, and 45.5 – 48.9 GHz within the 24 – 57 GHz range. The FCC's proposal in consideration of 5G mobile broadband in WRC-19 included 27.5 – 29.5, 37 – 40.5, 47.2 – 50.2, 50.4 – 52.6 GHz within the 24 – 57 GHz range.[41] These candidate bands are pictorially shown in Figure 4. Note that FCC's proposal (both in the 5G NOI and in the proposal for consideration in WRC-19) are well aligned with ITU allocations in which mobile service is primary in all 3 ITU regions.

Among these bands being proposed, we recommend that the mobile industry prioritize bands within the 25.25 – 29.5 GHz and the 36 – 40.5 GHz frequency blocks as primary targets to secure for 5G in WRC-19. These two frequency blocks are the two lowest multi-gigahertz frequency blocks with primary mobile allocation across the 3 ITU regions in the 24 – 57 GHz range. These frequency blocks are mostly desirable primarily because of the solid state device capability in these frequencies. It has been demonstrated that the desired per PA output (10 – 20 dBm linear power) and efficiency (>10%) can be achieved by GaAs, SiGe, and even CMOS power amplifiers in these frequencies. The commercial success of 5G hinges not only on designing and demonstrating the technological feasibility of mobile communication in mmWave frequencies, but also on achieving the aspiring performance goals at lower cost than previous generations. While this notion might invite suspicion, complaint, or even ridicule from telecom old timers, this is nothing new in the IT industry as computing has been getting cheaper and more powerful for decades. As the world

[41] Tom Wheeler, FCC Chairman, "Leading towards Next Generation "5G" Mobile Services," available at https://www.fcc.gov/blog/leading-towards-next-generation-5g-mobile-services

continues to observe and experience the convergence of IT and telecom, this is something that players in the converged ICT industry have to get used to and live with. It is therefore imperative for us as an industry to measure the investment required and risk associated with the technology innovations needed to accomplish this quantum leap.

The industry already has a lot of fundamental technological, economical, and business challenges ahead in order to make 5G successful even in these two frequency blocks, a few of which are highlighted as follows:

- Improve the performance of the solid state electronics (especially linear efficiency of power amplifiers) in these frequencies by at least 2x at the desired linear output power level of 10 – 20 dBm per PA
- Increase integration level of front end ICs by ~10x while at the same time driving down the cost by another ~10x (with total BOM cost reduction of ~100x for the front end)
- Drive down cost per site by ~10x with all cost inclusive, including equipment cost, real estate cost, backhaul, power, and cooling (if needed), and densify the network by ~10x
- Develop new "killer application" that leverage 5G to maximize the value proposition of Gbps mobility, *e.g.*, autonomous vehicles

Starting 5G deployment without any bands in the 25.25 – 29.5 GHz and the 36 – 40.5 GHz frequency blocks will significantly increase the technology challenges and business risks that may jeopardize the economic viability of 5G in its entirety, and fundamentally deprive the world of a much better broadband infrastructure with enormous economic and social benefits. On the contrary, a coordinated effort by nations prior to and during WRC-19 to make several bands in these two frequency blocks globally available will greatly increase economies of scale and economic surplus for 5G that will ultimately benefit consumers and economies of these nations. In the future, as device technology improves and as traffic demand makes it economically viable to further increase 5G network density, it may become possible to expand into higher spectrum beyond these two frequency blocks in future evolutions of 5G.

Even in these two frequency blocks, many services are already allocated and operations have commenced. These include fixed terrestrial services, fixed satellite services, mobile satellite services, radar detectors, high altitude platform station (HAPS), etc. To complicate things further, the allocation and utilization of these frequencies are different on a country by country basis. For example, in the United States, in addition to the point-to-point and point-to-multipoint deployment of backhaul and wireless broadband access in the LMDS bands (27.5 – 28.35, 29.1 – 29.25, and 31 – 31.3 GHz), the 25.25 – 29.5 GHz frequency block hosts airport body scanners, the NASA Tracking and Data Relay Satellite System, the NASA Deep Space Network, O3b, ViaSat, EchoStar XVII (Jupiter 1), and Iridium, with a few other services under development or being considered.[42] These existing operations and rights of incumbent licensees need to be protected while we expand mobile services into these frequencies. A few approaches could be considered to achieve such a goal:

1. *Expansion of service rules to include mobile services*. Regulatory bodies can consider expanding the service rules to allow the licensee of existing fixed services to additionally provide mobile services if there is only a single licensee in a certain frequency and geographical area. This is relatively straightforward if there is already a geographic service area based licensing mechanism in place, as is the case with the LMDS and the 39 GHz bands in the United States. In certain parts of the world (*e.g.* ITU Region 1), some of the bands in these two frequency blocks are extensively

