

# Dynamically Reconfigurable Metasurface Antennas for Mobile Connectivity in 5G Non-Terrestrial Networks

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**Abstract**—A 5G New Radio standard supporting non-terrestrial networks (NTN) is being defined in 3GPP Releases 17 and 18 that will provide for a common 5G protocol that operates across terrestrial and satellite networks. Kymeta has commercialized a novel electronically scanned array (ESA) technology for mobile satellite communications, utilizing reconfigurable holographic metasurfaces, that fills a critical gap in addressing 5G NTN. The latest advances in this antenna technology, as well as recent demonstrations of direct access over GEO satellite with the 5G New Radio Release 17 waveform and enhancements for mobile environments conducted in partnership with Fraunhofer IIS, will be reported.

**Keywords**—5G New Radio, Non-Terrestrial Networks (NTN), Satellite, Metamaterials

## I. INTRODUCTION

Kymeta has commercialized a novel electronically scanned array (ESA) technology utilizing reconfigurable holographic metasurfaces that fills a critical gap in the 5G terminal architecture. The 3GPP has identified non-terrestrial networks (NTNs) as a key aspect of the 5G architecture since Release 15, where satellite communications networks including non-Geostationary orbits (NGSO) and Geostationary orbit (GEO) will have a key role to play in providing global connectivity and intelligently routing data traffic to optimize 5G network utilization. In addition, a native 5G New Radio standard supporting NTN is being defined in 3GPP Releases 17 and 18 that will provide for a common 5G protocol that operates across terrestrial and satellite networks.

A critical challenge exists, however, with accessing satellite networks from mobile platforms. Fixed and mobile user terminals that meet size, weight, power, and cost requirements, as well as interoperability requirements between LEO and GEO satellites, are needed to address these new 5G standards. Kymeta has solved this challenge by leveraging high-birefringence liquid crystals and adapting flat panel display technologies to implement a dynamically reconfigurable holographic metasurface antenna. The use of liquid crystals (LC) as a tunable dielectric at microwave frequencies permits large-angle ( $\pm 75^\circ$  range) 2D beam scanning and fast tracking ( $\sim 30^\circ/\text{sec}$ ), electronically controlled polarization (linear/circular switchable) with antenna power consumption of  $< 35$  Watts and antenna thickness  $\sim 5.0$  cm and no moving parts. Additionally, Kymeta's engineering approach leverages a

shared aperture concept, whereby a receive sub-array and transmit sub-array are interleaved into the same physical aperture, resulting in full-duplex operation while minimizing size, weight, and power (SWaP). By using LC and optimizing the materials and design for compatibility with flat panel display (FPD) manufacturing processes, this shared-aperture metasurface approach is well-positioned for mass production by leveraging the capital infrastructure of the FPD industry.

In this paper the authors will report on the latest advances in this technology, as well as the results of recent demonstrations of direct access over GEO satellite with the 5G New Radio Release 17 waveform and enhancements for mobile environments conducted in partnership with Fraunhofer IIS.

## II. METASURFACE ANTENNA TECHNOLOGY

A metasurface antenna is an aperture antenna that consists of periodically arranged, resonant and scattering metamaterial elements, which are subwavelength in their size and their spacing. By exciting the metasurface elements with the fields from a waveguide a radiated field from the aperture can be generated [1]. In this report the authors have developed a reconfigurable metasurface in which the resonance frequency of each scattering element can be adjusted separately. This individual control enables the metasurface to arbitrarily shape and form the radiated wave and allows it to form a desired farfield beam pattern, steer the direction of the beam and change its polarization and operation frequency [2].

Figure 1 shows a schematic representation of a metasurface scattering element in which the resonant frequency (and thereby scattering strength and phase) is controlled through the voltage applied to the liquid crystal. The liquid crystal behaves as a tuneable dielectric to adjust the capacitance of the scattering element [3].

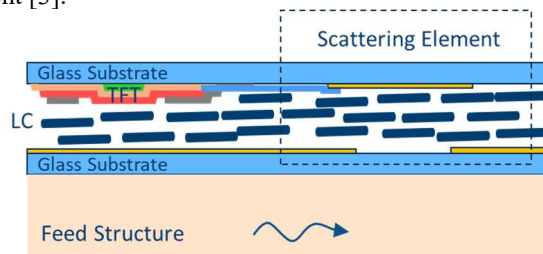


Figure 1. Metasurface construction and scattering element control

In Figure 1 the scattering element is comprised of a ground plane slot opposed by a patch electrode, with liquid crystal disposed in between. The patch electrode is connected to an amorphous silicon (a-Si) thin film transistor (TFT). The TFT is connected through an active matrix addressing network, as shown in Figure 2. In Figure 2, each of the patch electrodes that comprise the scattering element is connected to its respective TFT source terminal, while the slotted ground plane is connected to Vcom

