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Literature report on state-of-the-art mm-wave electronics

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Contents

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1 Introduction

1.1 Overview of mm wave electronics for active satellite antennas

1.1.1 Emergence of mmWave Electronics & Prospect in Satellite Communication

Millimeter-wave (mmWave) electronics, with their operation in the frequency range of 30-300 GHz, have emerged as a transformative technology in high-speed data communication [1]. The scope and potential of this technology are being harnessed especially in active satellite antennas to meet the demands of high-throughput satellite communication. The mmWave spectrum's expansive bandwidth capacity has been recognized as a solution to the bandwidth scarcity in lower frequency bands (i.e., 210 MHz – 7.125 GHz), accommodating high data rates necessary for modern satellite communication. With its high-frequency operations, mmWave electronics have been integral in supporting the shift towards faster, more efficient active satellite systems.

1.1.2 Antenna Miniaturization and the Role of mmWaves

The small wavelength characteristic of mmWaves has facilitated the design and development of compact, yet highly effective active antennas for satellites [2, 3]. The resultant miniaturization has been crucial in optimizing satellite payload while maintaining and/or enhancing communication performance. It has revolutionized beamforming techniques in active satellite antennas. With the ability to steer the beam dynamically and with high precision, these antennas ensure optimized transmission and reception paths. This results in efficient utilization of the satellite network and robust, interference-free communication.

1.1.3 Technological Advancements

Recent advancements in solid-state devices, such as Gallium Nitride (GaN) and Indium Phosphide (InP) amplifiers, have contributed significantly to overcoming these hurdles, paving the way for more robust and efficient mmWave systems [3, 4]. Furthermore, the rise of phased array technology has made it possible to construct mmWave antennas that can generate multiple, highly directional beams, further exploiting the spatial domain to enhance capacity and performance.

Note that promising mmWave electronics still present challenges, e.g., significant signal attenuation due to atmospheric conditions and complexity in component design and manufacturing. However, innovative technological developments in solid-state devices and phased array technology are progressively addressing these hurdles. Despite the challenges, mmWave electronics continue to reshape the landscape of active satellite antennas, pushing the boundaries of satellite communication capabilities. With ongoing advancements, the nexus of mmWave electronics and active satellite antennas promises to unlock unprecedented opportunities in space-based communication networks.

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1.2 Importance of higly integrated mm wave electronics for active antennas

Highly integrated millimeter-wave (mmWave) electronics are of utmost importance for active antennas in modern wireless communication systems. These antennas are vital in meeting the escalating need for high-speed data transfer and improved connectivity. The availability of mmWave frequencies, ranging from 30 to 300 GHz, offers a significant advantage in terms of bandwidth [1]. By utilizing highly integrated mmWave electronics, active antennas can capitalize on this bandwidth to enhance overall performance.

One key benefit of highly integrated mmWave electronics is the improvement in antenna performance. The integration of multiple components, such as amplifiers, filters, and mixers, into a single chip or module enables active antennas to achieve higher gain, wider bandwidth, and lower noise figure.This integration results in efficient signal processing, leading to improved signal quality, increased data rates, and enhanced coverage.

Moreover, highly integrated mmWave electronics contribute to a compact form factor for active antennas. By combining multiple functions into a single chip or module, the physical size of the antenna system can be significantly reduced. This miniaturization is particularly advantageous in applications where space is limited, such as small devices, Internet of Things (IoT) devices, and automotive applications. The reduced footprint allows for seamless integration into various devices without compromising functionality .

In addition to size reduction, highly integrated mmWave electronics offer power efficiency advantages for active antennas. The integration of power amplifiers, low-noise amplifiers, and other components into a single chip allows for higher power efficiency, resulting in longer battery life for portable devices and reduced power consumption in infrastructure systems [2]. This increased power efficiency contributes to sustainable and environmentally friendly wireless communication systems.

Furthermore, highly integrated mmWave electronics enable cost-effectiveness in active antennas. The integration of multiple functions into a single chip or module eliminates the need for numerous discrete components, simplifies manufacturing processes, and lowers production costs. This integration also enables economies of scale and facilitates mass production, making active antennas more affordable and accessible across various applications and industries [3].

In conclusion, the significance of highly integrated mmWave electronics for active antennas is undeniable. These integrated electronics enhance antenna performance, enable a compact form factor, improve power efficiency, and offer cost-effectiveness. Leveraging the benefits of mmWave technology and integration, active antennas can meet the growing demands of high-speed wireless connectivity across diverse applications and industries.

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1.3 Definitions and acronyms

IoT	Internet of Things
MCM	Multichip module
MEMS	Microelectromechanical Systems
NRDs	Nonradiative Dielectric Waveguides
CPW	Coplanar Waveguides
NTN	Non-Terrestrial Networks
AoC	Antenna on Chip
AiP	Antenna in Package
SOI	silicon-on-insulator
AMC	Artificial Magnetic Conductor
eWLB	Embedded Wafer Level Ball

2 MM-Wave Electronics for Satellite-based Active Antennas

2.1 Characteristics and design considerations mm wave electronics for space applications and environment

2.1.1 Evolution from traditional geostationary satellites to LEO constellations

In the Table below, the most significant milestones in the satellite communication industry are chosen, compiled and presented. [1]

1945	Arthur C Clarke first described a system of manned satellites in his article, Wireless World
1957	The launch of the first Earth-orbiting satellite, Sputnik 1
1958	The first communications satellite, Echo 1, a passive communication device
1958	The world's first active communication satellite, SCORE
1961	The world's first private sector communications satellite, AT&T's Telstar
1965	Intelsat Earlybird, the first continuous satellite communications link
1975	First satellite broadcast to cable TV stations worldwide
1976	Marisat, the first communications system to provide mobile service
1998	Activation of the Iridium's hand-held global satellite telephones
2010	HYLAS and KaSAT Ka band satellites launch in Europe
2012	Studies began on Terabit/s satellite for Europe
2014	INMARSAT S band satellite for Aero passenger services using hybrid approach.
2015/16	Proposals for massive constellations of non-GEO small sats
2017	ViaSat announces 3x 1Tbps satellites
2018	SpaceX and Telesat launch Demo sats for their constellations.
2023 -	Progress towards 6G

