

ENHANCING THE PCM/FM LINK - WITHOUT THE MATH

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ABSTRACT

Since the 1970s PCM/FM has been the dominant modulation scheme used for RF telemetry. However more stringent spectrum availability as well as increasing data rates means that more advanced transmission methods are required to keep pace with industry demands. ARTM Tier-I and Tier-II are examples of how the PCM/FM link can be enhanced. However these techniques require a significant increase in the complexity of the receiver/detector for optimal recovery.

This paper focuses on a quantitative approach to improving the rate and quality of data using existing PCM/FM links. In particular ACRA CONTROL and BAE SYSTEMS set themselves the goal of revisiting the pre-modulation filter, diversity combiner and bit-sync. By implementing programmable adaptive hardware, it was possible to explore the various tradeoffs offered by modifying pulse shapes and spectral occupancy, inclusion of forward error correction and smart source selection. This paper looks at the improvements achieved at each phase of the evaluation.

KEYWORDS: PCM/FM, Spectral Efficiency, Forward Error Correction, Best Source Selection.

1 INTRODUCTION

As flight test instrumentation becomes more sophisticated it has become increasingly desirable to have a high quality, high speed telemetry link between the aircraft and the ground monitoring station. PCM/FM has been the primary modulation scheme used for such links for over 30 years, mainly due to its simplicity and reliability. Due to the longevity of PCM/FM, most airborne telemetry facilities have invested significant capital in equipment specifically for use with this standard.

It is only in recent years that new modulation techniques (such as the ARTM Tier-I and Tier-II schemes) have been proposed in a standardized form with the goal of improving the spectral efficiency of these telemetry links. Although these modulation methods do accomplish this goal, optimal implementations require significantly more complex modulators, demodulators and detection schemes than those for PCM/FM as well as typically requiring longer lock times.

As part of discussions between BAE SYSTEMS and ACRA CONTROL, a proposal was made to evaluate ways to modify the traditional PCM/FM link to improve link quality and/or throughput. The intention is to compare the improved implementation against a Tier-I demodulator in terms of bit error rate, spectral efficiency, synchronization/lock time and tolerance of signal distortions such as frequency selective multipath. This paper describes the first phase of investigations in which the PCM/FM improvements were developed and evaluated.

2 TEST HARDWARE

The techniques and experiments described in this paper were tested on hardware developed by ACRA CONTROL. The two main components used in the hardware tests are described below.

2.1 Programmable Pre-modulation Filter

The ENC/106 is a module for the KAM-500 data-acquisition system that integrates a versatile PCM encoder with a programmable pre-modulation filter (PMF). Under normal circumstances the PMF is programmed to implement a 6th-order linear phase (Bessel) filter.

In addition to allowing variable bit rates and output amplitudes the PMF also facilitates changing the filter type used. This means pulse-shaping filters that are difficult or impossible to generate using analog circuitry (such as Gaussian, sinc and root-raised cosine) are straightforward to implement in the ENC/106.

2.2 Programmable Bit Synchronizer

The all-digital programmable bit synchronizer is part of a PCI bitsync/decomm board called the GTS/DEC/003 and its structure is shown below.

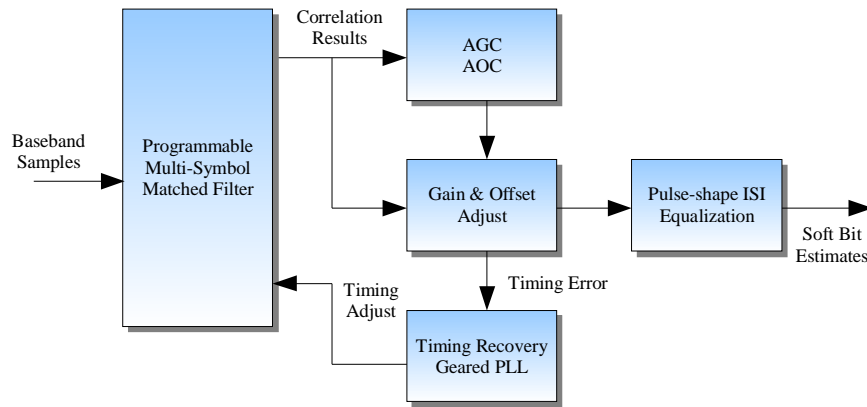


Figure 1 : Structure of the programmable bit synchronizer

The key to the flexibility of the bitsync is the programmable matched filter. As with the PMF described above, the matched filter can facilitate any pulse shape up to eight symbols wide. In the same way, the pulse-shape inter-symbol interference (ISI) equalization can be tailored according to the severity of the ISI in the chosen pulse shape. In addition the bitsync is implemented in a modular fashion, allowing multiple channels to be accommodated with relative ease.

3 LINK IMPROVEMENTS

This section describes the techniques that were used for improving the PCM/FM link.

