Simulation and Evaluation of 28GHz SHF Wave Beamforming with 4×4 Element Configuration Using RF Circuit Phase Control

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Received: September 9, 2020; Accepted: November 6, 2020; Published: November 20, 2020

Abstract. In the 5th generation mobile communication system (5G), there is a strong demand for higher speed and higher capacity. The beamforming technique using phased-array antennas is effective for long-distance radio propagation and for reducing interference signals in the high SHF (super high frequency) band because the phase shift of the antenna array elements can be controlled to produce a narrow-band beam and to control the directivity. We have developed the 28 GHz array antenna for small cells and evaluated the beamforming characteristics using an RF analog phase shifter control scheme. In this paper, we verify the computer simulation and evaluation results of the beamforming characteristics of a newly developed 4×4 phased array antenna.

Keywords: 5G, beamforming, phased array antenna, 28GHz

1. Introduction

In recent years, the development of the fifth-generation mobile communication system (5G) has been promoted worldwide due to the growing need for higher communication speed and capacity. The 5G system has new network requirements due to features such as its higher speed, multiple simultaneous connections, and low latency [1]. In Frequency Range 2 (FR2) specified in 5G New Radio (NR) [2], carrier bandwidth of up to 400 MHz in the high SHF band enables 20 times higher throughput than fourth-generation mobile communication system (4G). For the Ultra-Reliable and Low Latency Communications (URLLC) concept [3], the latency over the radio access is required to reduce from 10 msec to 1 msec. For the massive Machine Type Communications (mMTC) concept [3], the target for connection density is 1,000,000 devices/km².

In 5G, small cells are placed in the area of a macro cell that covers a wide area, and dif-
different frequency bands are used for macro and small cells. The additional small cells will use
the high super high frequency (SHF) (6-30 GHz) and extremely high frequency (EHF) bands
(30-300 GHz), which are higher than the existing frequency bands. The throughput is im-
proved by increasing the signal bandwidth.

High capacity is achieved by using an array antenna consisting of super-multi-element
arrays to form very thin beams and adaptively control the antenna directivity to compensate
for the large radio propagation losses in the high SHF and EHF bands [4]. A phased array an-
tenna system is a beamforming control technique for adaptively controlling the directivity of
an array antenna [5].

In this paper, we show the computer simulations of a square array antenna for a 5G small
cell in the 28 GHz frequency band. For the evaluation, to focus on the characterization of the
developed array antennas, we adopted the simplest RF analog phase shifter control method
for beamforming.

2. Design of Beamforming

2.1. RF Circuit-Phase-Control-based Beamforming

Beamforming is an antenna control technique for transmitting and receiving radio waves in a
specific direction by controlling the weight of each element of the array antenna to form a di-
rectional profile. The 28 GHz band under consideration for use in 5G has a wider bandwidth
than the low SHF band (3-6 GHz) used in 4G, but it is characterized by greater propagation
loss and more straight-line capability. The free space propagation path loss at 28 GHz is 101
dB at 100 meters. Beamforming is used to control the directivity of the antenna to compen-
sate for the power and make it possible to propagate radio waves over long distances. In addi-
tion, it is possible to improve the signal quality of the desired wave by concentrating radio
waves toward a device in a specific direction, thereby reducing the interference power with
other transceivers and increasing the signal-to-interference and noise ratio (SINR). In order to
achieve high SINR, a beamforming system is required to generate a narrow beam and precise
phase shift control.

There are four types of beamforming configurations: up-conversion, the analog control
method (direct antenna control method), the digital control method (baseband control meth-
od), and the hybrid control method [6].

The feature of the RF analog phase shifter control scheme is the simplicity of the circuit con-
figuration as the phase control is performed directly by the RF shifter. However, that scheme can
only produce one signal stream and only one beam at a time.

Digital beamforming has the same number of digital-to-analog signal converters and fre-
quency converters as the antenna elements. The feature is the high accuracy of beam generation with narrow accuracy due to the baseband control of phase shift. However, it requires the same number of digital-to-analog signal converters, frequency converters, and RF circuits as the antenna elements, which results in high power consumption.

Hybrid beamforming combines the features of analog and digital beamforming. The circuit configuration is simpler than that of the digital system because it can be limited to the same number of digital-to-analog signal conversions and frequency conversions as the number of generated beams, thus reducing power consumption.

2.2. Phased Array Principles

A model of a planar array antenna in which the antenna elements are arranged in a square in the xy-plane is shown in Fig. 1. The m-th in the x direction and the m-th in the y direction when the beam is deflected in the direction of the beam azimuth vector \( \mathbf{R} = (\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta) \) Compute the weight \( w_{m,n} \) of the n-th antenna element toward the direction.

