ORTHOGONAL DUAL-ANTENNA TRANSMIT DIVERSITY FOR SOQPSK IN AERONAUTICAL TELEMETRY CHANNELS

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ABSTRACT

Transmit diversity schemes such as the Alamouti space-time code have been shown to be viable candidates to enable robust dual-antenna transmission from maneuvering air vehicles. However, due to the complicated structure of shaped offset quadrature phase shift keying (SOQPSK) modulation, the Alamouti approach has not been applicable to SOQPSK systems. This paper develops a precoding and detection algorithm which allows implementation of dual-antenna Alamouti signaling for SOQPSK modulation. Performance simulations demonstrate the performance of the scheme for a realistic flight scenario.

KEYWORDS

Transmit Diversity, Dual-Antenna Transmission, SOQPSK

INTRODUCTION

Dual-antenna transmission is commonly used in aeronautical telemetry systems to overcome the signal obstruction encountered during aggressive air-vehicle maneuvering. However, in the frequent scenario where neither antenna is obstructed, such an approach leads to self-interference that can significantly degrade communication performance. We have recently shown that orthogonal transmit diversity schemes (space-time codes) can be used to allow reliable dual-antenna transmission from a maneuvering air-vehicle [1]. However, application of these schemes to spectrally efficient modulation schemes of current interest such as shaped offset quadrature phase shift keying (SOQPSK) is complicated by the offset modulation approach, inter-symbol interference associated with the overlapping pulse shapes, and differential encoding applied at transmission.

In this paper, we propose a modification of Alamouti's dual-antenna transmit diversity scheme [2] appropriate for SOQPSK modulation. The approach uses a bit-to-symbol mapping that works with the differential encoding currently used in aeronautical telemetry and enables the orthogonal transmission required for reliable communication performance. Detection of the received symbols requires implementation of a trellis decoder that incorporates knowledge of the inter-symbol interference and offset nature of the modulation. Detailed simulation results using a channel model that incorporates realistic air-vehicle motion and signal obstruction during flight demonstrate the performance of the technique.

TRANSMISSION SCHEME DEVELOPMENT

Alamouti Transmit Diversity

We will first review the basics of the dual-antenna Alamouti diversity scheme [2]. Let $s^{(n)}$ and $s^{(n+1)}$ represent two consecutive quadrature phase shift keyed (QPSK) symbols, where the superscript represents a time index. During symbol time n, antenna #1 transmits $s^{(n)}$ while antenna #2 transmits $s^{(n+1)}$. During symbol time $n+1$, antenna #1 transmits $-s^{*(n+1)}$ and antenna #2 transmits $s^{*(n)}$. For a single receive antenna collecting the radiation from both transmit antennas, we can write the signal received over these two symbol times as

$$\mathbf{r}^{(n)} = \begin{bmatrix} r^{(n)} \\ r^{(n+1)*} \end{bmatrix} = \frac{1}{\sqrt{2}} \underbrace{\begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix}}_{\mathbf{H}} \underbrace{\begin{bmatrix} s^{(n)} \\ s^{(n+1)} \end{bmatrix}}_{\mathbf{s}^{(n)}} + \underbrace{\begin{bmatrix} \eta^{(n)} \\ \eta^{(n+1)*} \end{bmatrix}}_{\boldsymbol{\eta}^{(n)}}, \tag{1}$$

where h_m is the transfer function from transmit antenna #m to the receive antenna, $\eta^{(n)}$ represents additive white Gaussian noise, and we have taken the conjugate of the signal received during the second symbol time to facilitate this expression. It is straightforward to show that symbol detection can be performed using the operation

$$\hat{\mathbf{r}}^{(n)} = \mathbf{H}^{\dagger}\mathbf{r}^{(n)} = \frac{1}{\sqrt{2}}(|h_1(\theta,\phi)|^2 + |h_2(\theta,\phi)|^2)\mathbf{s}^{(n)} + \mathbf{H}^{\dagger}\boldsymbol{\eta}^{(n)}. \tag{2}$$

We have shown that for traditional QPSK, this scheme provides excellent robustness against signal loss due either to obstruction of one of the transmissions by the air vehicle or by self-interference created by the simultaneous transmission from both antennas (i.e. array pattern). Our goal is now to show how this approach can be used with SOQPSK modulation.

