Design Considerations of mmWave Antennas for 5G Mobile Applications

Minseok Han
Department of Electronics and Control Engineering
Republic of Korea Naval Academy, Changwon-Si, Kyungsangnam-Do, South Korea

Sukmoon Chung
Department of Weapon system Engineering
Republic of Korea Naval Academy, Changwon-Si, Kyungsangnam-Do, South Korea

Abstract- This paper introduces the considerations necessary for the design of mmWave antennas for 5th generation mobile communications. In addition, based on design considerations including frequency band, channel modeling at mm-Wave, phased array and beamforming, and phased array antenna positions and configurations, current technology trends and directions are presented through various examples and practical use case such as AiP (Antenna-in-package), AoC (Antenna-on-Chip), and InFO AiP (Integrated Fan-Out WLP module with the AiP) concept.

Keywords – mmWave, 5G (5th Generation), Array Antenna, Beamforming, AiP (Antenna-in-package), AoC (Antenna-on-Chip), InFO AiP (Integrated Fan-Out WLP module with the AiP)

I. INTRODUCTION

5G (5th Generation) mobile communications technology will bring new experiences to industry and society, including higher data rates or greater capacity, higher bandwidth, increased security, and lower latency. These developments will create new opportunities for advancing society and businesses. The key enabling 5G technologies under development include novel multiple access strategies, massive MIMO, full digital beamforming or hybrid beamforming, ultra-dense networking, etc. The implementation of these high-level technologies will bring about new challenges for the designers of the physical infrastructure. These challenges undoubtedly include the antenna, but also the associated microwave systems and the characterization of the radio propagation environment. In spite of very active current research on 5G antenna systems, including academic and industrial efforts, many challenges still need to be addressed, or they need better and more efficient solutions [1, 2].

In this paper, the design considerations of mmWave antenna for 5G mobile communications are introduced. AiP/AoP improves 5G signal integrity and overcomes the challenges below, using small footprint-phased antenna array design and minimizing the space required to support mmWave inside 5G devices. Modules using AiP will miniaturize the antenna. These modules will also have more antenna elements, which increases radiation gain and enables more economical and energy efficient solutions. The rest of the paper is organized as follows. Design considerations of mmWave antennas for 5G mobile applications are explained in section II. Practical use cases are presented in section III. Concluding remarks are given in section IV.

II. DESIGN CONSIDERATIONS

2.1 Frequency bands

In 5G technology, two kinds of frequency bands are classified. First are Sub-6 GHz bands where the frequency transmitted from cell phone towers are less than 6 GHz frequency. This is very similar to 4G, where the frequencies transmitted from cell phone towers are below 6 GHz. On the other hand, the higher speeds that really set 5G apart from any of the 4G LTE flavors require mm-Wave (millimeter wave, above 24 GHz) high-frequency bands. These high frequencies have very large bandwidths, so they are ideal for keeping everyone connected in busy environments like stadiums. So in 5G, these two types of frequency ranges have been defined as: Frequency Range-1 (Sub-6 GHz, less than 6 GHz) and Frequency Range-2 (mm-Wave, above 24 GHz). Fig. 1 shows some of the candidate mm-Wave bands in various regions of the world for 5G NR (New Radio).

