ABSTRACT

A phase conjugation based method for full-duplex digital communications is discussed. The method uses a spatially confined and directive antenna pattern while a full-duplex digital communications link is maintained between moving platforms. The communications ability of the array is based on processing the phase associated with the message and the phase associated with the platform's motion separately. Preliminary measurements at 6 GHz indicate that the phase conjugation method does allow simultaneous tracking and communications.

INTRODUCTION

Microwave phase conjugation (PC) as a technique for retro-directive communications was discussed as early as 1955 [1]-[6]. However, its use in communication systems has not been pervasive. One of the reasons seems to be the lack of a method for establishing a fully duplexed communications link. This problem is due to the difficulty of separating the received message-phase from the signal while still retaining the geometry-phase of the signal and doing this while simultaneously receiving, tracking, and transmitting. Any received RF signal used in communications will contain both the geometry-phase and message-phase. The geometry-phase has the information needed by the receiver to radiate a new signal back in the direction of the original signal source and is associated with the phase of the RF carrier at the receiving antenna. Hence, geometry-phase is a function of the distance, velocity, and accelerations of the platforms engaged in the communication. The message-phase is that part of the phase at the transmitter or receiver which encodes the information of interest. Hence, we are restricting our discussion to different forms of angle modulation.

Not all modulation methods are equal in their ability to allow for an implementation of the full-duplex communications link using microwave phase conjugation. In particular, the phase of the message may not be independent of the phase due to geometry. In the case of analog phase modulation (PM) or frequency modulation (FM), the power spectrum of the phase of a voice signal for example could overlap the power spectrum of the geometry-phase, resulting in difficulty in separating the two signals. However, if one could choose a modulation technique that separates the message-phase and the geometry-phase in frequency then it may be possible to use the message-phase to reconstruct the message and the geometry-phase to maintain retro-directivity through phase conjugation. A system based on BPSK signaling was chosen as the method of choice to experiment on this idea due to the completely digital way in which the geometry-phase and message-phase could be separated by appropriate coding of the data. By using BPSK signaling, the IF processing electronics can be designed to operate on the phase signal alone. In addition, the power efficiency advantages that are a fundamental property of constant envelope modulation techniques make this approach attractive.
A consequence that follows from this is that phase modulating all the array elements at the same time by a coding angle, say $\pm \pi/2$ radians, will not impact the retro-directivity property.

Various methods for producing phase conjugation and full duplexed communications are possible. As an example consider figure 3 which shows a simple phase conjugation cell [7]. The cell consists of a transmit / receive antenna element. Followed by a single mixer driven from an LO at twice the RF frequency. The mixer’s low-pass output frequency is therefore the same as its input frequency. The mixer not only takes the difference of the frequency, but more generally the difference of the phases of the RF and LO signals. Hence, conjugation is achieved to within an additive phase constant. Unfortunately, this method does not easily allow for full duplex communications since it is hard to process the phase at such high IF frequencies. As a result only retransmission of the original signal is practical, making this approach useful for transponders but not for full-duplex communications. To achieve the full-duplex function more elaborate phase processing must be used.

Figure 4 shows a diagram of a phase conjugation cell that uses an intermediate frequency. A BPSK modulated signal is received at a frequency and phase of $(f_{RF1}, \phi_{RF1})$ and down converted to an IF via the first mixer with a local oscillator at frequency $f_{LO1}$. Since it is possible, through data encoding, to separate the message-phase and the geometry-phase of the signal in the frequency domain then the signal phase can be filtered at the IF. This leaves an IF reference with only the geometry-phase remaining. The filtered IF signal is then remodulated with a new message during the up conversion process by superimposing the message on $\phi_{LO2}$. This up-conversion process will not destroy the conjugation of the input signal since the phases of the IF and second LO are added during up-conversion. The use of a low IF increases the noise in the phase conjugated signal but allows access to the phase at a frequency where phase filtering may be performed. In order to ensure that image frequencies will not be processed in the conjugation cell, single-side-band mixers were used.

Next consider the process of phase conjugation of a PM signal received from a moving platform. There are two stochastic processes that act upon the phase. The first is the random sequence of data symbols being clocked at a known symbol rate. This process may have memory depending on the data format used. The second random process that acts upon the phase is due to the relative position, velocity, and acceleration of the platforms communicating. The frequency response of the phase of the signal therefore is the linear superposition of the frequency response of the two processes. These processes will in general occupy the same range of frequencies unless an appropriate type of digital PM is used. Heuristically, it is understood that the low frequency response of the power spectral density (PSD) of the phase is due to the slower characteristic response times of platforms under mechanical dynamics. The high frequency response of the PSD would be centered at the symbol rate or an integer multiple of the symbol rate.

Fig. 2: Tracking of a single moving antenna by a PC array that is focusing its energy back to the source. The PC array is along the y-axis and the source is moving in the x-y plane (represented by the large dots).
(depending on the digital data format) and is a result of the act of sending a message alone. Since the symbol rate is usually large the resulting separation of the geometry phase and the message-phase is orders of magnitude in frequency. Phase filtering can then be performed by using a phase lock loop designed to work with random information bit sequences. Since the symbol rate is usually large the resulting separation of the geometry phase and the message-phase is orders of magnitude in frequency. Phase filtering can then be performed by using a phase lock loop designed to work with random information bit sequences.