2.1.2 New-space approaches and evolutions to mm wave electronics design and qualificaztion

Non-terrestrial networks in 6G communications would require variety of antennas that operate in mm-wave bands, to provide wide coverage at all times and locations. One major design challenge involving the integration of antennas on satellites is the miniaturization of antenna arrays. Some preceding work towards miniaturization is discussed in [1]-[4].In [1], compact array configuration designed to operate at mm-wave is discussed. A low-cost planar phased array that can be operated in mobile satellite (MSAT) platforms is presented in [2].

The demand for high speed communications require the development of compact and efficient transceivers, capable of operating at high frequencies. Figure 1 shows the design of a hybrid analog-digital multi-beam multi-antenna transceiver architecture. Such hybrid multi-beam beamforming systems would provide support for data multiplexing with reduced power consumptions and costs.

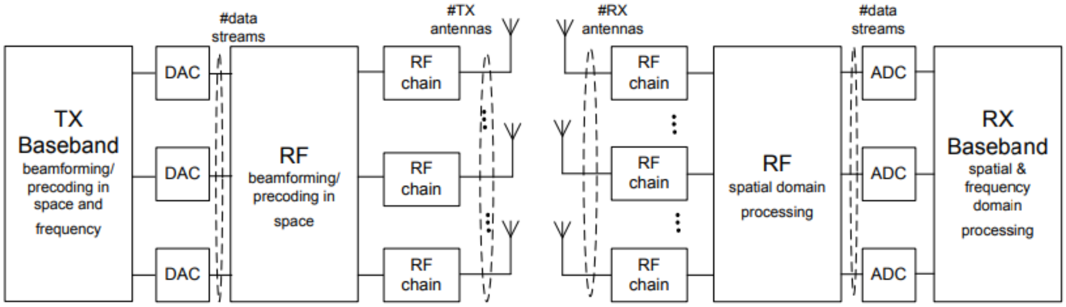

Figure 1: Tranceiver architecture for mm-wave communication[5]

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2.2 Main categories of mm-wave electronics for active antennas

2.2.1 Front-end electronics and technologies

Front-end elements may be considered to be those present in active array Transmit/Receive (T/R) Modules structures. They include everything from the antenna until entering the domain of digital signal processing. These blocks may be broadly classified into [1]:

- Radiating elements (REs): Compact antennas suitable for mmWave systems form the end. Patch, and horn antennas are all common choices for large arrays where efficient integration is key. Other promising types include Dielectric Resonator Antennas (DRAs), consisting of a high-permittivity dielectric resonator placed on a ground plane, and slot antennas, which consist on narrow slots cut into a metal plate or waveguide structure. They offer advantages such as low profile, wide bandwidth, and ease of integration with other components. Antennas employing metamaterials are also being studied [2][3].

- Power Amplifiers (PAs): Responsible for amplifying the signal to the levels required before they are radiated by the antenna. Due to the reduced available space in mmWave systems, Solid-State Power Amplifiers (SSPAs) are right now the most common choice, with the bulky Travelling Wave Tube Amplifiers (TWTAs) being mostly applied in the domain of high-power, fix beam GEO communication satellite systems. For SSPAs, while BJTs and MOSFETs are still common, a wide variety of other technologies have emerged, including heterojunction bipolar transistors (HBTs), metal-semiconductor FETs (MESFETs), high electron mobility transistors (HEMTs), with the latter being one of the most common recently [4].

  SSPAs are based on solid-state semiconductor technologies such as gallium nitride (GaN) or gallium arsenide (GaAs), although other III-V type semiconductors are also used. The choice of material is based on the type of PA and several complex criteria. Nevertheless, GaAs- and InP-based HEMT switches offer high isolation, low insertion loss and high switching speed but are limited in power-handling. On the other hand, wide band-gap, AlGaN/GaN HEMT might be useful for control and amplification [5].

  One very active area of research concerns the integration of PAs and REs into a single block, in order to eliminate the need for any isolators / circulators or matching networks between them. The authors in [6] obtain a PA + RE integrated block with a cavity-backed bowtie slot. They use a contactless coupling between the PA and the bowtie in order to minimize losses. The PA is a HEMT based in GaAs technology packaged into a separate MMIC.

- Low-noise amplifiers (LNAs): They are used to amplify weak incoming signals during reception. The most critical characteristic of LNAs is their Noise Figure, since they are the first element in the chain. Linearity and effective bandwidth are also key. In mmWave technologies, these become harder to achieve.

Among front-end electronics we also include Phase Shifter and Attenuators, which are the object of the following section.

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2.2.2 Beamforming electronics and technologies

Phase shifters and attenuators are the initial elements before the PA, as seen in Figure 1.

