

# Millimeter-Wave Beamforming as an Enabling Technology for 5G Cellular Communications: Theoretical Feasibility and Prototype Results

*Wonil Roh, Ji-Yun Seol, JeongHo Park, Byunghwan Lee, Jaekon Lee, Yungsoo Kim, Jaeweon Cho, and Kyungwhoon Cheun, Samsung Electronics Co., Ltd.  
Farshid Aryanfar, Samsung Research America*

## ABSTRACT

The ever growing traffic explosion in mobile communications has recently drawn increased attention to the large amount of underutilized spectrum in the millimeter-wave frequency bands as a potentially viable solution for achieving tens to hundreds of times more capacity compared to current 4G cellular networks. Historically, mmWave bands were ruled out for cellular usage mainly due to concerns regarding short-range and non-line-of-sight coverage issues. In this article, we present recent results from channel measurement campaigns and the development of advanced algorithms and a prototype, which clearly demonstrate that the mmWave band may indeed be a worthy candidate for next generation (5G) cellular systems. The results of channel measurements carried out in both the United States and Korea are summarized along with the actual free space propagation measurements in an anechoic chamber. Then a novel hybrid beamforming scheme and its link- and system-level simulation results are presented. Finally, recent results from our mmWave prototyping efforts along with indoor and outdoor test results are described to assert the feasibility of mmWave bands for cellular usage.

## INTRODUCTION

The bandwidth-intensive immersive media services that were earlier confined to wired transmission are now making a foray into mobile devices. Video traffic constitutes a significant 51 percent of the mobile traffic volume and is expected to increase to 67 percent by 2017 [1, 2]. Full high definition (Full HD) video is also being increasingly shared through social media such as YouTube, and ultra HD (UHD) and 3D

video content will eventually take over in the not so distant future.

For the last several years, the telecommunications industry and academia have been investing significant amounts of research effort in fourth generation (4G) Long Term Evolution (LTE) to provide higher data rates to end users by improving spectral efficiency, deploying more base stations, and/or aggregating more spectra. While some of the LTE enhancements, such as advanced multiple-input multiple-output (MIMO), coordinated multipoint (CoMP), heterogeneous networks (HetNets), and carrier aggregation (CA), deliver the additional capacity needed to sustain the traffic surge for the next few years, none of them is seen as a viable solution to support the hundreds of times more traffic demands foreseen in 2020 and beyond, the so-called 5G era.

The race to search for innovative solutions to enable the 5G era has recently begun worldwide. In early 2013, the European Commission announced that it would invest €50 million in 2013 for 5G research in multiple projects such as METIS, quickly followed by the formation of the Chinese government-led IMT-2020 Promotion Group in February 2013 and the initiation of the Korean government-led 5G Forum in May 2013. While the standardization of 5G specifications in standards bodies such as the Third Generation Partnership Project (3GPP) and the formal ratification of 5G standards by the International Telecommunication Union (ITU) are still several years away, many share the vision that the peak data rate of 5G should be tens of giga-bits per second and offer gigabits per second experience to end users.

We also believe 5G systems should be capable of providing significant improvements in cell capacity and boost user data rates to accommo-

date rapidly increasing traffic demands of the future. Specifically, from the data rate perspective, we expect 5G systems to offer a minimum of 1 Gb/s data rate anywhere to provide a uniform gigabits per second experience to all users, and up to 5 and 50 Gb/s data rates for high-mobility and pedestrian users, respectively [3, 4].

As one of the most innovative and effective solutions to realize the aforementioned 5G vision and requirements, the use of large chunks of underutilized spectrum in the very high frequencies such as the millimeter-wave (mmWave) bands has recently gained significant interest [5–7]. Traditionally, due to the high propagation loss and lack of cost-effective components, among other reasons, these frequencies have mostly been utilized for outdoor point-to-point backhaul links or for carrying high-resolution multimedia streams for indoor applications, but not for cellular access links. In order to reform these underutilized spectra for future outdoor cellular applications, two key hurdles must be overcome: sufficiently large geographical coverage and support for mobility even in non-line-of-sight (NLoS) environments where the direct communications path between the transmitter and the receiver is blocked by obstacles.

In this article, we present how these two technical challenges may be overcome based on our recent simulation and experimental results. We first start by clarifying a common misunderstanding of the Friis equation [8] and the propagation loss at higher frequencies by presenting measurement results with an actual patch antenna at 3 GHz and an array antenna at 30 GHz of the same physical size. Some results and insights from recent mmWave channel measurement campaigns carried out in the United States and Korea are also summarized. We then propose a novel hybrid beamforming scheme that fully benefits from both analog and digital domain beamforming with exemplary results of link- and system-level simulations. Lastly, we provide a detailed description of our mmWave beamforming prototype and its latest field test results in indoor and outdoor environments.

