Self-Tracking Duplex Communication Link Using Planar Retrodirective Antennas

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***Abstract*—In this paper, a compact architecture for an active planar retrodirective antenna array is presented and its application in a self-tracking duplex communication link discussed. The problem of beam-pointing error (BPE) is addressed and a method is suggested to reduce this error. The proposed architecture, which conventionally performs the function of the retransmission of an incident signal back in the direction of its source, is modified in order to include a receive function. Experimental verification of these architectures are performed at 1 GHz and the results from the prototypes are compared with a theoretical model. Finally, the utility of the architecture is demonstrated for its potential use in a duplex communication link.**

***Index Terms*—Pointing systems, retrodirectivity.**

I. Introduction

A retrodirective antenna reflects an incident signal back in the direction from which it was sourced without *a priori* knowledge of the position of the source. The most well-known retrodirective antenna is the corner reflector, where the geometry of the structure results in retrodirective beam formation [1]. The array equivalent of the corner reflector is the Van Atta array, where the particular form of array-element interconnection results in retrodirective beam formation [2], [3]. Active varieties of the retrodirective array make use of the amplifier gain provided in the transmission line paths interconnecting the antenna elements [4]. The advantage of this arrangement over its passive equivalent is that a smaller aperture is required for prescribed incident power density and radiated power.

The fundamental requirement for retrodirectivity is that each element in the array must have an outgoing wave, which is phase delayed with respect to a reference phase by exactly a much as the incoming wave was phase advanced, i.e., a phase-conjugate relationship between incoming and outgoing wavefronts must exist. In this case, the total path length from the source to the array and back to the source will be constant for all the elements in the array resulting in maximum field transmission in the direction of the source. In the Van Atta array, phase conjugacy is achieved by phase delays introduced by equal length transmission line links interconnecting element pairs in the array. Other techniques of phase reversal have also been reported, Lees [5], for example, utilized the side bands from a balanced mixer; here, the upper and lower side bands of an amplitude modulated signal bear a conjugate phase relationship with respect to the carrier frequency. In another circuit, Margerum and Perga [6] used a single-ended mixer with a vestigial side band produced by a parametric up converter as the local oscillator. Yet another method of achieving phase conjugacy is to introduce receive and transmit phaseshifters. Servoing the receive phaseshifter compensates for the phaseshift caused by the angle of arrival of signal [7].

A new architecture for the retrodirective antenna is presented in this paper, it uses a variation of Van Atta's method. An important modification in the new circuit presented here is the introduction of a frequency offset in the retransmitted signal with respect to the received signal. This modification simultaneously allows enhanced isolation between received and transmitted signals and gives a method for compensation of beam-pointing error (BPE). This architecture along with the detailed study of BPE is presented in the Section II of this paper. To our knowledge, BPE compensation has not been previously reported for retrodirective array structures. In Section III, a modified version of the retrodirective array that includes an additional receive function (called here a retrotransceiver array) is introduced. The transmit beam of the retrotransceiver array is retrodirective in nature, whereas its receive polar pattern is identical to that of a passive array. Section IV presents an application of the retrotransceiver array, where a self-tracking duplex communication link is presented.

II. Frequency Offset Retrodirective Array

Fig. 1(a) shows a classical active Van Atta array [4], here equal length interconnection of the elements cancel the phase difference between the array elements when a signal is received at angles other than boresight thereby, on retransmission, returning the signal in the direction from which it was incident. In this arrangement, circulators are used to isolate the received and transmitted wavefronts. A bilateral amplifier arrangement is incorporated to restore signal losses prior to retransmission.

Fig. 1(b) presents the modifications to the classical arrangement which forms the basis for the work presented here. These modifications are as follows: the circuit uses dual-port linearly polarized microstrip patch antennas [8] for the simultaneous transmission and reception of frequency offset signals. These antennas also perform the additional function

