Experimental Results with Space-Time Coding Using FQPSK

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Abstract: When using two antennas to transmit telemetry from an airborne platform, self interference results when both transmit antennae are visible to the receive antenna. This self interference can lead to link outages and severe distortion, especially as data rates increase above 5 Mbits/sec. Space-time coding can be used to provide transmit diversity to overcome this self interference problem. This paper describes the results of experiments (conducted at Edwards Air Force Base, California, USA) using FQPSK-JR waveforms coded with ARTM Tier-1 Space-Time Block Code.

Keywords: aeronautical telemetry, space-time coding, transmit diversity.

1. Introduction

The traditional method for transmitting telemetry data from an aircraft is to mount the transmit antenna on the underside of the aircraft fuselage. However, aircraft maneuvers can place the fuselage in between the transmit antenna and the ground-based receive antenna. When this happens, the line-of-site propagation path is blocked and it becomes very difficult to maintain a reliable telemetry link.

A commonly used technique to overcome this problem is to transmit the same signal from two antennas placed at different locations on the airframe. Typically, one antenna is mounted on the underside of the fuselage and the other on the top. This is done because when line-of-sight propagation between the bottom antenna and the ground station is blocked by the fuselage, line-of-sight propagation between the top antenna and the ground station is not.

Since the two antennas are located at different points in space, the signals transmitted from each antenna arrive with different delays and different phases at the ground station. This is not a problem when only one of the two signals is visible to the ground station. However, when both signals are visible to the ground station, the signals combine either constructively or destructively. When the interference is destructive, the two signals tend to cancel each other thus causing a link outage.

One solution to this problem is use a different carrier frequency to transmit the data on each antenna. However, this solution requires twice the bandwidth. Given the current pressures on spectrum availability, this solution is not promising.

An alternate solution, proposed by Crummett, Jensen, and Rice [1] is to transmit two *different* signals from the two antennas. The two different signals are related to the data stream by a simple *space-time code* that introduces spatial diversity at the transmitter. The space-time code, called the ARTM Tier-1 Space-Time Block Code is described in [2] and [3] and has the following desirable properties:

1. The data can be recovered when only one of the signals is available.
2. The instantaneous phases of the two signals are adjusted to avoid destructive interference on average.
3. The code can be used with any of the ARTM Tier-1 waveforms [4].

This paper describes the results of experiments, conducted at Edwards Air Force Base, California, USA, in 2004 using FQPSK-JR waveforms coded with ARTM Tier-1 Space-Time Block Code.

2. Mathematical Model

The basic system is illustrated in Figure 1. The signal transmitted from antenna 0 is an ARTM Tier-1 waveform which may be expressed as

$$s_0(t) = \sum_k \left[a_0(k) p_{I,k}(t - kT_s) + j b_0(k) p_{Q,k}(t - T_s/2 - kT_s) \right] \qquad [1]$$

where $a_0(k) \in \{-1,+1\}$ and $b_0(k) \in \{-1,+1\}$ are the inphase and quadrature symbols, respectively, transmitted during the k-th symbol interval; T_s is the symbol time (twice the bit time); and $p_{I,k}(t)$ and $p_{Q,k}(t)$ are the data-dependent pulse shapes used for the inphase and quadrature components, respectively. Similarly, the signal transmitted from antenna 1 may be expressed as

$$s_1(t) = \sum_k \left[a_1(k) p_{I,k}(t - kT_s) + j b_1(k) p_{Q,k}(t - T_s/2 - kT_s) \right] \qquad [2]$$

where $a_1(k) \in \{-1,+1\}$ and $b_1(k) \in \{-1,+1\}$ are the inphase and quadrature symbols, respectively, transmitted during the k-th symbol interval. The ARTM Tier-1 Space-Time Block Code defines the relationship between the symbols $a_0(k)$, $b_0(k)$ and $a_1(k)$, $b_1(k)$.

As described previously, the received signal is a mixture of the signals transmitted from the two antennas. Since each signal is received with a different delay, the received signal may be modelled as

$$r(t) = h_0 s_0(t - \tau_0) + h_1 s_1(t - \tau_1) + w(t) \qquad [3]$$

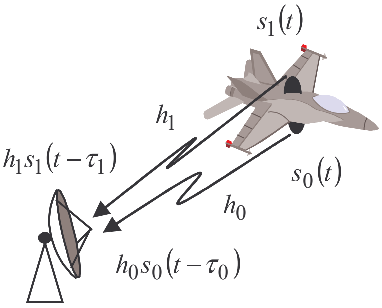

Figure 1: System-level illustration of a communication link using two transmit antennas and one receive antenna.

where h_0 is a complex channel gain which quantifies the attenuation and phase shift associated with the propagation path between antenna 0 and the receive antenna; τ_0 is the delay associated with the propagation path between antenna 0 and the receive antenna; h_1 is the complex channel gain for the propagation path between antenna 1 and the receive antenna; τ_1 is the delay associated with the propagation path between antenna 1 and the receive antenna; and $w(t)$ represents the additive noise (e.g. it is a complex Gaussian random process with zero mean and power spectral density N_0 W/Hz).

