Retrodirective Antenna Systems for Wireless Communications

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ABSTRACT

This paper presents an overview of retrodirective antenna systems developed for use in wireless communications. This multiple antenna system automatically reflects incident radiation in the direction of the source radiator by re-transmitting the phase conjugate of the received signal at each antenna. The overall system behaves as a directional antenna with omni-directional coverage and allows tracking of fast moving targets. The standard approaches to implementing these systems are discussed along with their advantages and disadvantages. Additionally practical design considerations are presented with recommendations for areas of future research.

Categories and Subject Descriptors

A.1 [**Introductory and Survey**]

General Terms

Performance, design.

Keywords

Retrodirective, transceiver, RF, smart antenna.

1. INTRODUCTION

With the availability of inexpensive devices using radio frequency the electromagnetic spectrum has become increasingly congested. Generally these mobile devices radiate energy in all directions so as to maintain a good quality of service.

Directional antenna systems can be built using more than one antenna by individually modifying the phase of signals received or transmitted. Spatially when in-phase these signals add constructively and when out of phase add de-constructively. The corresponding interference pattern is the antenna radiation pattern.

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Directing a signal in a desired spatial region effectively increases the signal to noise ratio of the system by reducing interference from/with other users of the radio spectrum and also interference due to multipath effects. A directional antenna system could also support spatial division multiple access, allowing for more users. Additionally, using more than one antenna element allows for lower transmit powers from each channel which eases design requirements and improves reliability.

To be implemented in a mobile environment the directional antenna of a transceiver must be able to continually track and focus energy on the source of the relevant received signal. A retrodirected signal is a re-transmitted version of the received signal and is directed toward the received signal's source. This is achieved by re-transmitting a signal whose carrier phase is the conjugate of the received carrier phase at each antenna element.

Consider a path in free space from a source transmitter to a receiver of length d. The phase of the signal arriving at the receiver: $\varphi_{rx} = (2\pi d)/\lambda$ rad. By retransmitting a signal with the conjugate phase ($\varphi_{tx} = -\varphi_{rx}$) the signal will be in phase with the transmitted signal at the source. By sampling the source transmission in space, by using *n*-receive antennas, *n*-retransmitted signals will be in phase at the source and add constructively. At other points in space the signals will not necessarily add. This system is therefore effectively focusing energy on the source.

A phase conjugator is relatively simple to construct without the need for computationally intensive algorithms or hardware based phase shifters. The formation of the retrodirected beam is limited in that it is directed only toward the source radiator however it achieves this with no knowledge of the source location and its simplicity allows the array to track fast moving sources. More traditional beam formers using relatively complex algorithms to determine antenna patterns are slower and more expensive to implement than the retrodirective system but have more flexibility over the antenna pattern created.

In a retrodirective system each channel is independent which implies that the system cannot determine from where a received signal originates. Without this information the system cannot allow for spatial division multiple access however this independence allows for arbitrary array element placement.

2. RETRODIRECTIVE TOPOLOGIES

2.1 Passive Arrays

Two well known passive phase conjugators are the corner reflector and the Van Atta array [1].

The corner reflector is constructed by placing two reflectors perpendicular to each other. This construction is used extensively for reflectors of visible light such as those used for road markings.

The Van Atta array is similar and is constructed using a linear array of reflectors interconnected by equal lengths of transmission line. Consider a plane wave incident on this array. The signals travel through the transmission lines and are re-radiated. Provided the array is linear and the lines are of equal length, the re-radiated signal will have the reverse phase of the incident signal and will be retro-reflected. This is shown in Figure 1.

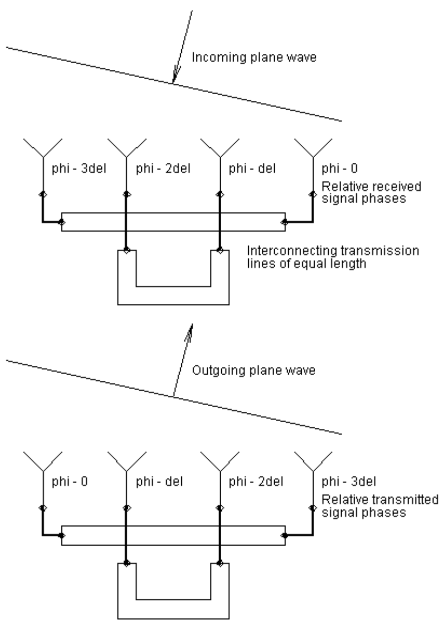

Figure 1: Van Atta array relative phase for received and transmitted signals

2.2 Heterodyne Based Arrays

A second method of achieving phase conjugation uses heterodyne mixing techniques.