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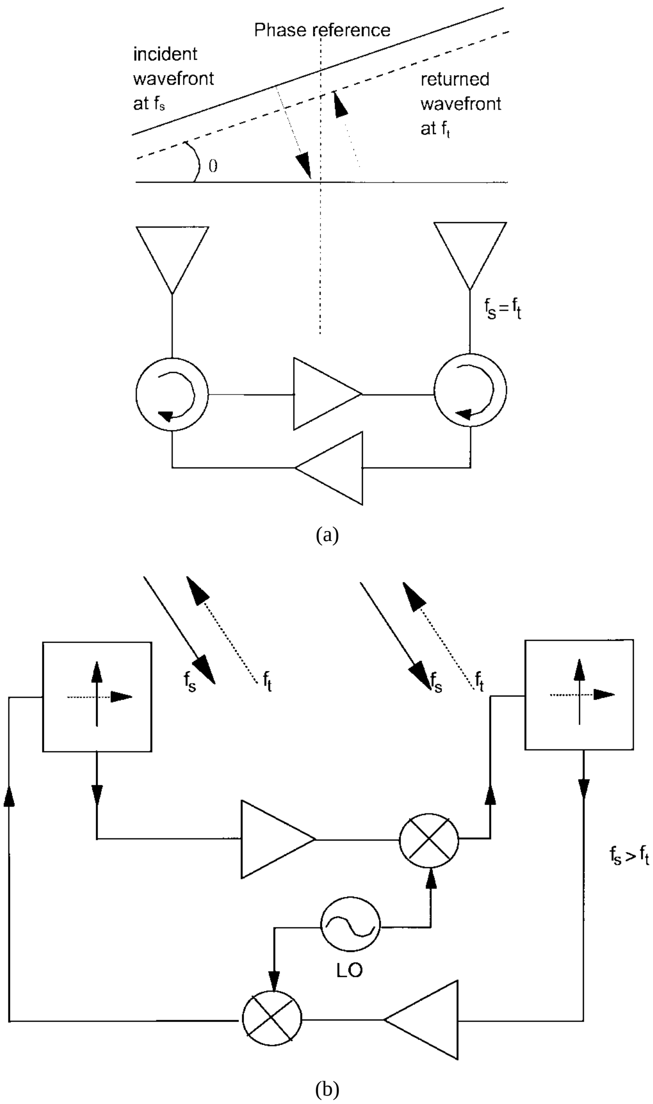


Fig. 1. (a) Classical active Van Atta retrodirective array. (b) Frequency offset retrodirective array.

of a quasi-circulator [9] to provide circuit and polarization isolation between transmit and receive signals. Here the reception and retransmission of the signal occur with orthogonal polarizations, thereby providing additional isolation between these signals and further removing the need for circulators. The measured polar patterns for the dual-port patch antenna are shown in Fig. 2, which uses 1.8 pf capacitors in order to match residual input reactance. The radiation patterns measured at each port are typical of a microstrip patch antenna with about -20 dB worst-case cross polarization obtained. This antenna has $S_{11} = -17$ dB, $S_{22} = -24$ dB, and $S_{21} = -35$ dB. The elements are constructed on $\varepsilon_r = 4.54$, $h = 1.5$ mm material.

The introduction of a small frequency offset into the received signal path prior to retransmission helps in reducing the mutual interference between the received and transmitted signals and also facilitates array characterization where a monostatic measurement is required. The choice of the local oscillator frequency used has to be carefully considered since the maximum deviation from the received signal frequency depends on the bandwidth of the array element. In addition, the actual frequency chosen can be made to compensate for BPE introduced by the polar pattern directivity of the retrodirective antenna array elements. In Fig. 3, when an incident signal arrives at an off boresight angle, the transmit beam of the array will be formed at an angle closer to the boresight than the actual angle of arrival of the incident signal. This is due to the reduction in the gain of the individual elements at positions far from boresight such that when the group pattern is formed the maximum response does not exactly align with the actual angle of arrival (AOA), unless some countermeasure is taken. In effect, this is a sort of beam-pulling effect on the radiation pattern of the retrodirective array such that the beam formed is steered back toward the nominal array boresight. It will be shown that the choice of lower side band of the heterodyning mixer output signal will always generate the best retrodirective response since it will always compensate for BPE [10].

A. Array Factor

The two-element architecture of the retrodirective transceiver antenna used here as demonstrator can be extended to any number of elements, the only condition being elements must be in pairs, i.e., elements are always even in number, as in the case of retrodirective array. The array factor for the frequency offset retrodirective array can be derived using the geometry shown in Fig. 4.

The resultant signal received E_R due to each element of the array

$$E_R = e^{-j(N-1)\psi} + \cdots + e^{-j3\psi} + e^{-j1\psi} + e^{j1\psi} + e^{j3\psi} + \cdots + e^{j(N-1)\psi} \tag{1}$$

where

$$\psi = kx \sin\theta + \beta \tag{2}$$

- $k = \frac{2\pi}{\lambda_0}$ free-space wavenumber;
- λ_0 free-space wavelength;
- θ AOA of the incident signal measured relative to boresight;
- β additional phase delay through electronic conjugation components.