It can be shown that the signal-to-noise ratio using the space-time code is

$$\text{SNR} = \frac{|h_0|^2 + |h_1|^2}{N_0}. \qquad [4]$$

By contrast, the signal-to-noise ratio using the traditional technique of transmitting the same signal from each antenna is

$$\text{SNR} = \frac{|h_0 + h_1|^2}{N_0}. \qquad [5]$$

Since the channel gains are complex valued, the sum in Equation [5] can have a magnitude that is quite small when the phase difference is 180º and the magnitudes are about the same. This is the case that leads to the link drop-outs using the conventional signalling technique. In contrast, the numerator Equation [4] is always larger than the magnitude squared of the channel gain with the largest magnitude. For this reason, space-time coding can offer substantial improvements over the traditional signalling technique.

3. Experimental Configuration

The experimental configuration is illustrated in Figure 2. A single data source was encoded into two parallel data streams using the ARTM Tier-1 Space-Time Block code described in [1]. The parallel data sources modulated a pair of FQPSK-JR transmitters at a rate of 5 Mbits/sec. The two parallel modulated signals were transmitted simultaneously from a pair of antennas mounted on the top and bottom of the fuselage of a Beechcraft C-12 airplane illustrated in Figure 3. The received waveform was received by a standard telemetry receiver and converted to 70 MHz IF. The IF signal was sampled by the deep memory oscilloscope (DMO) operating at 100 Msamples/sec in a "continuous mode." The data samples were recorded on a DVD and sent to the BYU Telemetry Laboratory for post-flight processing.

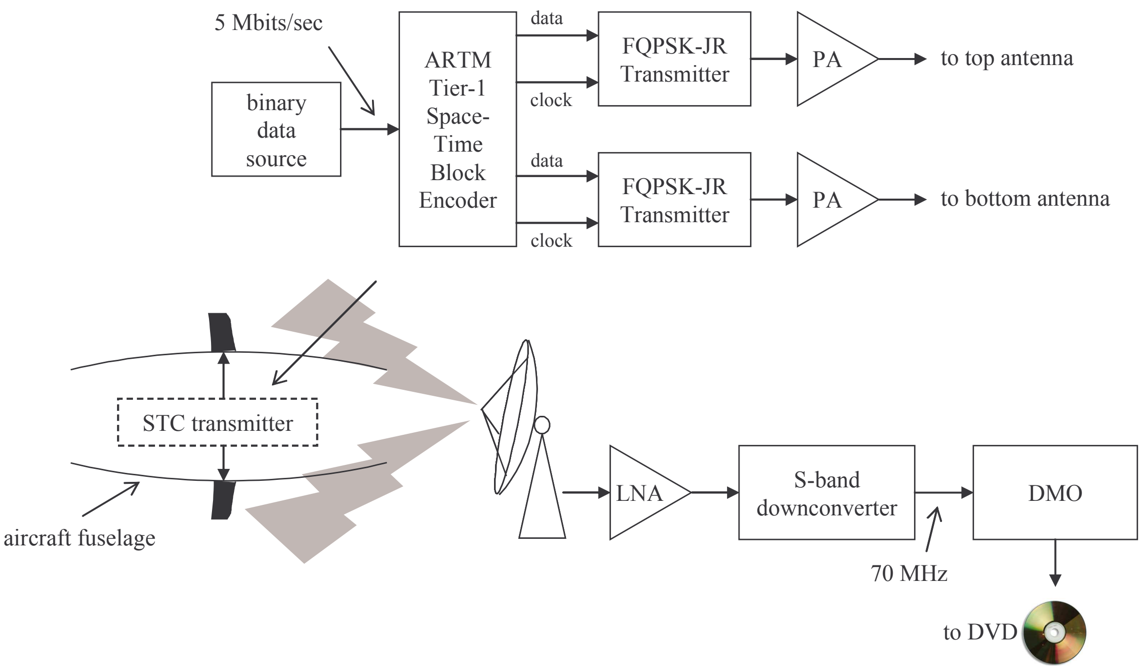

Figure 2: Block diagram of experimental configuration.

