Beam-Steering Antenna Technologies for Space-Related Applications

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Abstract— **The dramatic growth in the satellite terminal market up to a cumulative total of billions of US dollars by 2030 has been predicted by market analysts. Motivated by these predictions and based on customer feedback, established geostationary-orbit (GEO) satellite operators are investing in new high-throughput technologies. And new satellite operators have committed billions of dollars to low-earth-orbit (LEO) and medium-earth-orbit (MEO) satellite constellations. The beam-steering antenna is the most challenging and expensive subsystem in the ground segment of a modern satellite communication (SATCOM) terminal. New innovative beam-steering methods are required to meet the demands of the many new high-volume markets, such as low cost, low power consumption and aesthetically appealing shape.**

Both industry and academia have recognized these challenges and are developing and inventing innovative antenna beam-steering technologies that disrupt the way beam-steering antennas are designed. This paper outlines the challenges and briefly reviews some disruptive antenna beam-steering technologies for the next generation of SATCOM terminals.

Index Terms—SATCOM, COTM, communications-on-the-move, Comms-on-the-move, SOTM, satellite-on-the-move, beam steering, 4G, 5G, 6G, GEO, MEO, LEO, CubeSat, near-field, VI-CTS, electronic steering, ESA, holography, phased array, LCD, metamaterial, metasurface, phase shifting surface, Meta-Steering, phase transformation, phase gradient, optical beamforming, digital beamforming, Satellite TV, transmitarray, flat lens, reflectarray, lens antenna, CP, LP, RHCP, LHCP, vertical polarization, horizontal polarization, Satellite TV, DBS, DTH, DVB-S, FCC, ITU Introduction (*HEADING 1*)

I. INTRODUCTION

These days most of us can get decent data throughput from mobile broadband. However, satellite communication (SATCOM) is still the only resort for high-throughput connectivity in locations not served well by terrestrial telecom operators. This market includes fixed users in regional areas (businesses, government services, community centers, homes), aerospace (commercial & business airplanes), maritime (cruise ships, frigates), emergency operations during disasters (e.g., floods, fires), defense/military operations, and vehicles traveling in remote areas. Some satellite operators have already integrated their satellite networks with global terrestrial networks, and such integration is expected to be formalized and standardized in upcoming mobile standards. In some cases, the SATCOM terminal is on a moving platform; thus, such services are also called Satellite Communication On-The-Move (SOTM) or Communications On-The-Move (COTM). In other cases, the terminal is a rapidly deployable portable terminal that can provide connectivity when set up in a fixed location, known as Satellite Communication On-The-Pause (SOTP) or Communications On-The-Pause (COTP).

Traditional users of SATCOM terminals have been in the "high end," such as the army, navy, airplanes and cruise ships. However, the current civil mass market ("new" market) for SATCOM terminals is expected to increase and dominate over the next ten years. One difference is in price sensitivity. Thus, the cost of a SATCOM terminal must decrease significantly to make new SATCOM services successful in these new markets! The beam-steering antenna system is the most expensive part of a SATCOM terminal, so this is a considerable research and development (R&D) challenge for antenna engineers. Not just affordability, the "new" clients demand a low-profile, aesthetically appealing antenna terminal with "sleek" packaging that provides higher data throughput to play high-resolution videos, etc. and consumes low power. One objective is that a COTP terminal can provide high-throughput connectivity in an emergency without grid power using renewable sources such as batteries and/or solar panels or a COTM terminal fitted to the roof of an electric vehicle does not significantly compromise the range between charging, or such a terminal on a non-electric vehicle does not drain its small battery when SATCOM is active with the engine off.

Obviously, the highly reliable COTM systems developed over the last few decades, primarily for the defense market, are too expensive for these new large-volume mass civil markets and do not meet most of these new demands. This paper provides an overview of antenna beam-steering technologies employed in established commercial COTM products and, in addition, reviews a few modern disruptive beam-steering technologies that are being developed by industry and academia to address these new challenges.