After phase conjugation, the phase of the signals received at each of the elements are reversed and have a frequency offset so that the resultant retransmitted signals will be

$$E_T = e^{j(N-1)\psi} + \cdots + e^{j3\psi} + e^{j\psi} + e^{-j\psi} + e^{-j3\psi} + \cdots + e^{-j(N-1)\psi}. \tag{3}$$

Equations (1) and (2) are simplified in order to obtain the array factor

$$\mathbf{AF} = \mathbf{e}^{j(\omega t+\phi)} \sum_{i=-\frac{N}{2}}^{\frac{N}{2}} \mathbf{e}^{j\left(\frac{2\pi x_i}{\lambda_t}\sin\theta_t - \frac{2\pi x_i}{\lambda_r}\sin\theta_r\right)} \tag{4}$$

where

- N number of elements in the array;
- ϕ constant phase delay due to interconnecting transmission lines;

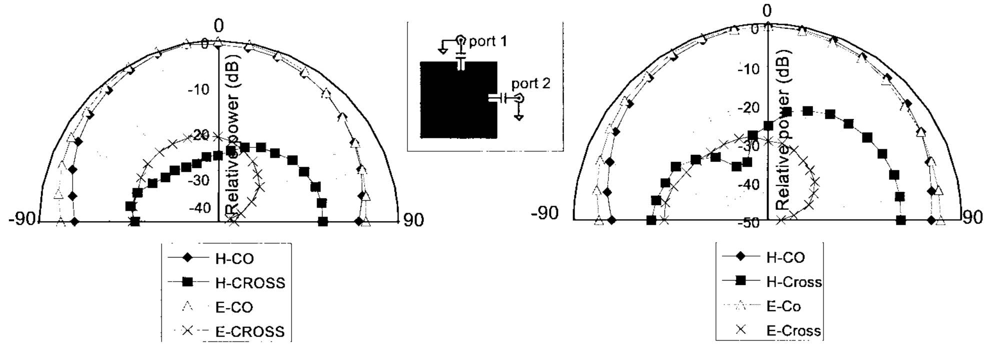


Fig. 2. Normalized radiation patterns for the dual-port microstrip patch antenna.

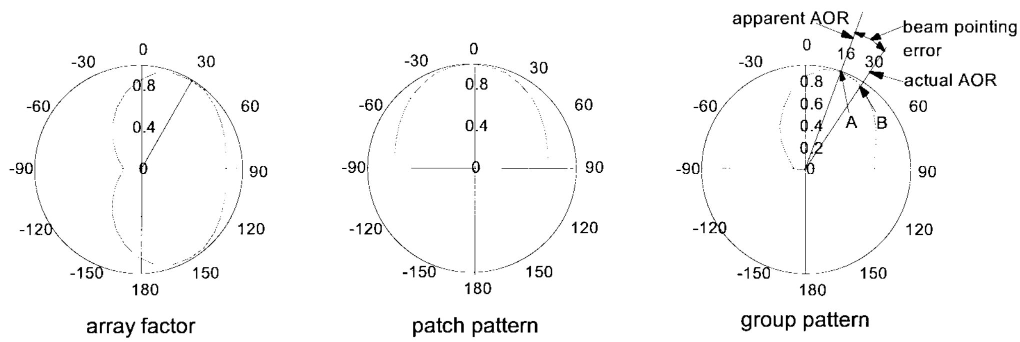


Fig. 3. Apparent BPE.

θ_t position of the transmitter measured from broadside;
θ_r position of the receiver measured from broadside;
λ_r wavelength of the received signal;
λ_t wavelength of the transmitted signal;
x_i distance of ith element from array center.

B. Beam-Pointing Error

As stated above for retrodirective arrays, BPE occurs due to the directivity of the individual elements comprising the array. For example, for a retrodirective array comprising of two $\lambda/2$-spaced microstrip patch antennas, when the incident signal arrives at an angle $+30°$, the maximum response of the transmit beam (calculated by multiplying the array factor with the element patterns) forms at an angle $+16°$— an error of 14°. This error is equivalent to a reduction of 0.5 dB in available signal strength between position A and B in Fig. 3. For an eight element microstrip patch antenna array with $\lambda/2$ element spacing the BPE for a AOA of $+30°$ would reduce to 3°, i.e., 0.1 dB down, as defined above. This error increases as the incident signal moves away from the nominal boresight of the array. The effect of BPE could be critical in some applications, such as those where it is required to resolve the angular position of the transmitter in presence of one or more transmitters in close proximity of first transmitter.

The effect of beam pulling can be reduced either by increasing the array aperture, i.e., increasing the number of elements in the array, or by using omnidirectional radiating elements in the array. In practice, both these possibilities may be difficult to implement because of size or operational constraints. Another way to reduce BPE is to introduce a