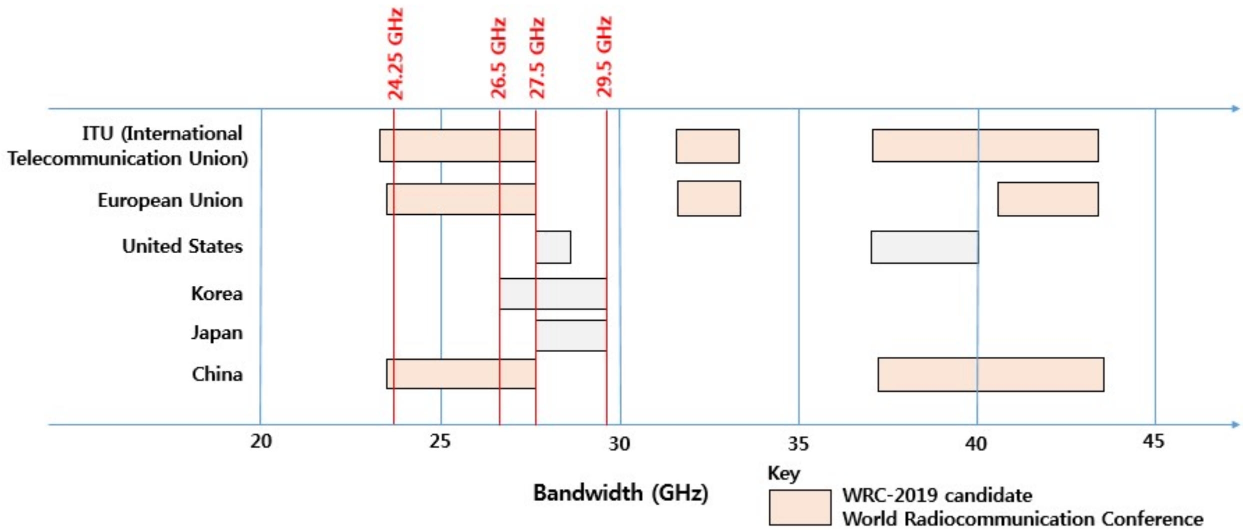

Figure 1. Candidate bands for NR deployment above 6 GHz [3]

2.2 Channel Modeling at mmWave

Understanding the transmission properties of mm-Waves in real-world environments is fundamental to the core design of the 5G NR UEs and base stations. As the wavelengths get smaller, physical processes such as diffraction, scattering, material penetration loss, and free space path loss, all make the channel properties of mm-Wave bands significantly different from today's sub 6 GHz bands. The 3GPP study on 5G channel model for frequencies from 0.5 to 100 GHz [4] considers several scenarios including Urban Micro, Urban Macro, Indoor, Backhaul, Device to Device (D2D), Vehicle to Vehicle (V2V), and Stadium. The number of spatial clusters and multipath components per cluster in the mm-Wave channel, and the spatial dynamics, has far-reaching implications on the design of the network components. For example, if the channel model defines a spatially rich channel, the antenna beam-steering requirements are not so important, and many Eigen-modes will be available for Single-User MIMO (SUMIMO) but the resulting fast fading caused by the addition of so many multi-path signals will be complex. On the other hand, a sparser channel will contain few Eigen-modes, less fading but require much better beam-steering. This is why realistic channel modeling is important for both device design and defining realistic and useful test cases. Since the publication of [5] mm-Wave channel modeling activities have been continuing at companies, universities, and at government institutions in an effort to develop a greater understanding of the mm-Wave channel and its behavior. Ignoring atmospheric effects, the received power for a transmitter and a receiver communicating via free space is easily calculated using the Friis transmission equation [5] given as Eq. (1).

$$\frac{P_r}{P_t} = \left(\frac{c}{4\pi R f}\right)^2 G_t\, G_r \qquad (1)$$

where P_r is the received power, P_t is the transmitted power, R is the distance between the transmitter and receiver, f is the frequency, G_t is the gain of the transmitter antenna, and G_r is the gain of the receiver antenna.