The phase filtering is done with a Costas Phase Lock Loop (CPLL). A CPLL with a narrow band loop filter of only about 300 Hz open loop bandwidth was used to obtain a recovered carrier that will reject message-phase without regard to the message symbol statistics. Note that a CPLL is necessary since a uniform distribution of data “ones” and “zeros” that is transmitted with the BPSK data format would yield a signal with a suppressed carrier and no spectral component to lock onto. The CPLL avoids this problem through the use of in-phase and quadrature-phase detection in the PLL phase detector. In short the CPLL effectively acts as a low pass filter to the phase signal.

Conjugating the phase of the carrier will only ensure that the retransmitted signal is retro-directed. Hence, the operation of phase conjugating the signal will ensure that power is directed along the line of sight of the platforms only when both platforms are equipped with PC arrays. If optimum coherent processing of the received signal is also desired then the spatial direction of the receiving array factor, which is different than the transmitting array factor, will need to be adjusted. Under these conditions additional phase processing will be necessary in order for the receive array factor to also point in the direction of the other platform. This more complicated case is not being considered in this paper.

**DATA FORMAT**

In order to ensure that there was separation of the geometry-phase and the message-phase a coding scheme was developed that forces the signal to always be in a state of transition even when there is no data to send. This allows the communicating platforms to maintain synchronized symbol clocks by providing timing information at all times. Although more sophisticated techniques might be used this method was easy to realize in hardware. The data is bi-phase (bi-φ) encoded at the base band in order to realize these properties. The bi-φ signal is then differentially encoded to remove the intrinsic ambiguity of π radians that BPSK introduces. The data then has a guaranteed spectral component at twice the symbol rate or about 300 KHz without regard to signal symbol statistics and is differentially encoded, filtered, and upconverted from the 10 MHz IF for retransmission.

**EXPERIMENTS**

A twelve element phase conjugating conformal patch antenna array was built which is capable of reproducing complex curves such as might be found on the section of a wing of an aircraft, figure 5. The array has a center frequency of 5.99 GHz and is constructed on Rogers Duroid 5880. In the experiments described in this paper only four of these elements were used.
Single side-band mixers were designed for performing the phase conjugation process, an example of which is shown in figure 6. These SSB mixers had a conversion loss of about 10 dB and required 6 dBm of LO power. Measurements on the resulting array were performed for both a simple uniform linear geometry as well as various complex curves in order to ascertain the performance of conformal phase conjugating arrays.

To measure the phase and amplitude balance of each of the phase conjugation cells in the array, network measurements were performed as shown in figure 7. A network analyzer operating in CW mode was phase locked to two synthesized sources and the single side band mixers that comprise a phase conjugation cell were connected together through a simple phase modulator. The phase modulator was a double balanced mixer that was used as a phase shifter by applying a digital modulated diode voltage drop at the IF port. The measurements consists of looking at the $S_{21}$ response on two different paths. The measurement path contains a phase shifter and single-sideband mixers. The reference path contains only the phase shifter and a variable attenuator to balance the amplitudes of the two paths. The resulting transmissions through each path are compared as the phase shifter varies the phase. The incremental phase change provided by this phase shifter represents a change in the geometry of two communicating platforms. As the phase shifter adds delay to the RF source at port one of the network analyzer the reference signal moves along the upper arc in figure 8. The signal that passes through the mixers moves in the opposite direction along the bottom arc, this represents conjugation. In addition there was a low frequency BPSK signal modulated on the carrier but this 180 degree data has been suppressed for clarity in the figure. Note the phase-noise added in the conjugated (lower) data may become an issue as higher levels of integration are performed.

Individual characterization of each of the mixers and loop components to determine offset errors in amplitude and phase was performed so that calibration of the entire array could latter be performed for pattern and link measurements. A signal source and single patch antenna element at 5.99 GHz were placed in the far-field and made to move across the field of view of the array from about -20 degrees to + 20 degrees. The limit in angle being due to a relatively narrow measurement facility. The basic set-up is again as shown in figure 7 but with the one original element replaced by a four element linear array and multiplexed RF switch. The interelement spacing was about 0.9λ due to constraints of the support structure. Since measurement of an adaptive array pattern is complicated by the PC array always changing it's pattern to point in the direction of the signal source, the array pattern presented here was constructed by moving the source in the far-field of the array and then collecting the $S_{21}$ data for each cell through a network analyzer. The array factor was then synthesized by using the phase information from $S_{21}$ and was found to track the source as is shown in figure 9.
envelope of such a system.

REFERENCES

[7] C. Pobanz, I. Itho (Chair) "Time Varing Active Antennas, Circuits and Applications", PhD Dissertation at UCLA

Fig. 9: Measurements of a four element PC antenna measured with 0.9A interelement spacing. Pattern based on vector network analyzer measurements.

CONCLUSION

Phase conjugation as a method for full-duplex communication could provide a solution to the problem of tracking and communicating digitally on the move. This technique may be useful for covert communications or for reducing interference between a number communicating platforms that use the same frequency for communications due to the spatial focusing property of the array. However, more work needs to be done to establish the potential operational