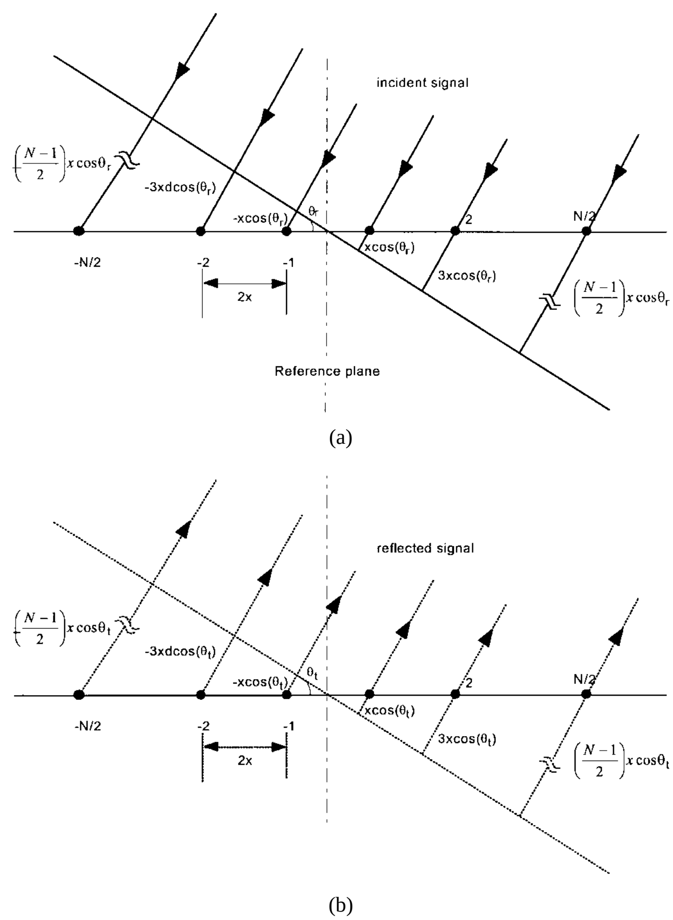


Fig. 4. Far-field geometry for the incident and retransmitted wavefront for the retrodirective array.

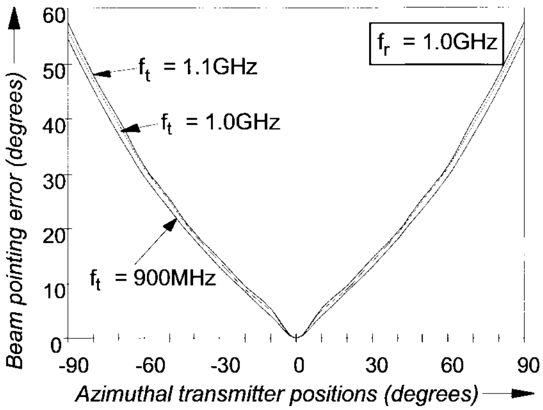


Fig. 5. BPE versus frequency shift for frequency offset retrodirective array.

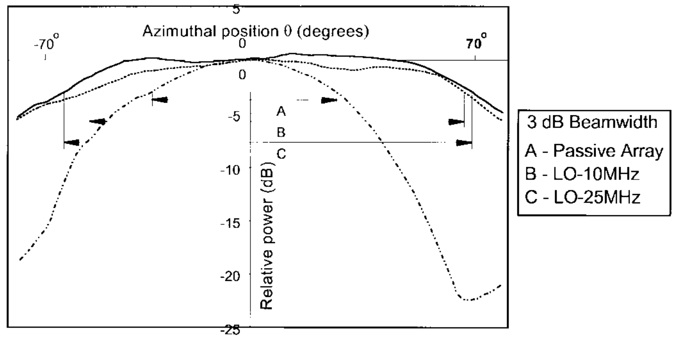


Fig. 6. Measured E-field monostatic radiation patterns for the two-element retrodirective array.

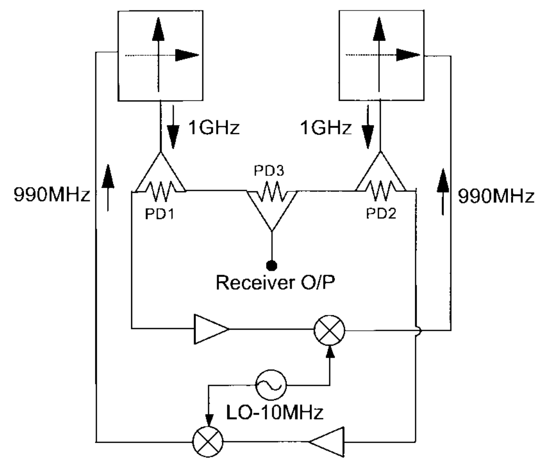


Fig. 7. Frequency offset retrotransceiver array.

frequency shift into the retransmitted signal, here appropriate choice of the retransmission frequency can be used to partially compensate for this error. If the frequency of the retransmitted signal is greater than the frequency of the incident signal then it has the effect of pulling the beam toward boresight, thus adding to the BPE. On the other hand, the frequency shift introduced by reducing the frequency of the retransmitted signal has the effect of pulling the resultant beam away from the boresight thereby nullifying the BPE introduced by the directivity of the elements (which had an effect of pulling the resultant beam toward the boresight). Thus, the choice lower retransmitted frequency as compared to the frequency of the received signal generates best retrodirective response since it always compensates for apparent BPE. Fig. 5 shows the calculated BPE at various azimuthal positions for different frequency offsets for the architecture in Fig. 1(b). Here the theoretical far-field radiation patterns given by [11] for microstrip patch elements have been used. By introducing a frequency offset (LO signal) on the lower side band of the carrier, the resultant beam formed will be predistorted so as to minimize BPE. Ultimately, the degree of the frequency offset is limited by the bandwidth of the antenna elements. The BPE compensation does not improve the antenna gain in the direction of angle of arrival (AOA). However, it reduces undesired radiation in other directions by shifting the peak of the beam toward the direction of the incident signal.