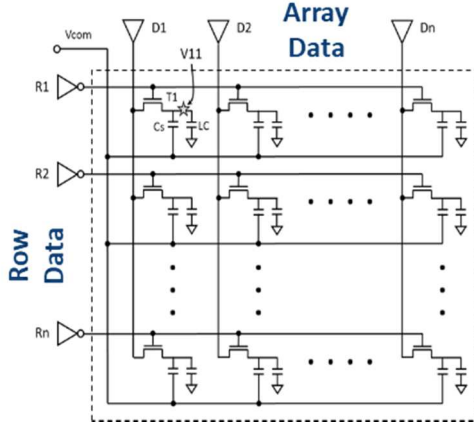


Figure 2. Active matrix addressing scheme for the shared-aperture metasurface antenna.

As can be seen from Figures 1 and 2, and in contrast to phased-array antennas, the metasurface antenna doesn't require active components such as phase shifters and amplifiers at every antenna element. This passive approach eliminates some of the fundamental challenges that active phased array technologies must deal with, namely high-power consumption and thermal management.

Unlike in phased arrays, the operation of the metasurface antenna relies on the principle of reconfigurable holography. Originated from optical holography, the holographic approach provides a closed-form expression for the metasurface modulation to achieve a desired scattering. The holographic approach in this design is predicated on the subwavelength scattering over the aperture, which can be conceptualized as continuous electric and magnetic current distributions [1]. The modulation defines the impedance profile of the metasurface required to transform the feed wave into a radiated wave with a requisite phase and amplitude distribution that results in the desired beam. The desired beam is typically defined through its pointing angle, polarization and frequency but can be extended to define other beam characteristics such as sidelobe profile and cross polarization discrimination. These attributes are implemented in the authors' metasurface antenna design and are controlled through software.

Another key aspect of the developed metasurface antenna is its ability to operate in full duplex with simultaneous receive (Rx: 10.7GHz – 12.75GHz) and transmit (Tx: 13.75GHz – 14.5GHz). To achieve that, a shared aperture (Rx, Tx) metasurface has been designed, in which two arrays of metasurface elements, one for receive and one for transmit, are

interleaved (Figure 3). Each sub-array is independently operable through the active matrix addressing scheme. The design has been optimized to minimize the interference between the Rx and Tx elements. Furthermore, the underlying waveguide is designed to provide proper matching across both bands. The antenna interface on the back is WR75 waveguide that acts as a common port of the antenna. A transceiver module consisting of a diplexer, low-noise amplifier (LNA) and bulk up converter (BUC) interfaces with the common port of the antenna.

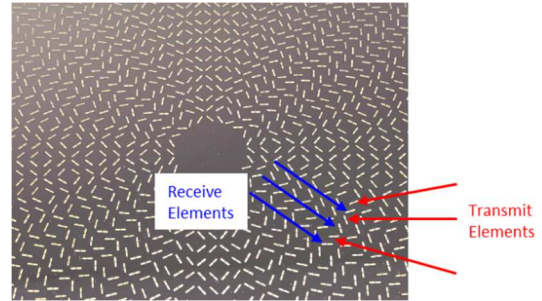


Figure 3. Picture of the reconfigurable metasurface with interleaved transmit and receive antenna elements

### III. 5G NTN NEW RADIO STANDARD AND WAVEFORM ENHANCEMENTS

#### A. 3GPP Standardization Roadmap to support Satellites

Satellite networks have been recognized as an important component in 5G with the introduction of non-terrestrial networks (NTN). In Rel-17, RAN currently specifies the extension of 5G New Radio to support Non-Terrestrial Networks until March 2022 [4]. As will be novel to the satellite sector, satellite communication will be supported from Rel-17 by the 3GPP standards, which were formerly limited to terrestrial cellular networks. The RAN work item [4] covers a frequency range from 2 to 30 GHz and GEO, MEO, and LEO satellite constellations.

#### B. 5G NR Waveform Enhancements for NTN

The 3GPP study item report on potential solutions to support Non-Terrestrial Networks [5] identifies the following topics on the 5G New Radio physical layer:

- Downlink synchronization to Synchronization Sequence Blocks (SSB) with large frequency offsets and drifts especially for NGSO satellites
- The initial access with the random access procedure needs a preamble design for large differential delays within a satellite cell. Despite the random access procedure needs to cope with the larger initial timing advance compared to terrestrial cells.
- The HARQ process requires multiple hops for transmitting redundancy versions, which is especially a challenge for GEO satellite communication. Enabling and disabling HARQ, together with other Block Error Rate (BLER) targets than for terrestrial transmissions ( $10^{-1}$ ) for the first redundancy version is required in NTN scenarios.

- The physical layer control procedures like open / closed loop power control, CQI reporting, AMC adaptation for long-term fading and timing advance updates for UL synchronization need to be adapted for the longer delays, compared to terrestrial propagation delays.

