Analysis of mmWave Performance

Feasibility of Mobile Cellular Communications
at Millimeter Wave Frequency
July 2017

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Introduction

One of the major challenges of using the millimeter wave (mmWave) frequency band for cellular communications is that it suffers from a severe propagation loss compared with the lower frequencies that are used for current cellular systems. However, because of the short wavelength of the mmWave frequency, it is possible to build an antenna array with a large number of antennas in a given physical size, and to form a highly directional beam pattern with a very large antenna gain. By having such high-gain antennas at both the transmitter and receiver sides, and steering their beams to their best communication path, the loss due to high frequency can be almost completely compensated for.

The mmWave beamforming technique is well suited to communications in a stationary environment in a point-to-point manner, and is already used in the latest air interface for the wireless personal area network (WPAN) and the wireless local area network (WLAN). However, adopting the mmWave beamforming technique for mobile cellular communications faces many technical challenges.
The current cellular system is designed based on the base station (BS) and the mobile station (MS) with sector-wide antennas and omni-directional antennas respectively, at frequencies below 6 GHz, so its specification and air interface design cannot be directly used. Various characteristics of beamforming at mmWave frequencies must be taken into account in the new design. For example, cell search, random access, measurement of cells or beams, and various physical channels and signals, which are of crucial importance for mobile cellular communications, must be redesigned for mmWave beamforming.

A testbed was built at Samsung Electronics, Korea, to test the feasibility of mobile cellular communications using the mmWave beamforming technique [1], [2].
The testbed was built at 28 GHz with a bandwidth of 800 MHz and the time division duplex (TDD) mode.
At first, the testbed achieved 7.5 Gbps by transmitting four data streams to two MSs from a BS with four antenna arrays in stationary positions. Next, adaptive beamforming was tested for an MS moving at the speed of 110 km/h in a single-cell environment, and the testbed achieved 1.2 Gbps by transmitting a single data stream to the MS with the BS-MS distance up to 800 m. Finally, the testbed achieved mobile cellular communication in a three-cell environment for an MS moving at the speed of 20 km/h, and attained an average handover interruption time of 21 ms, satisfying the IMT-Advanced requirement of 27.5 ms [3].

High Data Rate Test for Two Stationary MSs

A testbed for millimeter-wave beamforming was developed at Samsung Electronics, Suwon, South Korea [1].
Figs. 1 and 2 show the RF and antenna units of the testbed at the BS and the MS respectively. Each unit housed two antenna arrays and related RF components, generating two beams simultaneously for signal transmission or reception. The RF transceiver consisted of a set of power amplifiers (PAs), phase shifters, mixers and related RF circuitry.
The phase shifter changed the phase of the signal transmitted by or received from each antenna element of the array, and determined the beam pattern formed by the antenna array.
A set of beam patterns was generated in advance and each beam pattern was assigned a unique beam identifier (ID). The phase shifter values for each beam pattern were stored either in the modem or in the RF unit.

The antenna array of Fig. 1 for the BS side consisted of 48 antenna elements; 8 horizontal elements by 6 vertical elements. This would have required 48 sets of phase shifters, mixers and RF paths. However, in order to reduce the hardware complexity of the RF unit, three antenna elements in the vertical direction were grouped as a sub-array, such that all the elements in a sub-array were connected to the same phase shifter, mixer and RF path.
As a result, only 16 sets of phase shifters, mixers and RF paths were constructed instead of 48 for each antenna array. The price to pay for adopting this sub-array structure was a reduction in the beam-scanning range and an increase in the side lobe levels of the beam patterns in the vertical direction, which, however, was small enough to meet our needs. The RF/antenna unit of Fig. 1 contained two antenna arrays with an identical array pattern; the two antenna arrays were positioned to face the same direction in order to provide the same coverage. The distance between the center positions of the two arrays was about 17 cm.

As for the MS, two sets of RF and antenna were developed, and Fig. 2 shows one of them. The MS RF/antenna unit consisted of two antenna arrays; each array consisted of four elements and was positioned at one of the edges of the RF board to provide horizontal beam coverage of either 90° or 180°. Therefore, the MS RF/antenna unit provided a total coverage of either 180° or 360°.
Table I lists the key parameters of the RF/antenna units of the testbed, and the transmit powers chosen were similar to those of the current system. The power consumption of the RF units due to analog beamforming, except for the power amplifiers, was insignificant.

