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Contents

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1 Introduction

In the past few years, with the accelerated growth of information globalization (e.g., mobile cloud, Internet of Things (IoT), UHD 3D video, satellite and mobile communications), the capacity of the wireless networks has been scales up with the increasing data traffic. Recent studies find that data traffic is expected to experience a 1000-fold capacity increase in the incoming decade [1, 2] and the microwave band (300 MHz to 3 GHz) where various radio access technologies operate cannot provide this capacity demand. Thus, using new less-congested spectrum bands such as millimeter wave (mm-wave) bands, from 30 to 300 GHz, is a solution to increase network capacity mainly contributed by the improvement of the area spectral efficiency (bits/s/Hz/m2) [3, 4]. However, several open issues and technical challenges must be adequately addressed at this band. These issues can be classified into the following categories: channel propagation, antenna technologies, RF solutions, and modulation schemes [5-8]. This report provides an overview of the existing antenna technologies.

2 State-of-the-art on antennas design

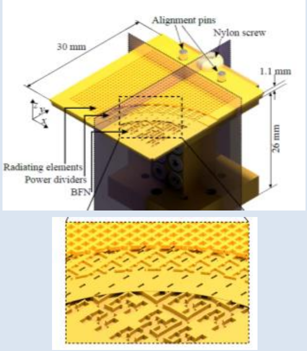
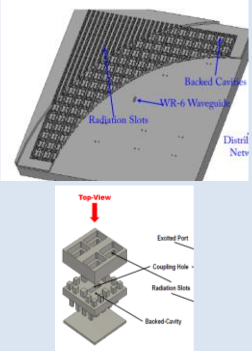
2.1 Array antennas

The shorter wavelength of a mm-wave signal enables a greater antenna gain by using an antenna array with a large number of elements. Among the planar array antennas, the architecture based on microstrip patches is one of the most common low-profile antennas used in microwave frequency bands. Over the last ten years, researchers and engineers have proposed several ideas and techniques to enhance the gain and the bandwidth of microstrip antennas to fulfill the new wireless networks requirements [9]. Hence, many antenna designs were put forth for dual band, triple band and multiband applications [11-15]. However, low radiation efficiency, caused by surface wave loss, radiation loss, and dielectric loss, restricts their applications in mm-wave frequency bands.

Antenna systems for 5G+ applications are required to have high effective radiated power to compensate for the high path loss experienced at mm-wave frequencies. Most mm-wave array antennas are based on waveguide structures (WG) [16] for high efficiency (50-70%) compared to LTCC (Low temperature co-fired ceramic) antennas [17] (eff.<50%). WG arrays are typically designed using multi-layer H-plane splits in WG blocks, which are then galvanically connected, e.g. by using diffusion bonding of laminated thin metal plates. In this way, a hollow WG based multi-layer structure is formed by stacking the etched metal plates in vacuum at high temperature and high mechanical pressure [18]. To avoid the disadvantages, micromachining with nanometer surface roughness allows for near-ideal joining of H-plane splits [19]. KTH institute of technology has already implemented several high-complexity devices, from 100 to 750 GHz, with up to 12 vertically stacked layers at losses equal to a single bulk material (see Figure 2.1 [20]).

In [21-30], the series-feed and corporate-feed slotted waveguides arrays have been proposed based on air-filled waveguide, laminated waveguide, gap waveguide, and substrate integrated waveguide (SIW), respectively. However, the conventional slotted waveguide arrays usually suffer from narrow bandwidth. Several representative methods have been implemented on these antennas to enhance the bandwidth and gain. In [31], the impedance bandwidths of the cavity-backed slot antenna and its array were improved by using hybrid cavity modes and loading some open-ended cavities, respectively. In [23], the impedance and the gain bandwidth of the array are improved by using the partially corporate feeding network in the E-band. In [32], the impedance bandwidth of the slotted waveguide array was enhanced by optimizing the height of the loaded cavities for decreasing the Q values of two eigenmodes. In [33], a 32×32 element high-gain slot array antenna is designed by utilizing chemical-plated polyetherimide, the operating bandwidth can cover the 71–86 GHz frequency band by adding the metal brick in the backed cavity. Also, gap waveguide technology enables low-loss propagation along artificial PMC surface waveguides. Slot array based on groove gap waveguide corporate feed can reach a relatively high efficiency using CNC-milling technology (see Figure 2.2 [34]).

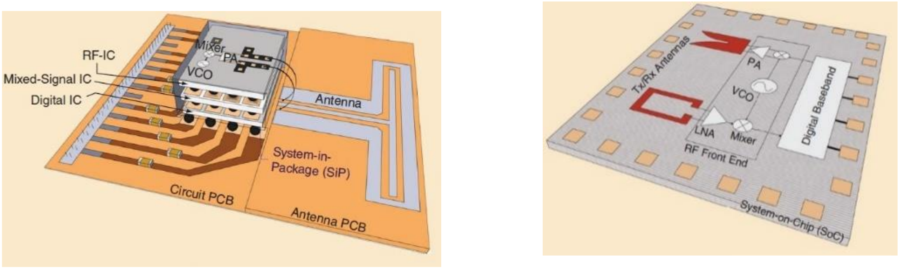
Besides, some composite structures, such as the SIW-feed (substrate-integrated waveguide) patch arrays [35-38], the SIW-feed complementary dipoles arrays [39,40], the inverted microstrip gap waveguide-feed dual-mode horn array [41], the gap waveguide-feed patch arrays [42], the airfilled waveguide-feed patch arrays [43], and the corporate-feed waveguide slot array loading with the double slit-layers [44], are also proposed to enhance the impedance bandwidth by combining multiple operating modes.