SOQPSK Transmission

To illustrate the difficulties associated with applying Alamouti's transmit diversity scheme to SOQPSK signaling, it is helpful to review some key details associated with this modulation scheme as implemented for aeronautical test-flight telemetry. Consider a stream of bits $c^{(k)}$ that can assume symmetric binary (± 1) values, where k represents an integer *bit* time index which is deliberately distinct from the symbol time index n. The offset nature of the modulation stems from the fact that the in-phase (I) component of the complex signal is constrained to change its value only for even values of $k = 2n$, while the quadrature (Q) component of the signal changes its value only for odd values of $k = 2n + 1$. This means that the signal can only change its phase by $\pi/2$ radians each bit time.

We will use $I^{(k)}$ and $Q^{(k)}$, which take on values of ± 1, to represent the complex symbol at bit time k. SOQPSK modulation is implemented using a differential bit encoding process expressed as

$$
\begin{aligned}
I^{(2n)} &= -c^{(2n)} \oplus Q^{(2n-1)} && (3)\\
Q^{(2n+1)} &= c^{(2n+1)} \oplus I^{(2n)} && (4)
\end{aligned}
$$

where $\oplus$ operates like an EXCLUSIVE-OR operator for symmetric binary signals as

$$
A \oplus B = \begin{cases} 1 & A = B \\ -1 & A \neq B \end{cases} \tag{5}
$$

This procedure naturally creates the offset transitions for the I and Q channels.

For each bit (and therefore I or Q transition), the output of the differential encoder can be represented using a ternary symbol $\alpha^{(k)}$ which takes values from the set $[-1, 0, 1]$. These values represent the phase change of $\pi/2$, 0, or $\pi/2$, respectively, that occurs for each bit transition. Given a pulse shape $g(t)$, the phase of the carrier is then modulated with the value

$$
\phi(t, \overline{\alpha}) = \frac{\pi}{2} \int_{-\infty}^{t} \sum_{k=-\infty}^{\infty} \alpha^{(k)} g(\tau - kT/2) d\tau \tag{6}
$$

where $\overline{\alpha}$ represents the vector with values $\alpha^{(k)}$.

Alamouti Precoding

While the SOQPSK bit-to-symbol mapping procedure results in excellent spectral properties of the modulated signal, because it constrains future symbols based on past ones, this does not allow the flexibility to transmit the symbols as required by the Alamouti scheme. We must therefore find a precoding that allows us to satisfy the constraints imposed by both algorithms. The architecture that we will use is shown in Figure 1, where the incoming bits are assumed first mapped to traditional QPSK symbols. Our goal is to find a relationship between these symbols and the bit-level inputs to two SOQPSK modulators that will drive the two antennas.

This precoding must ensure that the I and Q channels are at the values specified by the Alamouti scheme at the decision point for the symbol (i.e. after both values have completed their transitions). Using (4), the symbol $s_m^{(n)}$ transmitted out of the mth antenna at the end of the nth symbol time (decision point) is

$$
s_m^{(n)} = I_m^{(2n)} + jQ_m^{(2n+1)} = -c_m^{(2n)} \oplus Q_m^{(2n-1)} + jc_m^{(2n+1)} \oplus I_m^{(2n)}, \tag{7}
$$

where $c_m^{(k)}$ is the bit assigned to the mth modulator at the kth bit time. The right hand equality in (7) allows us to specify these bits in terms of the desired output symbols, or

$$
\begin{aligned}
c_m^{(2n)} &= -I_m^{(2n)} \oplus Q_m^{(2n-1)} \\
c_m^{(2n+1)} &= I_m^{(2n)} \oplus Q_m^{(2n+1)}. && (8)
\end{aligned}
$$

Furthermore, we can relate $s_m^{(n)}$ to the incoming symbol stream $s^{(n)}$ using the Alamouti

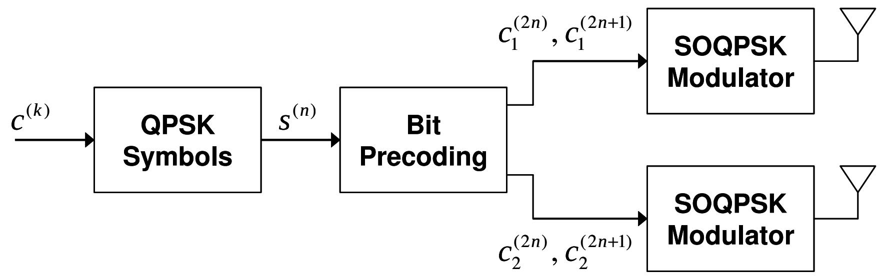

Figure 1: Block-diagram of an SOQPSK modulation system for Alamouti dual-antenna transmit diversity.