Consider a carrier signal with no message content. The signal can be represented as $\cos(\omega_{RF}t + \phi_g(t))$ where $\phi_g(t)$ represents the geometry phase information derived from the spatial location of the antenna. This signal is multiplied by a local oscillator at twice its frequency. Ignoring amplitude considerations the following signals are obtained.

$$\cos(\omega_{RF}t + \phi_g(t))\cos(2\omega_{RF}t) = \cos(\omega_{RF}t - \phi_g(t)) + \cos(3\omega_{RF}t + \phi_g(t)) \quad (1)$$

By transmitting the difference product a retrodirected signal is formed. This is shown in Figure 2

Now consider a system that uses an intermediate frequency. The signal is first down-converted to the IF using a low side LO.

$$\cos(\omega_{RF}t + \phi_g(t))\cos(\omega_{RF-IF}t) = \cos(\omega_{IF}t + \phi_g(t)) + \cos(\omega_{2RF-IF}t + \phi_g(t)) \quad (2)$$

The IF is then up-converted back to the RF using a high side LO.

$$\cos(\omega_{IF}t + \phi_g(t))\cos(\omega_{RF+IF}t) = \cos(\omega_{RF}t - \phi_g(t)) + \cos(\omega_{RF+2IF}t + \phi_g(t)) \quad (3)$$

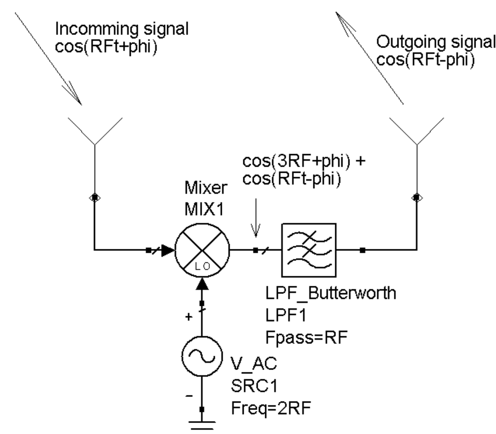

Figure 2: Heterodyne based retrodirective array element using an LO at twice the frequency of the incoming signal

The retrodirected signal is formed by transmitting the low side mixing product. This is shown in Figure 3.

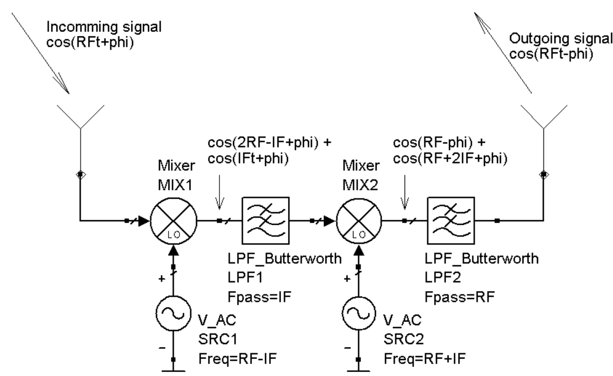

Figure 3: Heterodyne based retrodirective array element using an IF

A retrodirected signal can also be formed without the need for separate high and low side LOs by conjugating the IF signal directly. The IF is phase locked in this method to the RF carrier using a phase locked loop. By sampling the voltage control line to the IF voltage controlled oscillator, negating this, and using this to control a separate transmit IF VCO, a conjugated IF carrier is achieved.

3. DESIGN CONSIDERATIONS

3.1 Receive and Transmit Isolation

A retrodirective system is designed to operate with equal receive and transmit frequencies. If the frequencies are different then the conjugate of the received signal will no longer produce a transmitted signal directed at the received source. Heterodyne systems must also use some method of filtering to ensure that the received and transmitted signals do not influence each other and effect the phase conjugation. Various methods can be used to implement this filtering. Common methods use minimal frequency offsets, orthogonal polarizations [2] or directional couplers [3] to separate the received and transmitted signals.

3.2 Modulation

Passive retrodirective arrays re-radiate, without modifying, incident radiation. Consider this array moving with respect to the source radiator. This dynamic system will modulate the re-radiated signal and alter its phase information however this is the only modification of the signal. This system cannot be used to transmit information which is independent of the relative motion of the array.

Heterodyne retrodirective arrays using an LO at twice the frequency of the incoming radiation also re-transmit the original signal. Additional information can be re-transmitted by modulating the LO and makes this implementation useful for RFID applications [4].

To receive and transmit information independently of the array geometry the receiver must recover separately the incident carrier phase due to the array geometry and the modulation used to encode the desired information. A heterodyne based system using an IF can achieve this using a carrier recovery scheme. Most radio systems are improved by using coherent demodulation. Carrier recovery schemes are therefore often used in these receivers and can be adapted to be used in a retrodirective implementation.

Consider a received signal containing a message encoded using a phase modulation technique. If the array is moving relative to the source signal this will phase modulate the carrier and the geometry phase will have a frequency component. The relative motion of the array therefore places a lower limit on the bandwidth of the message phase modulation. Depending on the overall system the geometry phase can contain frequency components in excess of a few kHz [5]. A carrier recovery scheme used for a retrodirective system must be able to track these geometry phase changes.