## MMWAVE CHANNEL PROPAGATION: THEORY AND MEASUREMENTS

There have been concerns about utilizing mmWave frequency bands (as opposed to the traditional cellular frequency bands below 6 GHz) for mobile cellular communications. Some of these concerns regarding the propagation characteristics at higher frequencies such as higher penetration, precipitation, and foliage losses are legitimate even though the actual amounts of additional propagation losses vary depending on the material of the building, the strength of rain, or the thickness of foliage. The most common misunderstanding, however, of the propagation characteristics at higher frequencies is that they always incur a much higher propagation loss even in free space compared to lower frequencies, and thus are not adequate for long-range communications.

To clarify this misunderstanding, let us start with the Friis transmission equation, given by [8]

$$P_r = P_t + G_t + G_r + 20 \log \left( \frac{c}{4\pi R f} \right) [\text{dBm}] \quad (1)$$

where  $P_r$  is the receive power in unobstructed free space,  $P_t$  is the transmit power,  $G_t$  and  $G_r$  are the transmit and receive antenna gains, respectively,  $R$  is the distance between the transmitter and receiver in meters,  $f$  is the carrier frequency, and  $c$  is the speed of light. The received power can easily be seen as inversely proportional to the frequency squared when an ideal isotropic radiator ( $G_t = 1$ ) and an ideal isotropic receiver ( $G_r = 1$ ) are used at each end.

In reality, however, antennas or an array of antennas with antenna gains of  $G_t$  and  $G_r$  greater than unity are typically employed at both ends, and the antenna gains are proportional to the frequency squared given a fixed physical aperture size [8]. Given the same physical aperture size, therefore, transmit and receive antennas at higher frequencies, in fact, send and receive more energy through narrower directed beams, which is not commonly recognized [9]. In order to verify this, measurements have been conducted in an anechoic chamber using two antennas supporting 3 and 30 GHz, respectively, as shown in Fig. 1.

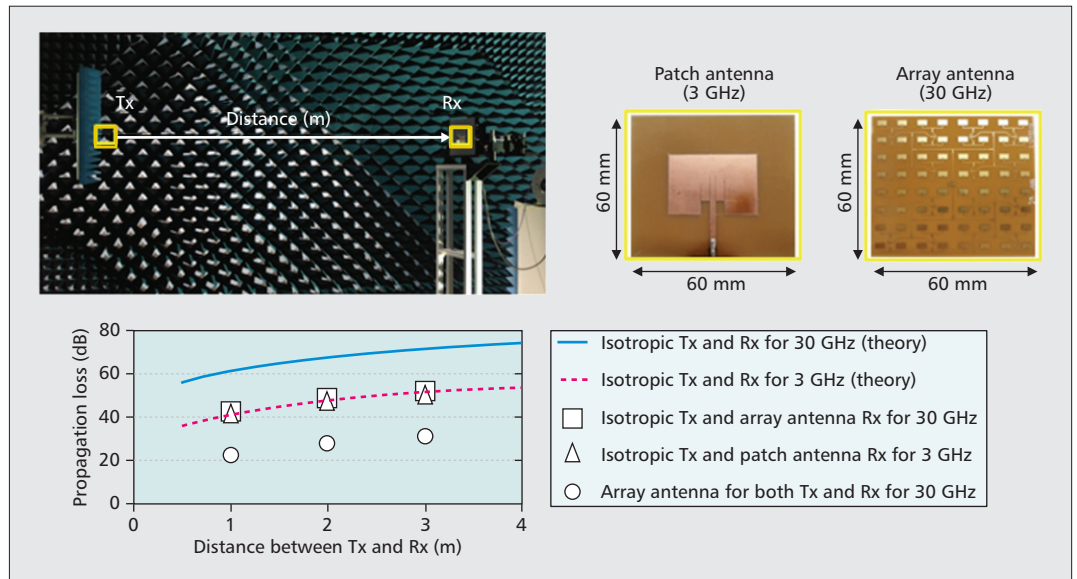
A patch antenna at 3 GHz and an array antenna at 30 GHz of the same physical size were designed for this measurement and placed within an anechoic chamber at each communication ends. As expected from the Friis equation and the argument above, the results in Fig. 1 show the same amount of propagation loss regardless of the operating frequency when an array antenna of the same physical aperture size is used at the 30 GHz receiving end. In addition, when array antennas are used at both transmitting and receiving ends at 30 GHz, the measured receive power is 20 dB higher than that of the 3 GHz patch antenna case.