C. Measurements

A monostatic measurement was carried out by moving a transmit/receive antenna in the azimuthal plane of the retrodirective antenna. Fig. 6 shows the measured E-plane monostatic radiation patterns of the retrodirective antenna at different LO frequencies. A passive two-element array response using identical radiating elements is given for reference. The operating frequency of the prototype array is 1 GHz; for all cases the element separation is 0.5 λ between element centers and all patterns are normalized to 0 dB at $\theta = 0°$. As the LO frequency is increased the pattern of the retrodirective antenna flattens, i.e., it becomes more like an ideal self-steering array indicating a reduction in the BPE. For a two-element passive array the measured 3-dB beamwidth is 60° while for the frequency offset retrodirective array architecture the 3-dB beamwidth is increased to 121° for a LO frequency of 10 MHz and to 131° for a LO frequency of 25 MHz.

III. Retrodirective Transceiver Array

Fig. 7 shows a further modification of the two-element retrodirective array given in Fig. 1(b). Its operation is as follows: the incident signal at the receive port of each of the elements comprising the array is split into two equal parts using power dividers PD1 and PD2. Outputs from each power divider are added together using a power combiner PD3, which forms the receiver section of the array. This section functions as a conventional passive array and the received beam is always formed in the direction of the nominal boresight of the array, i.e., $\theta° = 0$. Outputs from the remaining PD1, PD2 ports are used for retrodirective beam formation as in Fig. 1(b). As in the case of frequency offset retrodirective array, the two-element architecture of the retrotransceiver antenna demonstrator used here can be extended to any number of elements. However, circuit complexity and tighter phase control requirements could be limiting factors in the design of such an array with large number of elements, Table I shows the component requirement in such cases. Since only a low-frequency offset signal needs to be distributed in phase to each mixer [Fig. 1(b)], the components at least are not seen to be prohibitive.

TABLE I
COMPONENT REQUIREMENT CHART FOR THE RETRODIRECTIVE ANTENNA ARRAY

No. of elements in array	Mixers	Amplifiers	Power dividers/ combiners
2	2	2	3
4	4	4	5
6	6	6	7
8	8	8	9
16	16	16	17
64	64	64	65

The array factor of the receive beam of the retrotransceiver array is that of a conventional passive array [12] when normalized to the number of elements N given by

$$\mathrm{AF}_R = \frac{1}{N}\frac{\sin\left(\frac{N}{2}\psi\right)}{\sin\left(\frac{1}{2}\psi\right)}. \tag{5}$$

Group patterns for the transmitted and the received beams can be obtained by multiplying respective array factors with corresponding element patterns. Equations for the receive and transmit group patterns are given below:

$$\mathrm{GP}_R = f_R(\theta)\cdot \mathrm{AF}_R \tag{6}$$

$$\mathrm{GP}_T = f_R(\theta)\cdot f_T(\theta)\mathrm{AF}_T \tag{7}$$

where

- GP_R group pattern of the receive array;
- GP_T group pattern of the transmit array;
- $f_R(\theta)$ receive element pattern;
- $f_T(\theta)$ transmit element pattern.

Using (4)–(7), the theoretically computed and measured radiation pattern of the receive beam of a two-element retrotransceiver array are shown in Fig. 8(a). The theoretically calculated and measured monostatic radar cross section (MRCS) radiation pattern of the transmit beam for this array are shown in Fig. 8(b). Here ideal radiation patterns of the microstrip patch antennas are used for the element patterns [11].

The measured 3-dB beamwidth of the receive beam is 59° (theoretically calculated 3-dB beamwidth −58°). The measured 3-dB beamwidth of the MRCS radiation pattern of the transmit beam is 83° whereas the calculated value is 76°. The rolloff on both sides of the boresight of the transmit beam is due to the directivity of the microstrip patch antennas used as array elements.

