Alamouti coding scheme and virtual array concept for joint radar and communication systems

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Abstract—This paper focuses on the integration of radar and communication (RadCom) systems on a common platform. We consider a scenario with multiple transmit and receive antennas, where the integration of the two functionalities is achieved through the use of Alamouti coding and OFDM waveform. It is shown that by using the Alamouti coding scheme, the spatial diversity order is improved as in legacy communication systems, which has a favorable impact on the bit error rate (BER). Furthermore, as the Alamouti code is an orthogonal code the radar’s angle resolution is improved through the use of the virtual array concept.

Index Terms—Alamouti coding, OFDM, Radar, Communication, RadCom, convergence, MIMO

I. INTRODUCTION

Wireless communication and radar systems have been historically designed and developed in total isolation from one another. Although, both systems share similar features that can promote systems handling the trend towards less exclusionary spectrum policies and interference [1]. Nowadays, the scarcity of the radio spectrum is becoming a problem for the telecommunication sector, leading to the study of new manners for coexistence [2]. Joint radar and communication systems (RadCom) stands as one of the paradigms candidate endeavoring to achieve more efficient use of the radio spectrum, relieving the problem of scarcity.

The idea of combining these two systems in one is not new. However, finding practical RadCom systems is not usual. NASA Space Shuttle “Orbiter” is one of the rare cases, it could switch between radar and communication functionalities but not complete both at the same time [3]. Finding a suitable waveform represents a fundamental challenge to achieve functional joint radar and communications systems. Several approaches rely on embed information into well-known radar waveforms [4] [5] to converge both functionalities into a single platform. These schemes share the drawback of low data rates for the communication function as shown in [6], where data rates are limited to 100 kbps, which corresponds to the pulse repetition frequency (PRF) only.

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Other approaches rely on the use of communication waveforms to achieve such a convergence. In [7], the direct sequence spread spectrum (DSSS) waveform is employed, taking advantage of its good correlation properties, while [8] represents the first attempt to use orthogonal frequency-division multiplexing (OFDM) waveform for RadCom systems. Data dependency, which is inherent to the OFDM waveform, negatively influences the correlation properties of this waveform, which can be catastrophic for proper targets unambiguous ranging. A huge step seeking to relieve this effect was taken in [9], where the data dependency is removed by performing an element-wise complex division between the received signal and the transmitted symbols. More recently, [10] addresses the principles of OFDM waveform for radar processing, with particular focus on the Long Term Evolution (LTE) networks. Spectrum scarcity and the constant need for higher bandwidth has led to the study of new waveforms, this time in the millimeter-wave (mmWave) part of the spectrum as in [11] [12].

A system running both functionalities on a common hardware platform can result in a more efficient architecture in terms of spectral efficiency, prices and performance. Besides, a functional convergence between radar and wireless communication systems will pave the way and bring benefits for foreseen technologies like Intelligent Transportation Systems (ITS) [13], Internet of Things (IoT) [14] and many others.

This paper considers a scenario consisting of a monostatic RadCom terminal transmitting information, in millimeter-wave bands, towards one user’s equipment [15]. The combination of radar and communication systems is achieved by adopting OFDM as a waveform. The use of the Alamouti coding scheme improves the performance of the communication system, due to the spatial diversity obtained from the use of several antennas. Besides, given the orthogonality between the transmitted signals, the angular resolution of the radar is enhanced.

The remainder of this paper is organized as follows: Section II defines the system model for the RadCom transmitter, communication receiver processing and the radar processing required to estimate target parameters. Section III is devoted to the performance results for RadCom systems regarding BER and radar imaging. Finally, section IV concludes the proposal addressed in this paper.

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II. SYSTEM MODEL

As illustrated in Fig. 1, it is considered a RadCom access point that transmits a common waveform. The signal conveys information towards the user equipment, equipped with a single antenna.

At the same time, the signal is reflected from targets within the coverage area. The echoes, resulting from the impact of the transmitted signal with objects in the environment, are received by the monostatic RadCom transceiver, which through signal processing detects the presence of targets. The modulation scheme is well known by the receiver terminal, while the radar receiver perfectly know the transmitted signal. The orthogonality enables a virtual array comprised of 1 × PQ antennas, where P and Q represent the number of physical transmitter and receiver antennas. A virtual array is a technique where the number of virtual receiver antennas becomes more than the physical number of receiver antennas through a proper selection of antennas distribution and employing signal processing [16].

