Self-Steering Antenna Arrays for Distributed Picosatellite Networks

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***Abstract*—The potential for using self-steering arrays for secure crosslinks in picosatellite networks is investigated. The principle of operation and methods of characterization of these so-called retrodirective arrays is reviewed, and examples developed by our group are presented. New challenges for the space environment are identified, specifically the development of two-dimensional, circularly polarized retrodirective arrays optimized for size and power consumption.**

I. Introduction

The recent growth in small-satellite technologies has provided considerable momentum in making future small-satellite networks a reality. Such networks promise increased mission flexibility and success by distributing the tasks and subsystems typical of a single large satellite. An autonomous small-satellite network also reduces the possibility of catastrophic single-point failures and minimizes the power consumption of typical satellite-ground communications. However, the challenge in designing a distributed small-satellite network – especially a dynamically reconfigurable one – is in establishing and maintaining a reliable crosslink with other satellites in the network without *a priori* knowledge of their positions.

Omnidirectional antennas are the obvious choice for crosslinking satellites that are subject to constant repositioning, but this leaves the network susceptible to eavesdropping by unauthorized ground stations as well as by satellites outside the network but still within range of the constellation. Omnidirectional antennas are also inefficient, as power is radiated in all directions, not just in the direction of the receiver.

In covert or security-sensitive networks, signal interception can be prevented by employing direct crosslinks with dynamically beam-steered directional antennas. However, the design of beam steering arrays involves phase shifters or digital signal processing algorithms. For a 1000-cubic-cm picosatellite such as CubeSat [1], processing power is a valuable resource and dynamic beam steering would add another layer of complexity to the system, negating the advantages of the simple, low-cost nature of these small satellites.

For picosatellite applications, an attractive alternative to dynamic beam steering is a *self-steering* array that permits secure crosslink communications between satellites moving randomly in space (Fig. 1). Self-steering (also known as *retrodirective*) antennas are able to sense the direction of an incoming radio transmission and send a reply in that same direction, without the complexities associated with phase shifters in conventional phased arrays or digital signal processing in smart antennas. The high directivity associated with self-steered arrays not only improves network security, but also improves the communication link budget and minimizes power consumption.

A variety of self-steering antenna arrays have been demonstrated by our group, but through the University Nanosat Program, this is the first time to our knowledge that these arrays will be specifically developed for picosatellite crosslink applications.

This paper is organized as follows: Section II discusses the operating principles of retrodirective antennas, and presents some relevant examples developed by our group. Section III outlines the methods for characterizing retrodirective arrays. The unique constraints required for satellite applications are described in Section IV.

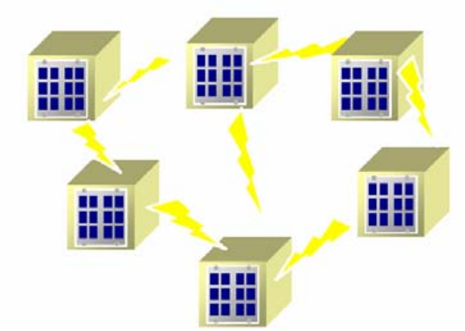

Fig. 1: A distributed network of CubeSat-class satellites, with secure communication crosslinks provided by self-steering (retrodirective) antennas. Using retrodirective rather than omnidirectional antennas not only improves security, but also improves the link budget since the beam is directive.

II. Principle of Operation

The simplest type of retrodirective device is a corner reflector consisting of orthogonal metal sheets. As shown in Fig. 2, multiple bounces at the corner redirects an incoming signal back to the same direction it came from. Though well suited for applications such as radar, their large size in wavelengths and difficulty in integrating electronics make corner reflectors unsuitable for high-frequency picosatellite crosslinks.

Another way of achieving retrodirectivity is through the use of the so-called Van Atta array [2], consisting of pairs of antenna elements equally spaced from the center with equal-length lines (Fig. 3). In this figure, the progressive phase shift associated with the incoming signal is phase-lagged going right to left across the array. The arrangement of the array causes a reversal of this phase progression for the outgoing signal, causing it to retroreflect back in the same direction. Unfortunately, the geometrical arrangement of the Van Atta array makes it spatially inefficient for realizing retrodirectivity on a Cubesat-class satellite.

