APPENDIX S

Space-Time Coding for Telemetry Systems

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Acronyms

SOQPSK	shaped offset quadrature phase shift keying
STC	space-time code

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APPENDIX S

Space-Time Coding for Telemetry Systems

1.0 Code Description

The space-time code (STC) used in this standard is based on the Alamouti STC[1] and applied only to shaped offset quadrature phase shift keying (SOQPSK)-TG or any of its fully interoperable variants. The Alamouti STC may be described in terms of the offset QPSK IRIG 106 symbol-to-phase mapping convention illustrated in Figure M-2 in Appendix M. Figure M-2 is reproduced here as Figure S-1.

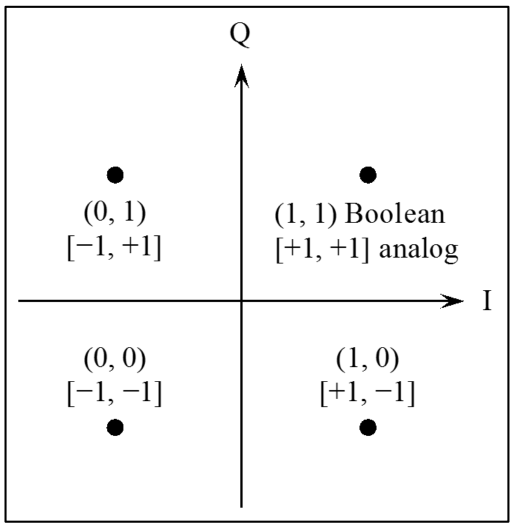

Figure S-1. Offset QPSK IRIG 106 Symbol-to-Phase Mapping Convention

The starting point is the normalized analog values corresponding to each of the offset QPSK symbols. Let $[a_n, b_n]$ with $a_n = \pm 1$, $b_n = \pm 1$ be the analog value of the n-th symbol. Suppose the bit sequence defines the sequence of symbols

$$[a_0, b_0], [a_1, b_1], [a_2, b_2], [a_3, b_3], \ldots, [a_{2k}, b_{2k}], [a_{2k+1}, b_{2k+1}], \ldots$$

The Alamouti STC organizes the symbols into blocks of two symbols, starting with the even-indexed blocks as shown. The Alamouti STC assigns the k-th block of symbols

$$[a_{2k}, b_{2k}], [a_{2k+1}, b_{2k+1}]$$

to antenna 0 and antenna 1 over two consecutive symbol times as shown below.

antenna	symbol time $2k$	symbol time $2k+1$
0	$[a_{2k}, b_{2k}]$	$[-a_{2k+1}, b_{2k+1}]$
1	$[a_{2k+1}, b_{2k+1}]$	$[a_{2k}, -b_{2k}]$

[1] S. Alamouti. "A Simple Transmit diversity Technique for Wireless Communications." *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451-1458, October 1998.

Using the bit (Boolean) assignments shown in Figure S-1, the Alamouti encoder can be restated in terms of the input bits as follows. Let the sequence of input bits be

$$b_0\ b_1\ b_2\ b_3 \mid b_4\ b_5\ b_6\ b_7 \mid \ldots \mid b_{4k}\ b_{4k+1}\ b_{4k+2}\ b_{4k+3} \mid \ldots$$

The STC encoder groups the bits into non-overlapping blocks of four bits each as indicated by the vertical lines. The STC encoder produces two bit streams in parallel: $\mathbf{b}_0$, which is applied to antenna 0, and $\mathbf{b}_1$, which is applied to antenna 1. The relationship between the input bit sequence and these two bit sequences is

$$\begin{aligned} \mathbf{b}_0 &= b_0 b_1 \bar{b}_2 b_3 \mid b_4 b_5 \bar{b}_6 b_7 \mid \ldots \mid b_{4k} b_{4k+1} \bar{b}_{4k+2} b_{4k+3} \mid \ldots \\ \mathbf{b}_1 &= b_2 b_3 b_0 \bar{b}_1 \mid b_6 b_7 b_4 \bar{b}_5 \mid \ldots \mid b_{4k+2} b_{4k+3} b_{4k} \bar{b}_{4k+1} \mid \ldots \end{aligned}$$

where $\bar{b}_n$ is the logical complement of bit b_n.

An important point here is the notion of even- and odd-indexed bits. The SOQPSK-TG modulator treats even-indexed and odd-indexed bits slightly differently. Each code block must begin with an even-indexed bit.