scheme. Letting $s^{(n)} = a^{(n)} + jb^{(n)}$, we can write

$$\begin{array}{lllllll} s_1^{(n-1)} & = & I_1^{(2n-2)} + jQ_1^{(2n-1)} & = & -s^{*(n-1)} & = & -a^{(n-1)} + jb^{(n-1)} \\ s_1^{(n)} & = & I_1^{(2n)} + jQ_1^{(2n+1)} & = & s^{(n)} & = & a^{(n)} + jb^{(n)} \\ s_1^{(n+1)} & = & I_1^{(2n+2)} + jQ_1^{(2n+3)} & = & -s^{*(n+1)} & = & -a^{(n+1)} + jb^{(n+1)} \\ s_2^{(n-1)} & = & I_2^{(2n-2)} + jQ_2^{(2n-1)} & = & s^{*(n-2)} & = & a^{(n-2)} - jb^{(n-2)} \\ s_2^{(n)} & = & I_2^{(2n)} + jQ_2^{(2n+1)} & = & s^{(n+1)} & = & a^{(n+1)} + jb^{(n+1)} \\ s_2^{(n+1)} & = & I_2^{(2n+2)} + jQ_2^{(2n+3)} & = & s^{*(n)} & = & a^{(n)} - jb^{(n)}. \end{array} \tag{9}$$

Using these results with (8) leads to

$$\begin{array}{lllllll} c_1^{(2n)} & = & -a^{(n)} \oplus b^{(n-1)} & \quad & c_2^{(2n)} & = & a^{(n+1)} \oplus b^{(n-2)} \\ c_1^{(2n+1)} & = & a^{(n)} \oplus b^{(n)} & & c_2^{(2n+1)} & = & a^{(n+1)} \oplus b^{(n+1)} \\ c_1^{(2n+2)} & = & a^{(n+1)} \oplus b^{(n)} & & c_2^{(2n+2)} & = & -a^{(n)} \oplus b^{(n+1)} \\ c_1^{(2n+3)} & = & -a^{(n+1)} \oplus b^{(n+1)} & & c_2^{(2n+3)} & = & -a^{(n)} \oplus b^{(n)} \end{array} \tag{10}$$

We now have a direct mapping between the incoming QPSK symbols and the bits feeding the SOQPSK modulators to ensure that Alamouti-encoded symbols are being transmitted from the two antennas.

Alamouti Detection

The offset nature of SOQPSK modulation as well as the pulse shapes which deliberately introduce intersymbol-interference combine to make it so that the simple Alamouti detection approach of (2) will not work with SOQPSK symbols. We must therefore devise an alternative scheme to process the received waveforms. Assume first a simple offset QPSK system with a pulse shape that allows matched-filtering at the receiver. With Alamouti transmission, the matched filter outputs sampled at $T_s/2$, with T_s the symbol duration, can be expressed as

$$
\begin{aligned}
x(2nT_s/2) &= h_1\left\{a^{(n)} + jR_p\left(\frac{T_s}{2}\right)b^{(n)} + jR_p\left(-\frac{T_s}{2}\right)b^{(n-1)}\right\} \\
&\quad +h_2\left\{a^{(n+1)} + jR_p\left(\frac{T_s}{2}\right)b^{(n+1)} - jR_p\left(-\frac{T_s}{2}\right)b^{(n-2)}\right\} \qquad (11) \\
x((2n+1)T_s/2) &= h_1\left\{jb^{(n)} - R_p\left(\frac{T_s}{2}\right)a^{(n+1)} + R_p\left(-\frac{T_s}{2}\right)a^{(n)}\right\} \\
&\quad +h_2\left\{jb^{(n+1)} + R_p\left(\frac{T_s}{2}\right)a^{(n)} + R_p\left(-\frac{T_s}{2}\right)a^{(n+1)}\right\} \qquad (12) \\
x((2n+2)T_s/2) &= h_1\left\{-a^{(n+1)} + jR_p\left(\frac{T_s}{2}\right)b^{(n+1)} + jR_p\left(-\frac{T_s}{2}\right)b^{(n)}\right\} \\
&\quad +h_2\left\{a^{(n)} - jR_p\left(\frac{T_s}{2}\right)b^{(n)} + jR_p\left(-\frac{T_s}{2}\right)b^{(n+1)}\right\} \qquad (13) \\
x((2n+3)T_s/2) &= h_1\left\{jb^{(n+1)} + R_p\left(\frac{T_s}{2}\right)a^{(n+2)} - R_p\left(-\frac{T_s}{2}\right)a^{(n+1)}\right\} \\
&\quad +h_2\left\{-jb^{(n)} + R_p\left(\frac{T_s}{2}\right)a^{(n+3)} + R_p\left(-\frac{T_s}{2}\right)a^{(n)}\right\} \qquad (14)
\end{aligned}
$$

where $R_p(\tau)$ is the matched filter correlation and we have assumed that the pulse shape is such that $R_p(\tau) = 0$ for $|\tau| > T_s$. Let $x(\tau)$, with τ given by the times indicated on the left of (11)-(14), represent the observed matched filter outputs. We then compute $\hat{x}(\tau)$ for an assumed set of symbols.

