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Dedicated to the memory of Academician Andrei Ţugulea

A NOVEL DIFFERENTIAL SPACE-TIME FULL-RATE BLOCK CODING FOR INTER-VEHICULAR COMMUNICATION

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The extended-Alamouti space-time block code is full-rate like the celebrated Golden code and it can be used for differential modulation like the Alamouti's scheme, which is only half-rate. It is thus fit to use for inter-vehicular communications over rapidly varying mobile channels, since its differential version does not require channel state information (CSI) to be known at the receiver. Both transmitter and receiver are each equipped with two antennas. A differential encoding scheme is used across two consecutive 4D symbol intervals. Each entry of the 2x2 transmit matrix simultaneously carries two 2D symbols taken from a phase-shift keying (PSK) signal constellation and they are separated by irrational coefficients in a novel way to be revealed in the body of the paper. No knowledge of the channel state information (CSI) is required. Noncoherent demodulation is applied at the reception. The performance of the differential extended-Alamouti space-time block code is evaluated by way of computer simulations and compared with that of differential Alamouti. Finally, using the new code for inter-vehicular communication is proposed with confidence.

1. INTRODUCTION

The vehicular industry is ever keenly interested in improved coding and modulation techniques for inter-vehicular communications [1, 2]. For advanced applications like the Internet of vehicles, larger bandwidth efficiencies are required [3]. To improve the reliability of mobile communications, antenna diversity at both transmit and receive ends is already a common practice. A well-known and proven 2×2 space-time block code is Alamouti's [4]. This is a half-rate space-time block code since it transmits two 2D symbols in two consecutive channel uses with two transmit antennas. A much celebrated full-rate space-time block code is the Golden code that transmits four 2D symbols in two consecutive channel uses [5–7]. Sphere decoding is frequently used at the reception [8, 9]. In [10], the decoding complexity of Golden code is tackled through a suitable modification such that a less complex sphere decoder is used without much compromising the error rate. In [11], a method is given to improve the performance of the Golden code by using octagonal reconfigurable orthogonal element (ORIOL) antennas instead of a conventional microstrip patch antenna. In [12], a performance comparison of Golden and Silver codes is made using sphere decoding. In [13], the performance of Golden code is compared to that of Spatial Division Multiplexing in a Bit Interleaved Coded Modulation – MIMO system. It is a well-known fact that the Alamouti's scheme can be used for differential modulation, while this is not possible for the Golden code. If the speed of the communicating vehicle is high, it may not be possible to use a coherent demodulation at the receiver. This means that we should look for a noncoherent transmission scheme. Vehicular communication helps in providing safer road conditions and road efficient driving. The inter-vehicular communication takes place in a very dynamic and mobile environment and is exposed to interference, shadowing and Doppler's effects. The vehicular communication requires flexibility against the mobility of the vehicles and the network. Therefore, new and improved wireless transmission techniques are welcome.

In this paper, we propose a differential space-time block coding dubbed extended-Alamouti. A wireless mobile communication system equipped with two transmit antennas and two receive antennas is considered. It is intended to transmit a string of symbols $s_0, s_1, \ldots, s_{2n}, s_{2n+1}, \ldots$ taken from a 2D signal constellation like phase-shift keying (PSK). Then a first antenna transmits s_{2n} and s_{2n+1} in two consecutive channel uses $2n$ and $2n+1$, where $n = 0, 1, 2, \ldots$. The Cartesian product of a 2D signal constellation by itself may be viewed as a 4D signal constellation, such that a two-tuple of 2D consecutive symbols s_{2n} and s_{2n+1} form a 4D symbol, indexed by n. It is customary to represent the operation of the transmitter with the help of a transmit matrix. An instance of Alamouti matrix is as follows [4]:

$$\boldsymbol{A}_n = \begin{pmatrix} s_{2n} & -s_{2n+1}^* \\ s_{2n+1} & s_{2n}^* \end{pmatrix} . \tag{1}$$