[42] *See* http://www.spectrumwiki.com/wiki/SelectEntries.aspx for frequency range of 25500 MHz – 29500 MHz

used by operators as backhaul links for mobile communication networks. Fundamentally, these operators are likely to welcome making these spectrum bands additionally available for mobile services if they can retain the existing fixed operation while gaining the rights to deploy mobile services in the same spectrum. In case there are multiple licensees in the same frequency and geographic service area (most likely for point-to-point links), frequency swapping or reassignment can be considered to reduce the number of licensees per frequency per geographic service area. Certain incentive mechanisms can be introduced to facilitate consolidation of frequencies used by stations of a single licensee. For example, in each geographic service area, regulators can give favorable consideration to the licensee with the most number of stations in a single frequency channel while expanding service rights to include mobile service on that frequency channel.

2. *Incentive auction & migration.* If there are still multiple licensees in some frequency channels in certain geographic service areas after channel swapping and / or reassignment, incentive auction & migration to other bands can be considered. For example, for many of the point-to-point links with distance less than 1 km, E-band (71 – 76 and 81 – 86 GHz) will be a good migration destination as the technology is sufficiently mature and cost effective in that band for point-to-point links with much wider bandwidth and higher data rate.
3. *Grandfathering & exclusion zones.* If there are still multiple licensees in some channels in certain geographic service areas after incentive auction and migration, grandfathering & exclusion zones can be considered to protect the legacy stations and a sufficiently long sunset period can be considered to allow continuing operation of these legacy stations.

Despite all of the aforementioned methods, it is not realistic to expect all of the 25.25 – 29.5 and the 36 – 40.5 GHz frequency blocks to be made available for 5G. Nevertheless, current utilization of these frequencies is relatively low across all 3 ITU regions in comparison with spectrum below 3 GHz. We are hopeful at least a portion of these two frequency blocks can be made available for 5G while still satisfying the current and future needs of other services.

6 5G STANDARDIZATION

As was the case with previous generations, a global standard will be needed before 5G networks and devices can be developed and deployed. This task is undertaken by ITU and Standard Development Organizations (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, and TTC) worldwide via the partnership project 3GPP. Recently, ITU published a timeline for IMT-2020 ("5G"), which calls for initial submissions of IMT-2020 technology by Work Package 5D meeting #32 (June 2019) and final specification submission by meeting #36 (October 2020).[43]

[43] "Workplan, timeline, process and deliverables for the future development of IMT," available at http://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020/Documents/Antipated-Time-Schedule.pdf

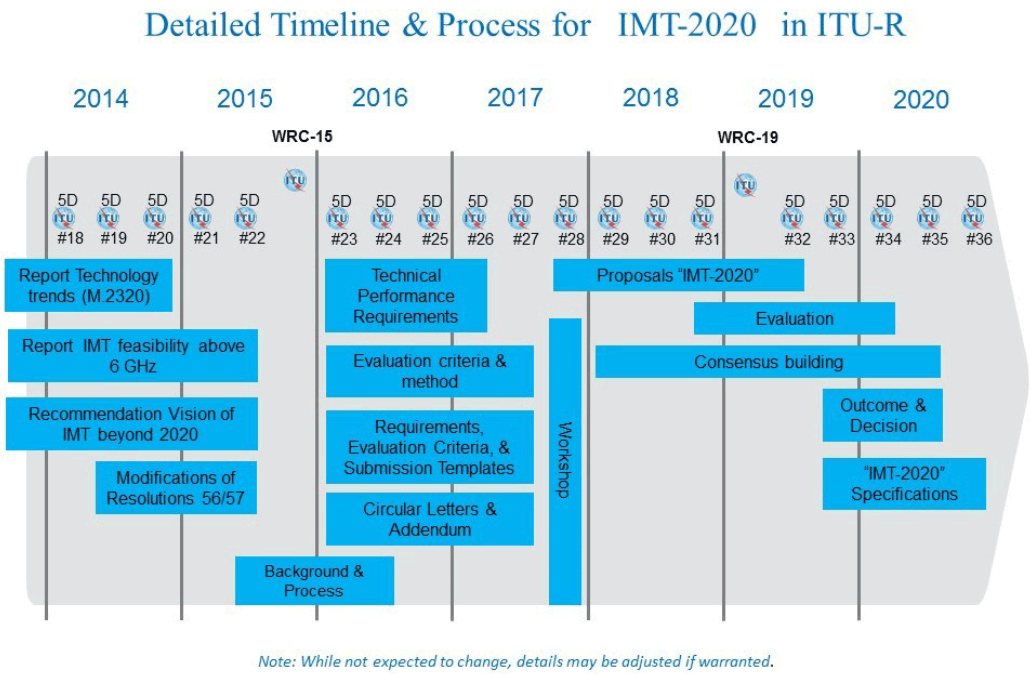

Figure 5. IMT-2020 Timeline[44]

In March 2015, 3GPP announced a tentative 5G development timeline in 3GPP (shown in Figure 6 below).[45] 3GPP decided to submit the final specifications at the ITU-R WP5D meeting in February 2020 based on functionally frozen specs available in December 2019. This early submission will allow enough time for the transposition of the specifications by the Organizational Partners of 3GPP prior to their own submissions into the IMT 2020 process before October 2020.