		
	Figure 2.1. high-gain flat array antenna designs	*Figure 2.2 Slot Array Antenna based on Ridge Gap Waveguide.*
Frequency	**320-400 GHz**, 20.6%	135- 151 GHz, 11.4%
Array gain,eff.	32x32, 38dBi, **>60%**	32x32, 37.5dBi, **55-63%**
Fabrication	Silicon-macromaching	CNC-miling

2.2 Antennas-in-package and Antennas-on-chip

With the new frequency ranges open for 5G systems, the antenna design has been a hot topic. Several technologies are available such as: Antenna on Chip (AoC), Antenna in Package (AiP), Gap Waveguide Antenna, Leaky Wave Antenna, etc. The most widely used technologies are the Antenna on Chip and Antenna in Package as those are proved technologies in previous mobile communication generations.

In the first one, the antenna element is designed separately from the rest of the IC. This way engineers can make use of low-loss substrates with good microwave properties to design antennas with the required characteristics. Radiation efficiencies above 90% can be achieved this way [45]. This approach is referred to as AiP, and it suffers from increased geometrical complexity of the system, excessive chip area usage, high manufacturing costs, interference with other IC modules, and most importantly – heat and power transfer problems [46-48]. Bonding wires or flip-chip interconnects are often used to connect the antenna module to the rest of the IC [49], and this not only reduces the bandwidth of a device and introduces interconnection losses, but also limits the amount of maximum power one can deliver to the antenna and creates a very weak heat link.



(a) (b)

Figure 2.3. (a) A typical AiP device (from [4]), and (b) A typical AoC device (from [4]).

In the second approach, antenna element is patterned into the top metal layers of an IC Back-End-of-Line (BEoL) together with the active Front-End-of-Line (FEoL) components during the single manufacturing cycle. It greatly reduces the fabrication costs, preserves the planar geometry of the system and offers integration possibilities beyond those of AiP systems. A comprehensive survey on AoC with several references to the state-of-the-art designs can be found in [50]. Silicon is the most desired substrate material for AoC applications due its low cost and ease of fabrication. The problems are its high permittivity, which makes antenna radiate mostly into silicon rather than air (>90% for an electric dipole), and high losses due to its low resistivity (10-100 Ωm). Backing the chip with a ground plane significantly improves antenna performance, but then the surface waves become an issue as the power coupled to them is either dissipated in silicon or results in the re-radiation into undesired directions [51]. One solution to this problem would be to use one of the dioxide's metal layers as a ground, but the proximity to the ground plane would deteriorate performance of many antenna elements. A cavity-backed slot antenna with a -2dBi gain and 15%

radiation efficiency at 140GHz [52] is one of the best solutions of this type at mm-frequency range. One can also follow a metamaterials-inspired approach and try to substitute a ground plane with an Artificial Magnetic Conductor (AMC). It might lead to more than 15dB gain improvement (with a peak gain of 5dBi) in case of dipole antenna [53] but limits the bandwidth to about 2% (which might still be sufficient at mm-frequencies). Another workaround is creating an air gap under the radiating element by either silicon etching or micromachining. A folded-dipole antenna above such a cavity can achieve high 8dBi gain with >50% radiation efficiency in 122-140GHz range [54], although requires costly chip-level modifications.

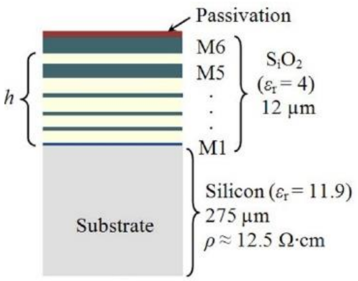


Figure 2.4. Cross section of a typical commercial silicon chip (from [52]).

In the following table a short comparison of these two technologies.

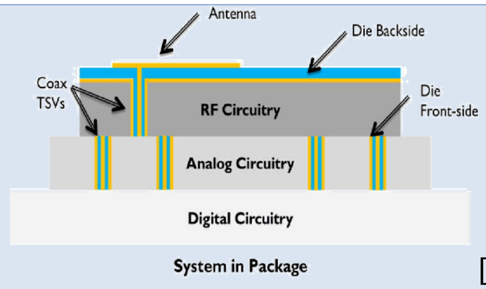
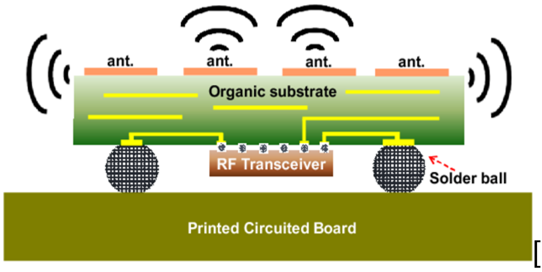
Antenna On Chip	 [55]	Cost effective Low resistivity High permitivity
Antenna In Package	 [56]	High gain Broad bandwidth Transmission loss

Table 2.1. Comparison of on Chip and in Package antennas.