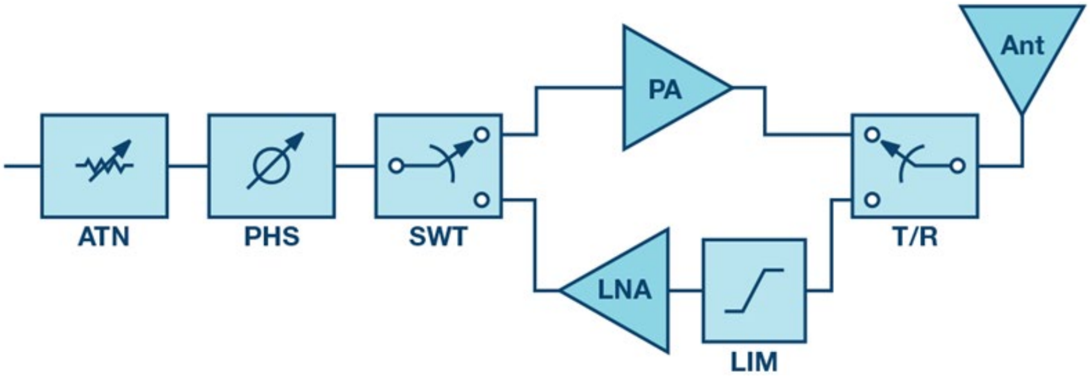

Figure 2. Front-end element diagram [1].

They are key elements in beamforming, with attenuator (with PA gain taken into account) controlling the amplitude component of the beamforming weights, and the phase shifter controlling the phase component.

While phase shifters can theoretically be analog, in practice they are almost always implemented digitally in order to avoid being affected by any noise present in the control line [2]. While quantization error is then present, its impact is much more limited. With mmWave components requiring further miniaturization and fine tuning, the most suitable approach is employing digital phase shifters with a higher bit count.

Regarding attenuators, the situation is similar: they are usually implemented digitally due to accuracy issues and switching speed requirements. Their role is also critical in performing array tapering to reduce side lobes in the active array. Technology employed usually consists on SiGe.

There have been some efforts into integrating everything, including phase shifters and attenuators, into a single IC. In [3], the authors employ SiGe BiCMOS technology to implement a full T/R module working at 28 GHz in an active chip area of only 1400x440 µm^2. It provides a total of 31.9 dB of gain and has a steering gain margin of 9 dB and phase margin of 360°. The digital control is implemented directly on top of the components.

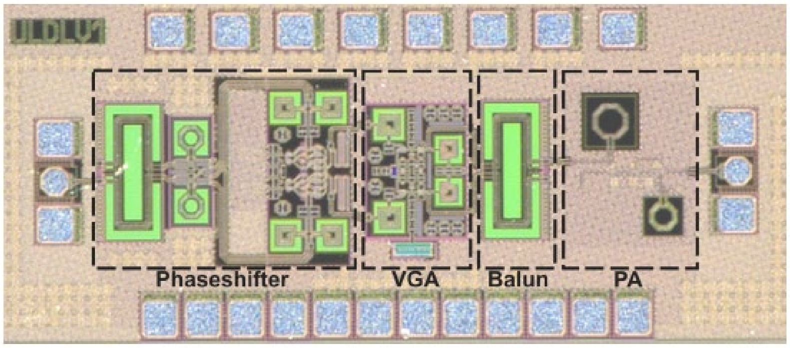

Figure 3. Micrograph of the fabricated 28 GHz transmitter front-end [REF GOES HERE]

In [4], a wideband (17.1-52.4 GHz) 4-channel Tx phased array front-end, also in SiGe BiCMOS, is presented. It includes Wilkinson divider cascading, phase shifters and attenuators in a footprint of 5x2.5 mm. The chip is tested using 5G NR MIMO protocols, performing adequately.

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2.2.3 Highly integrated electronics connections and packaging technologies

The need for millimeter-wave (mmwave) technology is growing swiftly for commercial and military applications. This is due to its inherent advantages such as high speed, bandwidth, and resolution for applications that include broadband wireless (together with 5G and Beyond), multimedia, the Internet of Things (IoT), space and defense, automotive radar, imaging sensors, and biomedical devices [2]–[4]. Hence, integration and packaging of mm-wave modules that are compact, reliable, repeatable and yet at a low cost is the prime challenge to industries [3]–[5]. To this context, the multilayer/3D multichip module (MCM) or system-in/on-package (SiP/SoP) with antenna-inpackage technologies, with highquality (high-Q) off-chip passive components and interconnects, are being considered as excellent ways for meeting these requirements [4]–[6]. Besides, additive manufacturing and microelectromechanical systems (MEMS) [4], [5], [8], [9] have shown promising results.

Herein, emphasize will be given in the advances in technologies that are mature, and cost effective for developing industrial products with manufacturing repeatability and high-performance reliability in adverse environmental conditions.

2.2.3.1 Multilayer MCM/SoP Fabrication Processes

The multilayer MCM/SOP integration processes is being used in the industry based on subtractive manufacturing technologies due to the performance reliability, process maturity, and repeatability with unfavorable environmental conditions. These methods are based on TF-based screen printing or thin-film deposition techniques [10].

2.2.3.2 Novel Multilayer Split-Ground CPW

Multilayer technology authorizes the developer to use numerous different transmission-line media with a wide scope of possible characteristic impedances. An optimum 3D SiP architecture will integrate various transmission-line components—MS, CPW, and SIW—side by side in a multilayer substrate.

2.2.3.3 Multilayer CBCPW and Ground Width

Multilayer CPW lines are preferred at mm-wave. In practice, conductor backing is utlilized to deliver mechanical strength to the substrate and to also provide a heat sink.

At the higher end of the mm-wave band, loss in traditional planar transmission lines (such as MS, TFMS, and CPW) rises rapidly due to limited track width, current crowding at conductor edges, and abnormalities along the conductor track [12].

2.2.3.4 Multilayer TFMS and Ground Width

A TFMS is created with a thin layer of dielectric/semiconductor. This was employed on semiconductors and is widely utilized as a replacement for traditional MS for the design of RF-integrated circuits/monolithic microwave integrated circuits (MMICs) [13], [14].