2.3 Phased Array and Beamforming

A phased array antenna is formed by an array of smaller antenna elements, such as individual patches or dipoles. By varying the relative phases and amplitudes of the signals applied to the individual elements, the antenna array can shape and steer a beam in a chosen direction. To see how an antenna array creates steerable high-gain beams, we start with an antenna array of a specific size, which is then divided into subarrays of different sizes. The array gain is referred to as the gain achieved when all subarray signals are added constructively (in phase). The size of the array gain relative to the gain of one subarray depends on the number of subarrays. For example, two subarrays give an array gain of 2 (therefore, 3 dB). By changing the phases of the subarray signals in a certain way, this gain can be achieved in any direction as shown in Figure 2 (a). Each subarray has a certain radiation pattern describing the gain in different directions. The gain and beam width depend on the size of the subarray and the properties of the individual antenna elements. There is a trade-off between subarray gain and beam width – the larger the subarray, the higher the gain and the narrower the beam width, as illustrated in Figure 2 (b). The total antenna gain is the product of the array gain and the subarray gain, as shown in Figure 2 (C). The total number of elements determines the maximum gain and the subarray partitioning allows steering of high gain beams over the range of angles. Moreover, the subarray radiation pattern determines the envelope of the narrow beams.

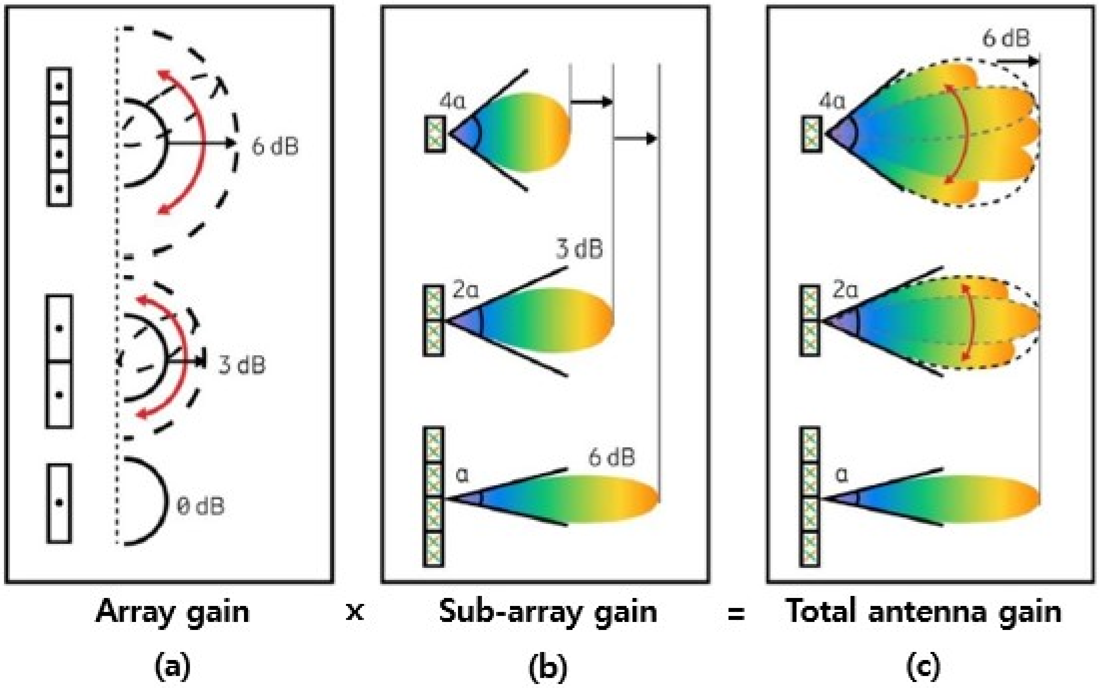

Figure 2. An array of subarrays supporting high total antenna gain and steerability.

In analog beamforming, the same signal is fed to each antenna and then phase-shifters are used to steer the signal emitted by the array. An array that uses analog beamforming only constitutes one antenna port per beam. It is usually called an adaptive antenna since the radiation pattern can be changed over time, but it is nevertheless a single antenna creating time domain beamforming. In contrast, the primary objective of a digital beamformer's design entails the sending of the same information symbol off each antenna, but with appropriate adjustment to both amplitude and phase (therefore, complex valued weighting factors) of the signal at each of those antenna elements. Doing so allows the effective radiation pattern of the entire array to be shaped and directed to the intended user.