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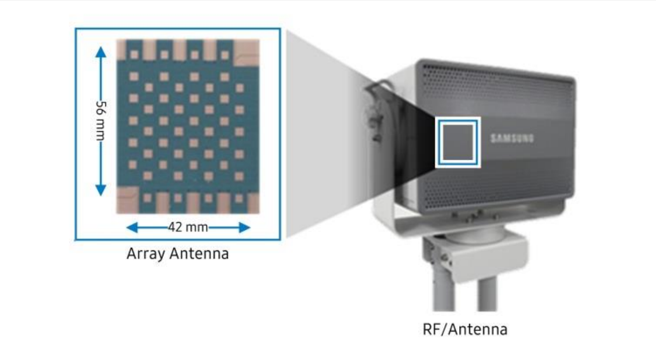

Figure 1. BS RF transceiver and antenna

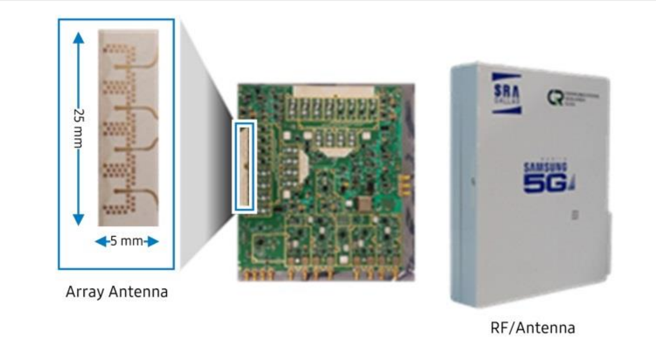

Figure 2. MS RF transceiver and antenna

Table 1. PARAMETERS FOR BS AND MS RF/ANTENNAS

Parameters	BS	MS
Carrier Frequency	27.925 GHz	
Bandwidth	800 MHz	
Max. Transmit Power	37 dBm	23 dBm
Number of RF Paths	16	4
Array Antenna Configuration	8 × 6 Planar	4 × 1 Linear
Max. Antenna Gain	21 dBi	7 dBi
Half-Power Beam Widths of the Center Beam	10° (H), 10° (V)	20° (H), 60° (V)
6 dB Antenna Coverage (Horizontal)	110°	90° or 180°
Effective Isotropic Radiated Power	58 dBm	30 dBm

Transmitting multiple streams of data to multiple users simultaneously using multiple beams is an effective way of increasing the data rate, and was tested as shown in Fig. 3. Two BSs were positioned in a near open space environment in close proximity to one another.

Each BS generated two beams and transmitted two streams of data simultaneously to an MS. The locations of the MSs and the directions of the beams from the BSs were chosen so that the interference between the MSs was minimized, and yet the angle between the directions towards the MSs from the BSs was less than 60°. The Data Slot in the testbed supported reference signals for four data streams with four transmit antenna arrays; each antenna array was assigned with unique reference signals that were different to those of other antenna arrays. This is equivalent to the case in which one BS with four antenna arrays transmits four data streams to two MSs. The Data Slot of the testbed can support various multi-antenna techniques of the 3GPP LTE.

However, digital precoding was not yet implemented in the test in Fig. 3. In the Fig. 3 test, each BS-MS path achieved the data rate of 3.77 Gbps by 2 × 2 MIMO, supporting two data streams with 64 QAM and 3/4 code rate with a block error rate (BLER) of about 0.017 %, so that the net data rate of 7.5 Gbps was achieved by the two MSs. Single User (SU)-MIMO in a Line-of-Sight (LOS) environment supporting multiple data streams is not always possible in general, but can be achieved when the BS-MS distance is short. For the antenna configuration of the testbed, 2 × 2 MIMO in LOS environment was supported for the BS-MS distance of up to about 20 m.