For 5G systems, the use of active antennas (Antenna + Power Amplifier) in large arrays is paramount. For this end, the use of different transistor materials as Gallium-Arsenide, Gallium-Nitride and Silicon is added up with different combining techniques to enhance directivity, gain and radiated power. The most important bands are the Sub-6 GHz, K, V and W bands, covering the 100 GHz range.

In the following table a brief summary of the Sub-6 GHz range is provided. These are mainly for base station.

REF	Year	Operating freq. (GHz)	R(UB/LB)	Array width (λ)	Polarization	Isolation (dB)	Gain of Unit (dBi)
[57]	2017	0.7-0.96 & 1.71-2.69	1.78	0.39	Dual	-	8.4 & 8.7
[58]	2016	0.7-0.96 & 1.71-2.7	1.78	0.42	Dual	-	8.6 & 8.3
[59]	2017	0.79-0.96 & 1.71-2.69	1.78	0.50	Dual	-	8.6 & 8.3
[60]	2016	1.71-1.88 & 1.92-2.17	1.02	1.14	Single	30	~8.2 & ~8.6
[61]	2017	1.71-2.17 & 2.49-2.69	1.15	~0.75	Dual	30	8.5 & 8.1
[62]	2018	2.5-2.7 & 3.3-3.6	1.22	0.41	Dual	25	8.4 & 7.7

Table 2.2. Sub-6 GHz active antennas.

R(UB/LB) is the ratio between the upper band and the lower band.

The table below comprises information for upper frequencies and more related to MIMO systems, which considers the MIMO order and peak capacity.

REF	Year	Bandwidth (GHz)	Isolation (dB)	Efficiency (%)	Peak channel capacity (bps/Hz, 20dB SNR)	MIMO Order
[63]	2019	3.4-3.6	>17	55	18	4
[64]	2017	3.4-3.6	>10	40	36	8
[65]	2019	3.3-3.6	>15	40	35	8
[66]	2018	3.4-3.8 & 5.15-5.93	>11	42	51	10

[67]	2019	3.4-3.6 & 5.15-5.93	>11	49	43.3	10
[68]	2019	3.3-3.6 & 4.8-5.0	>12	45	51	10

Table 2.3. Sub-6 GHz compact MIMO antennas.

For the K-Band, the phased array or large 2D array are very important. There are plenty studies for satellite applications in this range. In [69] a phased array module from an antenna in package is reported with 3.02dBi gain and an antenna efficiency of 82%, achieving a maximum peak 18.2dBm and maximum scanning angles of 50° at 28 GHz. Dual band antennas are also reported as in [70], where these are stacked antennas for RX/TX. In TX (29.4-31 GHz) the return loss is >10dB with an isolation >20dB, whereas the RX (19.6-21.2 GHz) reaches also >10dB return loss but with an isolation of >15dB. Also, a bow-tie topology demonstrated an isolation between ports of -20dB in a 2x2 MIMO array in [71], with a 2.41 GHz bandwidth at -10dB with center frequency in 28 GHz. In [72] an E-shaped patch dual band antenna achieve 4.55dBi & 1.72dBi gain, -21dB & 25.77dB isolation and 6.4 and 20.8 %BW at 29.2 and 37 GHz, respectively. With a 6-element array in [73] the minimum isolation is -14/-12dB and maximum -27/-28dB at 28/38 GHz with average gain of 5.8dBi in all antennas at both 28 and 38 GHz. A Vivaldi antenna covering 24 to 40 GHz is presented in [74] with average 10dBi gain and a 78% aperture efficiency.

In the V-Band a large attenuation due to oxygen peaking at 60GHz makes difficult the long-distance communication. Therefore, the short-range ultra-wideband application are more suitable for this range. Sensors, IoT and Wi-Fi are the killer applications in this section. At higher frequencies such as the V band, other options can be available, such as the slotted and the leaky-wave antennas. The use of leaky-wave antenna in [75] offers 2 bands in 40-52 & 52.5-65 GHz offers a gain of 18/18.7dBi and scanning angle of -78° to +69.6° / -65° to +69.7° respectively with an efficiency of 92.5%. Other publications as [76] demonstrates an impedance bandwidth of 35.41 GHz between 50.86 and 86.27 GHz covering a large portion of the V-/E-/W-Band with a return loss of -10dB and peak gain of 6.73dB.

The W-Band projects involve several antennas and considers the use of materials that provide larger power. Many of the tests are for radar applications. Therefore, the use of the antenna as a single element is discarded, instead the systems performance is crucial.