The noise samples out of the matched filter will generally not be temporally white. However, if we neglect the noise correlation created by the matched filter, then the approximate maximum likelihood detector must find the sequence of symbols that minimizes the difference

$$
|\Delta|^2 = \sum_{k=1}^{\infty} |\hat{x}(kT_s/2) - x(kT_s/2)|^2, \qquad (15)
$$

where $\hat{x}(\tau)$ represents the matched filter output computed from an assumed set of symbols using (11)-(14). This can be accomplished using the Viterbi Algorithm (VA) [3]. Specifically, we can represent the computation using the trellis shown in Figure 2, where only a fraction of the branches from time $(n+3/2)T_s$ to $(n+2)T_s$ are shown for clarity. The binary numbers represent possible states of the a and b values in (11)-(14), where states of 0 and 1 mean values of -1 and 1, respectively. Each path metric is one term in the sum of (15). After one traversal of the trellis in Figure 2, a decision can be made on the values of $a^{(n)}$, $b^{(n)}$, $a^{(n+1)}$, and $b^{(n+1)}$. The partial path metric computed up to this point can be saved, and the trellis can be retraversed for the next two symbols.

For SOQPSK modulation, the detector output is not precisely modeled by the offset QPSK development outlined here. For example, the detection uses an integrate-and-dump rather than a matched filter, and the inter-symbol interference extends beyond a time of $\tau = T_s$,

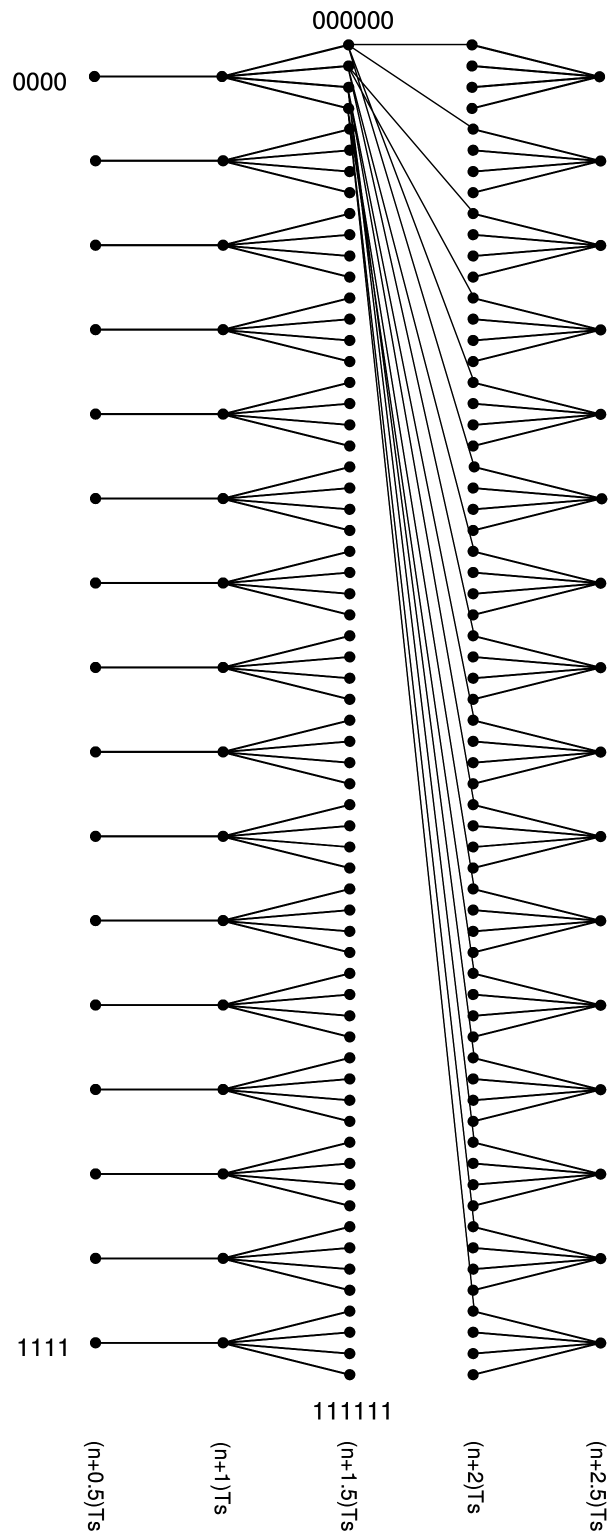

Figure 2: Trellis used for the Viterbi Algorithm detection of Alamouti SOQPSK transmission. Only a fraction of the branches from time $(n+3/2)T_s$ to $(n+2)T_s$ are shown.