Along with the aforementioned laboratory measurements, there have been recent studies regarding the outdoor channel propagation characteristics that have shown the potential for utilizing higher frequency bands for cellular communications [10–14]. In [10, 11], outdoor channel measurements were carried out at 38 and 28 GHz, respectively, on the campus of the University of Texas at Austin. Another channel measurement campaign was conducted at 28 GHz to produce measurement data for a suburban environment at the Samsung Electronics site in Suwon, Korea [3, 12]. In addition, investigation of the channel characteristics in a dense urban environment was done in Manhattan, New York [13, 14]. All these channel measurements were carried out at 38 and 28 GHz instead of 60 GHz and E-Band, with many aspects considered including regional regulatory status and availability of significant amount of licensed spectrum.

These study results reveal that the key parameters characterizing the propagation properties of the mmWave bands, such as the path loss exponent, are comparable to those of typical cellular frequency bands when transmit and receive antennas are used to produce beamforming

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The small wavelengths of mmWave frequencies facilitate the use of a large number of antenna elements in a compact form factor to synthesize highly directional beams corresponding to large array gains.



**Figure 1.** Results of verification measurements of propagation loss predicted by the Friis equation.

gains. For instance, transmission links were established for a distance of up to 200–300 m with path loss exponents in the range of 3.2–4.58 for NLoS and 1.68–2.3 for LoS environments, which are similar to those measured in the traditional cellular bands. Readers should note that path loss exponents below 2 are frequently observed due to constructive addition of the reflected and direct paths in street corridors or tunnels in LoS environments.

While more extensive measurement campaigns are currently being carried out by the authors of [10–14] in Korea and in the United States to build a comprehensive statistical mmWave channel propagation model, it is evident that the mmWave bands have strong potential as candidate bands for next generation cellular services. After the verification of the channel feasibility, the next step is to develop underlying core technologies to most efficiently utilize the abundant spectrum in the mmWave bands and prove commercial viability. We describe mmWave beamforming algorithms as a key enabler to practically obtain and manage high beamforming gains in cellular environments, followed by a detailed description of our mmWave prototype and its performance, respectively.

## MMWAVE BEAMFORMING ALGORITHM

As stated earlier, an appropriate beamforming scheme to focus the transmitted and/or received signal in a desired direction in order to overcome the unfavorable path loss is one of the key enablers for cellular communications at mmWave frequency bands. The small wavelengths of mmWave frequencies facilitate the use of a large number of antenna elements in a compact form factor to synthesize highly directional beams corresponding to large array gains.

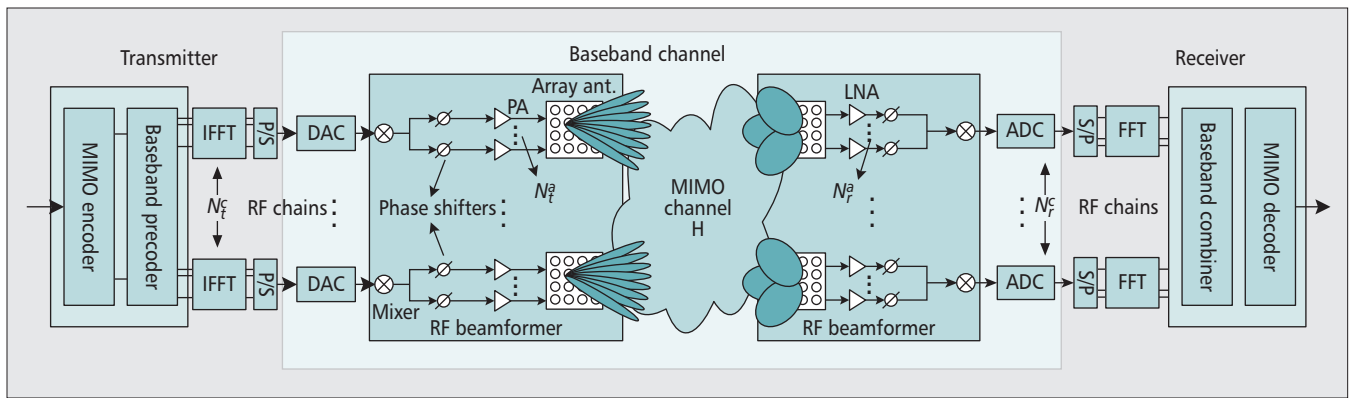
Depending on the beamforming architecture, the beamforming weights required to form the

directive beam could be applied in the digital or analog domain. Digital beamforming is done in the form of digital precoding that multiplies a particular coefficient to the modulated baseband signal per RF chain. For analog beamforming, on the other hand, complex coefficients are applied to manipulate the RF signals by means of controlling phase shifters and/or variable gain amplifiers (VGAs). When combined with an orthogonal frequency-division multiplexing (OFDM) system, digital beamforming is carried out on a subcarrier basis before the inverse fast Fourier transform (IFFT) operation at the transmitter and after the FFT operation at the receiver, whereas analog beamforming is performed in the time domain after the IFFT operation at the transmitter and before the FFT operation at the receiver.