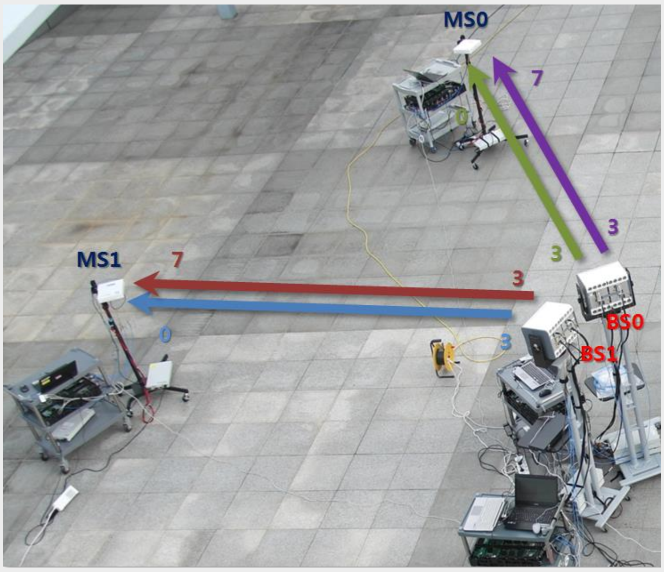

Figure 3. High data rate test with two BS-MS pairs

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Coverage Test

Using the mmWave adaptive beamforming testbed, indoor and outdoor field tests were carried out at Samsung Electronics headquarters in Suwon, South Korea [2].

In an outdoor range test in an LOS environment, the communication range with negligible errors (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. 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 Non-LOS (NLOS) sites. The tests were performed at sites surrounded by tall buildings where various channel propagation effects such as reflection, diffraction or penetration were 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, inter-cell coordination, relays or repeaters.

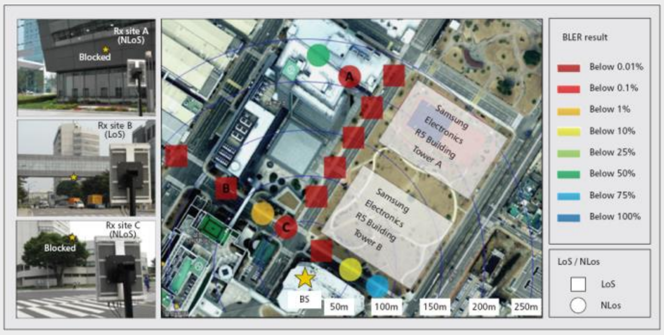

Figure 4. Outdoor coverage test results

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 and an indoor mobile station placed inside a typical modern office building with heavily tinted glass at a separation of more than 150 m. These types of buildings are representative of highly unfavorable propagation (penetration) conditions, even for current cellular frequency bands below 6 GHz.

As can be seen in Fig. 5, surprisingly promising indoor coverage results were obtained with only the totally obstructed farthest side of the building resulting in lost connections. While the spots showing BLERs of around 10-20 % 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 femtocells, as in traditional cellular systems.

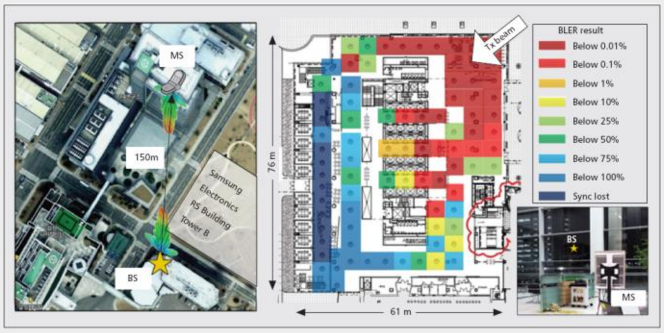

Figure 5. Outdoor to indoor penetration test results

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Adaptive Beamforming Test in Single Cell

Adaptive beamforming in a single-cell environment was tested in a motorsports park in South Korea [1], in which the MS moved at a speed of 110 km/h as shown in Fig. 6. A BS was located at the roof of a 3-story building at the height of approx. 15-20 m from the ground.

The BS generated eight beams in a horizontal direction. An MS was installed in a minivan and its RF/antenna unit was mounted on top of the vehicle. The MS had 2 antenna arrays that provided combined coverage of about 180° in horizontal direction; each array generated 8 beams and provided half of the 180° coverage.