Figure 3: The C-12 Beechcraft used in the space-time coding experiments.

The data source used in this experiment was a length-127 PN sequence. The combination of space-time code, a modulation requiring 2 bits/symbol, and differential encoding produced transmitted waveforms from each antenna had a period of 8 ×127 = 1016 bit periods (or 508 symbol periods).

4. Data Processing

A software version of the demodulator and space-time decoder was used to recover the data from the samples of the received waveforms. The basic structure of the algorithms is illustrated in Figure 4. The sampled data files were read from the DVDs, and processed by a quadrature demodulator using an FIR low-pass detection filter. The outputs of the detection filter corresponding to the inphase and quadrature components of the received signal were downsampled to two samples/symbol and processed by the space-time decoder.

The space-time decoder is a sequence estimator that used the Viterbi algorithm based on the trellis described in [1]. Since the signals transmitted from each of the transmit antennas arrive with different delays, the two delays must be estimated. The estimates are a function of the channel gains, which are unknown and must also be estimated. A joint estimator was used to estimate the channel delays and gains. Using the variables identified in Figure 4, the maximum likelihood estimates for the channel delays, $\hat{\tau}_0$ and $\hat{\tau}_1$, and the channel gains, $\hat{h}_0$ and $\hat{h}_1$, are given by

$$0 = \Re\left\{ \hat{h}_0^* \sum_{k=0}^{L-1} \left[a_0(k)\dot{x}(kT_s + \hat{\tau}_0) - jb_0(k)\dot{x}(kT_s + T_s/2 + \hat{\tau}_0) \right] \right\}$$

[6]

$$0 = \Re\left\{ \hat{h}_1^* \sum_{k=0}^{L-1} \left[a_1(k)\dot{x}(kT_s + \hat{\tau}_1) - jb_1(k)\dot{x}(kT_s + T_s/2 + \hat{\tau}_1) \right] \right\}$$

[7]

$$\hat{h}_0 = \frac{1}{2L} \sum_{k=0}^{L-1} \left[a_0(k)x(kT_s + \hat{\tau}_0) - jb_0(k)x(kT_s + T_s/2 + \hat{\tau}_0) \right]$$

[8]

$$h_1 = \frac{1}{2L} \sum_{k=0}^{L-1} \left[a_1(k)x(kT_s + \hat{\tau}_1) - jb_1(k)x(kT_s + T_s/2 + \hat{\tau}_1) \right].$$

[9]

Note that there is no closed form solution for the channel delay estimates. The estimate for $\hat{\tau}_0$ is obtained as follows:

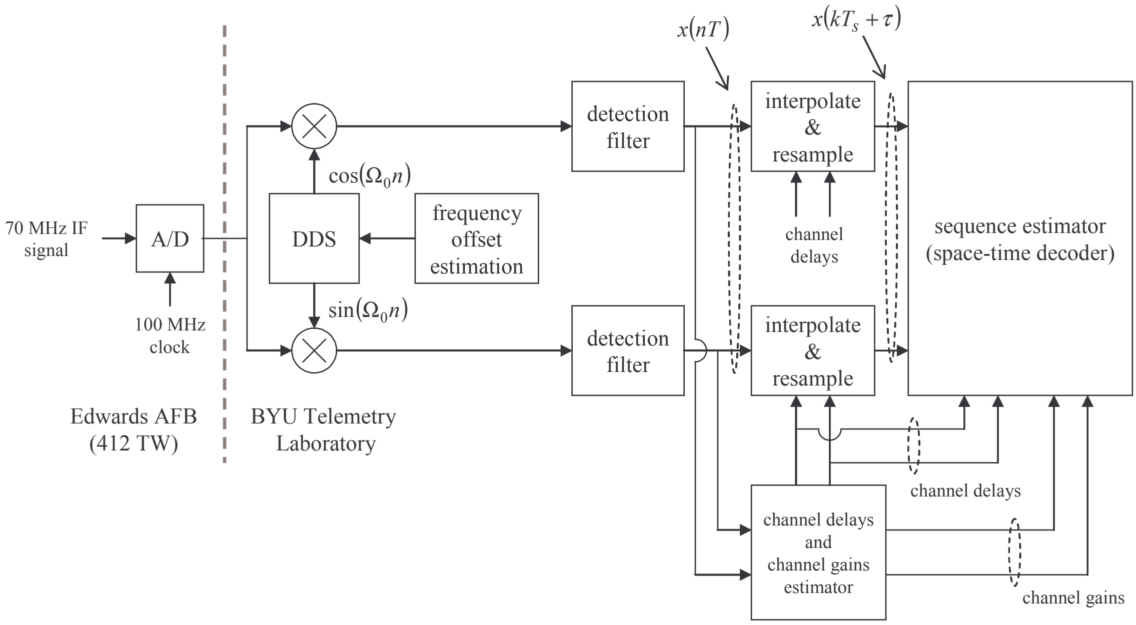

Figure 4: A block diagram of the processing used for the space-time decoder.