An example of encoding is as follows. Suppose the input bit sequence is

1 0 1 1 0 1 0 0

The two STC encoded bit sequences are

$$\begin{aligned} \mathbf{b}_0 &= 1\ \ 0\ \ 0\ \ 1\ \ 0\ \ 1\ \ 1\ \ 0 \\ \mathbf{b}_1 &= 1\ \ 1\ \ 1\ \ 1\ \ 0\ \ 0\ \ 0\ \ 0 \end{aligned}$$

To make provision for the estimation of frequency offset, differential timing, and the channels, a block of known bits, called pilot bits, is periodically inserted into each of the two bit streams. A 128-bit pilot block is inserted every 3200 Alamouti-encoded bits. The pilot bits inserted into $\mathbf{b}_0$ bit stream are denoted $\mathbf{p}_0$ and the bit pilot bits inserted into the $\mathbf{b}_1$ bit stream are denoted $\mathbf{p}_1$. These pilot bit sequences are

$$\begin{aligned} \mathbf{p}_0 = {} & 1\,0\,1\,0\,1\,0\,0\,0\,1\,0\,0\,0\,1\,1\,0\,1\,1\,0\,0\,1\,1\,0\,1\,0\,1\,1\,0\,1\,0\,1\,0\,0 \\ & 1\,1\,0\,1\,1\,1\,0\,0\,0\,1\,0\,0\,0\,0\,0\,0\,0\,1\,0\,0\,1\,0\,0\,1\,0\,1\,0\,0\,0\,1\,1\,1 \\ & 1\,1\,1\,0\,0\,0\,1\,0\,1\,0\,0\,1\,0\,0\,1\,0\,0\,0\,0\,0\,0\,0\,1\,0\,0\,0\,1\,1\,1\,0\,1\,1 \\ & 0\,0\,1\,0\,1\,0\,1\,1\,0\,1\,0\,1\,1\,0\,0\,1\,1\,0\,1\,1\,0\,0\,0\,1\,0\,0\,0\,1\,0\,1\,0\,1 \end{aligned}$$

$$\begin{aligned} \mathbf{p}_1 = {} & 1\,1\,1\,0\,0\,0\,1\,1\,1\,1\,0\,0\,0\,1\,1\,1\,0\,1\,1\,1\,0\,1\,1\,1\,0\,1\,1\,0\,0\,0\,0\,1 \\ & 1\,1\,1\,1\,0\,0\,0\,0\,0\,1\,1\,1\,0\,0\,0\,0\,0\,0\,0\,1\,1\,0\,1\,1\,0\,1\,0\,1\,1\,1\,1\,0 \\ & 0\,1\,1\,1\,1\,1\,0\,1\,0\,1\,1\,0\,1\,1\,0\,0\,0\,0\,0\,0\,1\,1\,1\,0\,0\,0\,0\,0\,1\,1\,1\,1 \\ & 1\,0\,0\,0\,0\,1\,1\,0\,1\,1\,1\,0\,1\,1\,1\,0\,1\,1\,1\,0\,0\,0\,1\,1\,1\,1\,0\,0\,0\,1\,1\,1 \end{aligned}$$

A notional diagram illustrating how $\mathbf{p}_0$ and $\mathbf{p}_1$ are periodically inserted into $\mathbf{b}_0$ and $\mathbf{b}_1$, respectively, is illustrated in Figure S-2. Note that the bits comprising $\mathbf{b}_0$ and $\mathbf{b}_1$ may change with every occurrence as defined by the input data, but the pilot bits $\mathbf{p}_0$ and $\mathbf{p}_1$ do not change with each occurrence.

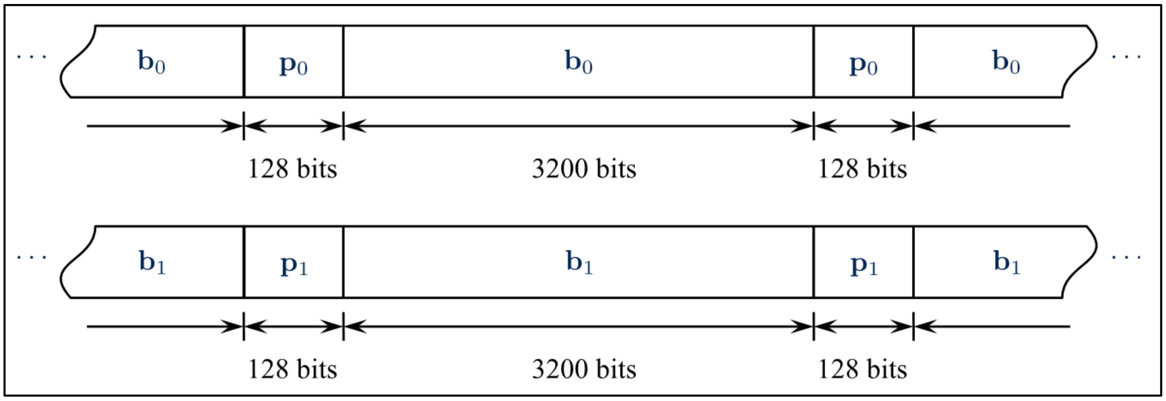

Figure S-2. Notional Diagram Illustrating the Periodic Insertion of 128 Pilot Bits Every 3200 Alamouti-Encoded Bits

2.0 Modulation

The bit sequences described in the previous section are modulated by a pair of SOQPSK-TG modulators (or modulator/transmitters). The modulators should be constructed and used as follows.