In general, digital beamforming provides a higher degree of freedom and offers better performance at the expense of increased complexity and cost due to the fact that separate FFT/IFFT blocks (for OFDM systems), digital-to-analog converters (DACs), and analog-to-digital converters (ADCs) are required per each RF chain. Analog beamforming, on the other hand, is a simple and effective method of generating high beamforming gains from a large number of antennas but less flexible than digital beamforming. It is this trade-off between flexibility/performance and simplicity that drives the need for hybrid beamforming architectures, especially when a multitude of antennas is required as in the mmWave bands.

Figure 2 illustrates a hybrid beamforming architecture applied at both the transmitter and receiver. In this architecture, the sharp beams formed with analog beamforming (phase shifters) compensate for the large path loss at mmWave bands, and digital beamforming provides the necessary flexibility to perform advanced multi-antenna techniques such as multi-beam MIMO.

The simulated performance of the hybrid beamforming architecture in mmWave bands are



**Figure 2.** Block diagram of a hybrid beamforming architecture.

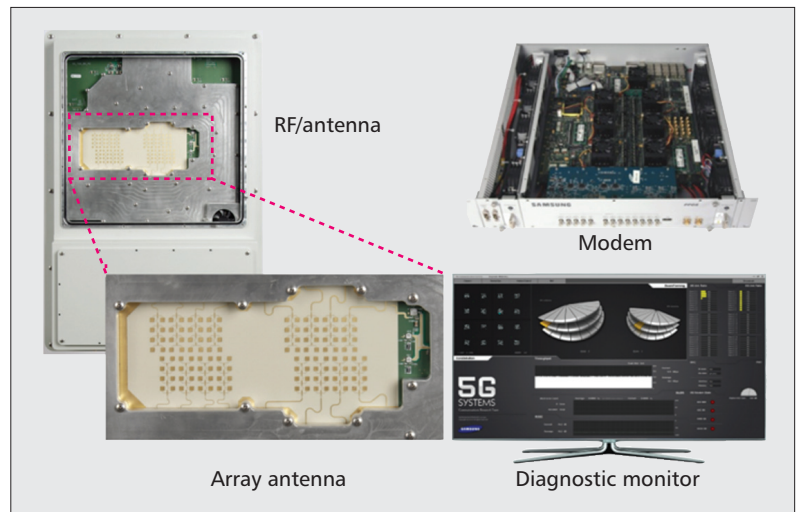
presented in [5], where link- and system-level simulation results are provided with various numbers of transmit/receive antennas and RF chains. Using a 500 MHz bandwidth at 28 GHz, [5] presents some notable results for the hybrid beamforming system including an 8 dB gain over the conventional spatial multiplexing scheme and 8 Gb/s average sector throughput with 16 antennas with 4 RF chains at the base station and 8 antennas with a single RF chain at the mobile station.

## MMWAVE BEAMFORMING PROTOTYPE

In this section, we present a detailed description of the mmWave beamforming prototype developed and tested at the DMC R&D Center, Samsung Electronics, Korea, including system configuration, key parameters, and capabilities. The main purposes of the mmWave prototype are to check the feasibility of mmWave bands for sufficiently large geographical coverage for cellular services and support for mobility even in NLoS environments. As a result, an mmWave adaptive beamforming prototype was developed including RF units, array antennas, baseband modems, and a diagnostic monitor (DM), as shown in Fig. 3.

Both transmit and receive array antennas have two channels and each comprises 32 antenna elements arranged in the form of a uniform planar array (UPA) with 8 horizontal and 4 vertical elements, confined within an area of 60 mm × 30 mm. This small footprint was made possible by the short wavelength of the carrier frequency at 27.925 GHz. Two channels at the transmit and receive array antennas are designed to support various multi-antenna schemes such as MIMO and diversity. The array antenna is connected to the RF unit, which contains a set of phase shifters, mixers, and related RF circuitry. The set of phase shifters control the phases of the signals sent to the antennas to form a desired beam pattern. Therefore, by setting the phase shifter values to a particular set, transmit and receive array antennas are capable of forming a sharp beam pattern in the intended horizontal (azimuth) and vertical (elevation) angles.