1. Substitute the expression for $\hat{h}_0$ given by Equation [8] into Equation [6].
2. Search for the value of τ_0 that forces the equation obtained in the previous step, to zero. This value is $\hat{\tau}_0$. (In the processing results presented in the next section, the search was implemented by quantizing the delay to 40 parts per symbol and evaluating the result of step one for each candidate value. The candidate value that produced the result closest to zero was selected as the estimate. More sophisticated approaches to implementing this search are described in [5].)
3. Using the value of $\hat{\tau}_0$ obtained in the previous step, compute the estimate $\hat{h}_0$ using Equation [8].

The estimates $\hat{\tau}_1$ and $\hat{h}_1$ can be obtained in exactly the same way using Equations [7] and [9].

The estimator is a "data-aided" estimator (e.g., the estimator requires knowledge of a pattern of L known symbols, often called a *training sequence*, embedded in the data transmitted data stream). The presence of a known training sequence was simulated by searching for the beginning of the length-508 symbol pattern and using the first 64 symbols as training symbols. The remainder of the symbols in the cycle were assumed unknown and used to test for decoder errors.

5. Experimental Results

The results of the estimation algorithms for carrier frequency offset, channel gains, and timing delay differentials are plotted in Figure 5 - Figure 8

The frequency offset algorithm performed well. A very small frequency offset (a few hundredths of one per cent of the symbol rate) was observed as illustrated in Figure 5. Since this experiment was not conducted in a laboratory, there is no way to know what the true value was and hence what the accuracy of the estimator was in this case. The value is consistent with properly functioning sources and downconverters. The noise on the frequency estimate is attributed to phase noise in both the transmitter oscillators and the receiver (ground station) oscillators.

The magnitude of the two channel gains, plotted in Figure 6, are fairly close to each other and relative constant during the 19 second window. This is to be expected given the flight path and air-speed of the airborne transmitter. The phase difference between the two channel gains is plotted in Figure 7. We observe that the channel gains are close to 180º out of phase during this portion of the test. As a consequence, the composite channel, plotted in Figure 9, is small. This is the cause of the data drop-outs in traditional two-antenna telemetry systems and is the reason this particular data segment is examined.

The timing delay differential $\Delta\tau = \tau_1 - \tau_0$ is plotted in Figure 8. The differential delay is approximately 1/3 of the symbol time and corresponds to 120 nsec. This value is consistent with the experimental setup: the system geometry, including cable length differences, produces a delay on the order of 10 to 30 nsec. The data formatter used to encode the data included a feature to introduce a controlled offset between the two clock signals driving the two modulators. (This was done to simulate the delay estimator performance at higher data rates.) The clock offset was set at 100 nsec for this experimental run. Thus we expect a delay in the 110 to 130 nsec range.

In all the data segments examined, no decoder errors were observed.

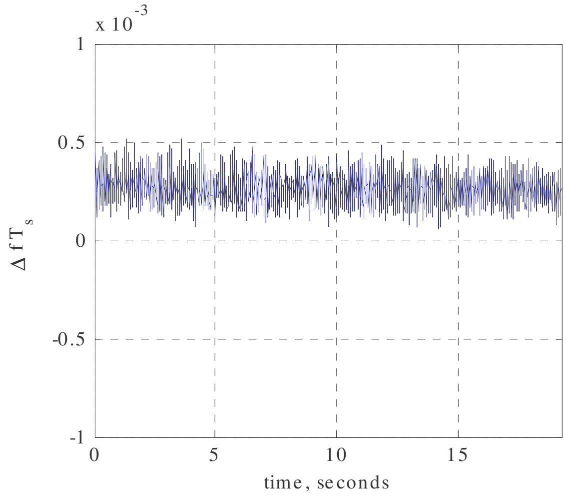

Figure 5: Carrier frequency estimates (normalized to the data rate) for a typical run in the experiments. These estimates correspond to the estimates plotted in Figure 6 - Figure 8.