A. RadCom Transmitter

Consider a RadCom system with two transmitting antennas, spacing by a distance of \( Q \lambda /2 \), where \( Q \) represents the number of receiving antennas and \( \lambda \) the wavelength. To enhance the diversity order achieved, it is implemented the well-known Alamouti space-time coding scheme. The orthogonality enables a virtual array comprised of 1 × PQ antennas, where \( P \) and \( Q \) represent the number of physical transmitter and receiver antennas. The coding matrix for subcarrier \( k \) and block \( l \) is

\[
C_{k,l} = \begin{bmatrix}
c_1(k,l) & c_2(k,l) \\
-c_2^*(k,l) & c_1^*(k,l)
\end{bmatrix},
\]

with \( k = \{0, \ldots, N - 1\} \), \( l = \{0, \ldots, M - 1\} \). Column 1 (2) of matrix \( C_{k,l} \) corresponds to the signal to be transmitted on antenna 1 (2). After the STBC block, an IFFT operation is performed, then a cyclic prefix (CP) is added to avoid intersymbol interference (ISI).

B. Communication terminal

Consider a communication device with one receiving antenna located within the coverage area of the RadCom transmitter. We aim to recover the original data sent from the RadCom system. Fig. 3 illustrates the scheme of the communication terminal considered.

Assuming the coherence time of the channel is higher than the duration of two consecutive OFDM symbols, the received signal model at the communication device for two consecutive symbols after removing the CP and performing the FFT operation can be expressed as

\[
r_{k,l} = C_{k,l} h_{k,l} + n_{k,l}
\]

where \( r_{k,l} \) denotes the OFDM received signal, \( h_{k,l} \) the channel frequency response between the two transmitting antennas and the single receiving antenna and \( n_{k,l} \sim \mathcal{CN}(0, N_0 I) \) denotes white Gaussian noise. The soft decision of \( c_{k,l} = [c_1(k,l), c_2(k,l)]^T \) is obtained by performing the operation

\[
\bar{c}_{k,l} = H^H_{k,l} r_{k,l}
\]

where \( H_{k,l} = [h_{k,l}(1), h_{k,l}(2); h_{k,l}^*(1), -h_{k,l}^*(2)] \) and \( r_{k,l} = [r_{k,l}(1), r_{k,l}^*(2)]^T \).

Substituting (2) into (3), the next relation is obtained, where is easy to see that the ISI is completely removed,

\[
\bar{c}_{k,l} = \| h_{k,l} \|^2 c_{k,l} + H^H_{k,l} n
\]

The equality (4) follows from the equality \( H^H_{k,l} H_{k,l} = \| h_{k,l} \|^2 I \)

C. Radar terminal

Consider a radar configuration consisting of a transmit antenna array composed of two antennas and a receive uniform antenna array with \( Q \) antennas with an inter-antenna distance of \( \lambda /2 \). The received signal model at the \( q \)-th receiving antenna, for sub-carrier \( k \) and block \( l \), is given by

\[
r_{k,l}^q = C_{k,l} h_{k,l}^q + n_{k,l}
\]

where \( r_{k,l}^q \) denotes the OFDM received signal, \( h_{k,l}^q \) the channel frequency response between the two transmitting antennas and the single receiving antenna and \( n_{k,l} \sim \mathcal{CN}(0, N_0 I) \) denotes white Gaussian noise.
At the radar terminal the objective is to recover the channel matrix \( \tilde{H}_{k,l} = [\tilde{h}_{k,l}^1, \cdots, \tilde{h}_{k,l}^Q] \). The channel relative to antenna \( q \) may be estimated as,

\[
\tilde{h}_{k,l}^q = C_k^H R_{k,l}^q = h_{k,l}^q + C_k^H n_{k,l}^q
\]  

where the last equality follows from \( C_k^H C_{k,l} = I \). Therefore, follows that

\[
\tilde{H}_{k,l} = C_k^H R_{k,l} = H_{k,l} + C_k^H N_{k,l}
\]

where \( R_{k,l} = [r_{k,l}^1, \cdots, r_{k,l}^Q] \) and \( N_{k,l} = [n_{k,l}^1, \cdots, n_{k,l}^Q] \).

Let us define the vector \( a_{k,l} = \text{vec}(\tilde{H}_{k,l}) \), where the operator \( \text{vec}() \) vectorizes the input matrix column by column, then assuming a target at an azimuth angle of \( q \), a range \( R \) and a speed \( v \) the entry \( p \in \{0, \cdots, 2Q - 1\} \) of vector \( a_{k,l} \) is

\[
a_{k,l}(p) = e^{j2\pi f_0 T_0 e^{-j2\pi k \Delta f e^{-j2\pi p \phi}}}
\]  

where \( f_D = 2v/\lambda \) denotes the Doppler frequency, \( \tau = 2R/c_0 \) the delay, \( \phi = \sin(\theta) \) the electrical angle, \( T_0 \) the OFDM symbol duration, \( \Delta f \) the sub-carrier spacing and \( c_0 \) the speed of light. Therefore, from \( \tilde{H}_{k,l} \) follows \( \tilde{a}_{k,l} = \text{vec}(\tilde{H}_{k,l}) \) where entry \( p \) is \( \tilde{a}_{k,l}(p) \). The channel response \( a_{k,l} \in C^{2Q} \) is identical to the channel response of a system with one transmitting antenna and a uniform linear array with \( 2Q \) receiving antennas with an inter-antenna distance of \( \lambda/2 \). This \( 2Q \) - element array is the virtual antenna array, which is obtained with just \( 2 \cdot Q \) physical antenna elements.