In (1), the asterisk denotes complex-conjugation. The second transmit antenna sends $-s_{2n+1}^*$ and s_{2n}^* in two consecutive channel-uses $2n$ and $2n+1$, respectively. Another instance of Alamouti matrix is obtained by shifting the minus sign from the first row to the second row, but in what follows we do not need this one. Clearly, the two rows of (1), as well as the two columns of it, are orthogonal. Moreover, if the 2D symbols are normalized such that $|s_{2n}|^2 + |s_{2n+1}|^2 = 1$, then (1) becomes a unitary matrix, that is

$$\boldsymbol{A}_n \cdot \boldsymbol{A}_n^H = \boldsymbol{A}_n^H \cdot \boldsymbol{A}_n = \boldsymbol{I}_2 \ . \tag{2}$$

In (2), $\boldsymbol{A}_n^H$ is the Hermitian (that is, complex-conjugate transpose) of $\boldsymbol{A}_n$. The Alamouti matrix (1) has very useful properties, for instance, it can be used for differential encoding, but it is only half-rate. The Golden code has a transmit matrix that is full-rate [5–7]:

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$$\boldsymbol{G}_n = \frac{1}{\sqrt{5}}\begin{pmatrix} \alpha(v_{2n}+\theta w_{2n}) & i\beta(v_{2n+1}+\overline{\theta} w_{2n+1}) \\ \alpha(v_{2n+1}+\theta w_{2n+1}) & \beta(v_{2n}+\overline{\theta} w_{2n}) \end{pmatrix}. \quad (3)$$

In (3), $\theta = \frac{1+\sqrt{5}}{2}$, $\overline{\theta} = \frac{1-\sqrt{5}}{2}$, $i^2 = -1$, $\alpha = 1 + i\overline{\theta}$, $\beta = 1 + i\theta$. The matrix $\boldsymbol{G}_n$ is full-rate since four 2D symbols v_{2n}, v_{2n+1}, w_{2n} and w_{2n+1} are transmitted out of the two antennas in two channel uses. Yet it is not a unitary matrix and thus cannot be used for differential encoding. However, differential encoding is applied when the mobile channel is highly variable and cannot be measured in real time. In such a case, only noncoherent demodulation is possible. The Alamouti matrix has been used with differential encoding in [14] and [15]. But it is only half-rate and we would like to have a full-rate matrix like the Golden code. In [16] and [17], it is shown using a testbed and also theoretically that the Golden code doesn't work properly if the distance between the two transmit antennas equals λ/3 or less. In contradistinction to the Golden code, the Alamouti code, while only half rate, keeps having a good performance to such small distance between the transmission antennas.

The rest of the paper is organized as follows. Differential Alamouti space-time block coding is briefly reviewed in Section 2. Our main contribution, the full-rate differential extended-Alamouti space-time block code, is introduced in Section 3. An illustrative example is then developed in Section 4. Concluding remarks are given in Section 5.

2. DIFFERENTIAL ALAMOUTI TRANSMISSION

For absolute transmission, that requires knowledge of the channel state information (CSI) at the receiver, one could use a matrix [4]

$$\boldsymbol{U}_n = \begin{pmatrix} u_{2n} & -u_{2n+1}^* \\ u_{2n+1} & u_{2n}^* \end{pmatrix}. \quad (4)$$

Instead, we use for transmission the matrix

$$\boldsymbol{M}_n = \begin{pmatrix} s_{2n} & -s_{2n+1}^* \\ s_{2n+1} & s_{2n}^* \end{pmatrix}. \quad (5)$$

In (5), s_{2n} and s_{2n+1} are symbols belonging to a PSK signal constellation which are normalized by $\sqrt{2}$ in order to have the same transmit energy as in the case of a single transmit antenna. Gray coding is used to map the selection bits on the points of the signal constellation. The encoding equation is as follows:

$$\boldsymbol{M}_n = \boldsymbol{U}_n^{\mathrm{T}} \cdot \boldsymbol{M}_{n-1}. \quad (6)$$

From (6), we easily obtain:

$$s_{2n} = u_{2n} \cdot s_{2n-2} + u_{2n+1} \cdot s_{2n-1}, \quad (7)$$

$$s_{2n+1} = u_{2n}^* \cdot s_{2n-1} - u_{2n+1}^* \cdot s_{2n-2}. \quad (8)$$

Conversely, we have:

$$u_{2n} = s_{2n-1} \cdot s_{2n+1}^* + s_{2n} \cdot s_{2n-2}^*, \quad (9)$$

$$u_{2n+1} = s_{2n-1}^* \cdot s_{2n} - s_{2n-2} \cdot s_{2n+1}^*. \quad (10)$$

Note that a price to be paid for differential modulation is that a first reference symbol, which carries no user information, should be additionally transmitted at the beginning of every frame.