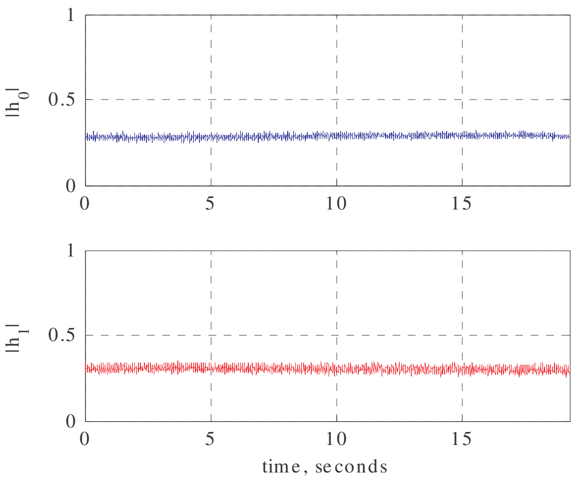

Figure 6: Magnitude estimates of the two channel gains for a typical run in the experiments. These estimates correspond to the estimates plotted in Figure 5 and Figure 7 - Figure 8

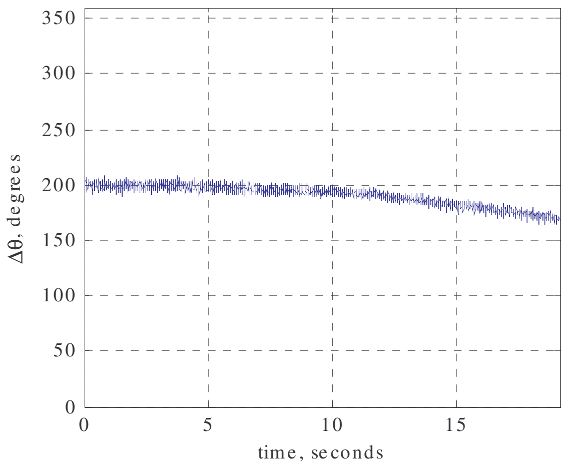

Figure 7: Phase difference estimates for the two channel gains for a typical run in the flight experiments. These estimates correspond to the estimates plotted in Figure 5- Figure 6 and Figure 8.

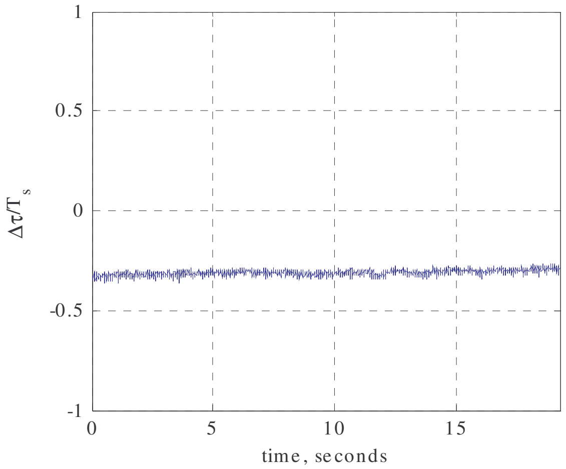

Figure 8: Estimates of the symbol timing offset between the two signals transmitted as part of the space-time coded signal. These estimates are normalized to the symbol rate. These estimates correspond to the estimates shown in Figure 5-Figure 7.

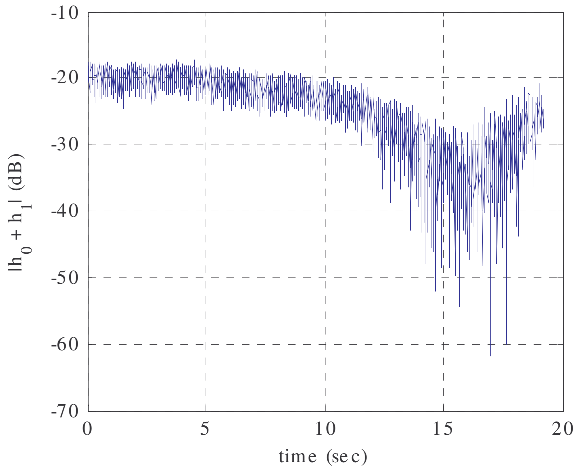

Figure 9: The composite channel for the data run corresponding to Figure 5 - Figure 8.

6. Conclusions

The experimental results demonstrate that transmit diversity, using a properly designed space-time code can be used to achieve reliable, high-rate data transfer in an aeronautical telemetry environment. The space-time code is able to maintain a reliable link, even in the case where the conventional method would experience a drop-out (due to channel gain cancellation).

7. References

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