Accordingly to (8) the target parameters may be estimated by performing an DFT or IDFT along the three dimensions \((k,l,p)\). The IDFT performed along the \( k \) dimension provides an estimative of the range, the DFT along the \( l \) dimension an estimative of the velocity and and the IDFT along the \( p \) dimension provides an estimative of the electrical angle (target angle).

**III. PERFORMANCE RESULTS**

In this section, the performance of the RadCom system proposed is evaluated and compared with the situation where there is only one transmitter antenna \((P = 1)\). The limiting properties of the channel are the Doppler spread and the maximum delay. The radar cross-section (RCS) of targets is not taken into account. For this system, we present the average maximum delay. The radar cross-section (RCS) of targets is \( \frac{1}{Q^2} \). The system parameters are chosen to fulfill a set of design criteria as, maximum unambiguous range \( R \) and range resolution \( \Delta r \). The system operates at \( f_c = 24 \) GHz ISM mmWave band, which has been used for research purposes as it is deregulated. To be able to detect targets in at least 1500 m, the maximum unambiguous range is defined by

\[
R = \frac{c_0}{2\Delta f} = \frac{T c_0}{2}.
\]

where \( T \) denotes the OFDM symbol duration, defining \( T = 11 \) \( \mu s \) a maximum unambiguous range of \( R = 1650 \) m is obtained. The range resolution is given by

\[
\Delta r = \frac{c_0}{2B},
\]

where \( B \) denotes the system bandwidth, since we need to ensure high data rates and good range resolution, the number of sub-carriers is set to \( N = 1024 \). Since \( \Delta f = 1/T \), a bandwidth of \( B = 93.1 \) MHz is required, resulting in a range resolution of \( \Delta r = 1.61 \) m. These and other radar parameters are summarized in Table II.

First, it is shown in Fig. 4 the radar image obtained in the case where there is one transmitter antenna \((P = 1)\), and ten receiver antennas \((Q = 10)\), considering scenario A.

The radar image, now for two transmitter antennas \((P = 2)\) and Alamouti coding scheme, are shown in Fig. 5 and 6 for the scenarios described in Table I.

![](image.png)

**TABLE II**

Radar Specifications: RadCom system.

| Parameter                        | Value   |
|----------------------------------|---------|
| Unambiguous range \( R \)         | 1650 m  |
| Range resolution \( \Delta r \)  | 1.61 m  |
| Velocity Resolution \( \Delta v \)| 2.22 m/s |
| Number of subcarriers \( N \)    | 1024    |
| Subcarriers spacing \( \Delta f \)| 90.09 kHz |
| Number of OFDM symbols \( M \)  | 256     |

**FIGURE 4**

Radar image obtained for one transmitter antenna \((P = 1)\) and ten receiver antennas \((Q = 10)\), scenario A and Radar Specifications in Table II.

The radar image, now for two transmitter antennas \((P = 2)\) and Alamouti coding scheme, are shown in Fig. 5 and 6 for the scenarios described in Table I.

It can be noticed from the Fig.4 and Fig. 5 how the angle resolution obtained for the case of two transmitter antennas outperforms the case of one transmitter antenna when maintaining the same number of receiver antennas. This is because the resolution of the electrical angle \( \varphi \) is proportional to \( 1/PQ \).
From Fig. 7 is possible to see that as in legacy wireless communication systems the use of two antennas transmitting orthogonal signals bring with an improving in the BER performance. As can be noticed, the slope of $2 \times 1$ MISO-OFDM Alamouti is larger than that one of Rayleigh SISO-OFDM, this is due to the diversity gain of 2 that $2 \times 1$ MISO-OFDM Alamouti system can achieve compared to SISO system that has a diversity order of 1.

IV. CONCLUSIONS

In this paper, the combination of radar and communication systems on a common platform is achieved by using Alamouti coding scheme, and OFDM as the chosen waveform. It was shown that the Alamouti coding scheme allows the achievement of spatial diversity, for the communication functionality, while improving angle resolution for the radar functionality by means of the virtual array concept. The flexible allocation of carriers was one of the motivation for choosing OFDM as the most suitable waveform. These scenarios represent the basis for future research, in which the use of more than two transmitting antennas can be accomplished by using other codes, even going to the implementation of massive multiple-input multiple-output (mMIMO).

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