This report aimed to show that the performance of the modern on-chip antennas is not as much worse than their in-package counterparts as to disregard the AoC approach for beyond-5G network systems. The advanced on-chip integration techniques such as direct on-antenna power combining [77] featuring high-performing Doherty amplifiers [78] and contactless interconnects [79] might lead to a more effective power consumption at mm-wave frequencies. Summary on the antenna-IC integration and the corresponding reference can be found in [80].

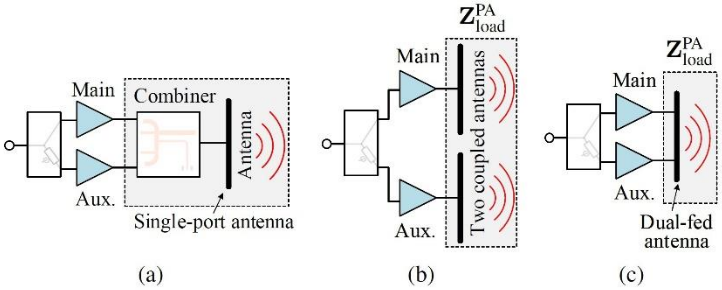


Figure 2.5 The evolution of DPA-antenna integration concepts (from [80]). From a lossy separate power combination (a), to the use of antenna elements for load modulation (b) and to electrically small DPA-antennas module (c)

Existing mm-wave array transmitters have poor efficiency. This is due to the output power limitations of semiconductor devices and due to major interconnect losses at these high frequencies. Improved circuit-antenna co-designs connect the power of multiple active devices on-chip to each antenna array element [81]. However, its circuit-level power combining/splitting networks are bulky and have inherently high insertion losses, which significantly increase with the number of devices and combined channels. Free-space power combining techniques, i.e. power combining directly by antenna without any additional circuitry, as well as non-galvanic transitions and ultra-low loss packaging concepts is a good alternative to enhance the overall energy efficiency. See Figure 2.6 [82]. In view of multi-functional active integrated circuit module for 5G+ base stations, gap waveguide technology enables the electromagnetic coupling from micro-strip line to waveguide, which is mechanically flexible compared to traditional lossy printed circuit board lines and bond-wires (See Figure 2.7 [83]).

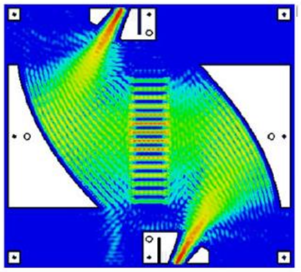


Figure 2.6. Time-averaged E-field amplitude @80 GHz inside single-layer spatial power splitter-combiner structure. The structure can be used as a stand-alone power splitter and/or combiner, a quasi-optical beamformer to excite an array of slot antennas.

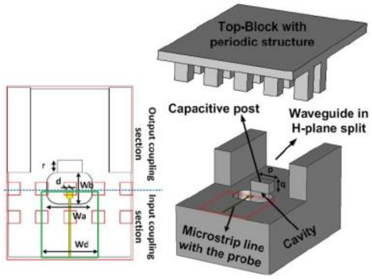
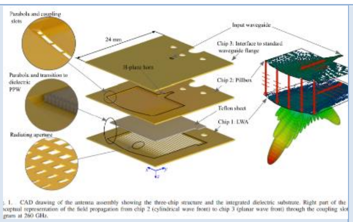
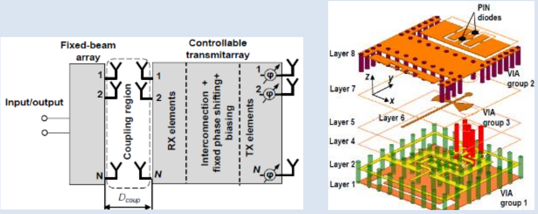


Figure 2.7. Transition from waveguide-to-microstrip line suitable for MMIC integration and packaging. @100GHz.

Due to complexities associated with the integration of active antenna elements in mm-wave band, multibeaming and beamsteering remains a major challenge. The currently developed solutions, thus far, have been limited to traveling-wave antennas with frequency-dependent beam steering [84, 85] and 1D electronic beam steering antennas [86], few for 2-D steering (except on-chip designs but in small bandwidth [87]); and most existing designs at 100+GHz frequencies are developed for fixed beam scenario. Compared to bulky and lossy corporate feeds, quasi-optical feeds can save most network loss but requires mode-transforming structure designs (see Figure 2.8 [85]): power through pill-box are transformed to planar wave, feeding leaky-wave array for frequency scanning.

For frequency-independent beamforming, antenna subarray modularization [88] is firstly considered to determine optimally sparse irregular architectures to relax the physical limitations of antennas, while reducing the number of amplitude-phase controls per element/subarray and keeping the design compatible with the semiconductor technologies.

At lower mm-wave applications, semiconductor switches are used as phase shifters, connected to each element [89], which are not feasible at 100G+ frequencies due to interconnection power losses and physical constraints. Recently, antenna element integrated with low-bit phase shifters are used in transmit-array for 2-D beam-steering. The reconfiguration is realized by an 8×8 array of cavity-backed patch resonator elements, where two AlGaAs PIN-diodes are integrated inside each element providing a 1-bit phase shift (see Figure 2.9 [90]). Furthermore, KTH's micromachined THz system platform also enables to implement MEMS (micro-electromechanical systems) waveguide switches [91], to make re-configurable antenna front ends.