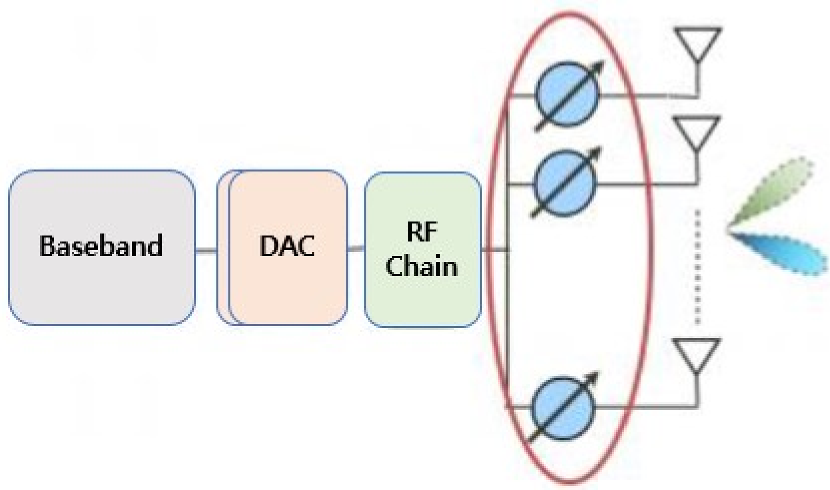

Figure 3. Sub-6 GHz analog beamforming architecture [6].

More recent digital beamforming designs adopt eigen-beamforming schemes which aim to maximize signal power at the intended user's location, based upon a pre-defined criterion. Cell coverage is therefore extended as transmission power is concentrated after determining the directions (eigen-direction of the channel) in which the RF channels provide the strongest paths. This is possible with an array of closely spaced antenna elements. The preferred choice entails pairs of cross-polarized antennas. Hence, signals from correlated antenna elements, when phased appropriately, add up constructively at that intended user's location. In digital beamforming, throughput maximization is also achieved by utilizing the multidimensional channel structure associated with multiple antennas at both transmit and receive ends. A single layer (one stream) beam formed transmission cannot simultaneously maximize the power at every receiving antenna. Hence, through precoding, multiple layers are transmitted each with their own beam formed weights associated with every antenna element. Leveraging the additional degrees of freedom in this manner maximizes the throughput of a digital beamforming system utilizing frequency domain beamforming.

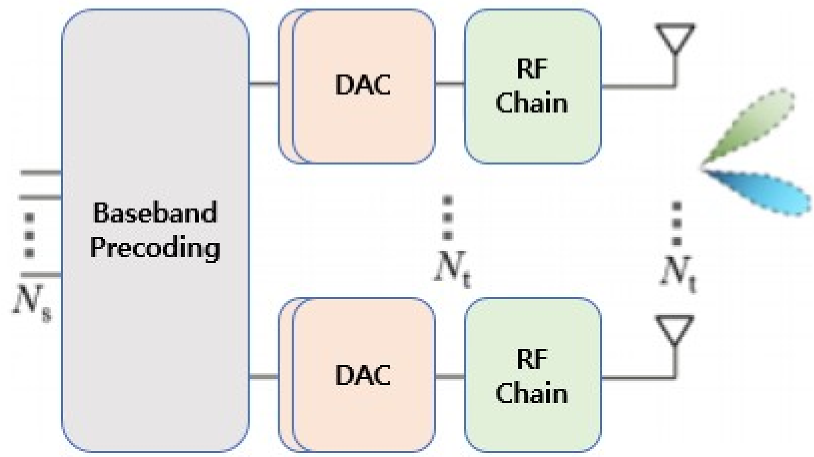

Figure 4. Sub-6 GHz fully digital beamforming architecture.