Fig. 6 shows the movement of the vehicle along the track during 30 seconds of testing, with the positions marked as 0 s up to 30 s and its distance from the BS ranging from 130 m to 800 m.

The vehicle speed was about 110 km/h approximately from the 15 s position until the end of the test.

The test was logged every 100 ms by the MS.

The beam measurement period was 10 ms and the MS determined the best DL beam pair and fed back the best beam information to the BS. The MS also reported the channel quality information (CQI) to the BS at regular intervals. Based on the feedback information, the BS updated the transmit beam and the modulation and coding scheme (MCS).

Fig. 6 shows plots of the beam IDs of the BS and the MS, the best antenna of the MS and the throughput during the test. The best BS beam ID changed from 1 to 7 one by one as the vehicle moved.

The best beam and antenna of the MS also changed similarly during the test, except at about 12 s.

This sudden change at 12 s was due to a guard post that blocked the LOS path between the BS and the MS.

The testbed achieved the DL data rate of over 1.2 Gbps with 16 QAM and code rate of 3/4 during the test when the LOS path was available, but the data rate fell to about 500 Mbps with QPSK and code rate of 3/4 when the LOS path was blocked. In this test, MIMO was not supported and only the best antenna was selected at the BS and the MS to deliver a single data stream.

In the testbed, the DL transmit power was fixed, whereas the UL transmit power was updated based on the DL received power without the control of the BS.

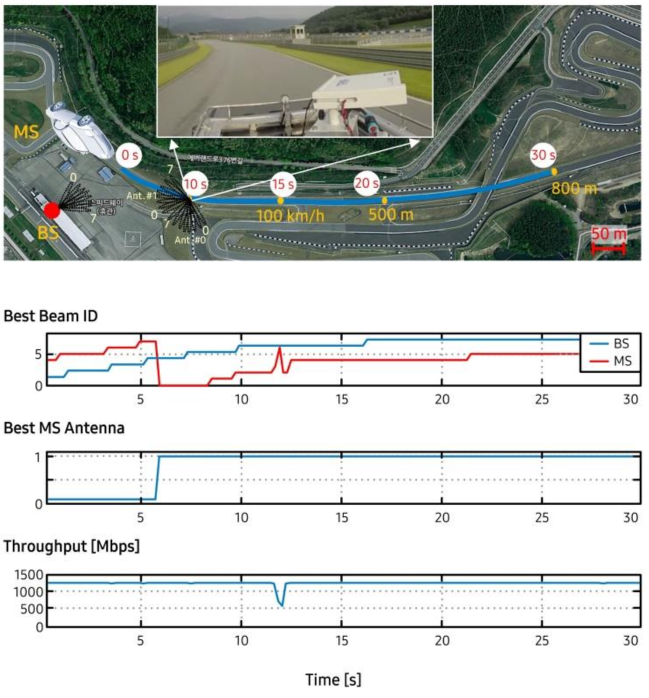

Figure 6. Adaptive beamforming test at 110 km/h in a single cell

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Handover Test in Multi-Cell Environment

Extensive multi-cell handover (HO) tests for the 5G testbed were conducted at Samsung Electronics, Suwon, South Korea [1]. The example HO scenario used for the field test is shown in Fig. 7. Three BSs were installed at different locations with cell IDs 0, 2 and 4 respectively.

Each BS generated 16 beams in total; 8 horizontal beams and 2 vertical beams. The coverage for each cell is illustrated in Fig. 7. These three BSs were connected to a common gateway with S1 interface. An MS was installed in a minivan and the MS RF and antenna unit were mounted on top of the vehicle. The MS had 2 antenna arrays that provided coverage of about 360° in a horizontal direction; each array generating 8 beams with coverage of 180°.

The path taken by the vehicle for these tests is illustrated in the figure by colored direction arrows. The colors of the arrows are chosen to match those of the serving cells in the test route. Throughout the tests, the vehicle moved at about 20 km/h.

