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High Directivity Beamformer for Millimeter-wave 5G Base Stations

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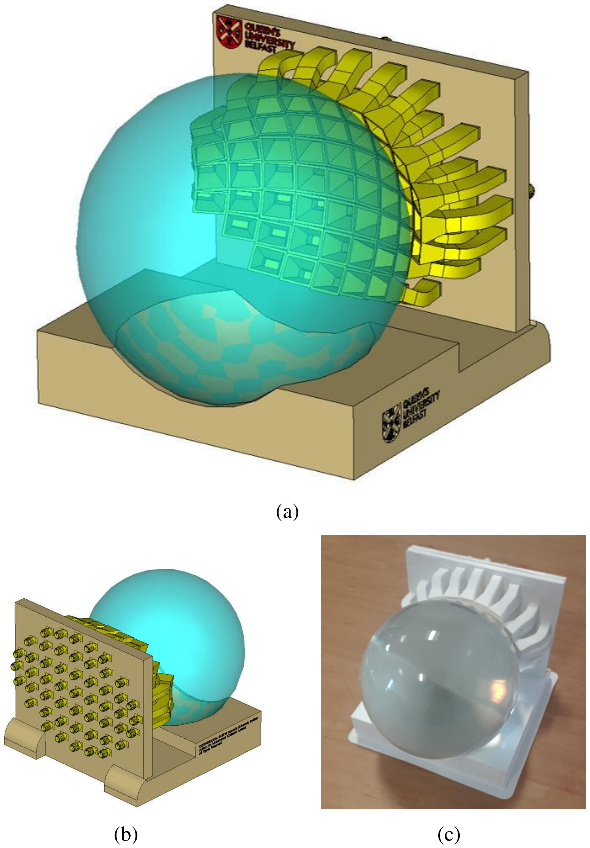
***Abstract*—This paper presents a high directivity beamformer for the millimeter-wave (mmWave) base station application. The beamformer is capable of generating high directivity radio beams along azimuth and elevation planes. Beamformer structure consists of a spherical constant–dielectric (ϵ_r) lens created from plastic material, while the lens is fed by multiple rectangular horn feeds that are individually connected to mmWave radio sources. The lens structure can be machined out from plastic raw material while the feed network of the beamformer can be 3D printed and metallic plated, making the proposed beamformer structure a good candidate for mass production. Prototype beamformer is developed for 28 GHz mmWave 5G communication band, while it is scalable to even higher frequency mmWave 5G bands (39 GHz) using the same synthesis approach discussed in this paper.**

***Index Terms*—5G, mmWave, beamformer, lens, antenna.**

I. Introduction and Motivation

First phase of 5G communication systems i.e. sub–6 GHz is already in the deployment phase, while the next stage, i.e. millimeter-wave (mmWave) 5G is expected to be launched in 2-5 years time. The standards are already settled, thanks to Release 15 standardization by the Third Generation Partnership Project–New Radio (3GPP–NR) and confirmation of mmWave bands for 5G mobile communication systems [1]. Beamforming is a necessity for mmWave 5G to work [2], while the technology is still struggling to find the best and cost effective beamformer solutions that should work in majority of the mmWave 5G communication scenarios, like base stations in urban streets, parks, roads, malls etc. Classical beamformers contain a high number of antennas connected to radio frequency chains (RF–chains) while the beamforming and beam selection is controlled by a bank of phase shifters and/or RF switches [3]. From the perspective of hardware implementation, phase shifters and switching networks require an integration of RF components, transmission lines at mmWave frequencies, along with voltage control biasing lines, making it a complicated engineering task. The state of the RF network also needs constant updating, synchronized to the mmWave channel coherence interval [4], which is highly dependent upon the terminal mobility rates. Such a dynamic reconfiguration posses a huge load to the RF hardware. Also constant updating of the states in milli–second intervals decreases the hardware stability, increases insertion losses due to thermal discharge and eventually deterioration of the network transition performance. It is also worth pointing out that at mmWave frequencies the cost of phase shifters and switches is high, since it is difficult to design fast, low–loss and low–cost networks for multi–antenna systems.


(a)

(b)

(c)

Fig. 1: (c) A constant–ϵ_r lens based beamformer for mmWave BS. Recommended lens dimension ranges from $105\times110\times100$ mm^3 to $155\times160\times140$ mm^3, depending upon the operation in the mmWave 5G sub–bands (b) Rare view, and (c) Machined lens and 3D printed feed network.

