Circular Polarization Modulation for Digital Communication Systems

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Abstract—Conventional approaches of digital modulation schemes make use of amplitude, frequency and/or phase as modulation characteristic to transmit data. In this paper, we exploit circular polarization (CP) of the propagating electromagnetic carrier as modulation attribute which is a novel concept in digital communications. The requirement of antenna alignment to maximize received power is eliminated for CP signals and these are not affected by linearly polarized jamming signals. The work presents the concept of Circular Polarization Modulation for 2, 4 and 8 states of carrier and refers them as binary circular polarization modulation (BCPM), quaternary circular polarization modulation (QCPM) and 8-state circular polarization modulation (8CPM) respectively. Issues of modulation, demodulation, 3D symbol constellations and 3D propagating waveforms for the proposed modulation schemes are presented and analyzed in the presence of channel effects, and they are shown to have the same bit error performance in the presence of AWGN compared with conventional schemes while provide 3dB gain in the flat Rayleigh fading channel.

I. INTRODUCTION

The concept of digital modulation by exploiting circular polarization is introduced in an active tagging system [1] in which an interrogator and a remote tag have a half duplex communication. Each of the orthogonal hands of circular polarization [2] represents an information bit as a modulation technique which simplifies demodulation process. The concept is extended to 4-state modulation in [3] where it is called CP-QPSK. I and Q streams without being summed traditionally in a QPSK modulator are fed to a dual fed microstrip patch antenna [6] resonant at 7.6 GHz to excite CP signals. As a fundamental requirement for the production of CP radiations, the feeds of the microstrip patch antenna need to be excited with sinusoids of equal magnitude of amplitude having a mutual phase difference of $\pi/2$ as an essential requirement [4]. The individual ports of the antenna will excite horizontal and vertical components of the generated circularly polarized electromagnetic wave (i.e. $\mathbf{E}_H$ and $\mathbf{E}_V$ respectively) as a result of spatial combination in the antenna far field [7].

Let us define sinusoidal functions $\mathbf{E}_{IP}$, $\mathbf{E}_{IN}$, $\mathbf{E}_{QP}$ and $\mathbf{E}_{QN}$ as ‘basis functions’ for the CP modulation as follows

$$\begin{aligned} \mathbf{E}_{IP} &= E_o \cos(2\pi f_o t) \\ \mathbf{E}_{IN} &= -E_o \cos(2\pi f_o t) \\ \mathbf{E}_{QP} &= E_o \cos(2\pi f_o t - \pi/2) \\ \mathbf{E}_{QN} &= -E_o \cos(2\pi f_o t - \pi/2) \end{aligned} \quad (1)$$

Figure 1. Rectangular coordinate representation of the basis functions of the CP modulation

The subscripts I and Q represent In-phase and Quadrature-phase components, while P and N represent positive or negative polarity with amplitude E_o and a frequency f_o . A pair of signals from the defining functions of (1), when fed to a dual fed microstrip patch antenna, will generate a CP signal out of 8 possible states with a unique set of phase shift and sense of polarization that could be exploited for BCPM, QCPM and 8CPM. We represent the basis functions in rectangular coordinate system as shown in Figure 1 which will be used in our later discussion for CP symbol constellations. Here I and Q represent the horizontal and vertical electric field components of propagating carrier.

We now define ‘Right hand Dot and Cross’ notation to represent CP symbols in 3D-constellations where a dot corresponds to left hand CP or counter-clock-wise (CCW) sense and a cross represents right hand CP or clock-wise (CW) sense. The CP symbol will be either *outward* or *into* the paper, indicated by the thumb of right hand while curling fingers in the direction of rotation described by the sense of CP as given in Table I. The phase angle of the generated CP signal will be the phase of axis coming first in this rotation.

TABLE I RIGHT HAND DOT AND CROSS NOTATION

Sense of CP	Symbol Representation	Thumb Direction
LHCP/CCW	Dot $\odot$	Outward the paper
RHCP/CW	Cross $\otimes$	Into the paper

Figure 2. Determination of Phase in CP symbol constellation

As an example, the phase angles of two arbitrary CP symbols in second and fourth quadrant of rectangular coordinate system are $\frac{\pi}{2}$ and 0 radian with CCW and CW sense of CP with a symbol representation of a dot and a cross, respectively as illustrated in Figure 2.

