Millimeter-Wave Antenna Circuitry for Inter-Satellite Communications at 60 GHz

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***Abstract*—With the growing complexity of communication systems, there is an increasing scope for antenna arrays with multi-beam capability for ultra-high broadband, inter-satellite links and inter-spacecraft communications. High data rate demands increased bandwidth requirements, the frequency of operation is increasing to the 60/70/80/90 GHz bands. These frequency bands are applicable to last-mile technologies for inter-satellite links and inter-spacecraft communications with data rates as high as 10 Gbit/s and even beyond. For these applications it is of paramount importance to develop planar technologies that can apply to millimeter-wave (MmW) frequencies with highly integrated system approach including smart antennas. This paper lays a robust foundation for MmW based smart antenna designs, its issues related to radio propagation and applications for inter-satellite links and inter-spacecraft communications. The intermediate and long-term objectives will create a unique and systematic understanding of the proposed innovative antenna array technology and its beamforming solutions.**

***Index Terms*—millimeter wave, smart antenna, inter-satellite communication, beamforming.**

I. Introduction

There is a strong correlation between technology evolution and the rate of socio-economic development. Communications infrastructure is one of the important keys for the development of a country [1]. Instant broadcast and transmission of information globally will considerably multiply the commercial revenues. The establishment of an improved and effective satellite system provides a cost effective and efficient solution for communication services and will enhance the economic growth and sustainable development [2]. The space-based services allow us to broadcast information over broad areas, and give us a global vision of the world [2]. In case of natural disaster management, remote sensing from space can provide information for prevention, mitigation and weather newscasts [3]. Timely satellite imagery and communication links will help reaching difficult places.

With the advancement from 4G to 5G and global virtualization architecture, it will not be a surprise that satellite communication will play an important role in providing seamless connectivity between terrestrial and satellite [4]. As newer technologies are being investigated the combination of existing technologies outlined are bedeviled with interferences from high rise buildings, absorption from trees and rain. These challenges are typical to terrestrial communication. To overcome these limitations satellite communication has been proposed [5]. Better space infrastructure and satellite systems will provide serval benefits over the existing ones, combining terrestrial facilities with enhanced satellite systems will provide end user with benefits such as decreased transaction time, cost savings, improved productivity and energy efficiency.

The USA, Russia, Europe, China, and India are taking the lead in the exploration of satellite technology for communications [6], [7]. South Korea, USA, UAE and China would be spearheading the implementation of this technology in terms of commercial launch [8], [9]. For South Africa to attain an increased economic growth and sustainable development, and to be among the leading nations, it is also important to work in the space science and technology sector. This necessitates the study and documentation of the likely concerns and the known facts in adopting MmW technology for satellite communication.

Satellite is launched from the earth into any of the Lower Earth orbit (LEO), Medium Earth Orbit (MEO) or Geostationary Earth Orbit (GEO) to revolve around the earth for the purpose of transmitting and receiving signals. The LEO is the closest to earth with its orbit about two thousand kilometer (km) above sea level [10] and the satellites in this orbit are used for wireless personal communication services (PCS). The GEO is thirteen times farther while MEO span in-between 10 and 20 km. Satellites in the LEO cover fewer footprints than that of the GEO [11]. The period for a satellite to complete one rotation depends on its distance from earth. A satellite should rotate faster around the earth as it gets the closer to the earth to compensate for the greater gravitational pull, and vice-versa [12]. A GEO (typically 35,800KM above sea level), is a one where the satellite rotates at the same rate as that of the Earth and hence would appear stationary to its coverage area all the time [13]. The further a satellite

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is away from earth, the greater the coverage area is, and this provides an edge to the satellite communication over terrestrial communication.

A satellite on GEO can cover up to one third of earth's surface area [12]. This would mean, a GEO satellite can cover the whole of South Africa and also several of its neighboring countries should a need arise. One disadvantage to with GEO satellites is that, because of their large distance from the earth, the signals would have to travel longer and typically a time delay of around 250ms is to be expected [13]. This time delay is not a problem for certain applications like continuous television systems, satellite navigation, etc. But for other applications such as real time control systems, this time delay has to be carefully factored in during their design [13].