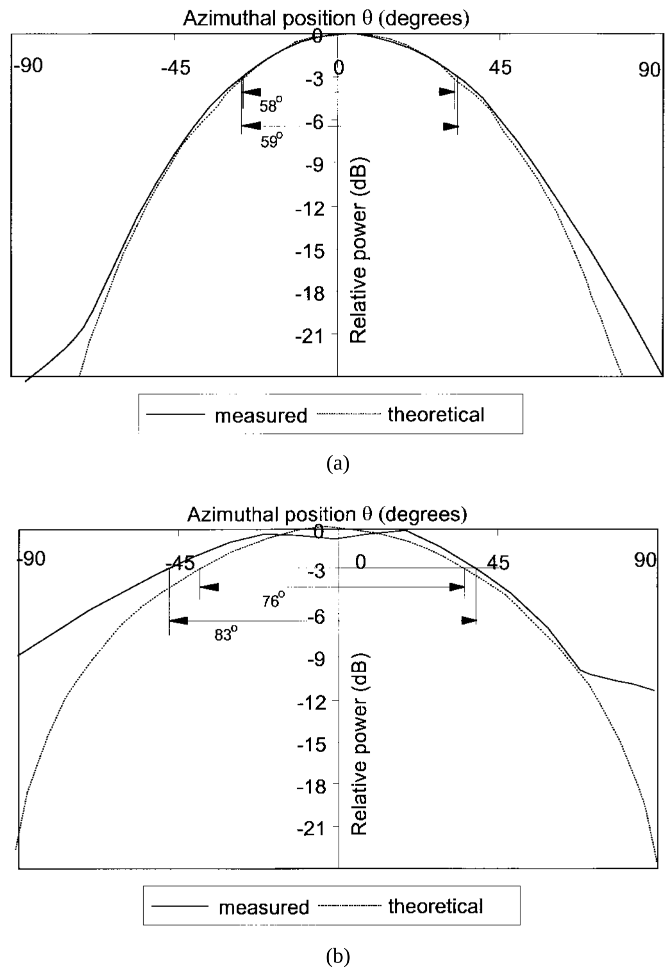


Fig. 8. (a) Theoretical and measured radiation patterns of the receive beam of the two-element retrotransceiver array. (b) Theoretical and measured MRCS radiation patterns of the transmit beam of the two-element retrotransceiver array.

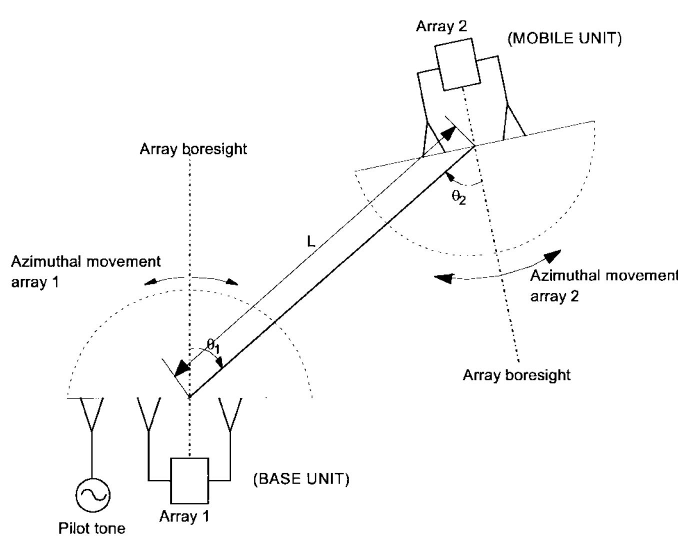


Fig. 9. Retrodirective communication link.

IV. DUPLEX RETRODIRECTIVE COMMUNICATION LINK

A. Theoretical Background

A duplex communication link can be formed using a pair of the retrodirective transceiver antennas described above, Fig. 9. Here a pilot signal is used to initiate the communication between cooperating antennas. Such a communication link is useful when the communicating antennas are mobile and it is necessary for these antennas to track each other without prior information regarding their relative positions. Improvements in gain with subsequent relaxation in the power budget together