In Fig. 1, the angle \( \theta \) is the rotation angle formed by the beam direction \( \mathbf{R} \) and the z-axis. Similarly, the angle \( \phi \) is the rotation angle between the beam direction \( \mathbf{R} \) and the zx-plane. The weight \( w_{m,n} \) is calculated by (1) [7].

\[
w_{m,n} = a_{m,n} \exp(-j k_0 d_x \sin \theta \cdot \cos \phi) \cdot \exp(-j k_0 d_y \sin \theta \cdot \sin \phi)
\]

where \( k_0 = \frac{2 \pi}{\lambda} \) is the free-space wavenumber, \( \lambda \) is the free-space wavelength, \( a_{m,n} \) is the excitation amplitude of the antenna elements, \( d_x \) is the distance between the antenna elements in the x direction, and \( d_y \) is the distance between the antenna elements in the y direction.

In Fig. 1, the angle EL is the rotation angle between the projection vector and the z-axis of the beam-directed azimuth vector \( \mathbf{R} \) to the yz-plane. This projection vector takes the orientation \((0, \sin \theta \sin \phi, \cos \theta)\); i.e., the angle of rotation from the z-axis to the projection vector in the yz-plane is EL.

Similarly, the angle -AZ is the angle between the projection vector and the z-axis of the beam-directed azimuth vector \( \mathbf{R} \) to the zx-plane. This projection vector takes the orientation \((\sin \theta \cos \phi, 0, \cos \theta)\); i.e., the angle -AZ is the angle of rotation from the z-axis to the projection vector in the zx-plane.

From Fig. 1, (2) is derived, and then (3) is derived.

\[
\tan(EL) = \frac{\sin \theta \sin \phi}{\cos \theta} = \tan \theta \cdot \sin \phi
\]

\[
\tan(-AZ) = \frac{\sin \theta \cdot \cos \phi}{\cos \theta} = \tan \theta \cdot \cos \phi
\]
\[ \cos \varphi = \begin{cases} - \cos \left( \tan^{-1} \left( \frac{\tan(EL)}{\tan(-AZ)} \right) \right), & \text{for } \frac{\pi}{2} < \varphi < \pi \\ \cos(\tan^{-1}(\tan(EL) / \tan(-AZ))), & \text{for } 0 < \varphi < \frac{\pi}{2} \end{cases} \]

\[ \sin \varphi = \begin{cases} - \sin \left( \tan^{-1} \left( \frac{\tan(EL)}{\tan(-AZ)} \right) \right), & \text{for } -\pi < \varphi < 0, EL \cdot AZ < 0 \text{ or } 0 < \varphi < \pi, EL \cdot AZ > 0 \\ \sin \left( \tan^{-1} \left( \frac{\tan(EL)}{\tan(-AZ)} \right) \right), & \text{for } 0 < \varphi < \pi, EL \cdot AZ > 0 \text{ or } -\pi < \varphi < 0, EL \cdot AZ > 0 \end{cases} \]  

Furthermore, if \( \tan(AZ) \neq 0 \) and \( (\varphi \neq \pi/2, -\pi/2) \), then (4) is derived. 

\[ \sin \theta = \text{sign}(EL) \sin(\tan^{-1} \sqrt{\tan^2(EL) + \tan^2(AZ)}) \]
\[ \cos \varphi = -\text{sign}(EL \cdot AZ) \cos \left( \tan^{-1} \left( \frac{\tan(EL)}{\tan(-AZ)} \right) \right) \]
\[ \sin \varphi = -\text{sign}(EL \cdot AZ) \sin \left( \tan^{-1} \left( \frac{\tan(EL)}{\tan(-AZ)} \right) \right) \]  

Equation (4) is substituted into (1) and the weight \( w_{m,n} \) is converted using the rotation angle EL and the rotation angle AZ. Here, if the spacing between the antenna elements between \( d_x \) and \( d_y \) is equal to \( 0.6\lambda \), since \( EL \neq 0 \) and \( AZ \neq 0 \) under \(-\pi/2 < \theta < \pi/2, 0 < \varphi < \pi\), the weight \( w_{m,n} \) is as shown in (5). 