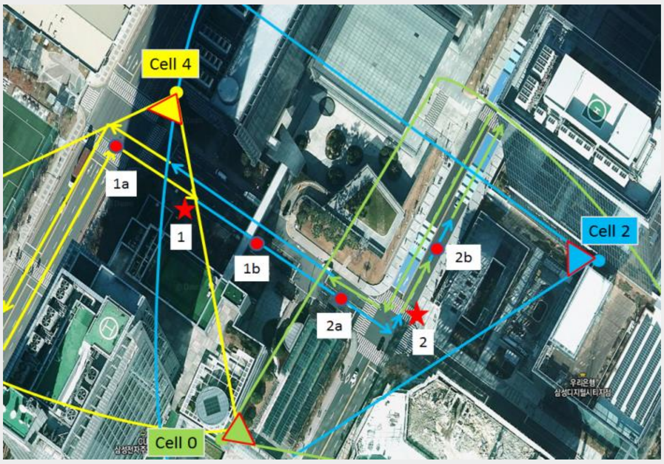

Figure 7. Handover field test scenario

Initially, HO tests were performed using the BS-initiated HO procedure of Fig. 8. Handover failure rates using this procedure were very high, especially at Location 2 (star-marked in Fig. 7). This high HO failure rate was mainly attributed to the UL radio link failure with the serving BS before completing the HO procedure.

Even for successful HO cases, around 30 % of trials incurred more than 500 ms of HO delay.

This was mainly due to the large delay incurred in Steps 7 and 8 (Fig. 8) caused by high interference from target cell and high DL and UL packet losses. To address the high HO failure rate and large HO delay issues of the BS-initiated HO procedure, the MS-initiated HO procedure detailed in Fig. 9 was implemented and tested.

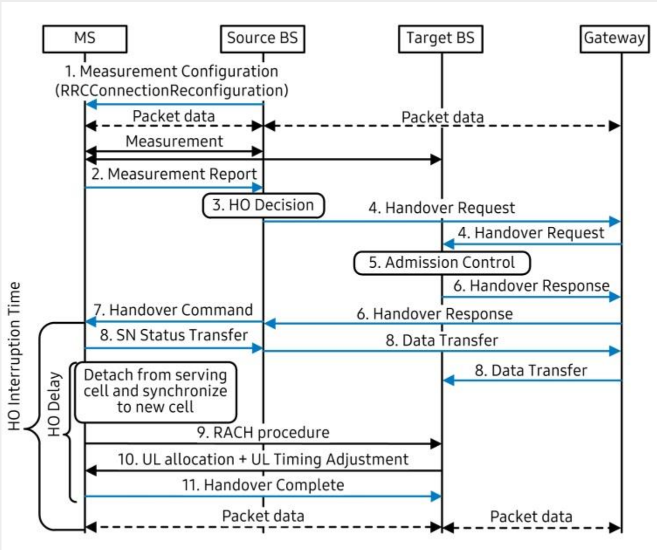

Figure 8. BS-initiated HO procedure

HO tests were repeated using the MS-initiated HO procedure in the same test environment as before.

The HO delay in Fig. 9 is defined as the time taken for the MS to successfully receive MSG4 from the target BS after the HO decision (HO_d). The HO interruption time is defined as the time taken for the MS to successfully receive the DL data packets from the target BS after the HO decision (HO_d). The average HO delay was about 12 ms, and the average HO interruption time was about 21 ms, satisfying the HO interruption time requirement of 27.5 ms of the IMT-Advanced [3]. UHD video ran smoothly without interruption at 98 % of the HO locations.

The MS kept track of the received power of the serving cell and that of the best target cell for the MS-initiated HO procedure. The HO decision was made at the MS when the average target cell received power was consistently higher than the average serving cell power by a predefined threshold.

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Fig. 10 shows the plots of the received powers of the serving cell and the best target cell, the serving cell ID, the best beam ID of the serving cell, the best beam ID of the best MS antenna and the timing advance (TA) values during 10 seconds of MS travel from Location 1a to 1b (marked in Fig. 7). Similarly, Fig. 11 shows those values from Location 2a to 2b (marked in Fig. 7). Ping-pong effects during the HO in Fig. 9 were minimized by taking the local average of the received power and applying 3 dB offset and hysteresis in the HO decision.