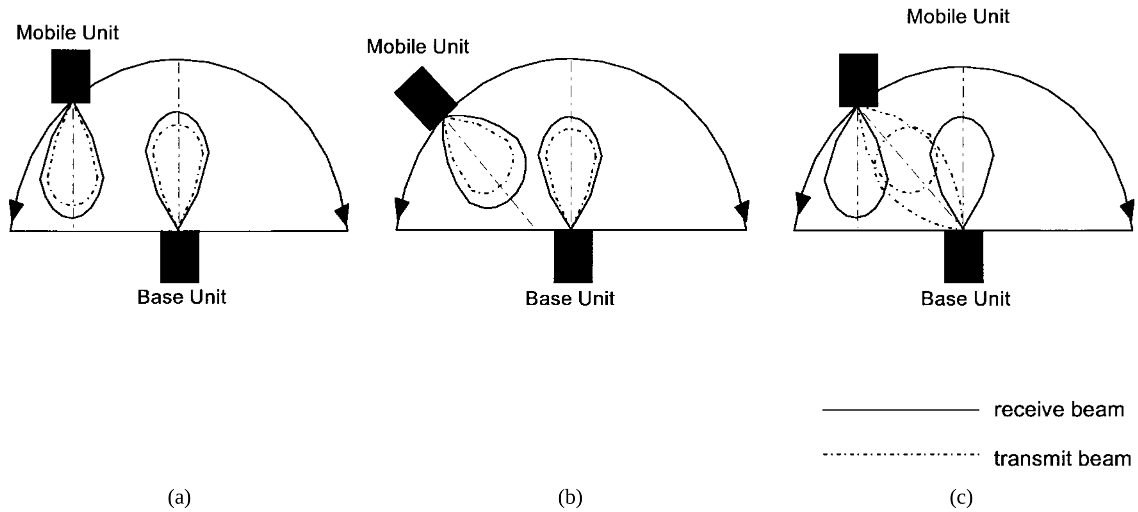


Fig. 10. Measurement setup for the communication link. (a) Passive link (parallel). (b) Passive link (radial). (c) Retrodirective link (parallel).

with reduced multipath effects accrue by using this approach. The power received by the receive sections of the arrays depends on the separation between receive and transmit units and their relative orientation with respect to each other. For the land mobile communications we need to consider only the azimuthal plane shown in Fig. 9.

The radiation pattern for the receive signal at the receive port of the array 1 is given by

$$Er_1 = Ae^{j\omega t}[\mathrm{GP2}_t(\theta_2)][\mathrm{GP1}_r(\theta_1)] \tag{8}$$

and the radiation pattern for the receive signal at the receive port of antenna 2 is given by

$$Er_2 = Ae^{j\omega t}[\mathrm{GP1}_t(\theta_1)][\mathrm{GP2}_r(\theta_2)] \tag{9}$$

where

- $\mathrm{GP1}_t$ and $\mathrm{GP2}_t$ group patterns of the transmit beams of array 1 and 2, respectively;
- $\mathrm{GP1}_r$ and $\mathrm{GP2}_r$ group patterns of the receive beams of array 1 and 2, respectively;
- θ_1 angle of arrival (and departure) of the signal with respect to the boresight of the array 1 in the azimuthal plane;
- θ_2 angle of arrival (and departure) of the signal with respect to the boresight of the array 2 in the azimuthal plane.

Equations (8) and (9) are also valid for the communication link using passive arrays, the only difference is that the group patterns for the receive and the transmit patterns are the same. The performance of a passive link using the same radiating elements as the retrodirective link is given for comparative analysis of the performance of the retrodirective link.

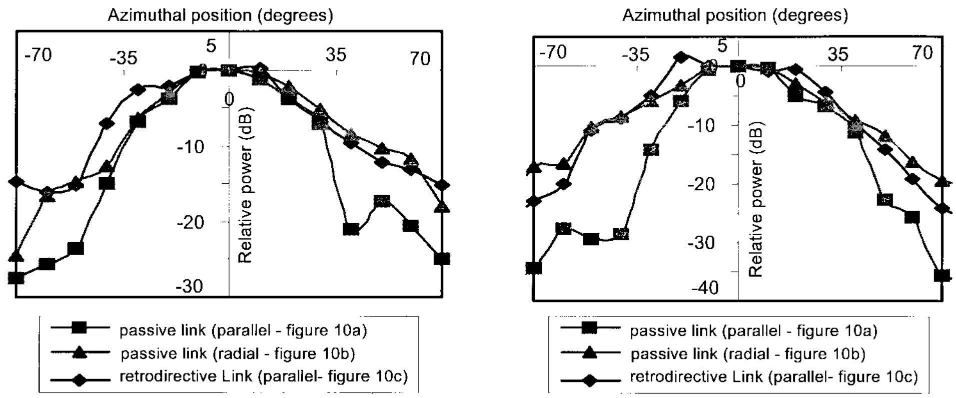
A comparative performance of the retrodirective communication link in receive mode is compiled in the Table II. Here the improvement in the 3-dB coverage area with respect to the 3-dB coverage area of a passive array is given for the retrodirective link as a function of number of elements in the array. These were computed using (8) and (9). It is assumed that in each case, the cooperating arrays are identical and the receive radiation patterns are obtained by keeping one array in the link stationary and moving the other array around it in the azimuthal plane at a fixed distance while always maintaining their nominal boresights parallel to each other at all the azimuthal positions [Fig. 10(b)].