Considering the apparent strong emphasis given by the new markets to a COTM terminal height, beam-steering technologies are first broadly classified into three groups according to the height of the antenna system. Each is discussed in the following three sections. One exception to this classification is SpaceX Starlink phased array technology. It is available directly from Starlink to signedup customers in some countries and is believed to be based on RF phase shifter integrated circuits (ICs). Yet current Starlink terminals do require some mechanical tilting. Due to the extremely limited information available about this technology, it is not discussed further in this paper.

II. Tall Dome Systems

The most common antenna inside these dome-shaped COTM terminals is a reflector (dish) antenna, and the beam steering method is mechanical rotation and tilting of the dish, often using heavy-duty motors. Due to their excellent performance and demonstrated high reliability, these systems are widely used in defense systems on land vehicles and ships. Another application is providing Satellite TV to ships and vessels.

Their radiation patterns can be tailored to have very low levels of sidelobes and cross-polarization, and the patterns do not get affected much when the beam is steered. That also means high uplink data throughput because more power can be transmitted without violating regulatory emission limits on radiation patterns. Their beam steering range is exceptional; some can steer the beam even below the horizon (i.e., elevation angle > 900). Another advantage is bandwidth flexibility. For example, some manufactured by EM Solutions, Australia, can operate simultaneously in the X-band and military Ka-band and can fall back to Commercial Ka-band automatically if required [1]. Antenna gain, and thus gain-over-noise temperature (G/T) and effective isotropic radiated power (EIRP), can be improved by increasing the dish diameter, of course, at the expense of system height. Some have incorporated precise monopulse satellite tracking methods into these types of terminals. On the other hand, these terminals are expensive, heavy, bulky and too tall for most new consumer markets.

III. Systems Of Medium Height

The beam-steering methods discussed in this section typically create antenna systems with total heights approximately in the range of three to ten wavelengths.

A. Systems with Tilting Antenna Panels

In these systems, the reflector antenna mentioned in Section II is replaced by a fixed beam planar (flat) panel two-dimensional antenna array. To steer its beam, the panel is rotated and tilted just like the previous section's dish. Although a square or circular array would give better performance, often, the array is made to take the shape of a rectangle to reduce the antenna system's maximum height. As a result, the antenna beamwidth is larger on the elevation plane than on the orthogonal plane. Further, this large beamwidth can cause pattern degradation when steering the beam to large elevation angles. This is a well-established beam steering technology, and these types of antennas are being used commercially (e.g., in airplanes for in-flight Wi-Fi). They are developed, manufactured and marketed by several companies including QEST, Germany [2] and Honeywell, USA [3].

B. Tilt-Free Antennas with A Flat Panel and A Medium-Gain Antenna

These are relatively new beam steering methods and are expected to produce antenna systems shorter than those in Section III-A, as they do not require mechanical tilting. The three types discussed here have a few common features to warrant their inclusion in one subsection, although they use significantly different beam-steering technologies. Two of them are illustrated in Figure 1.

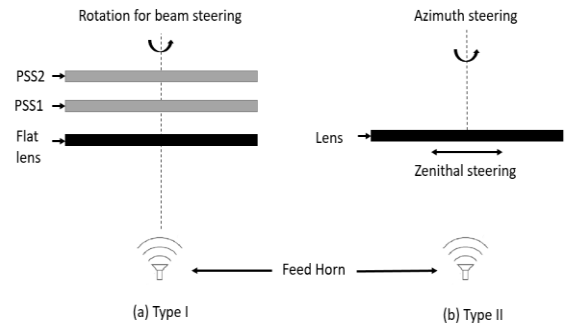

Fig. 1. (a) Type I and (b) Type II medium height tilt-free flat panel antenna system concept

The first similarity is that both methods use a horn antenna as the radiator, and a flat lens (or slightly bent, often a printed PCB) is placed several wavelengths away from the horn (in the far field or the Fresnel Zone) to collimate radiation to form a narrower beam. Such an electrically and geometrically large separation allows the antenna designer to apply ray optics methods and approximations when designing the flat lens for these antenna systems, significantly simplifying the design process. The second similarity is in the “top-heavy” shape - the lens has a much wider area than the feed antenna, and the “active” volume (where the electromagnetic field cannot be disrupted) of the antenna system is much wider near the top compared to the bottom. Some newer versions of these types of antennas are now called a transmitarray.