2.2.3.5 Via-Fence and Trench-Filled SIWs to 180 GHz

In planar transmission lines, loss advances extremely rapidly with frequency due to more elevated dielectric and conductor loss (surface finish and current crowding on conductor edges). As a consequence, for mm-wave and submm-wave modules, nonradiative dielectric waveguides (NRDs), MEMS-based waveguides, and SIWs [14], [15] have been considered as alternatives to MS, TFMS, CPW-STG, and CPW lines.

2.2.3.6 HSIW or ESIW

As defined earlier, with the increase in frequency toward mm-wave bands, the Q factor and losses from the SIW improve compared to planar transmission lines. To reduce this loss and hence increase the Q factor and power-handling capability, SIWs with a removed dielectric (air cavity) fully integrated into a planar substrate have been presented [16].

2.2.3.7 CPW Layer-toLayer Transition/ Interconnection

In a compact, multilayer mmwave system, the interconnection between different layers is one of the critical elements for a compact package. This is used to connect components and circuits on different layers, and a combination of two can be used as a feedthrough element between two circuits or systems, separated by an isolation wall, or between systems on different substrates. [17]

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2.3 Antenna front-end mm-wave electronics

2.3.1 Low-noise amplifiers

2.3.1.1 Introduction

One of the biggest problems with wireless communication is the high propagation losses, which increase as the frequency rises. In addition, if this type of communication is done via satellite, the losses increase considerably. Thus, the signal received at the receiver is very low level, making further post-processing almost impossible. For example, for imaging applications in the millimetre band, sensitivity is the most critical parameter since the received electromagnetic waves are due to thermal radiation, the level of which is not much higher than the thermal noise [1].

That is why one of the fundamental elements in this type of communications and the first to be implemented after the receiving element is a low noise amplifier, LNA. The LNA amplifies the received signal and, being the first amplification step, the noise figure plays an important role in the receiving system [2].

Therefore, the main element in designing the right LNA is to reduce its noise figure as much as possible, as well as to have a high gain with sufficient linearity range and low power consumption.

2.3.1.2 Semiconductor technologies (SiGe, GaAs, ecc.)

For applications in the millimetre band, LNAs have been manufactured with GaAs and InP technologies [3] [4], as they have proven to offer better noise figure performance than CMOS and SiGe BiCOMS [5]. The first mentioned technologies are normally used in the W-band and higher frequencies due to their high performance. Among them, InP technology has better performance but GaAs technology is more mature in its design and processing [1].

2.3.1.3 Applications

Thus, the increase of applications in the millimetre band needs to be cost effective, aiming to be low-cost, multifunctional, and multi-mode, i.e. with a shared frontend block [6]. This requirement means that LNAs must be reconfigurable. An example of this is shown in the article [7], where private networks are intended to be created from the 60 GHz band, as this frequency has a high absorption due to the oxygen molecule present in the atmosphere, and therefore high interference. In this way, short-range private networks can be created with very high speeds.

Another purpose of new configurations for LNA is multiband with a single transnceiver, as developed in the article [8]. For this purpose, a change of operational frequency by means of switches or varactors has been proposed, as shown in Figure 2.3.1. The LNA adopts a four-stage common source topology, where the matching networks are realised by microstrip lines, series capacitors and RF choke inductances.

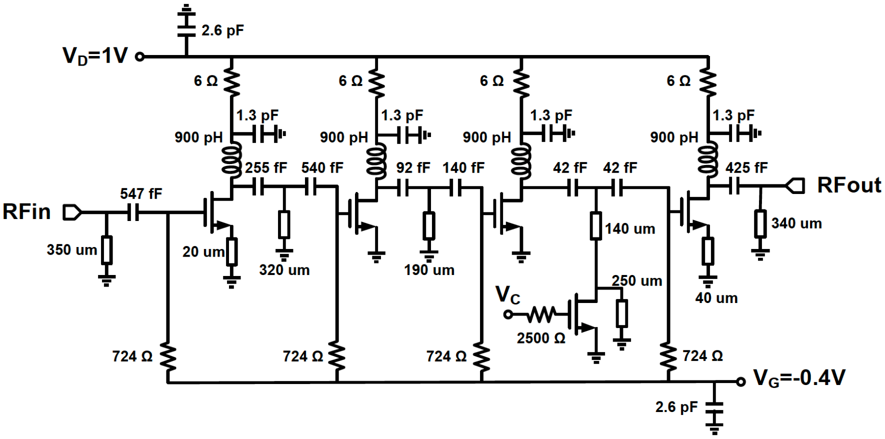

Figure 2.3.1. Schematic of the proposed LNA [8].

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2.4 Beamforming mm-wave electronics and technologies

2.4.1 Active and passive antenna beamformers

Antenna inherently is a passive device which can radiate the the input power into a specific direction generating a gain in specific direction. Signal received from the antenna is processed through an RF front end including Amplifiers, filters, TR switches and ADC. When a signal is connecting to the RF front end its impedance should be matched to the RF chain. Generally, all the components in a chain is matched to 50Ω and then cascaded with each other. In case of active devices, especially an amplifier (LNA for a receiver and power amplifier for a transmitter) impedance matching with a 50Ω can result in compromise on overall amplifier's performance. In order to optimize complete system's performance, an antenna is designed with an amplifier to achieve better performance. Output impedance of the system selected to enable a conjugate matching for which both amplifier and antenna can achieve better performance. This type of antenna system inlculing an active device like an amplifier is called an active antenna system. Active antennas can achieve felxibity and degree of freedom in terms of control in antenna radiation pattern. Consequently, this can improve overall system performance in terms of SNR, Received power and better matching performance.

For many applications like MIMO systems, active antenna can enhance spectral efficiency, spatial resolution and network overall capacity. Another component of the network like filter can also be added in the chain of amplifier and antenna. This can provide filtering for unwanted frequency signals, with an integrated system a compact low cost IC based solution can be achieved for many applications.