II. High Directivity Beamformer Development

In response to above challenges, in this work, we propose a practical lens based mmWave beamformer solution that is of high performance, cost effective and simple to deploy in mmWave 5G BS. Beamformer geometry is shown in Fig. 1. Lens based beamforming is analog, so it removes the need for phase shifter and biasing control network. Also, the beam separation strategy removes the requirement of beam

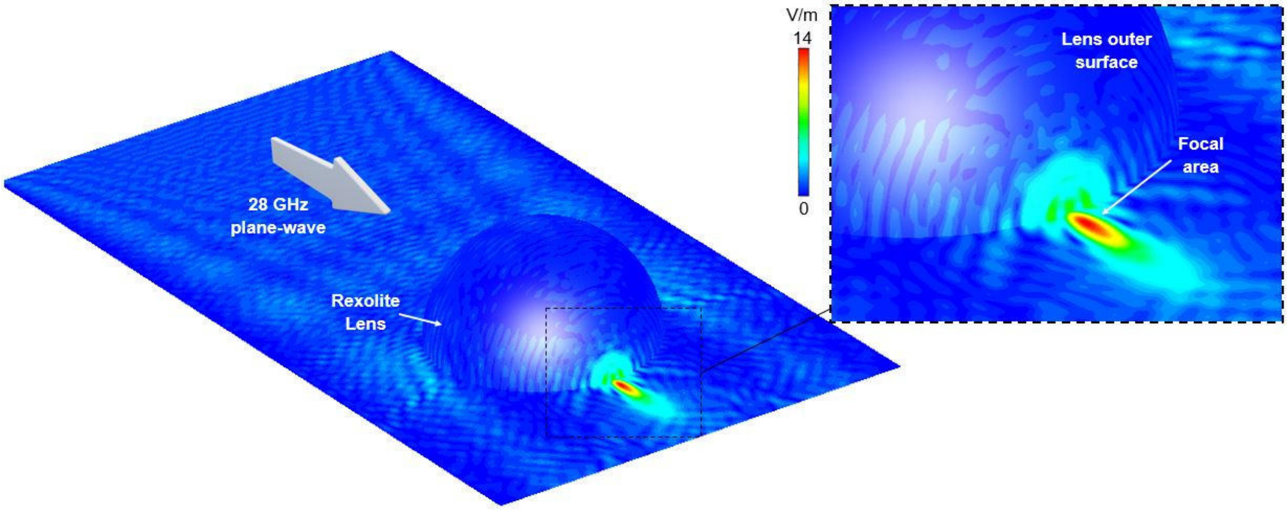


Fig. 2: Maximum electric field when a 28 GHz plane wave strikes the lens surface resulting in a high field intensity at the focal area outside the lens surface.

selection network. The beamformer structure shown in Fig. 1(a) have a spherical constant–ϵ_r lens fed by an array of horn–feeds. The dielectric constant and diameter of the lens are relative, and the synthesis approach to develop the spherical lens is presented in [5]. One unique property of constant–ϵ_r is that if the lens ϵ_r and diameter are carefully selected, the focal point can be made to lay outside the lens structure, which makes it possible to have an antenna feed outside the lens for transmission/reception of the radio signal. At microwave frequencies, the diameter of a constant–ϵ_r is too large [6] which makes it less likely to be a BS antenna, however, due to shorter wavelength of radio waves at mmWave frequencies, mmWave constant–ϵ_r lens is a practical solution. Energy focusing capability of constant–ϵ_r lens is far from being perfect due to inherent lens losses like chromatic, coma, spherical aberration and astigmatism. A plane–wave hitting a constant–ϵ_r lens do not focus on a single point, but form a focal area of high energy density. This is shown in Fig. 2 where a 28 GHz plane wave hits the lens surface and electric field plot show very high field concentration outside the lens surface. Horn–feed is a good choice to collect this field concentration and guide it to the subsequence associated RF–chain. Conversely, a horn–feed exciting the lens from the same focal area will result in plane wave leaving the lens surface [5]. In the beamformer prototype shown in Fig. 1(a), each horn–feed is optimized to operate at 28 GHz mmWave 5G band while the spacing between the lens surface and the feed is carefully optimized such that $\sim 92\%$ of energy focused by the lens is captured by the horn–feed.