The Golden code has excellent performance provided that there are two receive antennas [5]. Therefore, we also consider a 2×2 multiple-input multiple-output (MIMO) communication system. Denote the channel gain at the *k*th receive antenna from the *j*th transmit antenna by h_{kj}, where *k*, *j* = 1, 2. The channel gains are constant on a frame, but vary randomly from frame to frame. We then have

$$r_{2n-2}^{(k)} = h_{k,1} \cdot s_{2n-2} - h_{k,2} \cdot s_{2n-1}^* + z_{2n-2}^{(k)}, \quad (11a)$$

$$r_{2n-1}^{(k)} = h_{k,1} \cdot s_{2n-1} + h_{k,2} \cdot s_{2n-2}^* + z_{2n-1}^{(k)}, \quad (11b)$$

$$r_{2n}^{(k)} = h_{k,1} \cdot s_{2n} - h_{k,2} \cdot s_{2n+1}^* + z_{2n}^{(k)}, \quad (11c)$$

$$r_{2n+1}^{(k)} = h_{k,1} \cdot s_{2n+1} - h_{k,2} \cdot s_{2n}^* + z_{2n+1}^{(k)}. \quad (11d)$$

In equations (11), $r_m^{(k)}$ and $z_m^{(k)}$ are the complex-valued signal received by antenna *k* and the noise component, respectively, at the discrete time *m*, where *k* = 1, 2. Note that while the terms $r_m^{(k)}$ are measurable quantities, the noise terms $z_m^{(k)}$ are not so. Now, looking at (9) and (10), we define

$$R_1 = \sum_{k=1}^{2}\left(r_{2n-2}^{(k)*} \cdot r_{2n}^{(k)} + r_{2n-1}^{(k)} \cdot r_{2n+1}^{(k)*}\right), \quad (12)$$

$$R_2 = \sum_{k=1}^{2}\left(r_{2n-1}^{(k)*} \cdot r_{2n}^{(k)} - r_{2n-2}^{(k)} \cdot r_{2n+1}^{(k)*}\right). \quad (13)$$

By combining equations (11) with (7) and (8), we obtain:

$$R_1 = \sum_{k=1}^{2}\left(\left|h_{k,1}\right|^2 + \left|h_{k,2}\right|^2\right) \cdot u_{2n} + \textit{noise terms}, \quad (14)$$

$$R_2 = \sum_{k=1}^{2}\left(\left|h_{k,1}\right|^2 + \left|h_{k,2}\right|^2\right) \cdot u_{2n+1} + \textit{noise terms}. \quad (15)$$

The receiver computes the closest vector (u_{2n}, u_{2n+1}) to (R_1, R_2). Let us denote by *b* the number of information bits transmitted per channel use. We see that (u_{2n}, u_{2n+1}) depends on both (s_{2n-2}, s_{2n-1}) and (s_{2n}, s_{2n+1}). To select this 4D symbol, only 2*b* input bits are available, while twice as many would have been required to select an 8D symbol $(s_{2n-2}, s_{2n-1}, s_{2n}, s_{2n+1})$. To establish a bijection, we fix $s_{2n-2} = s_{2n-1} = 1/\sqrt{2}$ as in [14] and [15]. We then have

$$u_{2n} = \left(s_{2n} + s_{2n+1}^*\right)/\sqrt{2}, \quad (16)$$

$$u_{2n+1} = \left(s_{2n} - s_{2n+1}^*\right)/\sqrt{2}. \quad (17)$$

To determine a two-tuple of absolute values (u_{2n}, u_{2n+1}), *b* input bits select a signal point denoted in (16) and (17) by s_{2n} while another *b* input bits similarly select a signal point s_{2n+1} according to (16–17). Actually however, the symbols (s_{2n}, s_{2n+1}) transmitted over the channel in two consecutive channel uses $2n$ and $2n$+1 are not those in (16) and (17), but they are computed according to (7) and (8). To avoid any confusion, let us rewrite (16) and (17) as follows:

$$u_{2n} = \left(x + y^*\right)/\sqrt{2}\,, \qquad \text{(16bis)}$$

$$u_{2n+1} = \left(x - y^*\right)/\sqrt{2}\,. \qquad \text{(17bis)}$$

In (16bis) and (17bis), x and y belong to a PSK signal constellation and each of them is selected by b input bits. The asterisk denotes complex-conjugation.