	 *Figure 2.8. Leaky-wave antenna array fed by pill-box structures*	 *Figure 2.9. A block diagram of the transmit-array architecture; unit cell integrated with 2 pin-diodes.*
Beamforming	Frequency scanning	**2-D beam-steering: ±30, ±40°** (in 1bit phase control)

Frequency	220-330 GHz, 30%	23.7-25.1 GHz, 24.5%
Array gain, efficiency	28.5dBi 75%	17.5dBi scan loss ≤ 3.5dB, unit cell insertion loss ≤ 1.8 dB
Fabrication	Silicon-macro-machining	CNC milling + multilayer PCB

2.3 Passive Multibeam Antennas (PMBAs)

The PMBAs are a class of MBAs (Multibeam Antennas) that achieve the desired beamforming in the RF domain without using any active components [92, 93]. In general, the PMBAs contain a finite number of well-isolated input ports and can be divided into three categories: based on reflectors, based on lenses, and based on beamforming circuits.

The performance of a PMBA based on reflector can be improved by modifying the shape of the reflector, adjusting the feeding antennas design, and/or optimizing the relative orientation and positioning between the reflector and the feed antennas [94] (Figure 2.10). Particularly, to reduce the pattern distortion caused by the blockage due to the feeding antennas, offset-fed reflectors have been employed for multibeam systems [95, 96]. In addition, bifocal dual-reflector configurations, as well as shaped dual and triple reflectors, have been exploited to tailor the aperture illumination for enabling a high aperture efficiency [97- 99].

The dish reflector, made of metallic materials, increases the weight, size, and cost of this kind of system. Alternatively, due to the development of printed circuit technology, planar reflect-arrays have been investigated. These planar structures aim to replace the conventional reflector, allowing a lower profile, lower cost, and lighter weight. Various center-fed and offset-fed reflect-arrays that produce a single or multiple main beam(s) within a single- or multiple-frequency band(s) have been proposed and experimentally verified at microwave to mm-wave frequencies [100-106], which can potentially be further developed into MBAs by including more feed antennas.

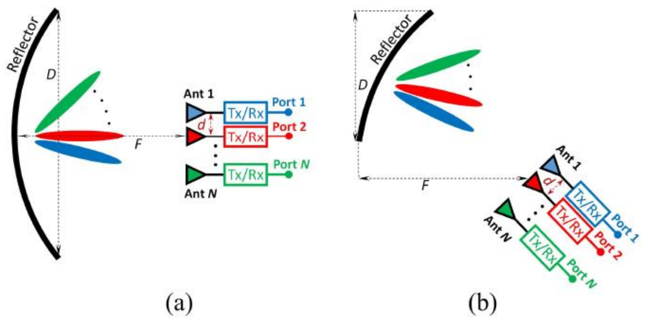


Figure 2.10. Configuration of the (a) center-fed and (b) offset-fed parabolic reflector fed by an array of antennas for producing N beams [113].

Regarding the lens-based PMBA, in order to achieve low-profile and low-loss planar beamforming lenses at mm-waves frequencies, the substrate-integrated waveguide (SIW) technology has been employed to implement high-performance lens-based PMBAs [107-110]. In contrast to the reflector- and lens-based PMBAs relying on quasi-optics beamforming strategies, passive beamforming circuit is a versatile approach that can be fully integrated with an array of antennas into a single substrate. Various beamforming circuits have been proposed and demonstrated, among which the most well-known ones are the Bulter matrix [111] and the Blass matrix [112]. In particular, the research efforts have been carried out in developing and miniaturizing Butler matrices based on SIW structures from microwave to MMW, due to the planar and low-loss properties of SIWs [113].

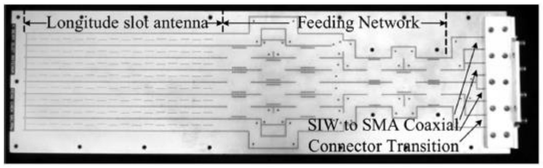
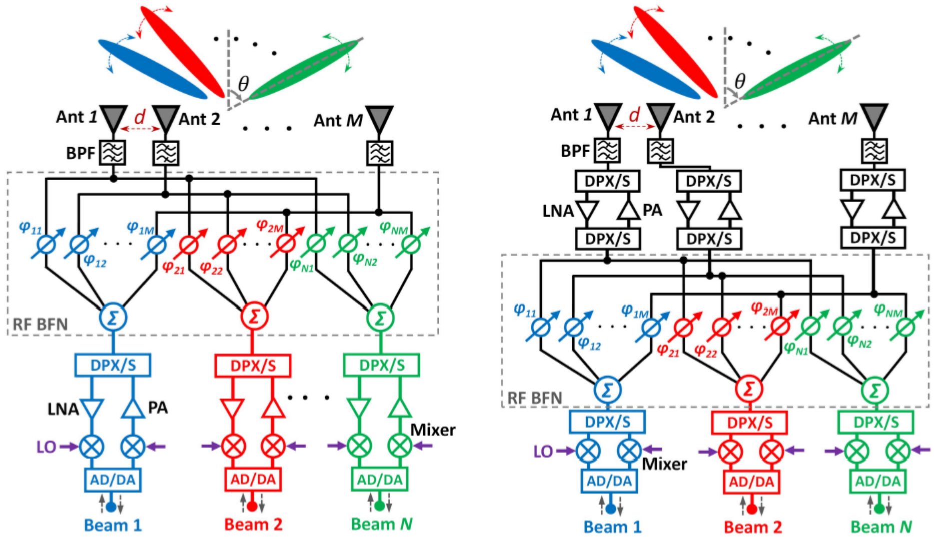