In order to reduce the hardware complexity, a sub-array architecture was employed to group



**Figure 3.** Configuration of the mmWave beamforming prototype.

8 antennas into a sub-array, thus requiring only 4 RF units per channel instead of 32. The reduction in the number of RF paths results in a reduction of antenna gain at the desired angle (except antenna boresight), a reduction of beam scanning ranges, and an increase in side lobe levels, but still meets the overall beamforming requirements. The resulting full width at half maximum (FWHM) of the beam at the antenna boresight is approximately 10° horizontally and 20° vertically with an overall beamforming gain of 18 dBi. In addition, a set of beam patterns is predefined to reduce the feedback overhead required for the adaptive beamforming operation between the transmitter and the receiver, where the overlapped beam patterns cover the intended service area with a unique beam identifier (ID) for each beam. These beam IDs are used by the baseband modem to control the phase shifter weights and to feed back the preferred transmission beam information to the transmitter. Table 1 lists key system parameters of the implemented prototype.

The baseband modem shown in Fig. 3 was designed and implemented for real-time operation with commercial off-the-shelf signal processing units including Xilinx Virtex-6 field programmable gate arrays (FPGAs), and an ADC and a DAC each with up to 1 Gs/s conver-



Key system parameters	Values
Carrier frequency	27.925 GHz
Bandwidth/FFT size	520 MHz/4096-FFT
Subcarrier spacing	244.14 kHz
Cyclic prefix size	0.18 × OFDM symbol
Modulation, coding (data rate)	QPSK, LDPC 1/2 (264 Mb/s) 16QAM, LDPC 1/2 (528 Mb/s)
Maximum transmit power	31 dBm (with 9 dB back-off), 1.26 Watts
Array antenna configuration per channel	8-element by 4-element (32 antennas) Uniform Planar Array
Array gain	18 dBi
FWHM	10° (Horizontal)/20° (Vertical)
Beam scanning range	±30° (Horizontal)
Effective isotropic radiated power (EIRP)	Max 49 dBm (Nominal 41 dBm)
Adaptive beam searching and switching time	45 ms

**Table 1.** Key system parameters of the mmWave beamforming prototype.

sion rate. The analog signal ports of the modem analog front-end (AFE) are connected to the RF/antenna input (output) port to transmit (receive) the complex analog baseband signal. Furthermore, the baseband modem is linked to a DM program developed to visualize the operational status of the system and collect system statistics including data throughput, packet error

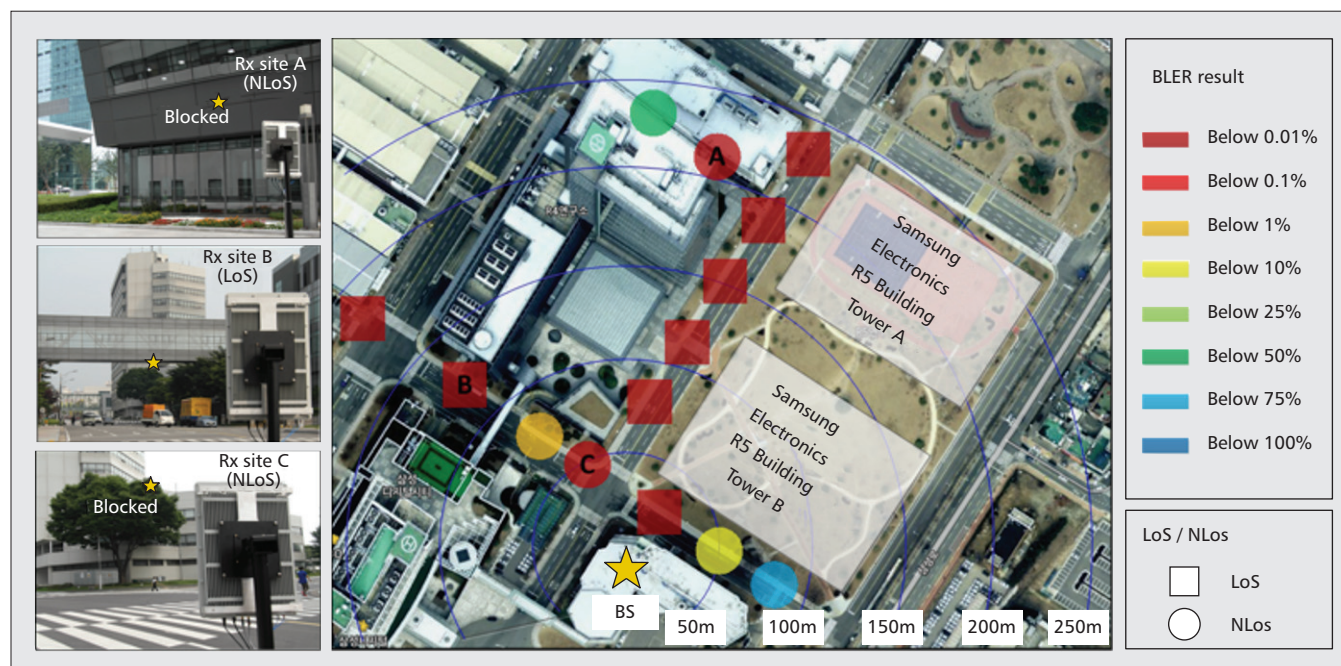
rates, transmit/receive beam IDs, received signal constellations, and signal strengths.