A third way of achieving retrodirectivity is the heterodyne technique [3], in which the incoming radio-frequency (RF) signal at each element is mixed with a local-oscillator (LO) signal at twice the frequency (Fig. 4). The mixing process results in the following intermediate-frequency (IF) signal:

$$V_{IF} = V_{RF}\cos\left(\omega_{RF}t+\varphi\right)\times V_{LO}\cos\left(\omega_{LO}t\right)$$
$$=\frac{1}{2}V_{RF}V_{LO}\left[\cos\left(\left(\omega_{LO}-\omega_{RF}\right)t-\varphi\right)+\cos\left(\left(\omega_{LO}+\omega_{RF}\right)t+\varphi\right)\right]$$

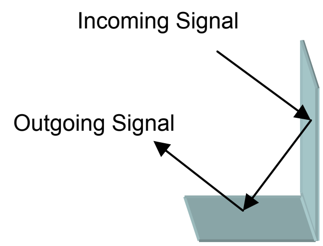

Fig. 2: Two-sided corner reflector, in which an incident signal reflects off both faces and back in the direction of the incoming signal.

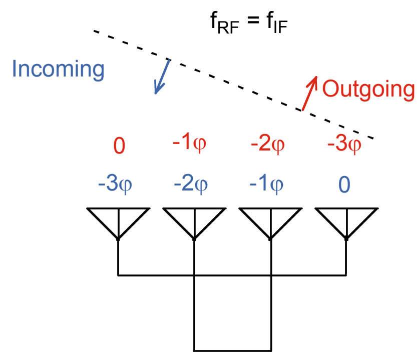

Fig. 3: Four-element Van Atta array. Retrodirection is achieved since the phase progression of the incoming signal is opposite to that of the outgoing signal.

If $\omega_{LO} = 2\omega_{RF}$:

$$V_{IF} \propto \cos\left(\omega_{RF}t-\varphi\right)+\cos\left(3\omega_{RF}t+\varphi\right) \qquad (1)$$

Note that the first term in (1) has the same frequency as the RF signal, but with a conjugate phase. The resulting phase conjugation across the entire array results in retroreflection of the IF signal back towards the RF source, just as in the Van Atta array.

The upper sideband product in (1) is an undesired, non-phase-conjugated signal that radiates in accordance with Snell's Law. Fortunately, this signal is easily filtered and suppressed due to the large difference between this frequency ($3f_{RF}$) and the RF (f_{RF}). For the same reason, any LO leakage ($2f_{RF}$) can also be easily filtered. A narrow-bandwidth antenna can contribute to this filtering process.

Most of the recently demonstrated retrodirective arrays are based on the heterodyne technique [4]. This technique handles the phase conjugation through hardware only slightly increasing the circuit complexity, while eliminating the need for complex digital signal processing. This also allows for the active tracking and self steering of a beam in the direction of a moving target, even without knowing its initial position, and thus is well suited for satellite applications.

Fig. 5 shows an example of a four-element retrodirective array [5] based on the heterodyne technique. This array operates at C-band, with a 12-GHz LO applied in phase to each microstrip antenna element through a corporate feed network. Grating lobes are avoided by spacing the elements approximately a half-wavelength apart at the RF frequency. Each antenna has only one feed shared by both the receiving and transmitting signals. The design details of the phase-conjugating circuitry, as well as the measurements, can be found in [5].

Fig. 6 illustrates an alternative architecture to the one in Fig. 4. In this array, the external LO is eliminated,

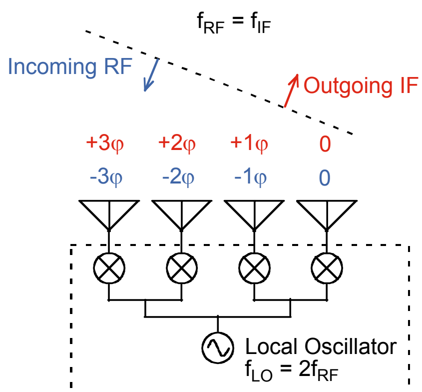

Fig. 4: Phase-conjugating array based on the heterodyne method. Mixing with the LO takes place at each antenna element and the IF signal is re-fed into the antenna elements to be transmitted back in the direction of the sender.

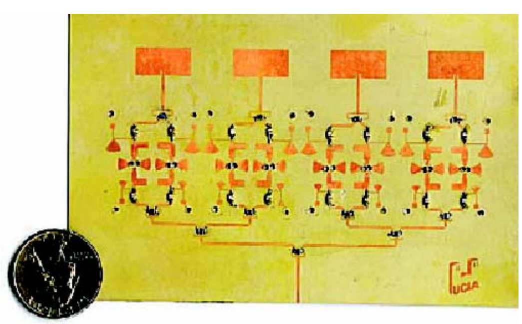

Fig. 5. C-band retrodirective array [5]. An external LO is connected to the phase-conjugating circuitry via a corporate feed network.

and the mixers are replaced with a set of synchronized oscillators. Because the oscillators are nonlinear, an external RF signal that is incident upon the array is mixed with the LO, generating signals at the sum and difference frequencies, just as in a conventional mixer. This type of device is known as a self-oscillating mixer (SOM). A retrodirective array can then by realized by phase locking the SOM elements at the LO frequency while isolating them at the RF frequency.