Therefore, phase and amplitude settings can be applied at an antenna level by generating specific weights through baseband processing for assignment to multiple layers across the entire transmission bandwidth, as long as there are the same number of RF chains and number of antenna elements. The result is not only improved cell coverage as a function of user location, but also the ability to steer nulls in the direction of interferers and implement multiuser MIMO schemes in massive MIMO systems to achieve high spectrum efficiency. Hybrid beamforming is a solution that combines the advantages of analog and digital beamforming architectures with frequency/time domain beamforming. Significant cost reduction can be achieved by reducing the number of complete RF chains. However, the number of simultaneously supported streams is lower compared to full blown digital beamforming. Hybrid beamforming is the more practical beamforming approach for mm-Wave in the near term.

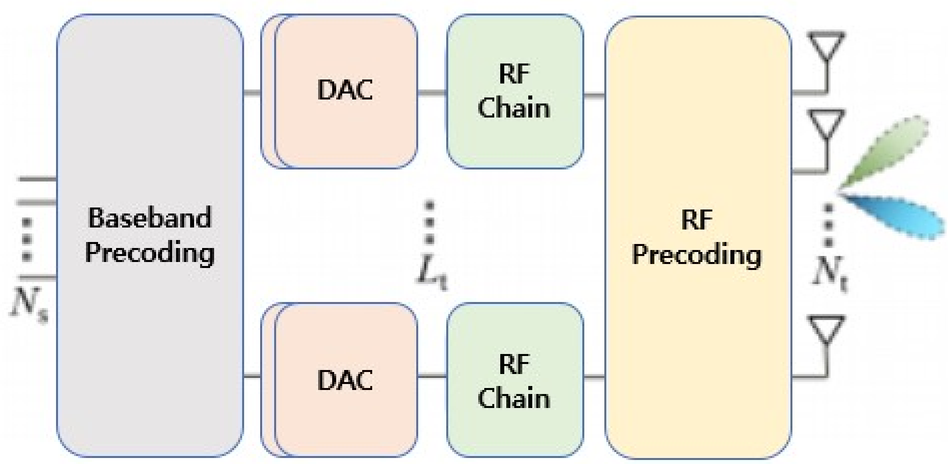

Figure 5. Hybrid analog-digital precoding architecture for mmWave transmission with Ns (# of data streams) < Lt (# of RF Chains) < Nt (# of Tx antennas).

2.4 Phased Array Antenna Positions and Configurations

For mmWave 5G UEs, another complicating factor in determining the value of D is that these devices are anticipated to have multiple antenna arrays to enable full spherical coverage. Multiple arrays also overcome situations where the signal is blocked by a human hand or head [7]. Figure 6 shows examples of possible array placements. There are two approaches that can be taken for measuring devices with one or more antenna arrays. The first "white box" approach is based on prior knowledge of the antenna array position on the DUT. This position could be determined either by design, declaration, or near-field scanning. The DUT is then positioned such that the center of radiation is placed at the center of the test zone. The far-field distance can then be calculated with D being set to the largest dimension of the array (assuming no significant ground plane effects). Typical array dimensions would then lead to a far-field distance of much less than 1 m for an UE. To test the entire device requires repositioning the DUT for each array. The alternative approach does not require knowledge of any antenna array position(s) and is known as the "black box" approach. In this instance, the geometric center of the DUT is placed at the center of the test zone and the D used for calculating the far-field is the maximum dimension of the DUT. The far field for this approach is much larger than for the white box approach (e.g., 4.2 m for a 150 mm DUT at 28 GHz, but the device does not need to be repositioned regardless of which antenna arrays are active. The use of the white box approach is attractive in a development environment since the far-field distance is much shorter and knowledge of the antenna structure more likely. However, for conformance testing, 3GPP has decided that only the black box approach can be used. This is due to the requirements for white box testing outlined in [8] not being accepted by UE vendors who preferred not to declare the antenna structure. In addition, no mechanism exists for the UE to signal when it changes its array, and the white box approach also rules out use of more than one array at a time.

Figure 6. Potential antenna array configurations for mm-Wave 5G User Equipment.