The larger/ heavier a satellite is, the greater the cost in launching it to the geostationary orbit. So in the recent years, due to cost constraints and advancement in electronic manufacturing, smaller mass-produced satellites are being preferred by several countries [14], [15]. This opens up a whole new class of satellite missions, involving cluster of satellites for remote sensing, navigation, communications and other research for both civilian and military uses. In addition to the economic viability, this cluster/constellation of small satellites also have other advantages compared to a single large satellite - better spatial and temporal resolution, fault tolerance (if one satellite in the constellation fails, the rest of them can still keep the system running) and more system resilience to collision with space debris [16].

As space missions venture further and further away from earth, the environment gets more hostile for human existence, so autonomous and remote controlled machines need to be launched into deep space [17]. This and with the advent of space tourism and asteroid mining, the space communication demands and subsequently the spectrum demands are only going to grow bigger in the near future [17]. More and more space agencies are planning missions into deep space and with each mission, the amount of data being collected increases and the demand for higher data rate also increases. So high speed data access is required in space to facilitate inter satellite communications, and other applications such as space craft and remote controlled robotic machines. So depending on the mission and its frequency demands, the wavelength and the antenna size and properties have to be chosen.

The FCC has established together with the allocation, band plan, service rules, and technical standards to promote development and use of the MmW spectrum in the 57-64 GHz, 71-76 GHz, 81-86 GHz and 92-95 GHz bands ("Unlicensed V & Licensed E" bands) [18]. It is worthy of note that all bands in 10 – 100 GHz are equally alike as a result of their radio propagation characteristics [19]. So there is no reason to favour one band in that range over other, frequencies above 30 GHz will enable usage of steerable array antennas which are known for their ease of circuit integration [19].

Also studies shows that frequency band 57- 66GHz has medium usage and a growing trend towards 66 – 71 GHz which currently has little or no usage. This scenario presents a suitable case for using 60 GHz frequency band for the inter-satellite links. Advances in chip design and manufacturing, digital signal processing, antenna technologies and availability of huge bandwidth are fueling MmW utilization [20]. Many wireless communication operators are also interested in the MmW bands for its low construction cost, quick deployment and flexibility in providing access to different services [21].

Antenna design has a major impact on optimum power budget and deployed data services demand, compact size and power-efficiency, which in turn leads to efficient transceiver that can be made at a low-cost. For the range 6 – 100 GHz, the feasibility and suitability of different bands can be better understood if further study is done on the physical elements like antenna arrays and RF components, and its radio wave propagation characteristics [19]. Other known enabling technologies are the use of smaller cell transceivers, massive MIMO, beam forming and full duplexing [8]. Massive MIMO involves the use of multiple (10s to 100s) antennas at the transceivers coupled with beam forming technology to reduce interfering signals at the receiver. Small cells promote transmitting at shorter wavelengths resulting in spectrum reuse and efficiency. Research into some of these issues is at a relatively early stage and the outcome of ongoing research may have an impact on which parts of the 6-100 GHz range and smart antenna system could be most useful for inter-satellite communication [19].

The role of 60 GHz satellite networks will be pertinent in future. This will in turn bring about new challenges that are not really factored out yet. For instance, the speed at which things will be done will be very fast. New ways to reverse unwanted user experience when not needed will be required. The application may be limited at the moment but prospects are there that its relevance will appreciate with the advent of new micro and nano devices. Therefore, more research and development of innovative active smart antenna systems for satellite communications and investigations on the issues related to MmW based radio propagation and deployment in the satellites and space crafts is needed.

This five sectioned paper is therefore structured by presenting an introduction in the first section. The second and third sections present the role of MmW in satellite communication. The fourth section reviews the smart antenna systems available for satellite communication. The fifth section proposes an innovative antenna circuitry for future works and brings this work to a conclusive end.

II. WHY MILLIMETER WAVE IN SATELLITE COMMUNICATION

At the lower frequency band due to the increase in number and size of the satellites, congestion has become a serious issue [22]. New technologies are being investigated so that higher bands can be used [23]. Recently, MmW based technologies have attracted a great deal of interest from the research community, industries and various standardization bodies due to its ability to provide multi-gigabit rates required in transmission links for emerging wireless networks [24].