[44] *i.d.*

[45] 3GPP SP-150149, "'5G' timeline in 3GPP," available at http://www.3gpp.org/ftp/tsg_sa/tsg_sa/TSGS_67/Docs/

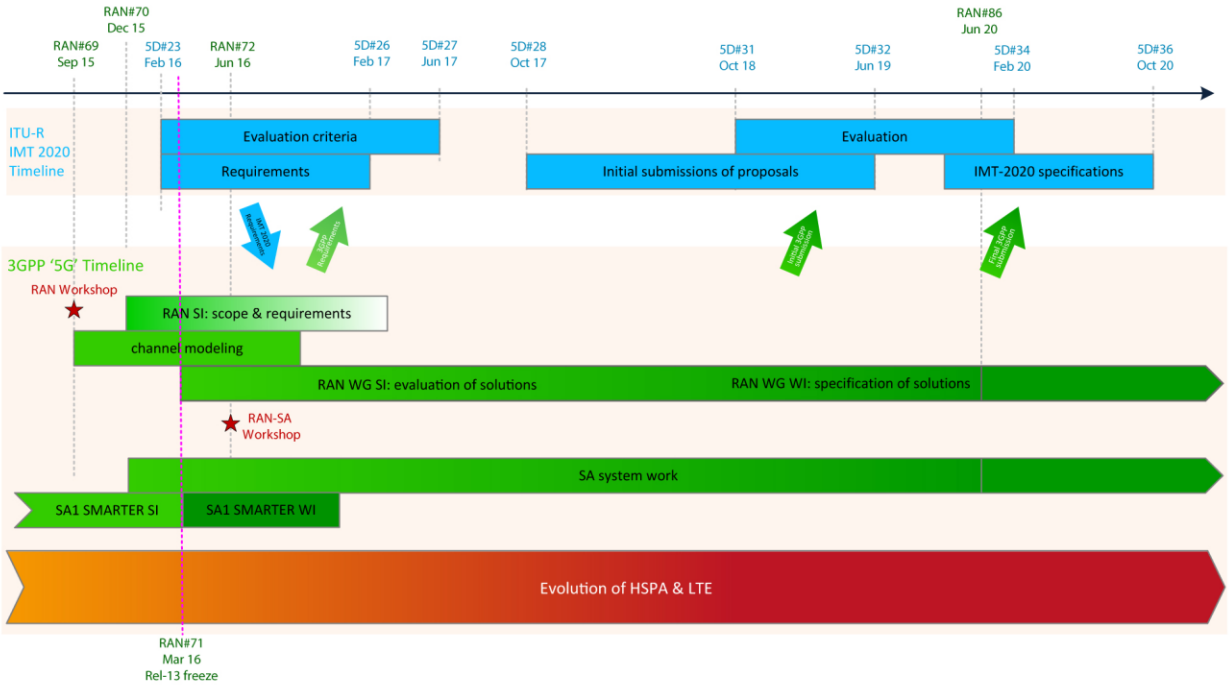

Figure 6. 5G timeline in 3GPP[46]

Some 5G related activities in 3GPP are already underway:

- 3GPP TSG RAN will hold a 5G workshop on September 18 – 19, 2015 co-located with RAN plenary meeting #69 in Phoenix, Arizona, U.S.A.
- 3GPP TSG RAN plans to start channel modeling activity for operations above 6 GHz in September 2015, and identify key bands of interest in Q4 2015. The channel modeling activity will be done on an ad-hoc/parallel session so as not to impact Release 13 schedule
- A RAN Study Item for next generation radio technology is expected to open in December 2015 to define use cases and requirements for IMT-2020 (5G).
- Discussion could start in the RAN working groups in March 2016, contingent upon the on time completion of Release 13 (the Release 13 spec is expected to freeze in March 2016).

As in previous generational evolutions, there will be dual tracks of standardization efforts, one for the continuous evolution of the previous generation and the other for the new generation. This has been the case in 3G evolution, during which an active GSM➔EDGE➔EDGE+ evolution path was ongoing. This has also been the case for 4G LTE, which was accompanied by 3G evolutions such as HSPA+. We expect the 4G LTE evolution path under 6 GHz will also continue in parallel with 5G standardization.