Figure 3. BCPM modulator

II. BINARY CIRCULAR POLARIZATION MODULATION (BCPM)

Figure 3 shows how the bi-state circular polarization modulation is implemented. It uses non-returning to zero, NRZ line coding scheme; to generate negative pulse for a bit '0' and a positive pulse for a bit '1', to feed one of the antenna ports while the other port is constantly fed with a positive level. The encoding scheme may be represented as Table II. Figure 3 shows that we have $\mathbf{E}_{IP}$ and $\mathbf{E}_{QN}$ for a bit '0' and $\mathbf{E}_{IP}$ and $\mathbf{E}_{QP}$ for a bit '1' which after amplification by high power amplifier (HPA) produces RHCP and LHCP signal, respectively.

For test bits 01001, the antenna feeds are plotted in Figure 4 which results in the generation of corresponding BCPM signals as shown in Figure 5. The BCPM symbol constellation is shown in Figure 6 in which orthogonal BCPM symbols are at 0° as determined by Right hand dot and cross notation.

TABLE II BCPM SYMBOL ENCODING SCHEME

Data bits	Encoded CP symbol	Electric field horizontal component	Electric field vertical component
0	RHCP	$E_o \cos(2\pi f_o t)$	$-E_o \cos(2\pi f_o t - \pi/2)$
1	LHCP	$E_o \cos(2\pi f_o t)$	$E_o \cos(2\pi f_o t - \pi/2)$

Figure 4. BCPM antenna feed signals for test bits 01001

Figure 5. BCPM signal for test bits 01001

Figure 6. BCPM Symbol constellation

III. QUATERNARY CIRCULAR POLARIZATION MODULATION (QCPM)

Table III illustrates the encoding scheme for QCPM which uses signals E_{IP} and E_{IN} as one of the feeds of the dual fed microstrip patch antenna, while E_{QP} and E_{QN} as the second feed with possible polarities providing 4 states of CP signal. The block diagram of QCPM modulator is given in Figure 7 in which incoming data bits are transformed into two parallel bit streams and then converted to bipolar signal level form using NRZ scheme and multiplied by orthogonal local oscillators (LO's) i.e. $E_o \cos(2\pi f_o t)$ and $E_o \cos(2\pi f_o t - \pi/2)$ in order to obtain required antenna feeds to generate a specific QCPM signal.

For test bits 00 01 10 11, the antenna feeds are plotted in Figure 8 which results in the generation of corresponding four QCPM signals as shown in Figure 9. The 3D symbol constellation for QCPM can be given using the Right hand dot and cross notation which shows symbols for dibits '11' and '10' are at 0° phase while for dibits '01' and '00' are at 180° phase values as represented in Figure 10.

TABLE III QCPM SYMBOL ENCODING SCHEME

Data bits	Encoded CP symbol	Electric field horizontal component	Electric field vertical component
00	180° shifted LHCP	$-E_o \cos(2\pi f_o t)$	$-E_o \cos(2\pi f_o t - \pi/2)$
01	180° shifted RHCP	$-E_o \cos(2\pi f_o t)$	$E_o \cos(2\pi f_o t - \pi/2)$
10	RHCP	$E_o \cos(2\pi f_o t)$	$-E_o \cos(2\pi f_o t - \pi/2)$
11	LHCP	$E_o \cos(2\pi f_o t)$	$E_o \cos(2\pi f_o t - \pi/2)$

Figure 7. QCPM Modulator

Figure 8. QCPM antenna feed signals for test bits 00 01 10 11

Generation of QCPM signals

Figure 9. QCPM signal for test bits 00011011

Figure 10. QCPM Symbol Constellation

IV. EIGHTSTATE CIRCULAR POLARIZATION MODULATION (8CPM)

The encoding of incoming tribits to respective 8CPM symbols can be performed as shown in Table IV where the phase angle of 8CPM signal will be 0° for tribits '010' and '011'; 180° for '000' and '001'; 90° for '101' and '111'; 270° for '100' and '110'. Figure 12 shows how the scheme can be implemented. Depending upon the MSB of the incoming tribit, the rest of the two bits would be directed to the upper or lower block of the modulator to have respective antenna feeds to generate the required 8CPM signal.