As high data rate demand increases bandwidth requirements, the frequency of operation for satellite communication is increasing to the 60 GHz band, the use of millimetre-wave frequency bands in satellite communications have been investigated and standardized [4]. Due to the unprecedented bandwidth available, the 60 GHz bands are ideal for very high capacity data distribution. With 5 to 7 GHz of bandwidth availability and the benefit of the fundamental relationship between signal wavelength and antenna size gigabit data rates can easily be accommodated with reasonably simple radio architectures towards Gigabit communication [25]. MmW antennas also provide interference immunity as high-gain/narrow-beam antenna will only receive energy from the same direction in which it is transmitting, thus reducing the probability of receiving an unwanted signal [21].

These higher frequency bands typically give access to wider bandwidths, but are also more susceptible to signal degradation due the absorption of radio signals by atmospheric rain, snow or ice. At 60 GHz and 120 GHz the absorption/attenuation is due to oxygen and at 180 GHz due to water vapour [13]. Table 1 gives the attenuation losses at and above sea level.

TABLE I. ATTENUATION LOSSES AT AND ABOVE SEA LEVEL

Frequency	60 GHz	180 GHz
Attenuation at sea level	19 dB/Km	36 dB/Km
Attenuation at 4 Km from sea level	4 dB/Km	5 dB/Km

MmW Radar systems and satellite communication systems for different applications can be realized by taking advantage of the selective atmospheric attenuation/absorption values of MmW frequencies. As space signals are subjected to only free space loss, since the radio path lies totally outside the atmosphere and the atmospheric oxygen belt surrounding the earth prevents the interference from and to ground stations, the 60 GHz frequency band is a suitable candidate for the inter-satellite links [13].

III. APPLICATIONS OF MILLIMETRE WAVE IN SATELLITE COMMUNICATION

For many years satellites have not only been used for radio communications, but also for navigation, weather forecasting, earth observation, mapping and many more applications. S-band (2–4 GHz), C-band (4–8 GHz), X-band (8–12 GHz), Ku-band (12–18 GHz), Ka-band (26–40 GHz) are designated for the satellite communication [22]. S-band (2–4 GHz) specially used by National Aeronautics and Space Administration (NASA) for communication with ISS and Space Shuttle and for other applications like weather, radar, surface ship radar. C-band (4–8 GHz) is used for satellite communications, for full-time satellite TV networks or raw satellite feeds. X-band (8–12 GHz) is primarily used by the military and in radar applications and phased arrays. X-band radar frequency sub-bands are used in civil, military and government institutions for weather monitoring, air traffic control, maritime vessel traffic control, defense tracking and vehicle speed detection for law enforcement. Ku-band (12–18 GHz) is used for direct broadcast satellite services. Ka-band (26–40 GHz) is used for high-resolution, close-range targeting radars on military aircrafts.

In the early 1980s, European Space Agency (ESA) and NASA investigated the application of the 60 GHz band for inter-satellite communication links [26]. NASA also proposed two 60 GHz inter-satellite cross-link applications: communication between satellites arranged in a cluster (spaced less than 50 km apart) and communication between a relay satellite and an orbiting space station. Further, people will also be able to travel into space which will require high-speed internet access in a space plane [27]. Also, the spacecrafts need to communicate with each other [28]. Satellites at MmW can be employed as repeaters. Satellite will act as a transponder in these cases and will receive signals in one frequency band and re-transmit the signals in another frequency band [13]. To avoid the signal interference during the communication a difference of 1-2 GHz in the uplink and downlink frequency is needed.

Millimeter satellites can be used for defence applications and can provide for secure global communication. Higher data rate satellite systems such as US MILSTAR and US MILSTAR II with the uplink frequency at around 44 GHz have been deployed and are under development [29]. MILSTAR II provides higher data rates up to 1.5 Mbps for 192 channels, anti-jamming and inter-satellite cross links at 60 GHz. Radio-astronomy has been key to many of the greatest contributions in space science from the accidental discovery of quasars, cosmic background radiation, galaxies and also contributes to blackhole research [30]. Radio-astronomy has now become a basic tool in astro-physics from the first discovery of MmW spectral signatures in extra-galactic molecular clouds.