2.4.2 Analog vs. Digital vs. Hybrid beamforming approches

In antenna array system, beamforming network is used to apply a specific magnitude and phase value to individual antenna element. Variation of phase and magntiude creates a unique shape at the array output, hence known the circuit can be aclled as a beamforming circuit. This process can be performed in analog as well as digital or a hybrid way. A comparitive analysis of each tecnology has been presented next.

2.4.2.1 Analog Beamforming

In analog beamforming circuit as the same suggests, both phase and magnitude variations are applied the analog/RF domain. When antenna is working in receiving mode, signal received from each array element is connected to a amplifier and a unique phase shifter element as shown. Output from this chain combined using a power combiner and one final signal entert he Analog to Digital Converter (ADC) for digital processing. Analog beamforming generates one final beam at the output and the radiation pattern of the array can't be modified after final system has been designed. Since only one ADC is required in analog beamforming this ist he most cost effective beamforming system.

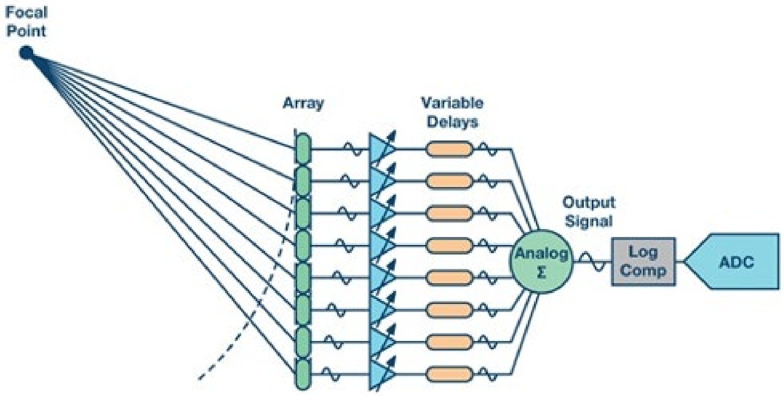

Figure 1- Analog Beamforming Architure [1]

2.4.2.2 Digital Beamforming

In digital beamforming architeure, beamforming weights (phase and amplitude) are applied in the digital domain. Each element of the array is directly connected to a ADC circuit and signal is processed in digital domain. Depending upon the number of elements of the array, the requirement for processing power of the system increases linearly. Digital beamforming generates an adaptive antenna system, pattern of the antenna can be shaped into any desired number of beams of shapes by varying the complex weights after fabrication. However, digital beamforming requires enormous processing power due to large volume of data from ADC. Since number of element is increased, overall size of the system is also greater as compared to analog beamformer. Lastly, the overall cost of a digital beamformer is the biggest challenge for its practical application.

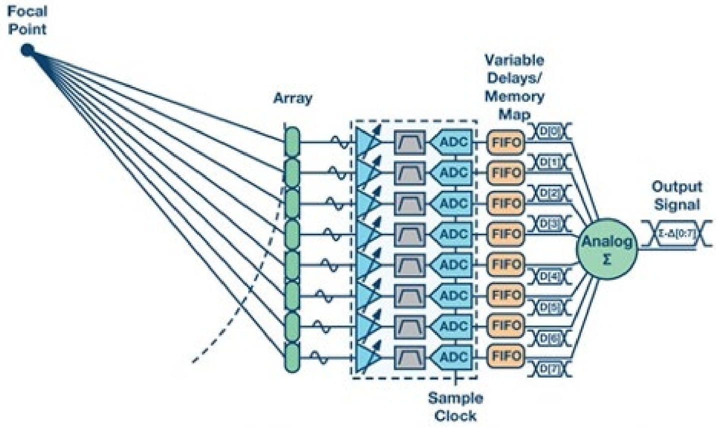

Figure 2- Digital Beamforming Architure [1]

2.4.2.3 Hybrid Beamforming

Hybrid beamforing scheme combines the best of the both analog and digital beamforming. In this scheme, array can be divided into sub-arrays through an analog beamforming unit. These sub-arrays can be then process digitally to achieve flexible beam pattern. Since, the number of ADC required for hybrid architecture is reduced as compared to digital network, signal processing power needed is reduced. This provides an excellent compromise between the performance and cost of overall system. Consequently, hybrid beamforming is the most popular choice for many applications.

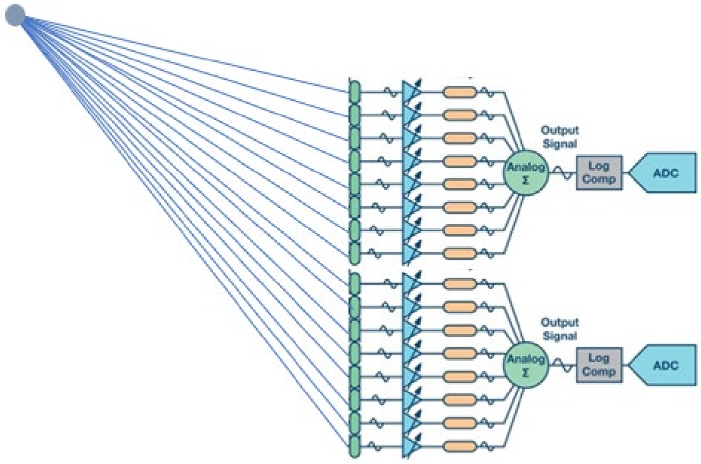

Figure 3- Hybrid Beamforming Architure [1]

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2.4.3 Direct RF and I/F beamforming approaches