- The modulators share a common clock. This common clock is 26/25 times the input clock to accommodate the periodic insertion of 128 pilot bits every 3200 Alamouti-encoded bits.
- The modulators should share a common carrier reference. If this is not possible, the two carrier references should be phase-locked ideally, or frequency-locked at a minimum.
- Randomization, if required, should be applied before the STC encoder.
- Differential encoding should be disabled. The periodically inserted pilot bits are to be used by the demodulator to estimate the magnitudes and phases of the antenna-0-to-receiver channel and the antenna-1-to-receiver channel. There is no need to use differential encoding because data-aided phase estimates do not possess a phase ambiguity.[2]

Figure S-3 is a notional block diagram that shows the relationship between the input data and clock, the bit-level space-time encoder, the periodic pilot bit insertion, and the SOQPSK-TG modulation.

[2] M. Rice. *Digital Communications: A Discrete-Time Approach*. Pearson/Prentice-Hall. Upper Saddle River, NJ, 2009.

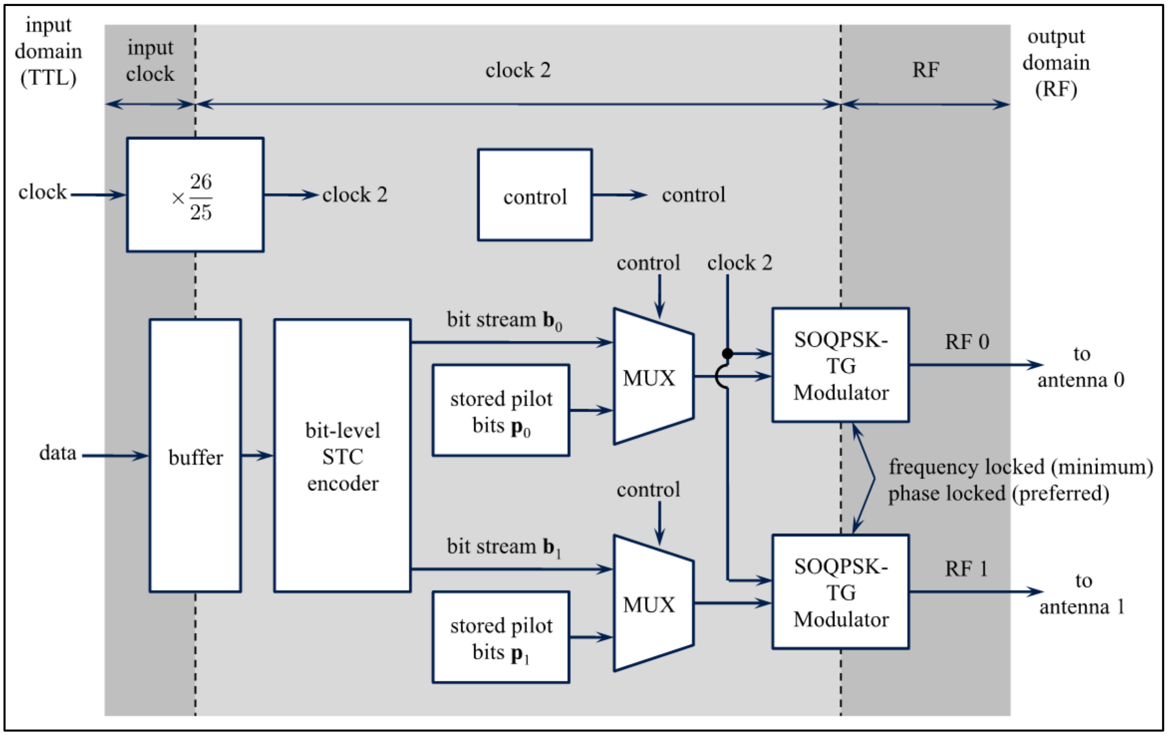

Figure S-3. A Notional Block Diagram of the Space-Time Code Transmitter

3.0 Resources

Jensen, et al.[3] first described the application of space-time coding to the two-antenna problem. Experimental flights confirmed the effectiveness of the technique.[4,5,6]

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[3] Jensen, M., M. Rice, and A. Anderson. "Aeronautical Telemetry Using Multiple-Antenna Transmitters." *IEEE Transactions on Aerospace and Electronic Systems*, vol. 43, no. 1, pp. 262-272, January 2007.
[4] M. Rice, "Space-Time Coding for Aeronautical Telemetry: Part 1 – System Description," in *Proceedings of the International Telemetering Conference*, Las Vegas, NV, October 2011.
[5] Rice, M. and K. Temple, "Space-Time Coding for Aeronautical Telemetry: part II – Experimental Results," in *Proceedings of the International Telemetering Conference*, Las Vegas, NV, October 2011.
[6] K. Temple, "Performance Evaluation of Space-Time coding on an Airborne Test Platform," in *Proceedings of the International Telemetering Conference*, forthcoming.

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Rice, M. and K. Temple, "Space-Time Coding for Aeronautical Telemetry: part II – Experimental Results," in *Proceedings of the International Telemetering Conference*, Las Vegas, NV, October 2011.

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