The difference between the third type is in how beam steering is achieved. In Type-I (Figure 1(a)), two phase-shifting surfaces are rotated about a common axis [4] [30]. In Type II (Figure 1(b)), a flat lens is laterally translated relative to the feed (or vice versa) for steering in elevation, and it’s rotated, alone or together with the feed horn, for azimuth steering. In Type III, the “lens” is electronically reconfigurable [23] [24].

Type I. The first prototype based on the rotation-based method has three printed panels: one is the flat lens (Fresnel-zone plate lens), and the other two are rotatable phase-progression phase shifting surfaces (PSS). The second prototype has a flat lens, and the first PSS is incorporated into one disk [4]. The measured peak gain of the system is 28 dBi at 30.1 GHz, which is reached when the beam direction is parallel to the antenna axis (i.e., elevation angle

= 00). The beam can be steered to an elevation angle of 72.50, but the gain dropped by 8.3 dB at that elevation. More importantly, the gain drop was only 2.8 dB at an elevation angle of 45.50. Apparently, R&D on this beam-steering technology did not continue in recent years. (Similar non-steering flat lens antennas are recently presented as "transmitarrays.")

Type II. In contrast, the translation-based method is newer [5], more developed and still being developed. It has advanced to demonstrate even dual-band operation with circular polarization in the SATCOM Ka-band [6]. With the dual-band steering technology, measured gains of 24.6 dBi and 27.2 dBi have been achieved at 20 and 30 GHz, respectively. Its elevation steering range is from 0^0 to 50^0 (with a gain loss of 3.6 dB relative to the peak at boresight) and the F/D ratio is less than 1. Recent advances in this method include the development of bi-focal planar lenses to reduce the pattern aberrations that generally occur during beam steering in elevation and curved (non-planar) transmitarrays to reduce the drop in antenna effective area during beam steering in elevation.

Type III. In this technology, the "transmitarray" is electronically reconfigurable [23], and it provides the required 2D phase shift distribution to collimate the beam and steer it in a specific direction. Thus, no mechanical motion is required. The reconfigurable phase-shifting cells in the transmitarray are 1-bit or 2-bit [24], but such phase approximations were not found to be a major limitation.

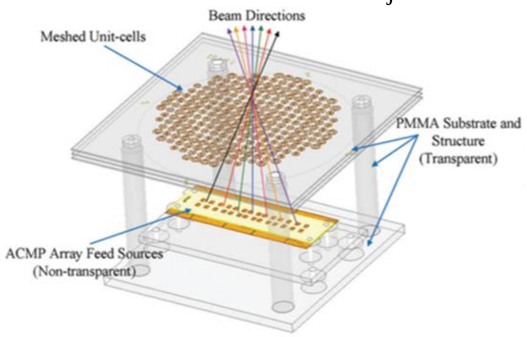

Fig. 2. (a) Reconfigurable beam-steering transmitarray [25].

IV. Thin Systems

The beam-steering methods discussed here create antenna systems shorter than three wavelengths at the mid-band. They are subdivided into three groups according to the mechanical movements associated with them or the lack of them.

A. Electronically Steerable Antennas

Standard phased arrays with RF phase shifters and microstrip feed distribution networks face serious challenges when scaled to gain levels required for SATCOM (often 30-40 dBi) due to high losses in phase shifters and feed distribution systems. All known electronically steerable antennas being developed for SATCOM are highly proprietary, and only minimal information is available to the public.