On the 5G NR protocol stack for user plane and control plane, the following topics are identified in [5]:

- Random access with long delay
- Adaptations of the control loop timers in MAC, RLC and PDCP layers
- HARQ operation as mentioned before, needs either extensions like higher number of HARQ processes to support medium delay in NGS0 satellite scenarios or should be disabled in the protocol stack.
- Tracking area handling and paging capacity in large satellite cells
- Mobility aspects in connected mode (inter- and intra-gNB handover)

The 5G RAN architecture needs to be extended by managing tracking areas with earth fixed & earth moving satellite beams, by registration update and paging of UE with and w/o GNSS capability as well as in architecture aspects with F1-, Xn-Interface and Multi-hop.

#### IV. MOBILE DEMONSTRATION RESULTS

##### A. Mobility configuration

The mobility testbed consisted of typical satellite network components illustrated in Figure 4, hub antenna, power and low noise amplifiers, up and down converters and a modem. On the mobile user terminal side, the reconfigurable holographic metasurface antenna, block up converter, low noise block downconverter, and a modem. Mobile demonstrations were conducted using a geostationary satellite with user terminal antenna mounted horizontally on a vehicle around Kymeta headquarters in Redmond, WA.

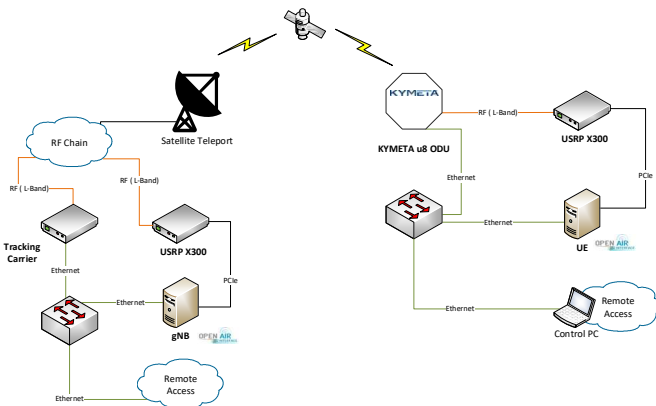


Figure 4. Block Configuration of Mobility Demonstration

The gNB and UE PCs were running a version of OpenAirInterface (OAI) [6] extended by Fraunhofer IIS for NTN usage. OAI is an open-source project implementing user equipment (UE), RAN and core network (CN) components

according to 3GPP mobile communication standards (4G LTE and 5G NR) completely in software. Fraunhofer IIS contributes code to that project and extended it within different projects (5G-ALLSTAR [7], 5G-AUTOSAT [8], 5G-EmuSat [9] and 5G-GOA [10]) covering different NTN aspects.

##### B. Mobility Adjustments

In the mobile satellite scenario, the perceived SNR was relatively low (about 2 dB in DL and 0 dB in UL). To comply with the regulatory limits regarding the UL power, but still achieving this SNR, the UL bandwidth was limited to 2.16 MHz, whereas the used DL bandwidth was 8.64 MHz. Due to implementation choices in OAI to achieve real-time capability, at least 0 dB SNR was required for the lowest 5G NR modulation and coding scheme (MCS) with QPSK modulation and a code rate of 120/1024.

The 5G NR RAN is a synchronized system where all UEs must strictly adhere to the frame timing given by the base-station (gNB). The required timing accuracy for successful UL reception is the length of the cyclic prefix (CP) of the OFDM symbol. For the used subcarrier spacing (SCS) of 30 kHz, the CP duration was 2.34  $\mu$ s. Therefore, the round-trip-time (RTT) from gNB via satellite to the UE and back had to be estimated quite accurately. In addition to timing synchronization, the UE must estimate and compensate the DL frequency error and pre-compensate the UL frequency offset accordingly. Thus, the up- and downconverters on the UE side must be synchronized, just like the up- and downconverters on the gNB side.

##### C. Results

Mobility demonstration of 5G NTN exhibited similar user experience as with currently available satellite modems. ICMP packets were initiated at the hub and user terminals, and pings ranged from 550-615ms. Throughput tests were also conducted and were within 90% of the expected throughput, 10% being overhead traffic. Blockages shorter than one second were conducted while driving and recoveries from blockages were similar to existing satellite modems.

#### V. CONCLUSION

The reconfigurable holographic metasurface antenna described in this report enables land-mobile connectivity to 5G NTNs. Land mobility presents new challenges for 5G NTN, some of which include compromised line of sight (total blockage, partial blockage), and antenna scan loss, both of which impact SNR levels. Adaptive modulation and coding was not tested in this release but is expected to improve the user experience as varying types of blockages and scan conditions would impact SNR levels. Of note is the 5G NTN release that was part of this demonstration has not been optimized for IP traffic. External WAN accelerators or multi-WAN devices can improve user experience.

#### ACKNOWLEDGMENT

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