

SOME INITIAL RESULTS FOR DATA-AIDED EQUALIZER EXPERIMENTS AT EDWARDS AFB

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ABSTRACT

This paper describes the results of flight tests designed to compare data-aided equalization to blind, adaptive equalization using SOQPSK-TG in aeronautical telemetry. The flight tests were conducted on 3 June 2016 at the Air Force Flight Test Center, Edwards AFB, at upper L band (1801.5 MHz) and at C band (4711.5 MHz). Five data-aided equalizers were implemented and compared to a commercially available blind equalizer. In addition, all equalized bit streams were compared to an unequalized reference. The results show that the blind equalizer tends to be either really good or really bad. In contrast, the data-aided equalizers tend to exhibit more graceful degradation. Which equalization method is “best” is not clear as of this writing. The answer depends on a number of factors that will become clear as more data from the experiments is analyzed.

INTRODUCTION

Equalization is one of the methods employed to mitigate distortion due to multipath propagation. The most commonly used type of equalizer is the linear equalizer, which takes the form of an FIR filter. There are two broad classes of linear equalizers:

1. **Data-Aided Equalizers** compute the FIR filter coefficients based on estimates of the equivalent discrete-time channel seen by the equalizer. To enable channel estimation, a known sequence of bits must be periodically inserted in the data stream.
2. **Blind Equalizers** compute the FIR filter coefficients based on some statistical property of the received waveform samples. By far the most common blind equalizer is based on the constant modulus algorithm (CMA). Because blind equalizers do not estimate the equivalent discrete-time channel, periodic insertion of pilot bits is not required. Instead, blind equalizers are adaptive filters that require a convergence period before attaining their optimum form.

To date, commercially available equalization products for SOQPSK-TG are blind, adaptive filters usually based on CMA [1, 2, 3, 4, 5]. The open question is how well *data-aided* equalization might perform in aeronautical telemetry. To answer this question, flight experiments were conducted on 3 June 2016 at the Air Force Test Center, Edwards AFB, using SOQPSK-TG with periodically inserted pilot bits to enable channel estimation on the ground. This paper outlines the results of the preliminary investigation of the data.

EXPERIMENTAL CONFIGURATION

The transmitted signal was SOQPSK-TG [6] modulated by a length-2047 PN sequence with the the iNET preamble (128 bits) and ASM field (64 bits) [7] inserted every 6144 bits. The PN bit rate was 10 Mbits/s. The periodic insertion of the 192 Preamble/ASM bit sequence every 6144 bits increased the over-the-air bit rate to 10.3125 Mbits/s. Two transmitters (one for upper L band and one for C band) were installed on a Beechcraft C-12 twin-engine aircraft and connected to two antennas on bottom of the fuselage. For the flight experiments in this paper, the upper L-band frequency was 1801.5 MHz and the C-band frequency was 4711.5 MHz.

The ground station used for the experiments was Building 4795 at the Air Force Test Center, Edwards, AFB, California. The ground station configuration is summarized by the block diagram in Figure 1. Antenna 6, a 10' parabolic reflector with conscan tracking and a tri-band feed, was used for the experiments. The LHCP antenna output was connected to four test-specific systems:

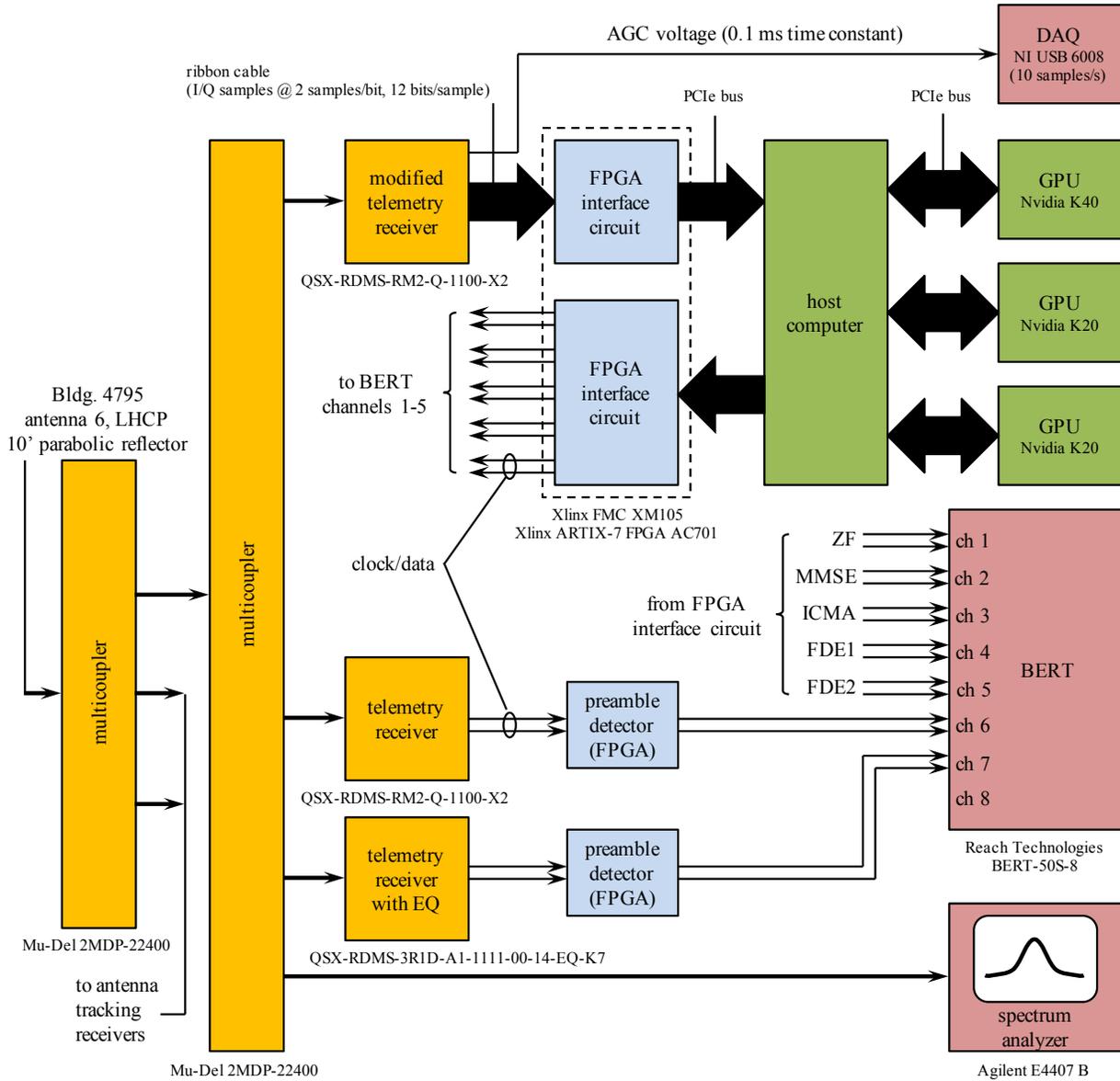


Figure 1: Ground station configuration for the flight tests.

1. A telemetry receiver modified to output I/Q baseband samples on a ribbon cable. The I/Q samples were loaded into three graphics processing units (GPUs) housed in a host computer. The data-aided equalizers, together with the required estimators and detectors, were implemented in the GPUs.
2. A standard telemetry receiver operating in the SOQPSK-TG mode.
3. A telemetry receiver operating in the SOQPSK-TG mode and with a blind equalizer.
4. A spectrum analyzer for recording the spectrum.

The GPUs performed frame synchronization as described in [8, 9, 10], frequency offset estimation as described in [11], channel and noise variance estimation as described in [12, 13], equalization as described below, and SOQPSK-TG detection as described in [14].

The telemetry receivers (connections 2 and 3) were used for comparison purposes. In the Analysis section below, the outputs of these receivers are referred to as “unequalized” and “blind equalized” systems.

Five data-aided equalizers were implemented for these experiments. The zero-forcing (ZF), minimum mean-squared error (MMSE), and initialized constant-modulus algorithm (ICMA) equalizers are described in [15, 16, 17, 18]. The other two equalizers are two versions of a frequency domain equalizer (FDE1 and FDE2) based on the MMSE principle and exploiting the periodic nature of the iNET preamble [7] to eliminate the need for a cycle prefix.

The system in Figure 1 captured the AGC voltage, the bit error statistics for the seven systems operating in parallel, and the RF spectrum of the received signal. The bit error statistics were computed by the Reach Bit Error Rate Tester (BERT). The BERT updates its information every second. In addition to the number of bit errors observed in the one second interval, the BERT also tracks the loss of pattern synchronization each second (called a “pattern loss second” or PLS) and indicates whether or not the one-second interval constitutes a “severely-errored second” (SES).¹

The unequalized and blind equalized systems do not use, and are therefore unaware of, the preamble and ASM bits. Consequently, neither the unequalized nor the blind equalized system removes the preamble and ASM bits. This necessitates the need for a circuit to find the preamble and ASM in the bit stream at the demodulator output. This circuit, labeled “preamble detector” in Figure 1 and described in [19], declares the preamble and ASM fields “found” after three occurrences of the bit patterns 6144 bits apart. (This was done to avoid erroneously identifying the start of the preamble and ASM with a sequence of data bits.) The implications on the presence of this circuit are discussed in the Analysis Section.