One of them is from Kymeta [7], and it is the only globally available electronically steerable COTM antenna technology at present, to the best of the authors' knowledge. It is said to use holography and a liquid crystal display (LCD) panel for beam forming. The Liquid crystal-based smart antenna technology has emerged as a cost-efficient enabler for future wireless communication systems [8]. Other commercial electronically steered antenna (ESA) technologies announced by industry include:

1) Phasor Solutions antenna array technology with radiofrequency and digital Application Specific Integrated Circuits (ASICs) [9],
2) Alcan Systems phased array technology that apparently has LCD-based phase shifting [10],
3) Isotropic Systems array technology, apparently with optical beamforming [11], and
4) C-COM phased-array antenna technology [12].

The losses in the radiofrequency (RF) system, in materials required to guide the microwave from the feed connector to all radiating elements and in RF devices (switches/phase shifters), if they are used, limits the gain for high-throughput electronic steering-based SATCOM terminals. Kymeta technology uses a radial air-filled TEM waveguide to excite the radiating elements, as in the radial-line-slot-array antennas [26], to minimize the said guided RF distribution loss. Thermal management is a substantial challenge due to excessive heat dissipation in a confined volume that limits cooling options. One common limitation of these technologies is the large operating power requirement.

B. Variable Inclination Continuous Transverse Stub Arrays

Continuous Transverse Stub (CTS) array is a fixed-beam linearly polarized antenna technology with very low cross-polarization. Invented at Raytheon, later it was extended by the same company in another patent to a beam-steering antenna called Variable Inclination CTS (VI-CTS) array [13]. It was later developed to a commercial COTM terminal by ThinKom [14], for use in airplanes for inflight connectivity.

According to photos in the public domain, three or more parts rotate around a common axis for each antenna. Yet, due to the lack of tilting parts, these antennas are thin and hence desirable for applications requiring a low profile. It appears that these parts are rotated by small motors using belts. The antenna system is passive, and the power consumption is claimed to be less than electronically steerable antennas. COTM terminals are available for both Ku and Ka bands, and their performance and beam-steering range appear very good. ThinKom ThinAir Ka2517 is possibly the thinnest Ka-band COTM terminal commercially available at present. Although the authors cannot verify, VI-CTS terminals are said to be more expensive relative to alternatives available for airplanes (nearly all of them are much taller tilting flat panels mentioned in Section III A). With their products, ThinKom has proved that extremely thin COTM terminals with excellent performance can be produced using tilt-free mechanical rotation methods.

A conventional CTS array can only make linear polarization (LP) with one polarization, not even dual linear polarization. Naturally, they are single-band antennas, but Ku-band COTM terminals must receive in one frequency band (around 10 GHz) and transmit in another band (around 12 GHz). Apparently, for this reason, VI-CTS-based commercial COTM terminals seem to have two different antenna systems, one for transmitting and the other for receiving. Their elongated shape does not seem to be an issue for commercial airplanes. Another challenge is generating circular polarization required for Ka-band COTM terminals. An apparent solution is to use another rotating part, a polarizer disk, to convert the LP of the antenna to CP. To the authors' best knowledge, dual-band dual-polar operation has never been implemented in a shared aperture of a commercial VI-CTS COTM terminal yet.

C. Systems with Rotatable Near-Field Metasurfaces

First published in 2017 in a paper co-authored by the author, this beam-steering method is a dynamic implementation of near-field phase transformation [15]. In the most popular form, it has two rotating near-field phase-transformation metasurfaces, which are placed very close to the aperture in the near field of a base antenna that has a fixed beam. The first prototype had a half-wavelength tall resonant cavity antenna (RCA) as the base antenna, but the total system height was still about 1.3 free-space wavelengths. It experimentally demonstrated beam steering in elevation and azimuth, with coverage up to 510 elevation angles with less than 3dB variation from its peak gain of 19.4 dBi. Further advanced later by the authors' group and several other research groups, this method is called Near-Field Meta-Steering [16], [27-30].