Although ITU targets to commercialize 5G worldwide by 2020, the global race to be the first in 5G is already on. South Korea and Japan have announced plans to demo and trial 5G technology in the PyeongChang Olympic Games[47] in February 2018 and in the Tokyo Olympic and Paralympic Games[48] in the summer of 2020. More recently, Verizon announced plans to begin field trials on 5G in 2016.[49] We

[46] *i.d.*
[47] http://www.koreatimesus.com/5g-network-defined-by-itu-as-20-gbs-per-second-demo-by-2018-olympics/
[48] https://www.nttdocomo.co.jp/english/info/media_center/pr/2015/0302_03.html
[49] http://www.cnet.com/news/verizon-to-hold-worlds-first-crazy-fast-5g-wireless-field-tests-next-year/

expect these activities to foster healthy competition among major industry players in developing and standardizing 5G technologies, and have positive impact on the 5G standardization schedule and equipment availability.

7 CONCLUSION

Innovation in the ICT industry will continue to flourish in the coming decade and will touch upon every part of the global economy and many aspects of our lives. 5G is a golden opportunity for the mobile communication industry to make mobile broadband one of the most valuable parts of the ubiquitous broadband infrastructure. To that end, the industry has set overarching goals for 5G, *i.e.*, Gbps mobility user experience and 1000x capacity increase over 4G. In this white paper, we detailed our 5G vision and explained why mmWave mobile broadband enabled by high-efficiency mmWave transceivers and massive MIMO signal processing is the best solution to that challenge from the perspectives of market, technology, and spectrum. We believe the most distinct value proposition and the strongest point of differentiation of 5G is Gbps mobility, whose value proposition can be maximally leveraged by applications in mobile content, mobile commerce, and autonomous transportation.

Internationally, we see a great opportunity for industry players and regulators to join efforts to make some of the bands in the 25.25 – 29.5 GHz and the 36 – 40.5 GHz blocks the "global bands" for 5G. Making multi-gigahertz spectrum globally available in these two frequency blocks is critical to achieving the capacity, data rate, coverage, and economics that are fundamental to the success of 5G. The ITU 5G timeline that targets June 2019 as the initial submission deadline of the IMT-2020 proposals brings clarity to the 5G timeline discussion. The global standardization is well underway with 3GPP expected to kick off 5G standardization activity in the 5G workshop in September 2015. The global race to be the first in 5G is fully on with South Korea and Japan announcing plans to demo and trial 5G technology in the PyeongChang Olympic Games in 2018 and the Tokyo Olympic and Paralympic Games in 2020, and Verizon announcing plans to begin field trials on 5G in 2016.

APPENDIX A – EXAMPLES OF 39 GHZ MOBILE NETWORK LINK BUDGET

39 GHz mobile network link budget	Downlink cell edge	Uplink cell edge	Downlink cell center	Uplink cell center
PA output power (dBm)	20	18	20	18
Number of PAs	64	16	64	16
Total output power (dBm)	**38**	**30**	**38**	**30**
Number of Tx antenna element	256	16	256	16
Tx antenna element gain (dB)	6	6	6	6
Antenna & feed network loss (dB)	3	5	3	5
Total Tx antenna array gain (dB)	**27**	**13**	**27**	**13**
EIRP (dBm)	**65.14**	**43.08**	**65.14**	**43.08**
Distance (m)	1000.00	1000.00	100.00	100.00
Path loss = 72 + 29.2log10(d) (dB)[50]	**159.60**	**159.60**	**130.40**	**130.40**
Received power (dBm)	-94.46	-116.52	-65.26	-87.32
Bandwidth (MHz)	500.00	500.00	500.00	500.00
Thermal noise (dBm)	-87.01	-87.01	-87.01	-87.01
Noise Figure (dB)	5.00	5.00	5.00	5.00
SNR (dB) per Rx antenna element	-12.45	-34.51	16.75	-5.31
Number of Rx antenna element	16	256	16	256
Rx antenna element gain (dB)	6	6	6	6
Rx antenna feed network loss (dB)	5	3	5	3
Total Rx antenna array gain (dB)	**13**	**27**	**13**	**27**
SNR after beamforming (dB)	**0.60**	**-7.42**	**29.80**	**21.78**
Implementation loss (dB)	3.00	3.00	3.00	3.00
Number of MIMO streams	1	1	8	8
Spectral efficiency (bit/channel use)	0.66	0.13	47.40	27.06
System overhead	40%	40%	40%	40%
Duty cycle	62.50%	37.50%	62.50%	37.50%
Throughput throughput (Mbps)	**122.86**	**14.09**	**8887.91**	**3044.15**

[50] Akdeniz, M.R.; Yuanpeng Liu; Samimi, M.K.; Shu Sun; Rangan, S.; Rappaport, T.S.; Erkip, E., "Millimeter Wave Channel Modeling and Cellular Capacity Evaluation," *Selected Areas in Communications, IEEE Journal on* , vol.32, no.6, pp.1164,1179, June 2014