3. DIFFERENTIAL EXTENDED-ALAMOUTI CODING

We now upgrade our inter-vehicular communication system from half-rate, which is differential Alamouti, to full-rate, which is differential extended-Alamouti. Let us denote by $M = 2^m$ the size of the PSK signal constellation and use the notation

$$\varphi_{2n} = \left(v_{2n} + \sqrt{2}w_{2n}\right)\cdot 2\pi/M\,, \qquad (18)$$

$$\varphi_{2n+1} = \left(v_{2n+1} + \sqrt{2}w_{2n+1}\right)\cdot 2\pi/M\,, \qquad (19)$$

where $v_{2n}, w_{2n}, v_{2n+1}, w_{2n+1} \in \{0, 1, 2, \ldots, M-1\}$. Then, the signals transmitted in two consecutive channel uses $2n$ and $2n$+1 are as follows:

$$s_{2n} = \frac{1}{\sqrt{2}}\mathrm{e}^{\mathrm{i}\varphi_{2n}}\,, \qquad (20)$$

$$s_{2n+1} = \frac{1}{\sqrt{2}}\mathrm{e}^{\mathrm{i}\varphi_{2n+1}}\,. \qquad (21)$$

For notational convenience, let us introduce

$$\alpha_{2n} = \left[v_{2n-1} - v_{2n+1} + \sqrt{2}\left(w_{2n-1} - w_{2n+1}\right)\right]\cdot 2\pi/M\,, \quad (22)$$

$$\beta_{2n} = \left[v_{2n} - v_{2n-2} + \sqrt{2}\left(w_{2n} - w_{2n-2}\right)\right]\cdot 2\pi/M\,, \quad (23)$$

$$\alpha_{2n+1} = \left[v_{2n} - v_{2n-1} + \sqrt{2}\left(w_{2n} - w_{2n-1}\right)\right]\cdot 2\pi/M\,, \quad (24)$$

$$\beta_{2n+1} = \left[v_{2n-2} - v_{2n+1} + \sqrt{2}\left(w_{2n-2} - w_{2n+1}\right)\right]\cdot 2\pi/M\,. \quad (25)$$

Then we have:

$$u_{2n} = \frac{1}{2}\left(\mathrm{e}^{\mathrm{i}\alpha_{2n}} + \mathrm{e}^{\mathrm{i}\beta_{2n}}\right), \qquad (26)$$

$$u_{2n+1} = \frac{1}{2}\left(\mathrm{e}^{\mathrm{i}\alpha_{2n+1}} - \mathrm{e}^{\mathrm{i}\beta_{2n+1}}\right), \qquad (27)$$

We see that $(u_{2n},\ u_{2n+1})$ depends on both $\left(v_{2n-2} + \sqrt{2}w_{2n-2}\right)$, $\left(v_{2n-1} + \sqrt{2}w_{2n-1}\right)$ and $\left(v_{2n} + \sqrt{2}w_{2n}\right)$, $\left(v_{2n+1} + \sqrt{2}w_{2n+1}\right)$. To select this 4D symbol, only 4b input bits are available, while twice as many would have been required to select the 8D symbol $(v_{2n-2} + \sqrt{2}w_{2n-2}$, $v_{2n-1} + \sqrt{2}w_{2n-1}$, $v_{2n} + \sqrt{2}w_{2n}$, $v_{2n+1} + \sqrt{2}w_{2n+1}$.