Two sets of the mmWave beamforming prototypes as specified above were built, playing the roles of a base station and a mobile station, and various laboratory and field tests in both indoor and outdoor environments were performed. For the downlink transmission, the base station periodically transmits a sequence of beam measurement signals in predefined beams so that the mobile station can carry out, also in predefined receive beams, channel quality measurements of the transmit-receive beam pairs and thus select the best beam pair for data transmissions. The selected base station transmit beam ID is fed back to the base station for the subsequent downlink transmission until the next update incident. In this fashion, the base and mobile stations quickly establish the wireless communications link and adaptively sustain the link even in high-mobility conditions. The communications link setup for the uplink is done in an analogous way where the roles of the base station and mobile stations are interchanged. The developed mmWave beamforming prototype was designed to complete the search for the best transmit and receive beam pair within 45 ms.

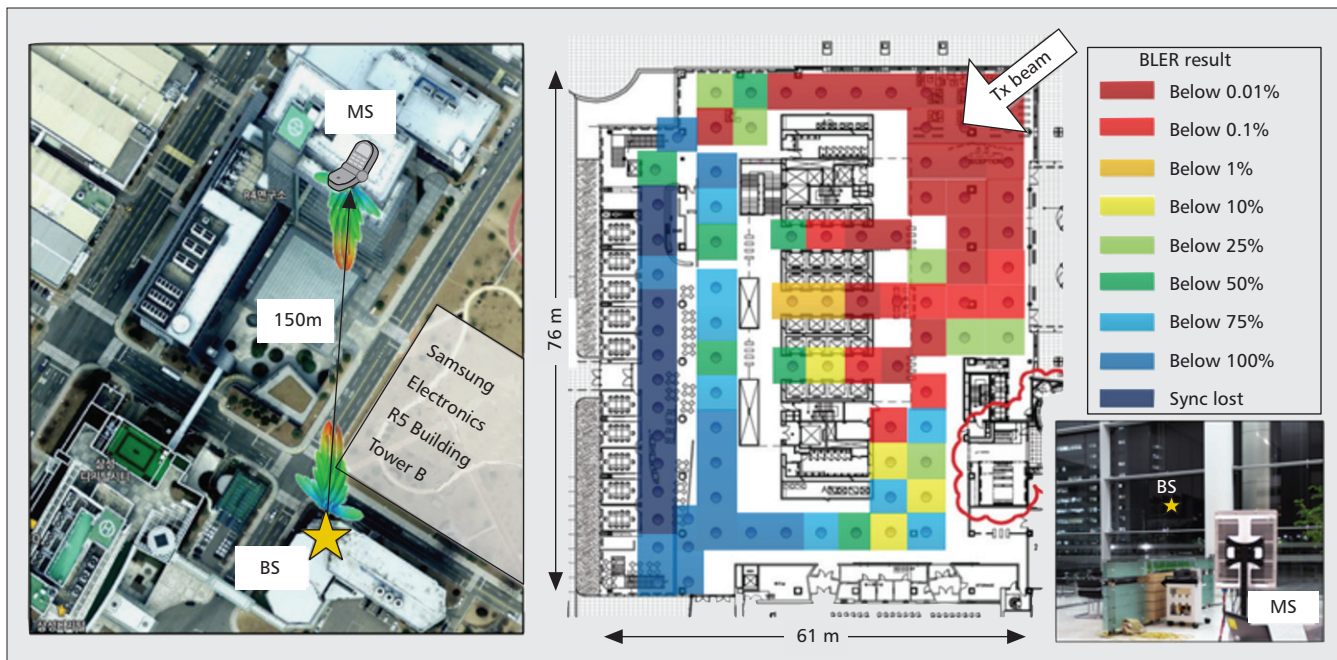
## PROTOTYPE TEST RESULTS

Using the mmWave adaptive beamforming prototype described in the previous section, rather comprehensive indoor and outdoor field tests were carried out at the campus of Samsung Electronics headquarters in Suwon, Korea in early 2013.