Figure 2.11. Photograph of a Ku-band SIW 4x8 Butler matrix MBA [113].

3 State-of-the-art on antenna systems

3.1 Multibeam Phased-Array Antennas (MBPAAs)

Different from the PMBAs presented in the previous section, which have a prefixed number of beams each pointing at a predefined direction once the system is manufactured, the PAAs (Phased Array Antennas) have agile beams, providing significant system advantages [114]. Phased-array technology has been developed in recent years for multiuser or multitarget applications due to its frequency reuse advantage and can be classified in passive and active MBPAAs. A dual-channel active MBPAA receiver with 4-bit phase shifters realized in the SiGe BiCMOS technology, which produces four linearly polarized independently scanning beams in the Ku-band for radar application is presented in [115]. Based on the same concept, a programmable phased-array receiver has been further developed that supports four simultaneous beams [116]. True-time delay circuits can be adopted for wideband multibeam generation using the RF phase-shifting scheme [117]. MBPAAs have also been deployed on geostationary satellites for satellite communications, which provide more versatile contour beam patterns that are adaptive to the dynamic market coverage on the ground [118, 119].



(a) (b)

Figure 3.1. System architecture of (a) passive and (b) active MBPAA [113].

3.2 Active Digital Multibeam Antennas

Comparing the PMBAs and MBPAAs using analog beamforming networks to obtain multiple independently controlled main beams, performing the beamforming in the digital domain at baseband is a more flexible and versatile approach. Various DMBA systems have been demonstrated for commercial satellite communications [116], [120], [121], wideband beam hopping [122], mobile communications [123], spaceborne interferometric synthetic aperture radar [124], massive MIMO [125-127], automotive radar sensing [128, 129], radio astronomy [130], personnel imaging [131], point-to-point links [116], and so on.

Generally, the active beamforming system can provide a higher transmitted power and a better beamforming flexibility compared with the passive multibeam antenna array. Combined with MIMO techniques, the performance of the active beamforming system can be further improved. With advanced beamforming precoding, the MIMO communication system can generate multiple beams to deliver multiple data steams for supporting single-user (SU) MIMO and multiuser (MU) MIMO communications [132]. The MIMO beamforming techniques can offer a high antenna array gain, anti-interference, a better signal coverage, and a high spectral efficiency for 5G millimeter-wave cellular communication.

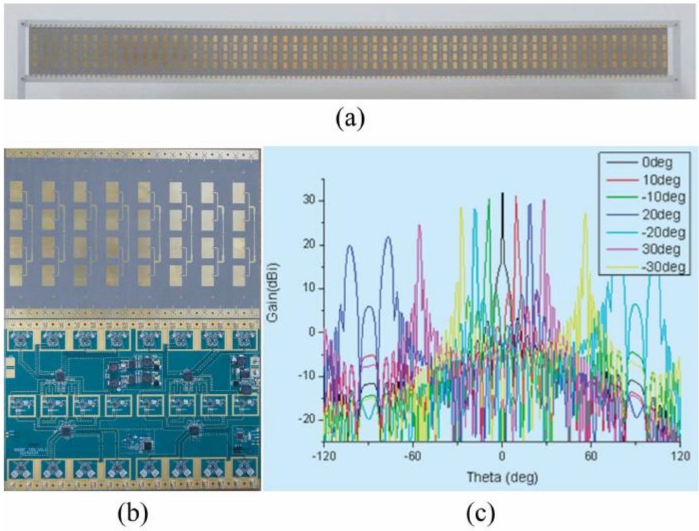

(a)
(b)
(c)

Figure 3.2. (a) Photographs of a 64-channel active DMBA transceiver. (b) Enlarged views of the fabricated antenna array (front side of PCB) and the RF front-ends (back side of PCB). (c) Synthesized multibeam radiation patterns (produced by [124]).