III. PRACTICAL USE CASE

The high-frequency bands, with small wavelengths used in 5G communications, will require an antenna pattern in the few millimeter range and, the antenna feed line should be as short as possible to avoid any unnecessary losses. The result; everything needs to be integrated into the RF FEM package [9]. The Antenna in Package (AiP)/ Antenna on Package (AoP) concept requires the RF antenna and the antenna feed line both be integrated into the RF FEM package. In the past, the RF antenna was patterned on a Printed Wiring Board (PWB) or made as a flexible cable attached to the RF FEM. This approach is known as a discrete antenna concept. The AiP/AoP concept introduces several advantages, including Package size-reduction, reduction of transmission losses between the RFIC chipset and antenna, improved transmitter efficiency and receiver noise figure of merit, and decrease system/assembly cost and time to market. AiP/AoP improves 5G signal integrity and overcomes the challenges below, using small footprint-phased antenna array design and minimizing the space required to support mmWave inside 5G devices. Modules using AiP will miniaturize the antenna. These modules will also have more antenna elements, which increases radiation gain and enables more economical and energy efficient solutions. Challenges arise when chip manufacturers are confronted with the key design constraints of phased array antennas. Since RF components are fully integrated into the self-contained module, conducted tests are no longer feasible. Requirements for module optimization and validations all point to over-the-air (OTA) tests during system level testing, integration and production. Millimeterwave beamforming demands accurate, reliable and efficient solutions. Qualcomm is making an antenna module [10] for 5G applications and Calterah Semiconductor Technology, China [11] announced a 77 GHz CMOS radar system chip for automotive applications. The Qualcomm AiP module includes several RFIC devices flip-chip mounted on the bottom surface of the PWB board while the top surface of PWB contains the dipole antenna, see Figure 7 below.

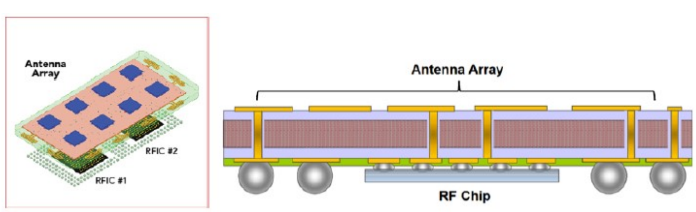

Figure 7. RFIC device is flip-chip mounted to the backside of the PWB having, on the frontside, the antenna pattern [10] and [12].

The second option is to insert the antenna on the upper surface of the molding compound, like the ASE antenna on package (AoP) concept [13], shown in Figure 8. Here, the AoP is produced by a metal stamping technology, which probably costs only a fraction compared to that of copper metal line pattering and TPV. This concept minimizes the antenna size at the package level, yielding a highly integrated RF SiP module. However, a dipole antenna array or similar will be a challenge for this technology.

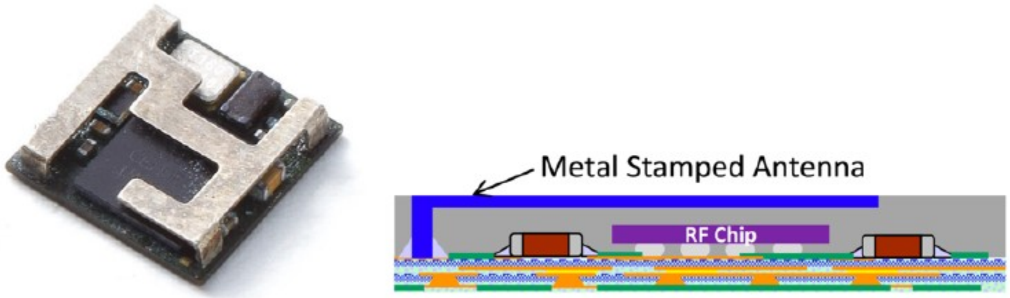

Figure 8. Antenna on Package (AoP) by ASE [13] on left and its artistic representation on right [14].