Satellite based remote sensing at MmW has provided valuable information about Earth's atmosphere and also for mapping resources [3]. MmW frequencies ranging from 10 to 183 GHz is generally used for this atmospheric sounding designed to measure the black body emissions from earth and other celestial bodies [29]. MmW communication instruments normally accompany and complement the other meteorological instruments and are used for multispectral infrared imaging and meteorology. This is possible because matter in its varying forms such as land, water, air and ice have different signatures in terms of brightness temperatures, and cane be uniquely identified. Another potential use for MmW in astrology is to detect oxygen and water in planets and asteroids by using the 60GHz oxygen and water vapor resonances and spectroscopic characteristics [29]. Generally the special resolution will be low if remote sensing of the celestial body is done by a satellite/spacecraft that is kilometers away; and are also restricted by the antenna aperture. There is scope for improvement in the detection of number of atmospheric constituents by increasing the range of frequencies detected.

IV. Smart Antenna System at Millimetre Wave

In the recent years the interest has grown in integrated planar antenna as smart antennas for satellite communications, as it offers increased capacity and superior interference suppression, by navigating the beam in the preferred directions and forming nulls towards interferences compared to current systems [31, 32]. The adjustable high directivity of the receiver antennas allow for frequency re-use within the same region by attaching several beamforming networks to the same array of antennas [33]. In high-interference setups smart antenna allows the coverage of larger area compared to the conventional communication systems [34]. These features are highly recommended for satellite communications. A smart antenna is an array of antennas with smart signal processing units which consists of beam forming functionality. The recent advancement in smart antenna system for satellite system at millimeter wave is given in [34]

A beam-steering smart antenna at Ka band (29.5 – 38.8 GHz) is given in [35] for satellite communication. It is dual polarized folded reflect array which consists of 116 slot antenna elements fed through a strip line. It consists of multi-layer and Rogers's 5880 with relative permittivity of 2.2 is used to design the antenna. To suppress the parallel plate mode and surface wave shorting pin are placed between the metal plates. These elements are placed in a circular topology and a circular horn is placed in the central position. To achieve the beam steering MMIC are incorporated behind the unit cell to control the reflected phase [36]. The radiation performances of the passive reflect array demonstrators depicts exhibit low side lobes with frozen beam pointing at different scan angles up to 60°. The measured and calculated maximum gain at broadside is 2l.7 dBi, which represents 42% aperture efficiency.

An active scanning array at 30 GHz, which is designed on the principle of a folded ReflectArray (RA) antenna with multilayer, dual-polarised patch antennas and SiGe MMICs including T/R switches is given in [36]. This initial version uses nMOS transistors, this design can then be improved to reduce losses by replacing nMOS transistors with MEMS switches. The MMICs include four channels each together with a digital circuitry to address and control the different channels.

To begin with passive array prototypes, made of 144 antenna elements, with different fixed beam directions was fabricated and successfully tested [36]. Of the 36 MMICs, 4 of them didn't work, regardless beam scanning up to 60° both in E and H-plane could be demonstrated. With this demonstration sample as a proof of concept, dedicated solutions for different applications in communications and remote sensing could be developed. Also, the need for complex RF power distribution networks for higher frequency Direct radiating array (DRA) can be overcome by using space feedling techniques such as reflectarray or transmitting array.

This paper presents a broadside folded reflect array antenna, with 108 dual-polarization antenna elements that operate in Ka band [37]. In order to reduce the mutual coupling between neighboring elements in this unit cell antenna, a dual-polarized aperture-coupled microstrip patch integrated with via-grid cage around the edges of the cells is proposed. To achieve the necessary polarization conversion and phase compensation, real-time microstrip delay lines connecting two different polarizations are to be used. Vertical RF transitions are used to connect the delay lines with feeding striplines. Simulations have shown that this folded reflect array can achieve over 20dBi gain across the whole operating spectrum. Also, with this proposed structure, for the purpose of electronic beam scanning, the antenna can be integrated with controllable phase shifter.

However, so far to the best of author's knowledge no significant developments have been reported at MwW frequencies targeting 60 GHz inter-satellite and inter-spacecraft communications.