\[ w_{m,n} = a_{m,n} \exp \left( \frac{j1.2m\pi \cdot \text{sign}(EL) \text{sign}(EL \cdot AZ) \sin(\tan^{-1} \sqrt{\tan^2(EL) + \tan^2(AZ)})}{\cdot \cos(\tan^{-1}(\tan(EL) / \tan(-AZ))) + \cdot \sin(\tan^{-1}(\tan(EL) / \tan(-AZ)))} \right) \]  

\[ \begin{align*} \tan(EL) &= 0 \text{ when } \tan(-AZ) = 0, \text{ and } \tan(EL) = 0 \text{ when } \tan\theta = 0. \text{ That is, it is a beam to the front. In this case, } \varphi \text{ is arbitrary. On the other hand, } \tan(EL) &= \tan(\theta) \text{ when } \cos\varphi = 0. \text{ In other words, } EL = \theta, \text{ where } \varphi = \pi/2, \text{ and the weight } w_{m,n} \text{ is as follows (6).} \\
\end{align*} \]

\[ w_{m,n} = a_{m,n} \exp(-j1.2n\pi \cdot \sin(EL)) \]  

when \( \tan(EL) = 0, \tan\theta = 0 \) or \( \sin\varphi = 0 \). When \( \tan\theta = 0, \tan(-AZ) = 0 \), i.e., as mentioned above, it is a beam to the front. On the other hand, when \( \sin\varphi = 0, \varphi = 0 \) to \( \cos\varphi = 1 \), the weight \( w_{m,n} \) is as follows (7). 

\[ w_{m,n} = a_{m,n} \exp(-j1.2m\pi \cdot \sin\theta) = a_{m,n} \exp(j1.2m\pi \cdot \sin(AZ)) \]
3. Simulation and Evaluation

In this chapter, we describe the radiation and beamforming characteristics of the developed planar array antenna.

3.1. Antenna Simulation

In this section, the computer simulations of the radiation characteristics of the planar array antenna designed in the previous section are characterized. The transmitting antenna has a strong forward directionality. The sharp forward directivity is effective for extending the propagation distance by narrowly focusing the beam and for reducing the interference with other terminals.

Table 1 shows the simulation characteristics of the planar array antenna. The transmitting antenna has a uniform rectangular array geometry to provide strong directivity at 28 GHz. The arrays studied were 4x4, 6x6, and 8x8.

Table 1: Simulation Specifications

| Parameter                       | Value                  |
|---------------------------------|------------------------|
| Carrier frequency ($f_c$)       | 28.0 GHz               |
| Propagation speed of light (c)  | $2.9979 \times 10^8$ m/sec |
| Wavelength ($\lambda$)          | $c/f_c$                |
| Array size                      | 4x4, 6x6, 8x8          |
| Array Geometry                  | Uniform Rectangular Array |
| Element type                    | Cosine antenna element |
| Element spacing ($d_x, d_y$)    | 0.6$\lambda$            |
The distance between the antenna elements was set to 0.6λ to suppress the generation of grating lobes in the direction $AZ = -\pi/2$ or $EL = -\pi/2$ and to reduce the number of elements.

The characteristics of the directivity pattern of the antenna gain of the designed planar array antenna are shown in Fig. 3. The characteristics of the directional pattern of normalized power are shown in Fig. 4, Fig. 5, and Fig. 6.

As shown in Fig. 3, the results for each device showed the strongest directivity in the frontal direction with the main lobe formed in the frontal direction when the azimuth angle ($AZ$) = 0 deg. and the elevator angle ($EL$) = 0 deg. The antenna gain in the frontal direction was 18.5 dBi for the device with 4x4 elements, 21.6 dBi for the device with 6x6 elements, and 23.8 dBi for that with 8x8 elements. The suppression of the grating lobes was also confirmed.

As shown in Fig. 4 to Fig. 6, the angle width of the main lobe power decrease by 3 dB from the peak was 10.8 deg. for the 4x4 device, 7.1 deg. for the 6x6 device, and 5.3 deg. for the 8x8 device at azimuthal angles AZ =0 deg., 45 deg., and 90 deg., while the angle width was 5.3 deg. for the 8x8 device. The power of the sidelobes relative to the main lobe decreased as the number of elements increased. The relative power of the side lobes was reduced to -12.7 deg. for the 4x4 device, -13.0 deg. for the 6x6 device, and -13.2 deg. for the 8x8 device at azimuthal angles AZ =0 deg., 45 deg., and 90 deg.

![Figure 3: Directivity of array antenna.](image)

(a) 4x4 elements, (b) 6x6 elements, (c) 8x8 elements

![Figure 4: Normalized directivity (4x4 elements). Polar plot, cartesian plot.](image)
3.2. Results of Beamforming

In this section, we show the beamforming characteristics of the developed 4x4 device. A frontal view of the planar array antenna is shown in Fig. 7, and a block diagram of the evaluation system is shown in Fig. 8.

Figure 7: Appearance of the phased array antenna.
Figure 8: Block diagram of evaluation system.

