Design and characterization of cost-effective planar antennas with steerable beams: Gap waveguides, SMT and Random-LOS

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Abstract – **This paper presents the recent developments of gap waveguide technology and random-LOS OTA test technology. The applications on beam-steerable massive MIMO antennas and the characterization with random-LOS are emphasized.**

Index Terms — **gap waveguide technology, steerable beam, massive MIMO, OTA test, random-LOS.**

1. Introduction

Gap waveguide technology was invented by Prof. Kildal in 2008 [1]. The main idea behind this invention is to create a wave stop in a gap between two metal plates with texture structure or make the electromagnetic contact with a physical contactless structure so that antennas, devices and MMIC circuits in mm-Wave and Terahertz regime can be fabricated and integrated in a cost-effective way. This technology is a disruptive one, which disrupts conventional rectangular waveguides, microstrip line, existing packaging, diffusion bonding, dip-brazing and wire-bonding for MMIC, etc. at mm-waves and THz-waves.

The best hardware can be selected only if we know how to characterize its system performance. We are going now towards a more system-oriented performance characterization of antennas and wireless devices, e.g., in terms of data bit streams throughput. Hence, the Over-The-Air (OTA) test with two limiting environments RIMP and Random-LOS will be emphasized to meet the demands of the future wireless communications technology.

2. Gap waveguide Technology and SMT

The gap waveguide technology makes use of the theory that PEC/PMC plates with a gap smaller than a quarter wavelength stop any wave prorogations in between, where the PMC plate is realized by a texture or a thin multilayer structure. Therefore, the gap waveguide has a similar low transmission loss to the conventional rectangular waveguides do and, at the same time with the openable structure, the similar integrable ability and fabrication cost (especially at THz) as the microstrip lines do. This innovative technology combines the advantages of the rectangular waveguides (low loss) and the microstrip lines (easy integrability, low cost), and avoids the disadvantages of the rectangular waveguides (complicated and difficult to be integrated) and the microstrip lines (large loss).

Fig. 1. 8x8 and 16x16 slot arrays with gap waveguide distribution networks for V-band (60 GHz) consisting of three metal layers, and simulated and measured radiation patterns of the larger 16x16 slot version.

Fig. 1 shows high-gain low-loss planar array antennas at V-band (60 GHz) by using the gap waveguide technology [2].

With the openable structure, gap waveguide technology opens up an easy integration of gap antennas with MMIC's and Surface-mount technology (SMT) employment for fabrication.

The coming 5G wireless communication systems employs Massive MIMO concept with a requirement of low-cost manufacturability. The consumer market prefers flat multi-beam antennas with antenna subarray elements excited by antenna feeding network. Each subarray of this big antenna has to be controlled in amplitude and phase to create several steerable beams out of the array, each one with a desired pointing direction and gain.

The gap waveguide technology introduces a new concept: gap bonding, where the electromagnetic (EM) bonding is achieved by a conductive contactless gap structure. This makes the SMT employment possible and low cost for integrating large gap array antennas and MMICs by picking and placing pre-produced gap waveguide components, sub-arrays, and MMIC components including phase shifters and amplifiers through gap bonding to make the systems.

One example of steerable beam antenna involving gap waveguide technology is the SMD (Surface-Mount Device) ultra-wideband (UWB) directive antenna elements (self-grounded bowtie antennas) [3] with gap feeding, gap bonding and gap packaging are integrated by SMT to make a multiple steerable beam antenna. The SMT placement machines can handle devices that have widths between 0.125 mm and a few cm, the speed is up to 3 devices per second, and the placement accuracy 10-15 µm. Therefore, this SMT solution can probably be used up to 100 GHz.

3. RIMP and Random-LOS OTA test concepts

In order to characterize OTA system performance of hardware such as smart phones or base stations, various parameters need to be known. We need to consider the type of propagation channel in which the antennas or devices are supposed to operate, the type of communications standard (e,g., cellular LTE or WiFi), system parameters (e.g., coding and modulation), the frequencies and bandwidths of operation (e.g., cm or mm-waves), the number of transmit/receive antennas (e.g., SISO/SIMO/MISO/MIMO), as well as the actual transmit/receive algorithms (e.g., MRC, ZF, SVD) used to produce single or multiple data bit streams.

Knowing the most representative propagation channel behavior for your specific application is not a trivial task. For handheld devices and small base stations it was early shown that the spatial behavior of the impinging waves could be approximated by the so-called Rich Isotropic MultiPath (RIMP) environment. If properly designed, a reverberation chamber can be used to emulate the RIMP channel with high accuracy. It has been shown that antenna diversity and MIMO performance can be determined for multi-port arrays in reverberation chambers, with well-defined diversity gains [4]. The standard deviation of the measurement errors obtained in RIMP is typically within 0.5 dB or smaller. At higher frequencies, e.g., up to 30, 60 GHz or higher the multipath waves (i.e., the RIMP contribution to the total receive signal fluctuation) will be weaker as compared to the direct line-of-sight (LOS) wave. The LOS component behaves randomly in real life. This randomness appears due to the randomness induced by the orientation and/or position of the wireless device, often at the user end. Hence, in addition to the well-known RIMP propagation channel the Random-LOS environment is proposed as a new complementing reference propagation scenario [5]. The RIMP and the Random-LOS provide two idealized yet well-defined edge propagation channels for this purpose. RIMP can be emulated in reverberation chambers, while Random-LOS is emulated in anechoic or rather in semi-anechoic chambers as shown in Fig. 3 (a) and (b), respectively.

In OTA characterization of active and passive devices, system related parameters are often fixed by the standards. Therefore, good system models are needed. The ideal threshold receiver model devised in [7] has been shown to work well for current LTE/LTE-A and WiFi communications standards. The model makes it easy to incorporate system specific parameters and receive/transmit algorithms over the whole bandwidth of operation of the device as well as the use of multiple antennas at both ends of the communication link. The probability of detection (PoD) of single or multiple bit streams is used as a measure of system performance in terms of relative data bit stream throughput. Excellent agreement has been achieved between theory and experiment [8].

In 5G systems, both the RIMP and the LOS propagation channels provide favorable propagation conditions for communications systems employing massive MIMO array antennas. The development, testing and characterization of new wireless technologies will heavily depend on OTA techniques. Especially, given the practical constraints by the huge number of antenna elements and the lack of a testing port at the mm-waves frequencies.

(a) (b)

Fig. 2 (a) Drawing of Bluetest´s RTS60 reverberation chamber for OTA chracaterization and testing of antennas and devices in RIMP. (b) Drawing of the OTA testing environment in semi-anechoic chamber in Random-LOS [6]

The combination of the ideal threshold receiver model with the two limiting environments RIMP and Random-LOS are linked together by a real-life hypothesis: “If a wireless device is tested with good performance in both pure-LOS and RIMP environments, it will also perform well in real-life environments and situations, in a statistical sense” [5].

4. Conclusion

Gap waveguide technology offers a great potential for mm-waves antenna systems with an easy integrability with MMICs by gap bonding and SMT. New OTA test characterization with RIMP and Random-LOS provides a tool for system evaluation for 5G communications.

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