V. Future Work

In order to make such systems commercially viable, three issues specifically need to be addressed. First, a broadband MmW antenna array need to be developed in order to utilize signal enhancement, noise reduction and interference cancellation. Second, low-cost MmW components for such systems will be developed as they are imperative for system integration and mass production. In this respect, substrate integrated waveguide (SIW) technology provides a golden opportunity for the integration of a complete system on a substrate that includes antennas and transceivers [38]. Third, innovative MmW architectures provide added value to the system design and integration that include special beam-forming networks and wide-angle and wideband scanning.

For these applications it is essential to develop highly integrated system antennas that can apply to MmW frequencies. The antenna designers around the world are concentrating in the design of compact antennas with efficient characteristics. It is now increasingly acknowledged that future wideband communication systems for ubiquitous networks will deploy separate transmit and receive antenna architectures. Several sessions at recent international conferences have addressed exactly this topic [39]. Whereas conception of the transmitter side is relatively straightforward, much attention is focused on the receiver, which includes smart antennas [40].

In many applications of millimeter-wave integrated circuits, power is either radiated or received by an antenna element. Ideally, one would then prefer to be able to integrate the antenna and the rest of the circuit on a single substrate or fabricate both parts of the subsystem as integrated components which can be joined easily [41]. Currently, the well-established planar techniques are not so efficient at millimeter-wave frequencies because of high transmission loss, high circuit cross talk, which fundamentally limits the circuit integration density, and also electrical performances required for the above applications. A planar broadband antenna called Tapered Slot Antenna (TSA) has been studied for years due to its salient features such as narrow beamwidth, high element gain, wide bandwidth and small transverse spacing between elements in arrays, also it attracts a lot of interest for many applications [42]. Its most common forms are the Linearly Tapered Slot Antenna (LTSA) and the exponentially tapered version, commonly referred to as Vivaldi antenna and several antenna systems have been proposed using Vivaldi antennas, e.g. [43]. Practically, the performance of the LTSA is mainly determined by the feeding system. In the previous research, some feeding strategies such as balanced microstrip, finline, coplanar waveguide, microstrip to slot line transition, and Inverted microstrip line have been reported, and some good performances are provided [42].

However, conventional microstrip like feeding systems suffer from significant tradeoffs between cost, size and performance at microwave and MmW frequencies. The Substrate Integrated Waveguide (SIW) technique is a promising technology finding application in wireless microwave and millimeter-wave systems [42]. Unlike printed circuit transmission lines, which suffer from inherently significant losses in high frequency, SIWs have high Q-factors and high-integrations. A state-of-the-art overview of this technology that belongs to the family of substrate integrated circuits has been presented in [44]. [42] have depicted the feasibility of feeding an Antipodal Linearly Tapered Slot Antenna (ALTSA) by SIW technology integrated on the same substrate. In order to lower the Side Lobe Level (SLL) and enhance the isolation between the ALTSA elements, a row of metallic via is inserted between the ALTSAs. A 1×8 ALTSA array fed by SIW feeding system at X-Band is fabricated and measured, and the measured results show that this array antenna has a wide bandwidth and good performances. [45] introduced a Dual V-Type Linearly Tapered Slot Antenna (DVLTSA) at the center frequency of 36 GHz, a modified version of the Vivaldi radiator. It was much more compact and retains the advantages of the conventional TSA. Furthermore, this antenna is suitable as monopulse antenna owing to its special configuration. Both the sum and difference beams can be generated by only employing a single DVLTSA respectively through the multimode SIW feeding technology. [46] proposed a multi-beam antenna by rotating the ALTSA with respect to a center. A 9 beams antenna is designed and experimented at 28 GHz. [47] proposed a paper on new ALTSA with unequal half-circular slots embedded on both edge-sides to improve an antenna gain. The proposed antenna operates over the frequency band from 3.1 GHz to more than 10.6 GHz, which is assigned to Ultra Wideband (UWB) wireless communication. The proposed antenna has been improved in gain and reduced in backward radiation due to the unequal half-circular slots on the ALTSA. [48] investigated the effect of stepped edge corrugations on the front-to-back ratio (F/B ratio) improvement for the antipodal DETSA over the frequency band from 3.1 GHz to more than 10.6 GHz. Three types of corrugation configurations with different combinations of slit length are investigated. The results revealed that the improvement in F/B ratio is directly related to the arrangement in corrugation configurations. [49] proposed a new configuration of TSA with improved radiation pattern, which is proposed and studied. This antenna is designed in the form of a SIW array with respect to side lobe level constraints. For side lobe reduction, a simple quasi-triangular distribution is proposed and is accomplished uniquely by means of 3 dB power dividers to achieve in-phase and non-equal amplitude distributions. The 12-way power divider was used to feed an antipodal LTSA array antenna. Experiments at 28 GHz have confirmed the generation of the desired distribution.