As shown in Fig. 8, in the evaluation system, the 28 GHz RF signal from the Vector Network Analyzer is divided into 16 parts by a power splitter, amplified by a power amplifier through an analog phase shifter, and supplied to each antenna element. Fixed weights calculated beforehand based on equations (6) and (7) derived in section 2.2 are set to the field programmable gate array device in the phase control block. Then the RF analog phase shifters are controlled by the digital-to-analog converted signal. In the measurement, the set values for the azimuthal angle AZ and the elevation angle EL were calculated by the PC up to ±20 deg. in increments of 10 deg. and were preset in the RF phase shifter. The planar array antenna is fixed and faces the receiving probe antenna in the frontal direction. For each setting of the beam direction, the receiving probe antenna was scanned in two dimensions using an X-Y planar scanner to measure the distribution of the radio wave intensity for two directions, the azimuth angle AZ and the elevation angle EL. The near-field measurement method [8,9] was used for the measurement.

Table 2 shows the antenna gain vs. the radiation angle setting. Table 3 shows the maximum position of the antenna gain vs. the radiation angle setting. Fig. 9 and Fig. 10 show the contour maps of the radiation intensity.

As shown in Fig. 9, the antenna gain in the frontal direction of the planar array antenna was 15.3 dBi. This result is a 3.2 dB degradation from the simulation result of 18.5 dBi in the previous section. Sidelobes were found around the azimuth angle AZ=±35 deg. and the elevation angle EL=±35 deg. which were in close agreement with the simulation results in Fig. 4.

From the results of Fig. 10, it was confirmed that the beam directionality of the maximal point at each radiation angle worked correctly. It was confirmed that the antenna gain was correct with a gain error of -1.55dB ~ 0.66dB, azimuth AZ= -4.6 ~ +7.3 deg., and an elevation EL= -8.12 ~ 6.4 deg. based on the antenna gain at azimuth AZ=0 deg. The imperfections in the antenna gain and radiation angle were due to the degradation of the S-parameter caused by the nonlinearity of the analog phase shifter at high dBm signal levels.
Figure 9: Power contour map of plane array transmit antenna

AZ: 0 deg. EL: 0 deg. (1 div = 10 deg.)

Figure 10: Power contour map of plane array transmit antenna

AZ: ±0~20 deg. EL: ±0~20 deg. (1 div = 10 deg.)
Center: AZ= 0 deg. EL= 0 deg.
Table 2: Beam Intensity v.s. Direction Setting.

| Azimuth Elevator | -20 deg. | -10 deg. | 0 deg. | 10 deg. | 20 deg. |
|------------------|----------|----------|-------|---------|---------|
| 20 deg.          | 14.7 dBi | -        | 15.9 dBi | -      | 14.0 dBi |
| 10 deg.          | -        | 14.1 dBi | 15.3 dBi | 15.8 dBi | -       |
| 0 deg.           | 15.4 dBi | 15.2 dBi | 15.3 dBi | 14.4 dBi | 14.7 dBi |
| -10 deg.         | -        | 15.5 dBi | 15.2 dBi | 15.7 dBi | -       |
| -20 deg.         | 13.7 dBi | -        | 15.0 dBi | -      | 14.9 dBi |

Table 3: Beam Max Position v.s. Direction Setting.

| Azimuth Elevator | -20 deg. | -10 deg. | 0 deg. | 10 deg. | 20 deg. |
|------------------|----------|----------|-------|---------|---------|
| 20 deg.          | (-19.2, 13.6) | -        | (0.0, 22.1) | -      | (19.2, 16.4) |
| 10 deg.          | -        | (-2.7, 16.4) | (5.4, 16.4) | (10.9, 16.4) | -       |
| 0 deg.           | (-22.1, -8.1) | (-10.9, -5.4) | (0.0, 0.0) | (8.1, -5.4) | (19.2, -5.4) |
| -10 deg.         | -        | (-13.6, -16.4) | (0.0, -10.9) | (5.4, -10.9) | -       |
| -20 deg.         | (-19.2, -19.2) | -        | (-2.7, -28.1) | -      | (19.2, -19.2) |

The parentheses in Table 3 show the coordinates of the point where the beam intensity is at its maximum at the azimuth angle AZ and elevation angle EL.

4. Conclusion

An array antenna for 5G small cells in the 28 GHz band, which enables high-speed, high-capacity communication, has been developed, and its basic beamforming characteristics have been verified through computer simulations and measurements by direct control of an RF analog phase shifter. As a result, the validity of the simulation analysis was confirmed by the agreement between the simulated and measured results of the beamforming antenna gain and by the intensity distribution characteristics in the characterization of the plane antenna.

In the future, outdoor operation in the high SHF and EHF bands is envisioned. In outdoor operations, the propagation loss due to the increase in communication distance becomes more pronounced. In such a scenario, a high SINR system with hybrid beamforming combining baseband digital precoding/combining and analog RF beamforming at the subarray level is envisioned. Such systems use large arrays to achieve the desired antenna beamforming gain, resulting in a very narrow beam and making efficient training of the RF a challenge. Therefore, our future research will be an extension of our current work and will focus on developing fast and efficient beamforming techniques for large scale MIMO systems.
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