From the above discussion it should be noted that the ability of the system to modulate the RF signal determines the complexity of the phase conjugator.

3.3 Phase Conjugation

Retrodirectivity is achieved by re-transmitting the conjugate phase of the incident signal. Each channel must therefore have an identical phase shift and any difference in phase shift from channel to channel will affect the radiation pattern of the array.

Additionally as the array increases in size phase balance becomes more critical as the array is capable of forming a narrower beam. When designing the array one must determine an acceptable phase difference between channels and, using this as a basis, design each channel taking into consideration appropriate tolerances.

Passive arrays require equal transmission line lengths and a symmetrical array. Due to the limited number of components in the passive array it is relatively easy to maintain a reasonable phase balance between channels. Heterodyne based arrays require more complicated RF circuitry and phase balance between the channels becomes more difficult to maintain especially as the operating frequency increases. For example at 2.5GHz a 1mm length of coplanar waveguide on a fiberglass substrate has a five degree phase shift. Additionally if lumped element components are used at such frequencies placement tolerance may become critical. These systems may require some form of phase compensation circuitry and an initial calibration during production.

3.4 Antenna Radiation Pattern

Each array element in a passive retrodirective array is dependent on all other elements. These arrays must therefore be fixed and this places limitations on the placement of the array and the radiation pattern which can be formed. Additionally this system requires a plane wave signal incident on the array for optimum retro-reflection.

For heterodyne based retrodirective systems each channel is independent. Therefore there is no restriction on how the array is located and this allows for completely arbitrary antenna radiation patterns.

Figure 4 shows simulated radiation patterns from a single omni-directional antenna and a retrodirective array using 4 omni-directional antennas radiating ¼ the power and placed in a square configuration. The simulation places a source in space indicated by the cross-hairs. By placing the antenna array in two dimensions omni-directional coverage is possible with good directivity. If the array was placed only along one axis the antenna pattern would be symmetrical about this axis producing two beams, one directed at the source and the other the mirror image about the array axis.

4. FURTHER RESEARCH

The ability of the retrodirective transceiver to reduce multipath effects and fading requires further research. The majority of research on retrodirective systems typically details only the beam forming ability of the system using a single source [1], [3] or of multiple sources at different frequencies [6]. There has been some research on multipath effects [7] however the array's response to real-world, dynamic conditions should be investigated.

Recent research on retrodirective systems has also generally focused on the performance of a single retrodirective transceiver [8]. Further research is required to establish performance of a full radio link consisting of two retrodirective transceivers.

Further research is also required to determine the most economic method of integrating a retrodirective system into a commercial product.

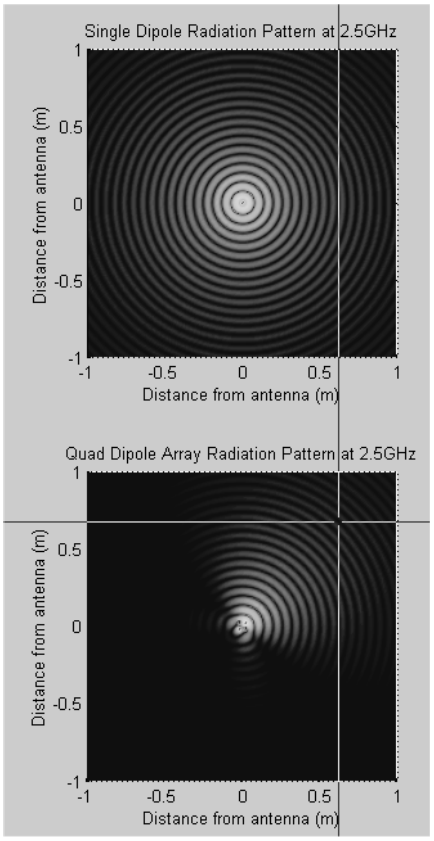

Figure 4: Single Dipole Antenna Pattern vs. Quad Dipole Retrodirective Antenna Pattern.

5. CONCLUSIONS

Retrodirective antenna arrays focus energy on the source of a received signal. This is achieved inherently by use of a phase conjugation element for each array element. The phase conjugation can be obtained relatively simply without the use of phase shifters or complex algorithms and therefore provides an inexpensive directional antenna array. For heterodyne based arrays each channel is independent and arbitrary array placement is possible.

The complexity of the phase conjugator is dependant on the system's ability to modulate the RF signal. A completely passive Van Atta array can be used if no modification of the signal is required however an IF based heterodyne system must be used for a full duplex communication link.

The beam forming ability of the array relies on identical phase shifts through each channel and the amount of phase error that can be tolerated depends on the number of antenna elements used. A commercially viable design must ensure that all sources of phase error (such as component placement tolerances) are kept within manageable limits.

Retrodirective systems have been built and exhibit beam forming abilities however additional research is required to determine their performance within a typical mobile wireless environment.

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