The main difficulty that the 60 GHz technology must face is the poor link budget, which is a result of the increased path loss and the extended transmission bandwidth of 60 GHz systems. Through electronic beam steering (as opposed to slower and less reliable mechanical steering), the receiving base station can adjust its beam direction to narrow in on the desired user signal. Simultaneously, beam nulls can be positioned in the direction of interfering signals, thus raising the effective signal-to-noise ratio (SNR) of the signal. This also allows the effective use of the power budgets of base stations as it may be very expensive at MmW frequencies. Therefore, it is imperative to use multi-beam or steering beam techniques for inter-satellite links and inter-spacecraft communications. In recent research papers on 60 GHz technology, antenna-array beamforming is indicated as the key-solution to mitigate the limited link budget problem. Analog Beamforming (ABF) is the technique that best suits the low-cost and low-complexity requirements for 60 GHz radio transceivers [50]. [51] proposed a paper which overviews the state-of-the art of substrate-integrated-waveguide techniques in the design and realization of innovative beamforming networks, and multibeam antenna arrays for low-cost satellite and wireless systems. [52] [53] introduced a novel multi-folded SIW Butler matrix beamforming network at the center frequency of 60 GHz and 24 GHz for automotive radar system applications. The proposed low-cost SIW structure can be used to develop a highly integrated multibeam antenna platform in automotive radar systems and other applications.

Design and development of ALTSA array utilizing SIW technology with different corrugations has been carried out at various UWB, X and Ka bands by above mentioned overseas researchers [42], [45]-[49] and beamforming solution are applied for the 60 GHz indoor propagation, in LOS and NLOS scenarios and for different array sizes [50]-[53]. In South Africa, antenna array and beamforming technologies have been mainly developed by the various organizations for radar applications only, but its usage in satellite communication is not well studied this research proposal seeks to address that.

Currently authors are engaged in design and development of an ALTSA utilizing SIW technology feeding system and its beamforming solution for the 60 GHz inter-satellite communication links keeping in view of inter-satellite and inter-spacecraft links. Further the objective is to analyze various characteristics like gain, return loss, beamwidth, directivity and front to back ratio utilizing 3D Electromagnetic simulators and Matlab simulations. A corrugation in the antenna design will be introduced to optimize the bandwidth and antenna characteristics of the ALTSA antenna element. The optimized antenna element will be used in an array configuration to realize a beamforming antenna array. The Analog Beamforming (ABF) networks operate on the RF or IF frequencies will be applied to the antenna design. Broadly they can be classified into two types fixed and reconfigurable. The Reconfigurable Beamforming (RBF) network requires variable phase shifters and variable power dividers which will increase the complexity of the system. Therefore, in this project work we will focus on the fixed ABF network with associated power dividers, phase shifters and butler matrix. RBF will be pursued as future extension of the work, if desirable. The targeted antenna array gain for this purpose is around 20 dBi (or more, if possible). The 3dB beamwidth we are targeting is around 3°- 10°(or even less, if possible). Further design and simulation of other planar antenna arrays like 4×4 or 8x8 depending on flexibility of fabrications challenges/constraints) along with power dividers without SIW structures will also be done while trying to achieve gain of around 30 dBi which could be a candidate to be used for inter-satellite links for various image processing, remote sensing, radar, tracking and data relay applications. The research and development will be conducted for a frequency operation at 60 GHz in order to facilitate fabrication-related issues and allow for cost-effective faster prototyping by South African foundries. It is needless to say that the innovative concepts and design techniques in this project will be applicable to other MMW frequency ranges as well.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

The authors have done equal contributions to the paper.

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