To establish a bijection, we fix $v_{2n-2} = w_{2n-2} = v_{2n-1} = w_{2n-1} = 0$. Using again equations (11) this time for extended-Alamouti, we obtain:

$$u_{2n} = \frac{1}{2}\left(\mathrm{e}^{\mathrm{i}\left(v_{2n} + \sqrt{2}w_{2n}\right)2\pi/M} + \mathrm{e}^{-\mathrm{i}\left(v_{2n+1} + \sqrt{2}w_{2n+1}\right)2\pi/M}\right), \quad (28)$$

$$u_{2n+1} = \frac{1}{2}\left(\mathrm{e}^{\mathrm{i}\left(v_{2n} + \sqrt{2}w_{2n}\right)2\pi/M} - \mathrm{e}^{-\mathrm{i}\left(v_{2n+1} + \sqrt{2}w_{2n+1}\right)2\pi/M}\right). \quad (29)$$

As for differential Alamouti, the receiver computes the closest vector (u_{2n}, u_{2n+1}) to (R_1, R_2). In the next Section, we illustrate our method with differential QPSK (Quadrature PSK), that is $M = 2^b = 4$.

4. ILLUSTRATIVE EXAMPLE: DIFFERENTIAL QPSK

There are many sources of error in data transmission, like the imperfect clock and carrier recovery at the reception. Some of them can be mitigated by careful implementation. In this study, we are concerned with the main sources of error, that is, the additive noise and the fading, the last one including the influence of the spacing between the two transmit antennas and also of the spacing between the two receive antennas. Indeed, when in deep fading, there are errors even if the power of noise is vanishingly small.

In two consecutive channel uses $2n$ and $2n$+1, eight information bits are gathered at the input of the transmitter and they are denoted by $b1_n \div b8_n$. Together, they select a two-tuple of absolute symbols (u_{2n}, u_{2n+1}). To establish a bijection between the set of the 256 words made with the input bits and the set of all two-tuples (u_{2n}, u_{2n+1}), in the equations (28) and (29) we put:

$$v_{2n} = 2b2_n + b1_n\,, \qquad (30)$$

$$w_{2n} = 2b4_n + b3_n\,, \qquad (31)$$

$$v_{2n+1} = 2b6_n + b5_n\,, \qquad (32)$$

$$w_{2n+1} = 2b8_n + b7_n\,. \qquad (33)$$

The transmitter has already stored the relative symbols v_{2n-2}, v_{2n-1}, w_{2n-2}, and w_{2n-1}. Having computed the absolute symbols u_{2n} and u_{2n+1} as well, it can form the transmission matrix $\boldsymbol{M}_n$ according to (6). The receiver cannot acquire CSI; instead, it computes an estimated (R_1, R_2) and looks for that two-tuple $(\hat{u}_{2n}, \hat{u}_{2n+1})$ which is nearest to it. For maximum likelihood (ML) detection, a suitable metric is as follows:

$$m_n = \left|u_{2n} - R_1\right|^2 + \left|u_{2n+1} - R_2\right|^2. \qquad (34)$$

The two-tuple (u_{2n}, u_{2n+1}) that minimizes m_n of (34) will be chosen as decision. Then, using the inverse mapping, the receiver recovers $\hat{v}_{2n}$, $\hat{v}_{2n+1}$, $\hat{w}_{2n}$, $\hat{w}_{2n}$ and thus estimates the transmitted bits using (30) – (33).

We wrote two simulation programs using MATLAB that take into consideration a number of system parameters including the distance between the two transmit antennas and also the distance between the two receive antennas. The first simulation program is for the differential Alamouti block code, while the second one is for the differential extended-Alamouti block code. In our simulations, a frame has L = 50 transmit matrices.