which was the limit assumed in the development above. However, if we assume that this development does model the SOQPSK output samples and simply estimate $R_p(T_s/2) = R_p(-T_s/2) = 0.5$, we can test the operation of the VA detector on this modulation scheme. This evaluation will be performed by first modeling the air vehicle motion by an initial position, velocity, attitude (yaw, pitch, and roll), and a rotation rate for each of the attitude angles. Using Eulerian angle transformations [4], the angular position of the ground station in the vehicle coordinate frame is computed at each sample time (one sample per transmitted symbol). This angle information is then used to compute the transfer functions h_1 and h_2 from each transmit antenna to the receive antenna.

In the computations, we assume that antennas 1 and 2 are placed at $(0, 0, 0)$ and $(10, 0, 10)$ on the air vehicle, respectively, where the dimensions are in wavelengths (10 wavelengths = 2 m at 1.5 GHz). The flight simulation assumes that the air vehicle travels at 300 m/s and is initially 3000 m away from the ground station (horizontally) at an altitude of 2000 m above ground. The initial direction of flight is perpendicular to the line between the aircraft and ground station, and the vehicle is engaged in a roll at 1 revolution per second. The QPSK communication is performed at 1 Msymbol/second, and 1×10^6 bits are sent to determine the performance.

Figure 3 shows the bit error rate (BER) versus the bit energy over the noise power spectral density (E_b/N_0) for Alamouti SOQPSK modulation. Also shown for comparison are the performance when a single transmit antenna (without any signal obstruction included) is used as well as when two antennas are used with the same waveform transmitted out of both (No Diversity). The final curve on the plot results from using the VA algorithm, but only using the two states at $(n + 1/2)T_s$ and $(n + 1)T_s$ to make a decision. These two states are chosen because they only depend on the two symbols $s^{(n)}$ and $s^{(n+1)}$. As can be seen, the performance of the Alamouti scheme with VA detection with only two states results in a small degradation in performance. However, the performance of both schemes far exceeds the performance obtainable when two antennas are used without applying the diversity scheme. We also notice that both schemes work far better than dual-antenna transmission without a proper diversity scheme implemented, and only suffer a limited performance degradation relative to what is possible for a single antenna with no signal obstruction.

CONCLUSIONS

This paper has discussed the application of the Alamouti diversity scheme with SOQPSK modulation for dual-antenna transmission from air vehicles. A method for precoding the bit stream to ensure that the transmitted symbols conform to the Alamouti format as well as a VA detection scheme have been proposed. The performance of the scheme is shown to be very good in a realistic flight scenario. A simplified VA scheme using a smaller number of trellis states was also evaluated, with the performance degradation being on the order of 1.5 to 2 dB. With additional development, this Alamouti scheme shows promise for enabling dual-antenna transmission for flight tests using SOQPSK modulation.

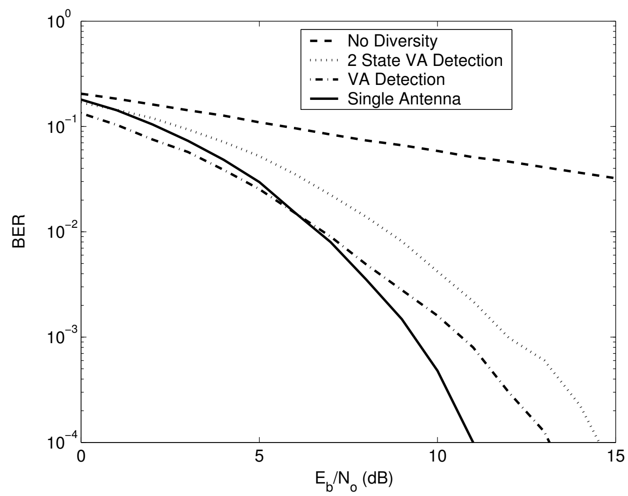

Figure 3: Bit error rate versus E_b/N_0 for Alamouti SOQPSK detection compared to the results for single-antenna SOQPSK communication as well as the case when the same waveform is transmitted out of each antenna (No Diversity).

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