3.3 Hybrid Beamforming Antennas

In a fully digital multibeam antenna system, each antenna is connected to its own radio frequency (RF) chain and the radiation beam steers by shifting the signal phase of channels in the baseband. However, it is a problem to implement many RF chains in a system since the cost and the power consumption are significantly increased. Furthermore, due to the wide signal bandwidth employed in 5G communications, the high-speed data captured from all the RF channels would add up, a real-time processing for a huge amount of information is needed in the system. To improve both cost and power efficiency, the hybrid analog-digital beamforming system has been reported in recent years [133-137]. In [134-136], the beam selection scheme is proposed where a subset of the available antennas is adopted, and the signals associated with them are processed. The dynamic beamspace hybrid analog-digital beamforming systems are quite common. However, they are costly and complexity. A static beamspace structure is realized by a lens array in [135] and narrow beam width is achieved even by reduced RF-chains. In [137], a hardware-oriented modelling method for predicting the performance of an mm-wave hybrid beamforming transmitter is presented. The study reveals that array dimension and the linearization must be accounted for when designing a beamforming transmitter since these affects directly on the distortion level and its variations vs. steering angle. Thus, this work can provide guidelines for developing and optimizing large-scale arrays.

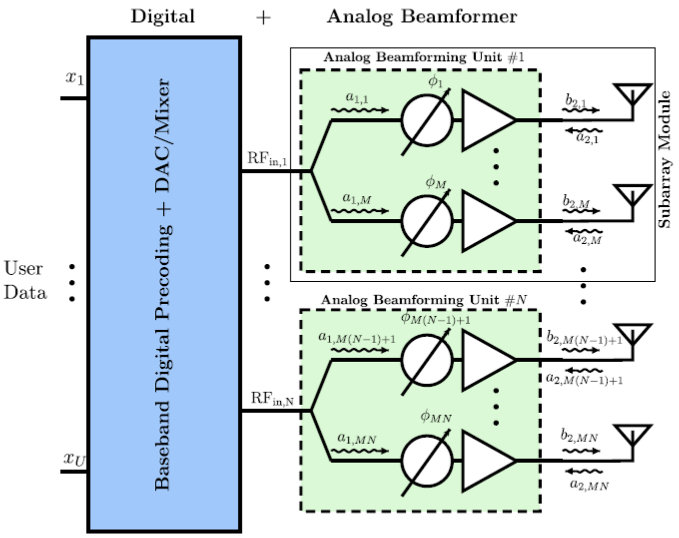


Figure 3.3. Block diagram, of a hybrid digital and analog beamforming transmitter [137].

3.4 Distributed Massive MIMO (DM-MIMO)

One of the critical building blocks for the evolution and deployment of wireless communication systems is accurate synchronization. Massive MIMO has gained a lot of attention in recent years. Earlier massive MIMO systems have been modeled as co-located, where a common local oscillator is used. Hence, there is no issue of antenna frequency that necessitate a synchronization procedure to be in place in this case. Practically, having a common local oscillator to drive massive number of antennas may be challenging. Moreover, in some situation, distributed massive MIMO may be more useful and suitable compare to the co-located counterpart [138].

In a communication system, receiver must be synchronized with the incoming signals to work properly and the accuracy of the synchronization will determine whether this system is able to perform well. Synchronization is defined between the receiver and incoming signal that including timing synchronization (the receiver needs to determine at which time instants the incoming signal has to be sampled) and carrier synchronization (for bandpass communications, the receiver needs to adapt the frequency and phase of its local carrier oscillator with those of the received signal). Conditions that makes the acquisition of the synchronization parameters burdensome are low SNR, strong fading, and (multiuser) interference.

The receiver must estimate the parameters of timing offset (TO) and carrier frequency offset (CFO) and compensate for their effects from the received signal in order to decode it. Massive MIMO relies heavily on accurate synchronization to work. The four salient synchronization parameters are timing, phase, frequency, and amplitude (some of which may include multi-path effects). Timing errors occur because of the small mismatches in the transmitter and receiver oscillators and from the unknown time of flight between transmitter and receiver. Phase errors occur because of mismatches in the transmitter and receiver carrier references and from the unknown time of flight between the transmitter and receiver. Amplitude errors arise mostly because of attenuation in the channel, but also are contributed to by mismatches in the transmitter and receiver front-end gain stages. Frequency errors, more correctly termed carrier frequency errors, are cause by a frequency mismatch in the transmitter and receiver carrier references.

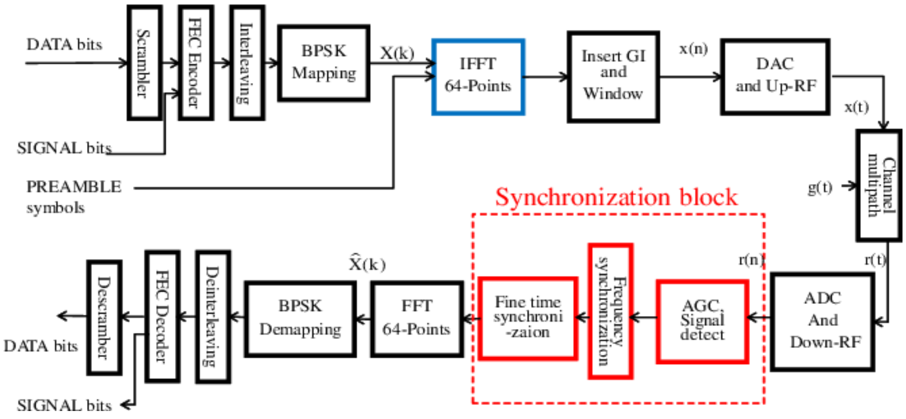


Figure 3.4. Wireless communication system using OFDM [145].