Table 1

The parameters of the setup

Antenna spacing	Transmission side	Receiving side
1	1/2λ	1/2λ
2	λ	λ
3	3λ	λ

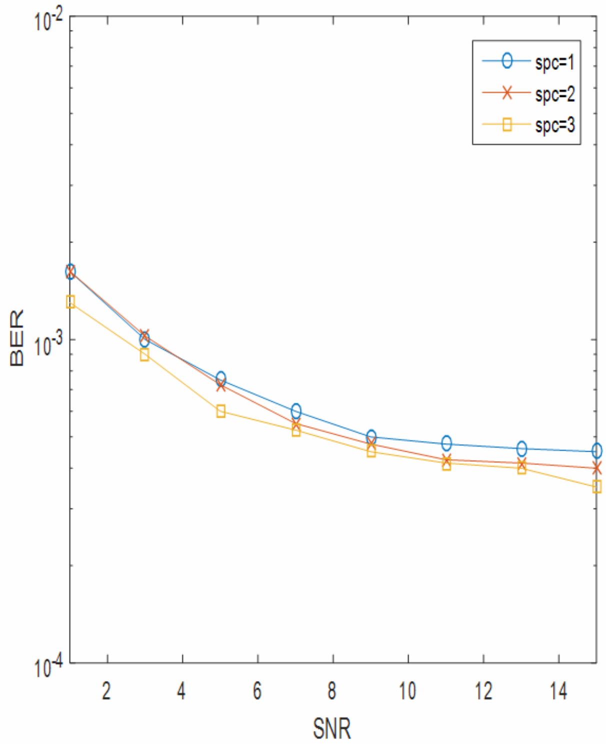

Fig. 1 – Performance of differential QPSK Alamouti space-time block code.

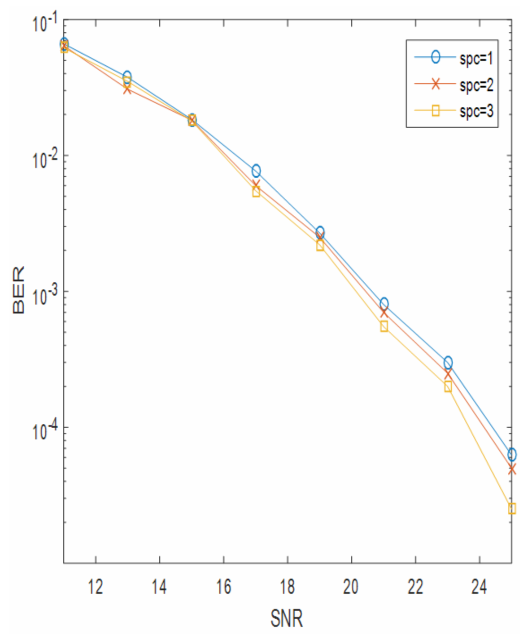

Fig. 2 – Performance of differential QPSK extended-Alamouti space-time block code.

The plot of the bit error rate (BER) versus signal-to-noise ratio (SNR) for the differential Alamouti space-time block code with the antenna spacing (spc) as parameter is reported as Fig. 1.

We present the simulation results for three couples of spacing between antennas. In Table 1, the distance between the two transmit antennas and the distance between the two receive antennas are given for three different setups, where λ is the wavelength of the radio frequency carrier.

The worst case is for spc = 1, while the best case is for spc = 3. However, the performance diminishes graciously when reducing the distance between collocated antennas. The plot of the BER versus SNR for differential extended-Alamouti space-time block code is given here as Fig. 2.

It is to be noted that extended-Alamouti QPSK has the same data rate as Alamouti 16QAM (Quadrature Amplitude Modulation). However, there is no differential transmission possible with QAM. Therefore, the novel space-time block code introduced in this paper can be advantageously used to enhance the data rate of inter-vehicular transmission when only noncoherent demodulation is possible. Like the Alamouti's, the extended-Alamouti presents itself in two versions, a nice feature that allows one to design super-orthogonal space-time trellis codes. This is an interesting assignment for a future research.

5. CONCLUSIONS

In this work, we took inspiration from the celebrated Golden code that can transmit no less than four 2D symbols in two consecutive channel uses with two transmit antennas. Nevertheless, it was our intention to design a noncoherent transmission technique to be used for inter-vehicular communications where it is not possible to acquire channel state information at the receiving vehicle.

To this end, we enhanced the differential Alamouti space-time block code by introducing a clever yet simple and efficient separation between the two 2D symbols transmitted by an antenna in a single channel use. We illustrated our novel differential space-time full-rate block coding method for the case of QPSK modulation format. Finally, we reported simulation results in the form of BER plots. Those results encourage us to confidently propose our transmission method for inter-vehicular communication.

We contemplate furthering our research work by considering both forms of Alamouti matrices in order to design differential extended-Alamouti space-time trellis codes for still better performance.

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