For test bits 000 001 010 011 100 101 110 111, the antenna feeds are plotted in Figure 12 which results in the generation of corresponding 8 QCPM signals as shown in Figure 13. Figure 14 shows 8CPM symbol constellation.

TABLE IV

8CPM SYMBOL ENCODING SCHEME

Data bits	Encoded CP symbol	Electric field horizontal component	Electric field vertical component
000	180° shifted LHCP	$-E_o \cos(2\pi f_o t)$	$-E_o \cos(2\pi f_o t - \pi/2)$
001	180° shifted RHCP	$-E_o \cos(2\pi f_o t)$	$E_o \cos(2\pi f_o t - \pi/2)$
010	RHCP	$E_o \cos(2\pi f_o t)$	$-E_o \cos(2\pi f_o t - \pi/2)$
011	LHCP	$E_o \cos(2\pi f_o t)$	$E_o \cos(2\pi f_o t - \pi/2)$
100	270° shifted RHCP	$-E_o \cos(2\pi f_o t - \pi/2)$	$-E_o \cos(2\pi f_o t)$
101	90° shifted LHCP	$-E_o \cos(2\pi f_o t - \pi/2)$	$E_o \cos(2\pi f_o t)$
110	270° shifted LHCP	$E_o \cos(2\pi f_o t - \pi/2)$	$-E_o \cos(2\pi f_o t)$
111	90° shifted RHCP	$E_o \cos(2\pi f_o t - \pi/2)$	$E_o \cos(2\pi f_o t)$

Figure 11. 8CPM modulator

Figure 12. 8CPM antenna feed signals 8 possible test tribits

Generation of 8CPM signals

Figure 13. 8CPM signal for 8 possible test tribits

Figure 14. 8CPM symbol Constellation

Figure 15. Demodulation scheme for CP modulation

Figure 16. Reference signal X convolved with the basis signals

Figure 17. Reference signal Y convolved with the basis signals

The reciprocity of a dual fed microstrip patch antenna enables us to regenerate horizontal and vertical components E_H and E_V respectively of received EM radiation for demodulation purpose. As depicted in Figure 15, these electric field components after amplification by a low noise amplifier (LNA) are convolved with reference signals, E_x and E_y such that $E_x = E_{IP}$ and $E_y = E_{QP}$. Figure 16 and 17 show continuous time signals obtained by the convolution of reference signals, i.e. X and Y with the defining signals respectively. The magnitude of central samples (say at 100 in Figs. 16 and 17) in the convolved waveform can act as *signature* in detection process. These two sets of *quad-signatures* are used by ML detector for estimation of data transmitted by seeking these signatures out of received signal to estimate the transmitted CP symbol based upon suitable thresholds in case of BCPM, QCPM or 8CPM.

VI. ANALYSIS IN THE PRESENCE OF CHANNEL EFFECTS

Matlab simulations of standard Monte Carlo technique [5] for the performance evaluation in terms of Bit Error Rate (BER) vs. Signal to noise ratio (SNR) were performed and compared with conventional Phase Shift Keying (PSK) scheme. The probability of bit error for BCPM in Additive White Gaussian channel (AWGN) was found close to the conventional BPSK. The simulations for bit error performance evaluation of BCPM in flat fading (FF) Rayleigh channel shows 3dB gain compared with BPSK due to inherent diversity of circular polarization as depicted by the plot of Figure 18.

Figure 18. Analysis of BCPM in AWGN and Flat fading channel

The paper presents a novel concept in the field of digital communication by exploiting circular polarization as a characteristic to modulate data. This is different from conventional approaches that modulate data using amplitude, frequency or phase of electromagnetic carrier as modulation attributes. Circular Polarization Modulations for 2, 4 and 8 states have been presented with thorough concept of symbol encoding, constellation, modulation, demodulation and the waveforms of the propagating carrier. The proposed CP-modulation techniques provide inherent benefits of circular polarization as well as diversity gain in fading channels.

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