Implementing distributed massive MIMO system introduces a practical challenge since each individual or a cluster of individual antennas may have its own independent local oscillator. Hence, there will be differences amongst frequencies generated by the local oscillators [139], which cause Inter-Carrier Interference (ICI) [140]. Therefore, a dedicated procedure must be implemented in order to synchronize the antennas' frequency so that the received signals can constructively combined. Hence, the benefit of massive MIMO can be realized.

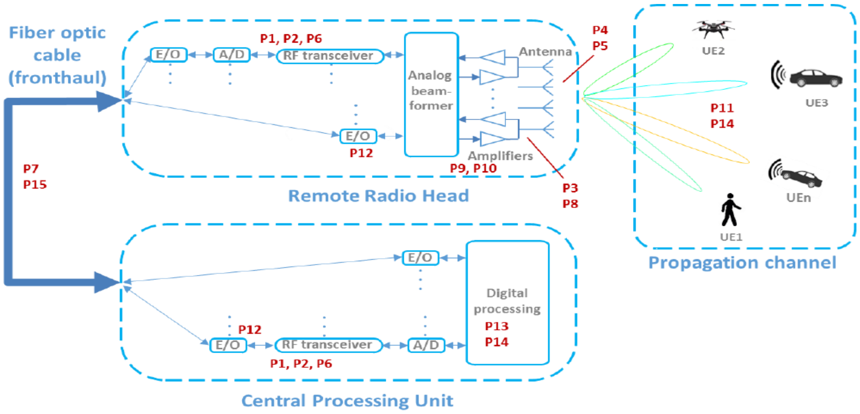


Figure 3.5. The overview of the project, P14. Digital array calibration techniques and synchronisation for DM-MIMO.

Several antenna frequency synchronization algorithms such as Joint Multi-User Beamforming (JMB) [139], AirSync [141] and Fine and Accurate Synchronization for Large Distributed MIMO Wireless Networks (FASTER) [142] have been proposed in recent years. These algorithms focused entirely on the downlink channel. The JMB and AirSync algorithms rely on master-slave relationship among the massive antennas, where a particular antenna is selected as the master and all other antennas (the slaves) have to adjust their frequencies according to that of the master. On the other hand, FASTER algorithm performs its synchronization by iteratively refining the frequency offset estimates [143].

In the paper [138], that focus on uplink mode, the master-slave method used in JMB and AirSync is adapted to provide antenna frequency synchronization at the receiver. In addition, pre-mitigation strategy is employed at the transmitters in order to compensate the effect of eventual multiple Carrier Frequency Offsets (CFOs) caused by multiple simultaneous users.

In [144], the effect of frequency offsets on the uplink sum-rate performance of massive MIMO systems is studied for both collocated and distributed antenna architectures, in the case of flat fading with pilot assisted estimation. The system performance may degrade when frequency offsets are present in the system. Frequency offsets are inevitable in practical systems due to the presence of carrier frequency mismatches and Doppler shifts caused by movements of the user terminals.

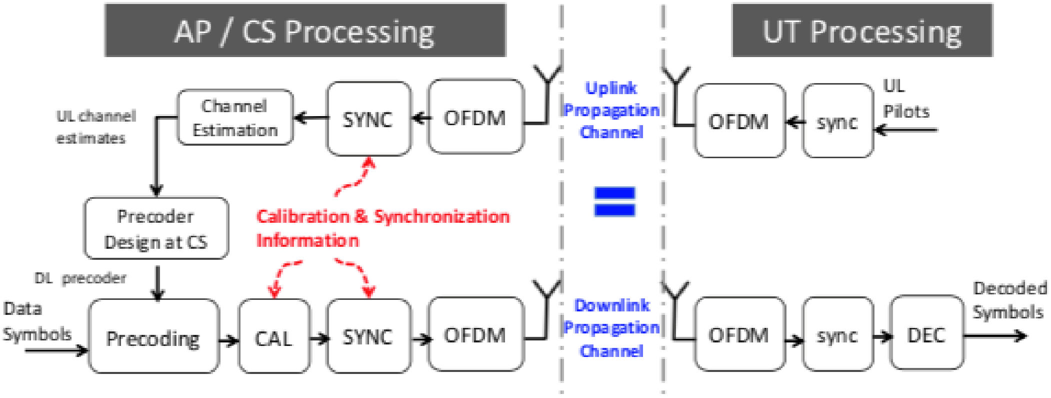


Figure 3.6. Uplink training and downlink transmission for distributed channel-reciprocity based MU-MIMO [146].

In order to make use of the reciprocity assumption and rely on the uplink CSI to compute precoding coefficients, the non-reciprocal transceiver responses need to be calibrated. Such a procedure is often termed reciprocity calibration and contains two steps: (i) estimation of calibration coefficients, and (ii) compensation by applying those to the uplink channel estimates [147].

Paper of [10], propose a convenient calibration method mainly relying on mutual coupling between BS antennas to calibrate its non-reciprocal analog front-ends. It makes no assumptions other than channels due to mutual coupling being reciprocal.

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