IF and RF beamforming are two mmWave communications techniques with advantages and challenges. IF beamforming performs beamforming at a heterodyne receiver's intermediate frequency (IF) stage, while RF beamforming performs beamforming at the RF stage of a direct digital to RF transmitter. This summary reviews recent works on IF and RF beamforming, comparing and contrasting their design and performance. [1] proposes a 140 GHz IF beamforming phased-array receive channel with low noise performance in a 45 nm RFSOI process. A high-IF (9-14 GHz) beamforming architecture achieves lower loss and power consumption than RF and LO beamforming and better image rejection without external filtering. [2] designs a self-directed beamforming method that can be easily applied to broadband communication. Phase information extracted from the low-frequency component of the received signal is utilized to control beams. IF receiver modules are fabricated, and their operation is verified at the IF band. The SNR improvement is proportional to the number of synthesized modules using a 2 Gbps QPSK signal. [3] develops a vector-sum phase shifter (VSPS) for heterodyne transceivers with IF beamforming. The phase shifter is controlled at 16 states with phase intervals of 22.5°. They achieved low phase error, insertion loss, and power consumption across 6.5-9 GHz using a 0.18 μm RF-mixed signal CMOS process.

[4] presents a 6 GHz 160 MHz bandwidth MU-MIMO eight-element direct digital beamforming TX utilizing FIR H-bridge DAC in 28 nm CMOS. A sigma-delta modulation chain enables an inherently linear 1b RF DAC to suppress sigma-delta DAC noise and H-bridge to combine current-DAC, FIR-filtering, and RF up-

conversion for efficiency. [5] proposes a digital eight-element beamforming RF modulator that allows accurate steering of multiple independent beams. An area-efficient bandpass sigma-delta modulation is used with an N-path filtering to suppress quantization noise. Beamforming is enabled by careful frequency management, efficient digital phase shifting, upsampling, and upconversion. Compared to state-of-the-art digital-to-RF modulators, an order-of-magnitude improvement is achieved in area and power consumption per element. [6] demonstrates a 7.5 GHz-band digital beamforming using a 1-bit direct digital RF transmitter with a 10 GbE optical module (SFP+). A low-cost implementation and low hardware complexity are obtained by using SFP+. The RF signals above 5 GHz are handled using a direct digital RF transmitter which uses the folded image component of a 1-bit delta-sigma modulated wave.

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2.4.4 Digital beamformers ICs and solutions

2.4.4.1 Digital beamformers architectures and topologies

Digital beamforming (DBF) is a technique that performs beamforming in the digital domain rather than in the analog domain. This technique has advantages over analog beamforming, such as higher flexibility, precision, and performance. However, it poses some challenges, such as high hardware complexity and power consumption. This overview summarizes recent works on digital beamformer architectures and topologies for various applications, such as 5G mm-Wave communications, synthetic aperture radar (SAR) systems, and MIMO systems.

Some works focus on the design and implementation of the DBF receiver and transmitter channels, such as [7], which proposes an improved receiver architecture that reduces the hardware complexity and improves the dynamic range of the input signal by using ADCs with a smaller range and one RF down-converter, one ADC, and one DDC for an N-element beamformer. [8] proposes some applications of microsystem technology in DBF SAR system that combines electronics, photonics, and MEMS to achieve high integration, high speed, and low cost. [9] introduces a path-based MIMO channel model for hybrid beamforming architecture analysis that allows the generation of arbitrary propagation paths with distributions of the direction of departure (DOD), the direction of arrival (DOA), and phase and amplitudes. [10] presents a comparison of beamforming schemes for 5G mm-Wave small cell transmitters, including fully-digital transmitters, hybrid beamforming systems with different phase shifter topologies, and analog beamforming systems.

Some works focus on the design and implementation of specific components or technologies for DBF systems, such as [4] which proposes a 6 GHz 160 MHz bandwidth MU-MIMO eight-element direct digital beamforming TX utilizing FIR H-bridge DAC in 28 nm CMOS that uses sigma-delta modulation chain to enable an inherently linear 1b RF DAC to mitigate sigma-delta DAC noise, and H-bridge to combine current-DAC, FIR-filtering, and RF up-conversion for efficiency. [11] presents a wideband digitally controlled true time delay for beamforming in a 40 nm CMOS technology that uses an N-path switch capacitor delay cell to break the tradeoff between bandwidth and delay range by introducing tunable sampling clocks.

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2.4.4.2 A/D and D/A converters

Millimeter-wave (mmWave) electronics are advancing rapidly, and A/D and D/A converters are crucial components for enabling high-speed data conversion in applications like 5G communication systems, automotive radar, and high-resolution imaging. [12] proposes a novel C-2αC ladder-based non-binary DAC for medium to high-resolution successive approximation ADC (SAR-ADC) applications. Conventional C-2αC capacitive array DACs have advantages such as small areas, low power consumption, and high-speed operation. However, achieving the required linearity for medium to high-resolution SAR-ADCs becomes challenging due to the parasitic capacitance of the floating node and capacitor mismatch issues. In [13], a 12-bit 20-MS/s SAR ADC is presented, incorporating a fast-binary-window DAC switching scheme in 180nm CMOS technology. The proposed scheme effectively reduces capacitor-DAC transition errors, improving DAC linearity and suppressing DAC switching errors to enhance the signal-to-noise ratio (SNR). To maintain a good production yield, a dual-reference capacitor-DAC is applied to have a small total capacitance. The ADC achieves a peak signal-to-noise-and-distortion ratio (SNDR) of 61.9 dB, a spurious-free dynamic range (SFDR) of 81 dB, and a peak effective-number-of-bits (ENOB) of 10 bits, equivalent to a peak figure-of-merit (FOM) of 59.6 fJ/conversion-step [13]. In [14], the authors discuss high-speed ADC/DAC technology trends, including challenges and limitations on ASIC implementation, for optical networks (long & shorter reach) and possible future 5G applications.