EXPERIMENTAL RESULTS

The test flight that generated the data in this paper was conducted on 3 June 2016. Consequently, only an initial assessment of the data obtained during the test flight is performed in this paper. The Black Mountain test point, shown by the horizontal flight paths in Figures 3, 5, 7, and 9 is the focus

¹In aeronautical telemetry, a “severely-errored second” or SES is defined as a one-second interval during which the measured bit error rate exceeds 10^{-5} .

of this paper.

For the west-to-east Black Mountain flight path at 1801.5 MHz, the recorded AGC voltage and measured bit error rate are plotted in Figure 2. The corresponding flight path is plotted in Figure 3. The markers on the flight path are “error events” captured by the BERT. (For the purposes of this analysis, an “error event” is defined by occurrence of a non-zero bit error rate during a one-second interval.) For this test run, there are five error events, labeled “Event A,” “Event B,” and so on. The locations corresponding to the error events are indicated by the markers along the flight path in Figure 3. A summary of the measured error statistics for each error event in this test point are listed in Table 1. In this Table “EQ” means equalizer type, “SES” stands for severely-errored second, “PLS” stands for pattern-loss second, “LA” stands for Link Availability as defined by Jefferis [20], and “TBE” stands for total bit errors. Figures 4 and 5 along with Table 2 comprise the summary for the west-to-east Black Mountain flight path at 4711.5 MHz. Figures 6 and 7 along with Table 3 comprise the summary for the east-to-west Black Mountain flight path at 1801.5 MHz. Figures 8 and 9 along with Table 4 comprise the summary for the east-to-west Black Mountain flight path at 4711.5 MHz.

ANALYSIS

For the purpose of reducing the large data set to a manageable size, we restrict our attention to those cases where the unequalized link exhibits errors. The “error events” are obvious in Figures 2, 4, 6, and 8. The locations of these events are plotted on the maps in Figures 3, 5, 9, and 7, respectively. The first observation that stands out from Figures 3, 5, 9, and 7 is that multipath interference can happen anywhere. Multipath propagation is largely a geometric phenomenon where the geometry is defined by the aircraft, ground station, and reflecting surfaces (the ground or close-by background mountains) [21]. The interesting observation here is that simply changing the direction of flight alters the geometry enough to change the locations of the multipath events: compare Figures 3 and 7 for upper L band and Figures 5 and 9 for C band. Also note the change in locations of the multipath events as a function of carrier frequency. For this reason, comparisons between the behavior of equalizers at upper L and C bands (in the sense of propagation to the ground station from a fixed location in space) is not possible. But some general conclusions are possible.

The comparison here focuses on the performance of the following three classes: 1) data-aided equalization (ZF, MMSE, ICMA, FDE1, and FDE2 equalizers described in the Experimental Configuration Section), 2) blind equalization, and 3) unequalized systems. There are two main chal-

lenges with a comparison. The first is that the data-aided equalized systems are fundamentally different from the non-equalized and blind equalized systems. The source of this difference is the packetized nature of the data-aided equalized systems. Here, “packetized” means the 6144 bit data field is associated with the preceding iNET preamble and ASM bits. When something goes wrong with the data-aided equalizers, the system must wait until the next occurrence of the preamble and ASM bit fields to correct itself. This is in contrast to the unequalized and blind systems: they are able to correct themselves as soon as channel conditions permit, and this often takes only a few hundred bits as opposed to several multiples of 6144 bits.

The second main challenge is a natural consequence of the first. The unintended (and unavoidable) consequence of the insertion of “preamble detection” circuit between the demodulator output and the BERT input (see Figure 1) is that it lengthens the resynchronization time of the unequalized and blind equalized systems. This bias can add an additional second to the number of PLS’s for the unequalized and blind equalized systems.

The reader should keep these facts in mind while reading the following analysis.

The data in Tables 1 – 4 demonstrate that, for the most part, the blind equalizer has more PLS’s but fewer SES’s than the data-aided equalizers. Part of this is due to the insertion of the preamble detection circuit described above. But this observation is also a fundamental characteristic of the blind equalizer. When the blind equalizer encounters a situation it cannot handle, it tends to produce a lot of errors, hence the relatively high error count shown in the tables and the high number of PLS’s. But because the blind equalizer does not have to wait until a packet boundary to recover, the blind equalizer recovers more quickly than the data-aided equalizer, hence the lower number of SES’s.

CONCLUSION

In conclusion, the blind equalizer tends to be either really good or really bad. In contrast, the data-aided equalizers tend to exhibit more graceful degradation. Which equalization method is “best” is not clear as of this writing. The answer depends on a number factors that will become clear as more data from the experiments is analyzed.