An aggregated peak data rate of 1.056 Gb/s was achieved in the laboratory with negligible packet error using two channels at the base station supporting two stationary mobile stations with 528 Mb/s each. In an outdoor range test in an LoS environment, the communication range



**Figure 4.** Outdoor coverage test results of the mmWave beamforming prototype.



**Figure 5.** Outdoor to indoor penetration test results of the mmWave beamforming prototype.

with negligible errors (block error rates, BLERs, of less than  $10^{-6}$  with a block size of 672 bits) was verified up to 1.7 km with transmission power headroom of 10 dB left over [15]. The 1.7 km limit was due to spectrum license issues, and the authors are confident that much longer ranges are in fact possible.

In addition, outdoor coverage tests were conducted to demonstrate the service availability in a typical outdoor environment for both LoS and NLoS sites. The tests were performed at sites surrounded by tall buildings where various channel propagation effects such as reflection, diffraction, or penetration are expected to take place, as shown in Fig. 4.

As can be seen from the test results in Fig. 4, satisfactory communications links were discovered even in NLoS sites more than 200 m away, mostly due to reflections off neighboring buildings. On the other hand, there were a few locations where a proper link could not be established (i.e., coverage holes), which necessitate solutions for coverage improvement such as optimized cell deployment, intercell coordination, relays, or repeaters.

Considering one of the important operation scenarios in practical cellular networks, communication between an outdoor base station and an indoor mobile station was also investigated. The test results, shown in Fig. 5, present link qualities between an outdoor base station to an indoor mobile station placed inside a typical modern office building with heavily tinted glass at more than 150 m separation. These types of buildings are representative of presenting highly unfavorable propagation (penetration) conditions even for current cellular frequency bands below 6 GHz.

As can be seen in Fig. 5, surprisingly amicable indoor coverage results were obtained with only the totally obstructed, farthest side of the building resulting in lost connections. While the

spots showing BLERs around 10~20 percent can be improved with conventional error correction schemes such as hybrid automatic repeat request (HARQ) and modulation/coding adaptation schemes, remaining coverage holes would need to be covered with other alternative schemes, such as repeaters and indoor femto-cells, as in traditional cellular systems.

Lastly, mobility support was also tested in an NLoS setup where the direct path was blocked by a tall building, and the mobile station was moving at a speed of 8 km/h in random directions [15]. The test results were extremely encouraging and resulted in error-free transmission at 264 Mb/s and less than 1 percent BLER at 528 Mb/s transmissions due to the fast adaptive beamforming algorithm running at both communications ends. As mentioned in the previous section, the design capability of the adaptive joint beam searching and switching algorithms implemented in our prototype could easily support mobility higher than 8 km/h. The verification of higher mobility support and hybrid beamforming schemes is currently underway, and the results will be published upon completion. We believe that these and ensuing results will provide a firm ground for the development of mmWave-beamforming-based 5G cellular networks.

## CONCLUSION

Wide bandwidth is the most effective and straightforward method to provide the foreseen data demands for 5G cellular services expected to be commercially available in 2020 and beyond. As the additional availability of spectrum for cellular usage in the lower frequencies becomes scarce, the significant amount of underutilized spectrum in the mmWave bands could potentially provide the answer to the very large bandwidth requirements for 5G. In this article, we show how these high frequencies exhibit them-



We believe our initial test results provide valuable insights and understanding of the high frequency bands for future cellular usage and urge experts in the industry to endeavor to research in this promising area.

selves as strong candidates for cellular bands with recent channel measurement, simulation, and prototype results.

First, the measured results for the propagation loss in free space that match the theoretical Friis equation are provided with actual patch antennas at 3 GHz and array antennas at 30 GHz of the same physical aperture, thereby clarifying the common misconception regarding the propagation loss at higher frequencies. A high-level summary of recent outdoor channel measurement campaigns carried out in the United States and Korea is also presented, highlighting the measured path loss exponents, which were comparable to those of conventional cellular bands. Then an advanced hybrid beamforming algorithm is described, exploiting both analog and digital domain beamforming, which not only offers sharp beamforming to cope with the propagation loss but also allows advanced digital domain processing such as multi-beam MIMO with manageable complexity.

The main portion of the article is dedicated to presenting the results of our recent mmWave prototype, which features a large system bandwidth in excess of 500 MHz at 28 GHz and supports tens of antennas placed in planar arrays at both ends of the communications. The prototype incorporates a real-time baseband modem, full mmWave RF circuitry, and relevant software. With this innovative adaptive beamforming system, we successfully demonstrated that the mmWave frequency band is capable of supporting a few-hundred-meter radius of outdoor and indoor coverage with more than 500 Mb/s data rate with support for mobility as high as 8 km/h even in NLoS environments. We believe our initial test results provide valuable insights and understanding of the high-frequency bands for future cellular usage and urge experts in the industry to endeavor to research in this promising area.