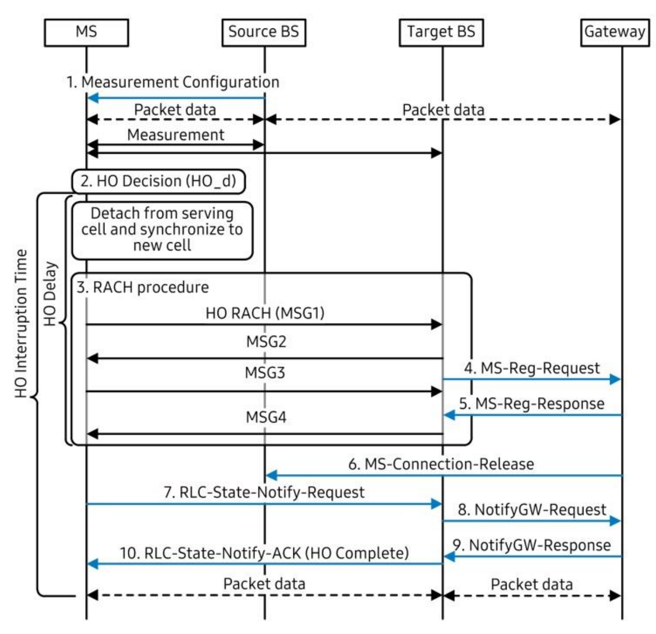

Figure 9. MS-initiated HO procedure

During the test in Fig. 10, the antennas of BS 4 were not adequately down-tilted to cover the test route very close to BS 4 (test route from Location 1a to 1b in Fig. 7). In this test, as the MS moved from Location 1a towards 1b, the received power from BS 4 decreased by almost 15 dB until time 4 s, while at the same time the TA value decreased, albeit very slightly. This is against our intuition that when the TA value is decreased, the received power should be increased in a LOS environment. This strange phenomenon happened because the MS was so close to the BS that the elevation angle of the LOS path from the BS to the MS was way off from the best elevation angles for both the BS beams and the MS beams.

As the MS moved even closer to the BS, the MS moved further away from the best elevation angles of the beams, and the received power dropped significantly.

However, at time 4.1 s, the MS began to receive a signal reflected by the building across the street as the best signal. This is evident from the sudden increase in the TA value by about 300 ns at time 4.1 s with increased received power and change of the best MS beam. At time 5 s, the TA value increased by almost 900 ns and the serving BS changed to BS 2. This test illustrates a case in which a Non-LOS (NLOS) path is used in the mmWave beamforming communications.

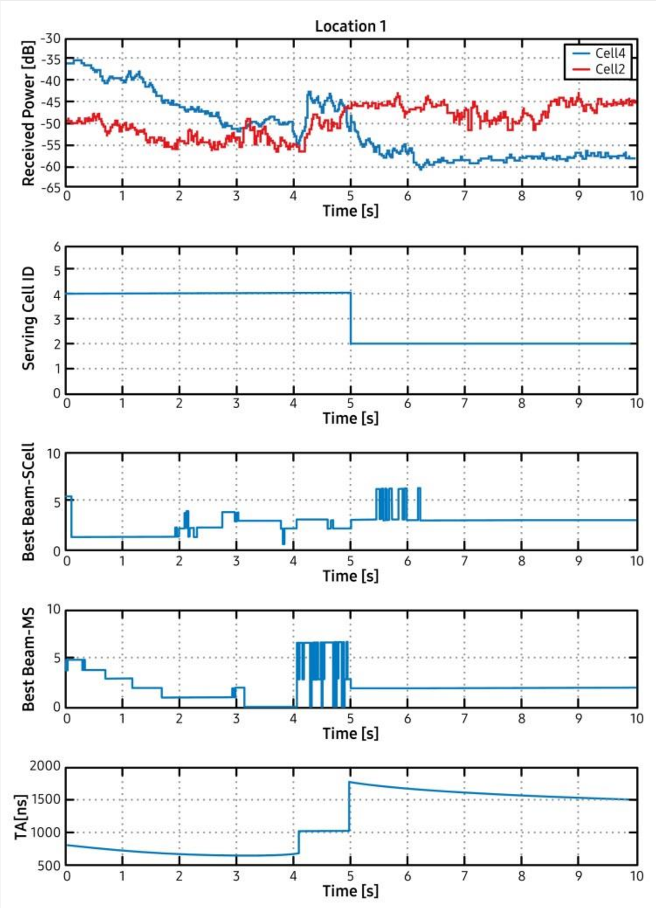

Figure 10. Received powers of cells, Serving cell ID, Best serving cell beam, Best MS beam, and Timing advance values at HO Location 1