Although some implementations of Near-Field Meta-Steering (Fig. 2) may look similar to a VI-CTS system at first sight, mainly due to the presence of closely placed rotating parts in a thin flat case, its principle of operation is entirely different. Unlike a VI-CTS array, the Near-Field Meta-Steering can be achieved using any base antenna with a fixed beam, including any linearly polarized, circularly polarized or dual linear polarized or dual circular polarized base antenna. Thus, this method can natively produce any polarization (single or dual) without a rotating polarizer plate.

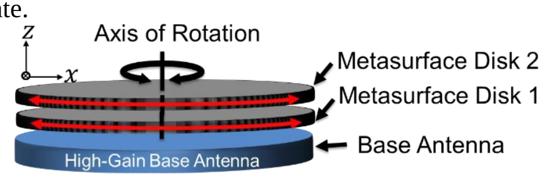

Fig. 3. Near-Field Meta-Steering Antenna System concept.

This method is claimed to have several advantages over some other beam-steering methods:

1) Lack of tilting;
2) Planar and low profile due to very little separation between the base antenna and metasurfaces;
3) Very low operating power, only a few watts for two motors to steer and none when the beam is stationary;
4) Any polarization can be produced natively;
5) High aperture efficiency, based on the base antenna;
6) Very high overall efficiency values up to 30 GHz;
7) Relatively low material and fabrication costs;
8) Absence of non-linearity, intermodulation, caused by active components;
9) Absence of thermal management challenges due to high efficiency and low RF loss;
10) Capability to handle high power;
11) Absence of mechanical translation;
12) Does not require powerful motors or rotary joints since the base antenna is stationary in many instances; and
13) Operates with any fixed beam base antenna.

This method has been tested with several different types of base antennas with gains (up to 36 dBi), bandwidths (up to 40.5%) and polarizations (LP, CP and dual CP) in addition to the RCA in the seminal paper, by the authors' group and other research groups. Among them are horn antennas, CTS antennas (not VI-CTS) and radial line slot array (RLSA) antennas. One system has a metal horn antenna and waveguide-based metallic metasurfaces for a high-power microwave system [18], and another has a dual-polarized CTS antenna with a fixed beam as the base antenna [19]. A large steering range of 40.5% was demonstrated (from 26.5 GHz to 40 GHz) when the two metasurfaces were replaced with two 3D-printed dielectric near-field transforming structures at the expense of system height [20]. Recently, an all-metal metasurface-driven NFMS antenna system has been demonstrated in [21]. The system is low-cost, lightweight, and has a ±420 steering range in the zenith with a maximum scanning bandwidth of 800 MHz. The overall antenna profile is 4.9λ only, which is 71% and 66% less than the reported design in [18] and [20], respectively. Later, those tall structures were replaced by planar all-dielectric phase transforming disks and still an excellent 29% overall (steering and matched) bandwidth was achieved experimentally [22].

Due to the close proximity between the lower metasurface and the base antenna, ray methods cannot be used to design or analyze these antenna systems. Another major difference between the placement of rotating metasurfaces in the near field of a base antenna, as opposed to the far field or Fresnel zone of a horn as in Subsection II B, is that the entire field of the base antenna is fully "processed" by the metasurfaces and there is no noticeable spill over. The areas of the metasurfaces are equal to or only slightly larger than the aperture of the base antenna.

Therefore, unlike far-field methods, very high aperture efficiencies can be achieved where required. Aperture efficiency can be fully controlled in the design of the base antenna, for example, to maximize G/T or to accommodate an amplitude taper to tailor the antenna radiation pattern.

V. CONCLUSION

The advantages and limitations of the established beam-steering methods used in commercial COTM terminals are well understood, but the newer and relatively thinner disruptive technologies are still under the microscope. However, there is a range of challenging requirements to meet in the SATCOM market. These include low terminal price, size restrictions (height, length, and width), low power budget, data throughput limits, large beam steering range, wide bandwidths, multiple polarization support, extreme operation conditions, extended warranty periods, tight regularity limits including maximum EIRP mask that limits the spectral emission on the radiation pattern including the side lobes etc. Therefore, it is unlikely that a single beam-steering method will meet all these challenging demands in the emerging SATCOM markets.

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