TABLE II
PERCENTAGE IMPROVEMENT IN THE 3-dB COVERAGE FOR THE RECEIVE BEAM IN A DUAL-POLARIZED RETRODIRECTIVE LINK WITH RESPECT TO A CONVENTIONAL PASSIVE LINK USING THE SAME RADIATING ELEMENTS

No. of elements	Percentage improvement in the 3dB coverage: Vertical receive beam (%)	Horizontal receive beam (%)
2	10	2
4	29	24
6	33	33
8	38	38
10	42	42

B. The Experimental Link

Figs. 9 and 10 shows the layout for the link based on dual polarized retrotransceiver array. Here for ease of measurement one unit is held stationary—the base unit—while the other unit is allowed to roam—the mobile unit. However, in general, the base station can also be mobile. The base station houses a separate microstrip patch antenna for the transmission of the pilot signal. The pilot signal is required in order to initiate cooperative retrodirective action. When synchronized retrodirective action has been established the pilot tone can be switched off and mutual self-tracking communication is initiated. The base station retrodirective transceiver antenna transmits the signal with a vertical polarization and receives it in horizontal polarization. At the mobile unit, the signal is received in the vertical polarization and transmitted in horizontal polarization. Frequency offset and other array details are as discussed earlier in this paper. The frequency allocation for the base station and the mobile unit are given in Table III. This frequency allocation results in BPE correction in the case of the base station while positive BPE error adds in the case of mobile unit, actual values can be determined from Fig. 5. Here, a 10-MHz frequency offset is used between transmit and receive signals for



(a) (b)

Fig. 11. Measured radiation patterns for the communication links. (a) Measured received pattern at mobile unit. (b) Measured received pattern at base station.

TABLE III
FREQUENCY ALLOCATION FOR THE BASE STATION AND THE MOBILE UNIT

	Receive frequency (MHz)	Transmit frequency (MHz)
Base station	1000	990
Mobile unit	990	1000

two reasons. First, it is used to keep the additional BPE introduced due to frequency offset in the mobile unit to a minimum and second, it is used to maintain the transmit and the receive frequencies within the bandwidth of the microstrip patch antenna. Although not implemented in the prototype described here, the retransmitted signal from each unit can be suitably modulated to communicate information between the units.

Measurements on the link were obtained by keeping the base station stationary and moving the mobile unit around it in an azimuthal plane, as shown in Fig. 10(c). To evaluate the performance of the system, a reference measurement was also performed on the passive communication link with arrays oriented as per the passive configurations in Fig. 10(a) and (b).

Two different types of measurement were carried out on the communication links. In the first measurement, the mobile unit is moved in the azimuthal plane and has its nominal boresight facing radially inward [Fig. 10(a)]. In this situation, the measured receive/transmit radiation pattern is essentially the radiation pattern of the base station array. In the second measurement, the nominal boresight of the mobile unit was always kept parallel to the nominal boresight of the base station array [Fig. 10(b)]. In this situation radiation patterns of both arrays come into play and the resultant radiation pattern represents a multiplication of each respective array radiation pattern. Hence, in this case, the received power decreases rapidly as the array moves away from the boresight position. The measurement shown in Fig. 10(c) was carried out for the retrodirective link. In this case, although both the arrays have parallel relative movement at all azimuthal positions, because of retrodirective nature their transmit beams are locked to each other.

Fig. 11(a), shows the measured receive radiation patterns at the mobile unit and Fig. 11(b) at the base station. Here it can be seen that with the measurement performed on the retrodirective link [Fig. 10(c)] and the passive link [Fig. 10(a)], the results obtained are as expected almost identical. Similarly, in Fig. 11(b), identical results were obtained for the passive array Fig. 10(a) and the retrodirective array Fig. 10(c). Relative to the measurement in configuration in Fig. 10(b), configurations in Fig. 10(a) and (c) show a gain of 12 dB at $\pm 70°$ positions. This gain occurs because the power received for the passive link is the product of the multiplication of radiation patterns of the receive beam at the mobile unit and the transmit beam at the base station, both of which are that of a two-element passive array. In the case of retrodirective link, again, the received power is the product of radiation patterns of receive beam at the mobile unit and the transmit beam at the base station, but now the receive beam is that of a passive two-element array and the transmit beam is retrodirective in nature and remains relatively flat at all the azimuthal positions as if the transmitter was radially directed.

V. CONCLUSION

In this paper, a retrodirective antenna has been discussed that does not require circulator elements for incident and return signal isolation. Instead, isolation is produced by the antenna element and a frequency offset circuit. In addition, this frequency offset circuit is used to compensate for array pointing error to ensure best azimuthal gain flatness response. It is shown that the architecture of the retrodirective array can be modified to include an additional receive function, thus, such an array can be used in transceiver mode with the advantage of retrodirectivity on the transmit path. This use was demonstrated with the help of a prototype duplex communication link. It was shown that such a link allows the potential with far more freedom of movement for the communicating at a reduced power budget and with reduced multipath effects when compared to classical passive communication links. Such a structure has a variety of applications in mobile communications and transponder applications.

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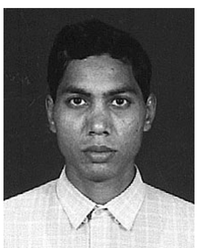

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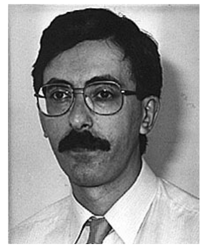

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