A novel active noise-shaping SAR ADC with on-chip digital DAC calibration is presented in [15]. The ADC utilizes correlated double sampling (CDS) and correlated level shifting (CLS) to relax the single operational amplifier (OPAMP) design used as an integrator, minimizing offset and reducing flicker noise while boosting gain and reducing power consumption. A two-step incremental ADC-based digital DAC calibration scheme is implemented to cancel DAC mismatch errors and parasitics effects. The ADC achieves an 85.1 dB dynamic range (DR), 82.6 dB signal-to-noise and distortion ratio (SNDR), and 90.9 dB spurious-free dynamic range (SFDR) within a 2 kHz signal bandwidth with an oversampling ratio (OSR) of 32. A discrete-time four-step reconfigurable incremental ADC (IADC) is proposed in [16], which consists of a first-step SAR conversion, a second-step IADC operation, and double extended binary counting (EBC). The ADC utilizes 7b capacitive DAC-based integrator operation to reduce chip area and power consumption, achieving additional resolution with the EBC. The prototype ADC fabricated in a 180-nm CMOS achieves 179.7 dB FOM and consumes 176 µW.

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2.4.4.3 Digital beamformers semiconductor technologies

Digital beamforming, an essential aspect of modern wireless communication and radar systems, involves the manipulation of antenna array signals to optimize the direction of the transmitted or received signal. This literature overview analyzes the state-of-the-art research on digital beamformer semiconductor technologies. [17] demonstrates an optical phased array antenna-based true-time delay (TTD) beamforming for radio-over-fiber (RoF) applications. A semiconductor optical amplifier (SOA) and a tunable dispersion medium are employed to achieve full true-time delay by adjusting the dispersion value, showcasing high TTD performance for various output beam angles. [18] describes a VLSI implementation of an integrated adaptive beamforming processor and a QAM demodulator. This implementation, suitable for 2.4-GHz industrial, scientific, and medical (ISM) band applications, incorporates various processing blocks, including square-root Nyquist filters and multipliers, to reduce chip area while maintaining high link quality and adaptive beamforming capabilities.

[19] presents a 22-nm CMOS receiver prototype that allows reconfiguration between true-time-delay analog and digital beamforming. The receiver uses time-interleaved resampling delay setup and high-speed ADCs to achieve beamforming mode reconfigurability. [20] reports a mixed signal chipset based on a 128-channel Δ-Σ ADC for a handheld wireless ultrasound imaging system. This integrated chip, fabricated in a standard 0.13 µm CMOS process, showcases high-resolution performance at a fast sample rate, making it suitable for full digital beamforming in handheld ultrasound imaging systems. In conclusion, the literature reviewed above presents significant contributions to digital beamformer semiconductor technologies, showcasing novel approaches to true-time delay beamforming, adaptive beamforming processor and QAM demodulator integration, reconfigurable analog and digital beamforming, and high-resolution mixed signal chipsets for ultrasound imaging.

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2.5 Highly integrated mm-wave connections and packaging technologies

2.5.1 Electronics integration issues in active antenna

A high-level of integration is essential for Radio frequency integrated circuits for mm-wave communication systems in a single package. They require low insertion losses, low reflections and low costs as general constraints but additional constraints related to the application such as satellites or bas station creates challenges in the integrated designs. To name a couple important constraint for NMTN would be power, size, thermal and cost [1], [2]. To solve those constraints solutions such as Antenna-on-Chip and Antenna-In-package and if issue arise regarding using dielectric as those are the dominant losses from a antenna point of view. Also, for NTN application not all material are suitable due to the requirement to withstand high radiation in space to ensure long lifetime. Overall, Electronics used for mm-wave in NTN networks require new material knowledge and have challenges that requires solutions.

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2.5.2 Antenna-on-Chip and Antenna-in-Package Solutions

Nowadays, academia and industry have a huge interest on the implementation of high performance, low-cost and low-power transceivers by providing the high constraints, demanded from the new paradigm of Non-Terrestrial Networks (NTN) jointly with terrestrial networks. Currently, in the state of the art, is clearly identified and distinguish two antenna packaging approaches Antenna on Chip (AoC) and Antenna in Package (AiP). Basically, the AoC features poor radiation efficiency and low gain but minimize the connection loss. In the other hand, AiP present higher radiation efficiency and antenna gain but uses loss interconnections between the antenna and package [1].

The RF front-end and antenna chip are integrated on the same silicon die for AoC. In fact, eliminates the need for the external linkages that have historically been utilized to connect ICs with antenna feed, such as bond wires or solder balls. It has been proven that doing so significantly reduces the complexity and expense of packaging. Its avoidance of lossy linkages between components, which improves repeatability and system integration, is another asset. Additionally, it lessens the reliance on manufacturing accuracy for reliability. Additionally, the antenna can be made smaller to less than a millimeter in size at mm-wave frequencies, making an on-chip implementation possible [2].

One of the main drawbacks in their performance is the lower radiation efficiency and gain that provides due to the high permittivity and low resistivity available substrates. A low resistivity produces that a portion of the radiated power is dissipated inside the lossy substrate and decreases the antenna efficiency. Furthermore, this issue is made worse by the silicon substrate's high dielectric constant, which directs a greater portion of the radiated energy into the substrate. To increase overall performance, research has been done on novel post-processing stages such as micromachining, proton implantation, and the use of quartz substrate on top of a silicon stack while also raising production costs. [2].

In order to lower substrate losses and hence increase antenna efficiency, an expensive high-resistivity silicon-on-insulator (SOI) wafer has been suggested in the literature. The usage of Artificial Magnetic Conductor (AMC), which serves as an electromagnetic barrier between the antenna and the lossy substrate and enhances antenna performance, has also been studied. However, there are drawbacks to this approach.[2].