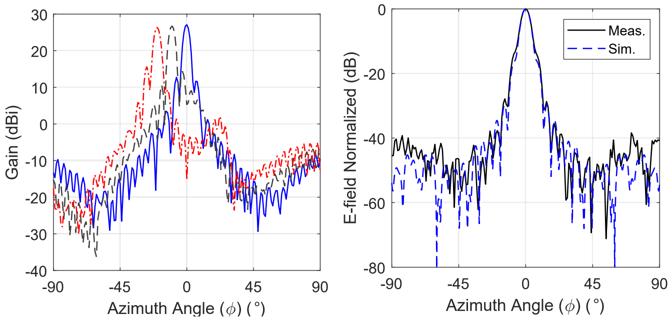
Horn–feeds are placed in azimuth and elevation planes along the lens surface. The maximum achievable number of horn feeds in azimuth or elevation planes should not cover the area of the lens surface more than corresponding to conical angle 90°. In other words, maximum allowable horn–feed location should be less than 45° from the central horn–feed. A standard waveguide fed horn–feed can be rectangular so the number of horn feeds along azimuth and elevation planes are generally not required to be equal. Given these limitations, maximum number of horn–feeds in beamformer given in Fig. 1 are 51. Each beamformer can be connected to RF–chain via an intermediate waveguide to K-type converter (see Fig. 1(b)). This makes the beamformer easy to mount to a radio units PCB either directly or via low–loss mmWave coax cables.

The beamformer consists of two parts; a lens and a feed network. This beamformer design is close to one specific embodiments of the general lens antenna proposed in [11]. The lens structure can be developed by machining it out from raw material of highly homogenous plastic like Rexolite. Properties like high homogeneity and consistent electrical properties in mmWave frequency bands makes Rexolite a very good candidate for lens development. The feed network can be created using a number of processes, easiest of which is the 3D printing as shown in Fig. 1(c). Since the mmWave waveguides requires skin depth of less than a micron, the 3D printed structure can further be processed to have a thin metallic coating sufficient enough to host low–loss mmWave signal propagation. Moulding and metallic machining can be used as alternative development methods to create the feed network.

III. BEAMFORMER OPERATION AND APPLICATIONS

The beamformer in Fig. 1 is capable of generating spatially orthogonal high directivity beams to serve user equipments (UE) in the BS coverage area. As per the results presented in Fig. 3(a), each beam's half–power beamwidth (HPBW) is $< 4.3°$ while the highly directive beam has a peak gain of $\sim$27 dBi. The side–lobe level for each beam is around –12 dB less compared to the direction of maximum radiation. Practical beam directivity is comparable to the simulated predictions as shown in Fig. 3(b).

To this end, mmWave lens structures are vastly reported as a purely analogue architecture or as a part of hybrid beamforming architectures [3, 7–9]. The hybrid architecture



(a) (b)

Fig. 3: (a) Realized gain plot in azimuth plane when three neighbouring horn–feeds are excited (b) Measured normalized E–field recorded in anechoic chamber and comparison with the simulation.

interfaces suggests that a lens based beamformers like the one presented in this study can be connected directly to the base–band signal processing (SP) unit. This needs to be done at each channel coherence interval to reduce the SP complexity, while ensuring high sum spectral efficiency of the system. Consider an uplink operation at a BS, when the UE signal is received at the beamformer, it enters in a wave superpositioning area within the lens body, where the collected EM energy is steered into a specific direction illuminating a subset of horn–feeds. Since each horn–feed is separately connected to the RF–chain and eventually to the SP unit, beam selection is handled directly by the SP unit. The proposed beamformer is mountable to ceiling of a shopping mall, street corners, walls of a tall building, or simply to an already deployed radio mast. Due to small size and fixed beam operation, the beamformer can also be mounted to a moving vehicle like car roof for urban radio planning, channel data execution and mmWave 5G drive testing.

IV. CONCLUSION

This paper summarizes design, function and application of a constant–ϵ_r lens beamformer for mmWave 5G base station. The beamformer design is simple, has a practical size, supports a large number of simultaneous multi–beams, and is a good candidate for mass production. Simulation and measurements results reveal a very high directivity radiation by the beamformer, which is desirable for the fast and reliable mmWave 5G wireless communication system. Moreover, it is shown that the beamformer is capable of generating 51 spatially orthogonal radio beams making it a good choice for sectoral coverage in a mmWave 5G cell.

ACKNOWLEDGMENT

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