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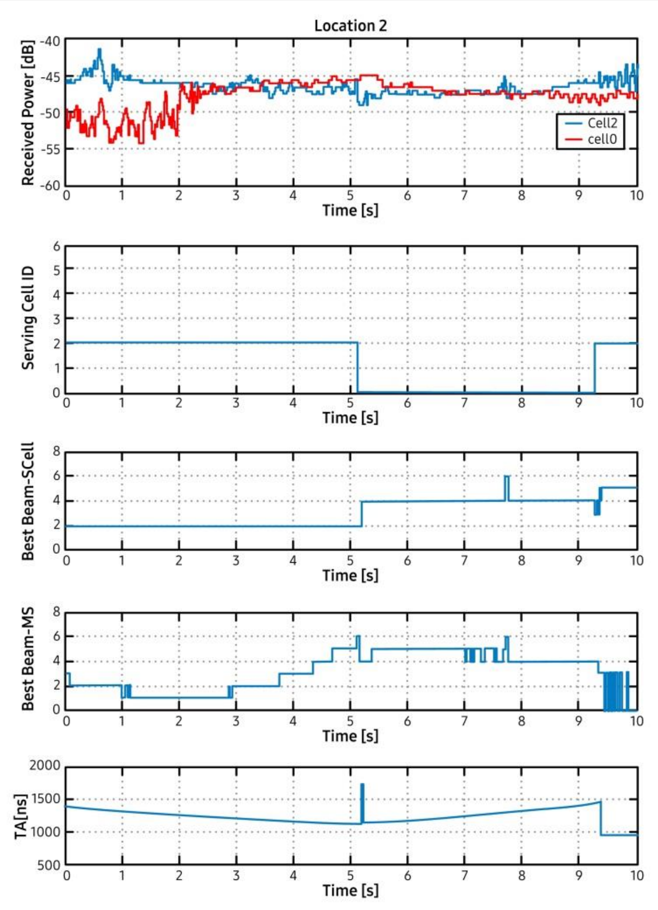

Figure 11. Received powers of cells, Serving cell ID, Best serving cell beam, Best MS beam, and Timing advance values at HO Location 2

Conclusion

A testbed for mobile cellular communication at 28 GHz was built at Samsung Electronics, South Korea. Both the base station (BS) and the mobile station (MS) of the testbed were constructed using beamforming antennas with a signal bandwidth of 800 MHz and TDD mode. The testbed achieved an aggregated data rate of 7.5 Gbps for two stationary MSs in the downlink by supporting 2 × 2 MIMO to each MS. In an adaptive beamforming test in a single-cell environment, the testbed achieved a data rate of 1.2 Gbps for an MS moving at the speed of 110 km/h. Finally, the testbed successfully achieved mobile communication in a three-cell environment, and attained an average handover delay of 12 ms and an average handover interruption time of 21 ms, satisfying the IMT-Advanced handover interruption time requirement of 27.5 ms [3].

The testbed successfully demonstrated the feasibility of mobile cellular communications at millimeter-wave frequency.

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Terminology

3GPP	3rd-Generation Partnership Project
BLER	BLock Error Rate
BS	Base Station
CQI	Channel Quality Information
DL	Down-Link
Gbps	Gigabits per second
HARQ	Hybrid Automatic Repeat reQuest
HO	Hand Over
LOS	Line-of-Sight
LTE	Long-Term Evolution
Mbps	Megabits per second
MCS	Modulation and Coding Scheme
MIMO	Multi Input Multi Output
mmWave	Millimeter Wave
MS	Mobile Station
NLOS	Non-LOS
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift-Keying
RF	Radio Frequency
TA	Timing Advance
UHD	Ultra-High-Definition
UL	Up-Link
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network

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