An important advantage of the SOM array is that the corporate LO feed network is eliminated. This is important in large 1D or 2D arrays, in which the feed network can be quite large, and sufficient LO power must be provided to each mixer.

A prototype 1D SOM retrodirective array is shown in Fig. 7. Each of the three modules (SOM, diplexer, and antenna array) is built and tested independently and then integrated to form the phase conjugating array. Commercial fabrication of the entire system would be realized on a single board.

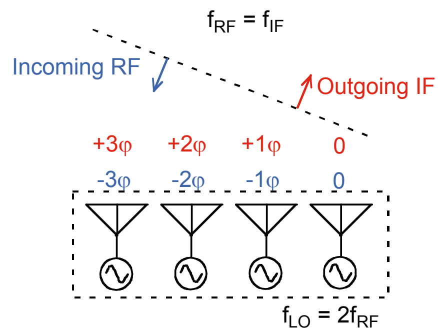

Fig. 6: Phase conjugating array based on self-oscillating mixers. Unlike conventional retrodirective circuitry this method eliminates the need for an external LO by integrating self-oscillating mixers into a compact antenna structure.

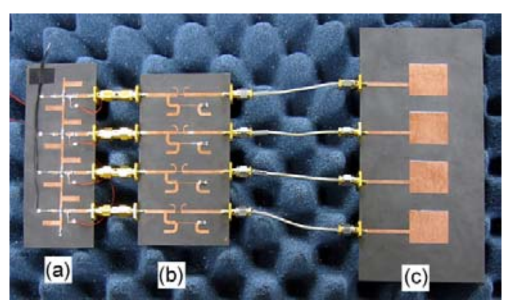

Fig. 7. Prototype phase conjugation array based on self-oscillating mixers: (a) SOMs, (b) diplexers, and (c) antenna array [6].

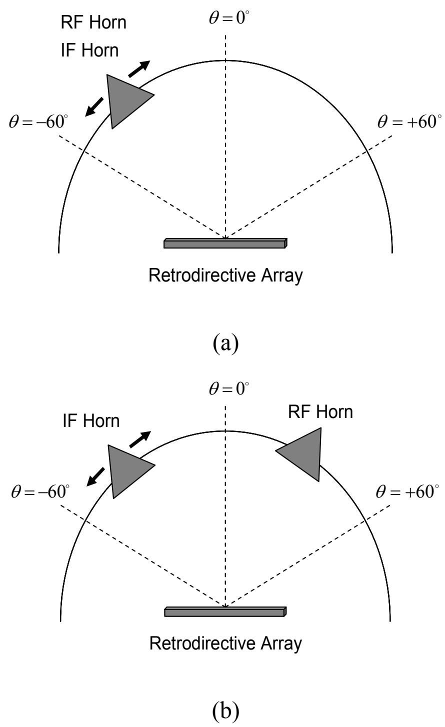

Fig 8. A retrodirective signal is characterized by (a) monostatic RCS and (b) bistatic RCS measurements.

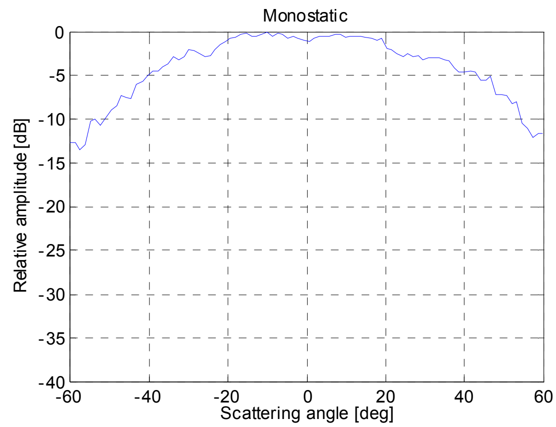

Fig. 9. Example of a monostatic RCS pattern [7].