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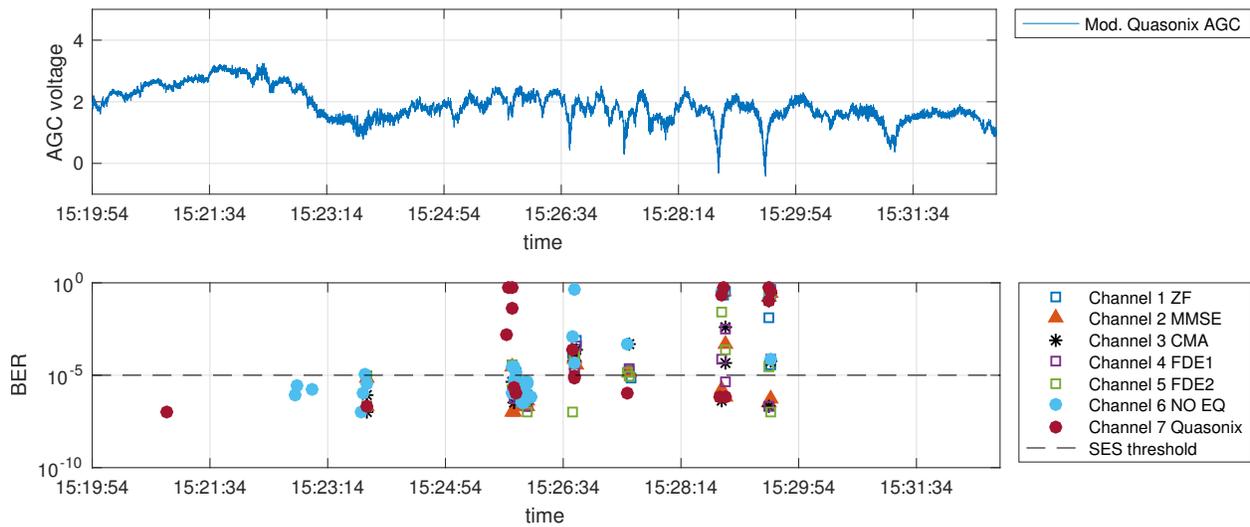


Figure 2: The measured AGC and BER corresponding to the entire west-to-east Black Mountain flight path at 1801.5 MHz.

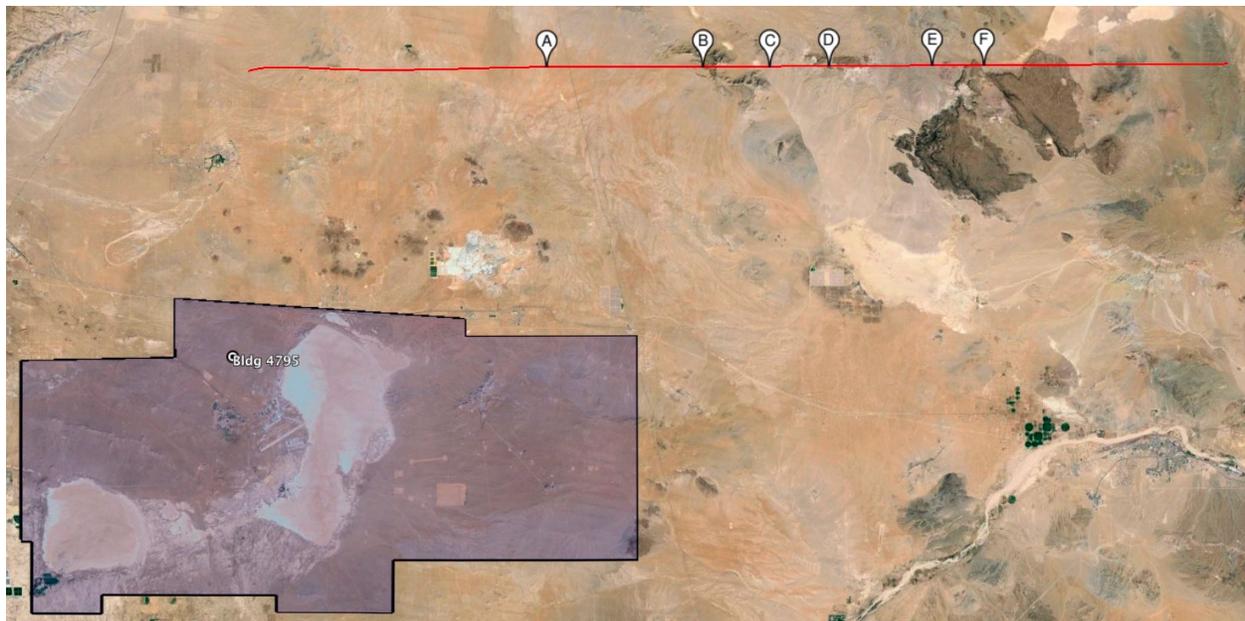


Figure 3: The west-to-east Black Mountain flight path at 1801.5 MHz. The markers show the locations of the registered multipath events (cf., Figure 2).