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## BIOGRAPHIES

WONIL ROH (wonil.roh@samsung.com) is currently a vice president and head of the Advanced Communications Lab at Samsung Electronics in Korea, responsible for research of next generation mobile communications technologies since 2011. He started working at Samsung in 2003 on development of CDMA and mobile WiMAX base stations, and led overall WiMAX standardization while serving as Chair of the Technical Working Group of the WiMAX Forum from 2006 to 2011. He holds a doctorate in electrical engineering from Stanford University, California.

JI-YUN SEOL (jiyun.seol@samsung.com) received B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from Seoul National University (SNU), Korea, in 1997, 1999, and 2005, respectively. He has been with Samsung Electronics Co., Ltd., Suwon, Korea, since 2004. He has years of experience in development of modem algorithms and standardization for mobile WiMAX. His current fields of interest include research/development of next generation mobile communication systems and advanced PHY algorithms.

JEONGHO PARK (jeongho.jh.park@samsung.com) received his B.Sc., M.Sc., and Ph.D. degrees in electronic engineering from Yonsei University, Seoul, Korea. Since he joined Samsung Electronics in 2005, he has mainly been engaged in standardization and algorithm development of wireless communications including IMT-Advanced systems. Currently, he is a director of the Communications Research Team at Samsung Electronics, and his research interests include beyond-4G and 5G technologies.

BYUNGHWAN LEE (bhsy.lee@samsung.com) is a senior engineer in the Advanced Communications Lab at Samsung Electronics. He received his Master's degree in electrical engineering from the Korea Advanced Institute of Science and Technology (KAIST). He has diverse experiences in wireless modem and signal processing system design. Since 2012 he has been involved in research on 5G mobile communication systems. His current research interests include millimeter wave beamforming system design and advanced modulation.

JAEMON LEE (today@samsung.com) is a principal engineer in DMC R&D center at Samsung Electronics. He received the B.S. degree from Hanyang University, Korea in 1991 in Electronic Engineering. He has experiences in development of wireless communication systems including 2G/3G/4G and Digital Multimedia Broadcasting, his current fields of interest include development of next generation mobile communication system.

YUNGSOO KIM (y2.kim@samsung.com) received his B.S. degree from Yonsei University, Korea, in 1987 in electronic engineering. He received his M.S. degree from the University of Wisconsin-Madison in 1989, and his Ph.D. degree from KAIST in 2000, respectively, both in electrical engineering. He joined the Samsung Advanced Institute of Technology, Korea, in 1991, and then transferred to DMC R&D Center at Samsung Electronics Co., Ltd., Suwon, Korea, in 2006. His current research interests are in beyond 4G and 5G mobile and wireless communications.

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JAEWEON CHO (jaeweon.cho@samsung.com) received his B.Sc., M.Sc., and Ph.D. degrees in electronic engineering from Sogang University, Seoul, Korea, in 1995, 1997, and 2002, respectively. From 1997 to 1998, he was with the R&D Center, Dacom Corporation, Daejeon, Korea. From 2002 to 2003, he was a postdoctoral associate at the School of Electrical and Computer Engineering, Cornell University, Ithaca, New York. In 2003, he joined Samsung Electronics Co., Ltd., Suwon, Korea. His research interests are in wireless communications and next-generation issues, including system architectures, physical and MAC layer algorithms, and performance analysis.

FARSHID ARYANFAR [S'01, M'05, SM'06] (f.aryanfar@samsung.com) received M.S. and Ph.D. degrees from the Universities of Tehran and Michigan, respectively. From 2000 to 2004, he was with RADLAB, building a W-band transceiver for characterizing wave propagation. He then joined Motorola, working on a holistic approach to MIMO

channel modeling. Later, he was with Rambus Inc. designing RF and millimeter-wave (mm-wave) circuits. He is currently a senior manager with Samsung, working on 5G cellular transceivers.

KYUNGWHOON CHEUN (kw.cheun@samsung.com) received his B.S. in electronics engineering from Seoul National University in 1985. He earned his M.S. and Ph.D. degrees from the University of Michigan, Ann Arbor in 1987 and 1989, respectively. He was an assistant professor at the University of Delaware from 1989 to 1991 and joined the Pohang University of Science and Technology (POSTECH) in 1991, where he is currently a full professor. Aside from his academic duties, he served as the CTO for Pulsus Technologies Inc. during 2004 to 2011, a Qualcomm partner company. Since 2012, he has been with Samsung Electronics DMC R&D Center as a senior vice president, and leads the Communications Research Team in the area of next generation cellular and Wi-Fi networks.