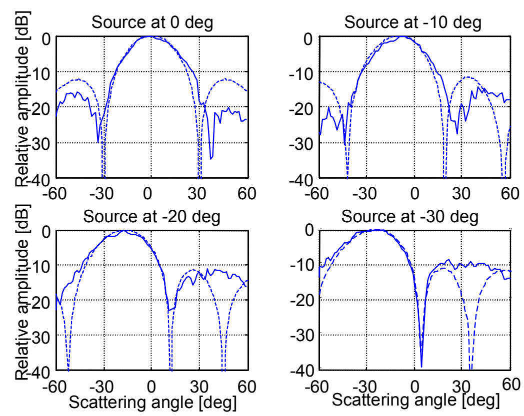

Fig. 10. Example of a bistatic RCS measurement [7]. These plots show the bistatic patterns when the RF source signal is incident at 0°, -10°, -20°, and -30°.

III. Characterization

Fig. 8 illustrates the typical method of characterizing a retrodirective antenna array. A horn antenna provides the RF interrogating signal. Once the RF signal impinges on the array under test, the retrodirected IF signal is reflected back, ideally in the same direction as the RF horn. A second horn antenna picks up this reflected IF signal. Since the incident RF and retroreflected IF signals share common frequencies, there is always unavoidable leakage from the RF horn to the IF horn. In practice, this problem is overcome by slightly offsetting the frequencies so that the two signals can be resolved on a spectrum analyzer. For example, we could use the following frequencies: RF signal of 4.99 GHz, LO signal of 10.00 GHz, and IF signal of 5.01 GHz. Two measurements are carried out to characterize the retrodirective behavior: monostatic and bistatic radar cross sections (RCS).

In the monostatic RCS case [Fig. 8(a)], both the RF and IF horn antennas are simultaneously scanned over a 120° azimuthal range. Since the incident RF and retrodirected IF signals are both in the same direction, the peak of the array factor will always be in the direction of the source, and thus the monostatic pattern should not exhibit any nulls. An example of a monostatic RCS pattern is shown in Fig. 9.

In the bistatic RCS case [Fig. 8(b)], the RF horn remains stationary while the IF horn is scanned over the 120° azimuthal range. Unlike the monostatic case, a characteristic peak in the pattern should occur in the same direction of the source. Nulls should also occur as a result of the array directivity. An example of a bistatic RCS pattern is shown in Fig. 10.

IV. Considerations for Picosatellite Crosslinks

The self-steering features of retrodirective antennas make them attractive for secure picosatellite crosslink applications. For this reason, the University of Hawaii is currently investigating this problem as its contribution to the University Nanosat Program, sponsored by the Air Force Office of Scientific Research and administered through the Air Force Research Labs (Albuquerque, NM) and NASA Goddard Space Flight Center (MD).

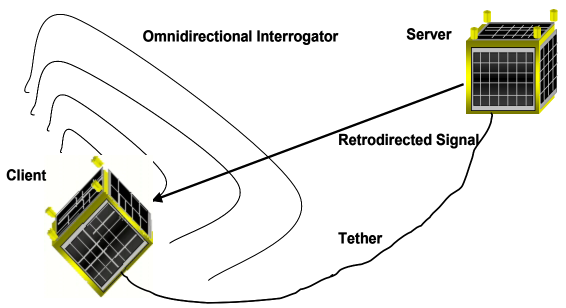

Fig. 11: Retrodirective communication between server and client satellites within a satellite network.

Our project consists of an elementary picosatellite network consisting of two tethered CubeSats. One satellite emits an omnidirectional interrogating signal, and the other satellite contains a retrodirective array that returns the signal (Fig. 11). This project expands upon our previous work on CubeSat antenna technology [8]-[9].

Although retrodirective technology has been around since the 1960s, designing for space applications presents new challenges. First, the zero gravity, free-floating nature of the satellites necessitates 2D tracking – and therefore a 2D retrodirective array. To date, very few 2D arrays have been demonstrated, but our group has produced a preliminary prototype.

Since significant retrodirectivity is achievable for arrays that have at least four elements per dimension, a 4 x 4 retrodirective array is needed. The limited size of the satellite also requires an operating frequency such that a 4 x 4 element array would physically fit on a 10 cm x 10 cm face of the CubeSat, and the operating frequency must lie within an allowable amateur satellite band. Fortunately, 10.5 GHz meets both requirements, and would make an ideal operating frequency. The phase-conjugating circuit size must also be optimized to fit inside the satellite along with all of the other subsystems.

Since it is impossible to know the orientation of each satellite, the antennas will have to provide circular polarization to allow signal reception regardless of each satellite's orientation with respect to each other.

V. Conclusions

With smaller satellites becoming more and more cost efficient, the retrodirective antenna array technology reviewed in this paper could lay the groundwork for future small-satellite networks. The simple, power-efficient characteristics of retrodirective antennas are extremely applicable to small satellites. Furthermore, the high directivity of the communication cross-link makes it suitable for security-sensitive missions.

Acknowledgments

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