The foundation of AiP is the cointegration of the silicon-based chip and antenna through the use of a standard packaging process. Currently, it offers high flexibility, minimal loss in the mm-wave region, and simple multi-component integration. Its shortcomings include comparatively high cost and process limitations [3]. There are two approaches to be attached to the system substrate: with a chip pad connected by wire bonding or solder bumping or the chip is embedded into the substrate using fan out redistribution layers (RDL) for interconnections. Further, this design required one wire network two feed the antenna another for the chip pad of the antenna [4].

LTCC, Embedded Wafer Level Ball (eWLB), and HDI technologies are currently the most useful packaging methods for AiP. Both LTCC and eWLB have fairly good electrical properties. However, the thermal conductivity of the latter is low. Furthermore, LTCC processing temperatures are too high for active devices, requiring additional processing. As a traditional process, HDI technology has satisfactory electrical properties and low cost subject to continuous improvement. This could be a low-cost alternative to LTCC and eWLB [5].

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2.5.3 PCB and LTCC technologies

Printed Circuit Board (PCB) has been a mainstay low-cost manufacturing technology of the electronics and antenna industries for decades [1]. PCBs realize a "sandwich structure" of alternating conductive and dielectric layers, as shown in figure 2.5.3.1. The conductive layers usually consist of copper due to its relatively low cost and high conductivity. A wide variety of materials have been used to realize the dielectric layers of PCBs, for example, FR4, Teflon, PTFE and ceramic/glass fiber-filled composites [2], [3]. An important factor in choosing the appropriate dielectric is a material's dielectric constant (ε), with high-ε materials preferred for transmission lines due to their smaller physical dimensions and low-ε materials preferred for antenna applications to realize higher bandwidths [2]. While FR4 is the material of choice for low-cost applications and is flame-resistant, its high loss tangent (tanδ) makes it unsuitable for high-frequency applications. PTFE substrates on the other hand, require specialized processes for the realization of plated vias [4]. Additionally, composite laminates are inherently anisotropic owing to their composite structure [5]. Of particular importance for satellite applications is material outgassing, with composite laminates having an advantage [6]. Finally, PCBs are compatible with high-density interconnect (HDI) processes that are vital for device miniaturization. [7]

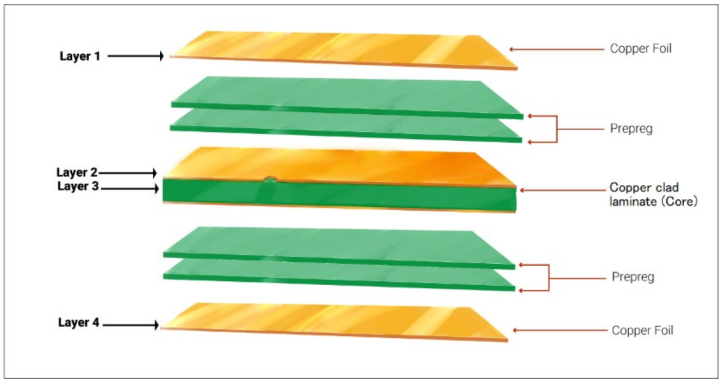

Figure 2.5.3.1: Typical structure of a PCB

An alternative to PCBs is offered by low temperature co-fired ceramics (LTCC). Originally a process that was used for manufacturing capacitors, its use has expanded to electronics and antennas [9] due to low conductor and substrate losses, as well as the capability of stacking tens of thin ceramic layers [8]. An illustration of the design process is given in figure 2.5.3.2. The multilayer nature of the process and the ability to form cavities enables highly integrated systems, such as antennas in package (AiP) [10].

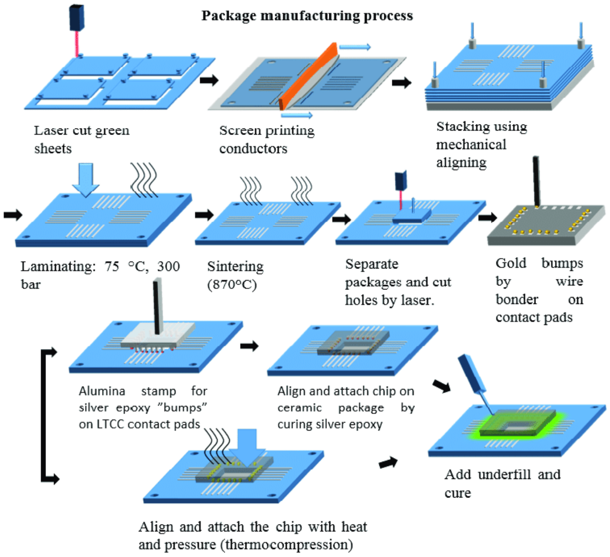

Figure 2.5.3.2 Process flow of the LTCC manufacturing process

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2.5.4 Power dissipation and power management ion highly integrated antenna electronics

Highly integrated antenna systems are usually manufactured using PCBs and LTCC technologies. A major disadvantage of both is that they utilize materials that exhibit low thermal conductivity, making the dissipation of heat generated from both the electronics and antenna challenging. In reference [11], thermal vias are utilized to conduct heat from an electronics package to a cooling surface. Enabled by the capability of manufacturing small features and cavities in LTCC designs, the authors in [12] have integrated a liquid cooling circuit in an 8x8 antenna array. An alternative to antennas including dielectric takes the form of fully-metal antennas that can be used as a heatsink. In reference [13], a 3D-printed Vivaldi antenna array that integrates a liquid cooling circuit is presented. Finally, the gap waveguide technology offers a viable alternative for antennas with severe cooling requirements due to the non-hermetical nature of its structure, as opposed to traditional solid metal wall waveguides [14].

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