The third option is to insert the antenna on the upper surface of the molding compound, like the ASE antenna on package (AoP) concept [13], shown in Figure 8. The third option is to use a FOWLP (Fan-Out Wafer Level Package) module with the Antenna in Package (AiP) concept. An actual product with this approach was not located, but some manufactures have presented the AiP concept on their website or in at conferences. First, TSMC describes an Integrated Fan-Out WLP module with the AiP concept (InFO-AiP) on its website [15]. The defined concept is very flexible and allows the integration of the dipole array and the patch antenna in the same package. TSMC could use this for their existing technology to provide a through InFO via (TIV) and a fan-out, accommodating all antenna layout requirements without a significant change in their InFO process flow, see “TIV/Chip-Frist (Die-Up)” [16]. A dipole antenna pattern may exploit the advantages and technological flexibilities of the Post Passivation Isolation’s (PPI) fine pitch and the patch antenna associated with the fine pitch of TIV.

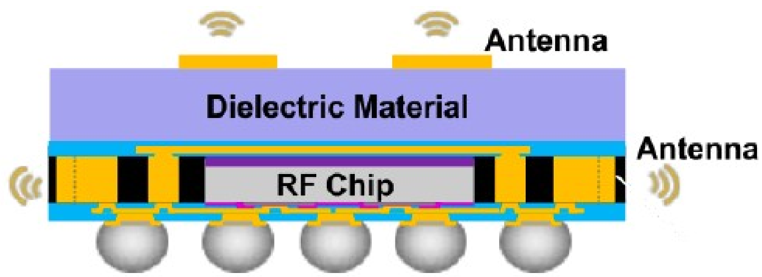

Figure 9. InFO AiP (InFO with Antenna in Package) according to [15].

The antenna of a mmWave RF system can also be manufactured as a discrete component, like an FC device [17], and then attached to the RFFE (Radio Frequency Front-End) assembly. In this configuration, the top PoP package is the FC antenna package that is designed to work at mmWave range, and the bottom package is, for example, RF FEM FOWLP, as shown in Figure 10.

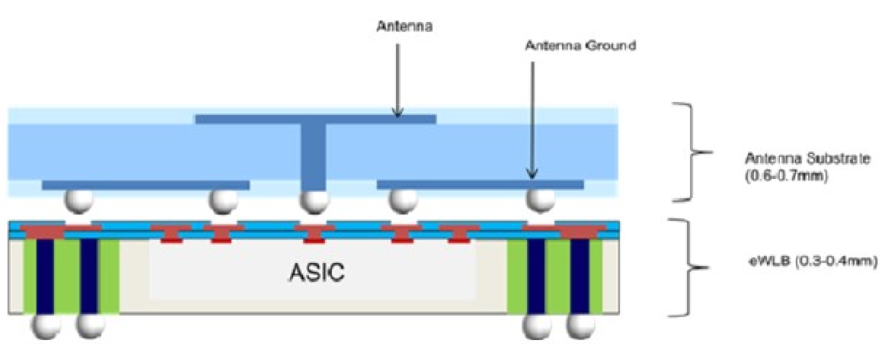

Figure 10. Package-On-Package with antenna package flip-chip mounted on FOWLP package [17].

IV.CONCLUSION

Design considerations of mmWave antennas for 5G mobile applications are introduced. For 5G smartphones and other mmWave applications, antenna integration based on design considerations, either through AiP or AoP technologies, simplifies the challenges associated with designing products that operate at these high frequencies. A variety of AiP/AoP design methodologies provide the required form, fit, and function for these applications and can include more than one antenna or an antenna array. Today's AiP/AoP technologies can be implemented through standard as well as custom SiP (system-in-package) modules to achieve a complete RFFE subsystem. In mmWave applications, signal loss becomes critical and the design challenges increase in complexity. Through this paper, we look forward to understanding the research on the antenna array of mmWave 5G, which is currently the most radically studied, and its direction, and to be used as a guide for future 5G antenna research.

ACKNOWLEDGEMENT

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