3.1 Smart Source Selection

Many PCM/FM links include some form of transmit or receive diversity. Diversity is a method of improving link quality by transmitting or receiving two or more versions of a signal and adaptively combining or selecting the best signal so that the resultant bit error rate is lower than for any one version of the signal alone. There are a variety of schemes for separating the diversity signals including spatial diversity, frequency diversity and polarization diversity.

In PCM/FM systems diversity combining is often performed at the IF frequency based on relative noise power in the received signals – this is known as pre-detection diversity combining. Other forms attempt to weight two or more demodulated streams of data at baseband frequencies (called post-detection combining) or use metrics such as lost sync words or baseband noise level to dynamically switch between streams (called best source or best data selection). For this paper we use a form of source correlation called maximum ratio combining (MRC) as shown below.

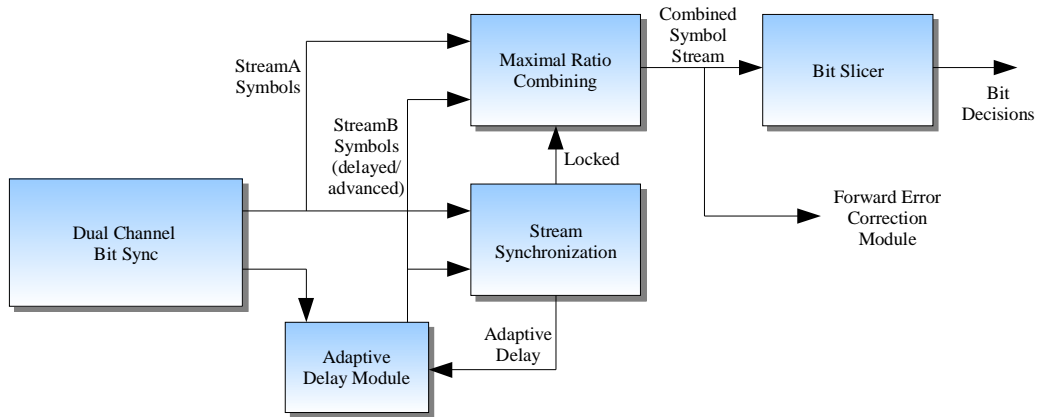


Figure 2 : Structure of the MRC module

A dual channel bitsync is used to recover soft symbol values from two diversity streams of baseband samples. The independent symbol streams are then synchronized in time by applying an adaptive delay to one stream. This stream synchronization operates on a continuous basis such that if the path delay for one of the streams changes the system remains in lock. Soft bit values for each received symbol are then combined using a maximal ratio technique to provide a single soft symbol on which bit decisions are made.

The MRC scheme has the advantage of being highly integrated, decreasing the system cost and complexity. The system is also very robust and is currently capable of synchronizing data streams that are separated by up to 256 bits. In addition, the combined soft symbol estimates can be used directly in a forward error correction (FEC) decoder, thus enabling both link improvement techniques to be used simultaneously.

3.2 Pulse Shaping

A typical PCM/FM transmitter assembly consists of a PCM encoder, pre-modulation filter, FM transmitter and transmit antenna. A pre-modulation filter may be thought of as component that accepts a sequence of impulses generated from the data stream and filters these impulses for the purpose of spectral containment after modulation.

Traditional pre-modulation filters are implemented using analog components and as such are limited to a specific characteristic and data rate. However implementing an all-digital pre-modulation filter as described in section 2.1 provides a greater degree of integration, thus saving on space and equipment costs. This type of filter has the capability of handling multiple data rates and variable output amplitude. Moreover the digital nature of the filter allows selection of virtually any pulse-shape. The following pulse shapes are examined in this paper:

- PCM/FM 6th-order Bessel Filter (also known as ARTM Tier-0)
 - This filter type accepts antipodal impulses from the set $\{+1, -1\}$ and has a raised cosine impulse response.
- Binary Root-Raised Cosine pulses (BRRC)
 - This filter type accepts antipodal impulses from the set $\{+1, -1\}$ and has a root-raised cosine impulse response.
- Quaternary Root-Raised Cosine (QRRC)
 - This filter type accepts impulses from the set $\{+3, +1, -1, -3\}$ and has a root-raised cosine impulse response (as for BRRC). Thus a pair of bits are combined to make a single symbol.
 - Encoding of symbols from bits uses a grey coding scheme. This means that a symbol error is most likely to result in only a single bit error.

The major advantage of the root-raised cosine pulse shapes is that when filtered by the same shape (as in the matched filter of a bit synchronizer) there is no inter-symbol interference (ISI) at multiples of the symbol period from the ideal sampling point. This fact removes the requirement for ISI equalization that is necessary for other pulse shapes. An example of each of the pulse shapes used is shown below, with average pulse amplitudes normalized to equalize bit energy.

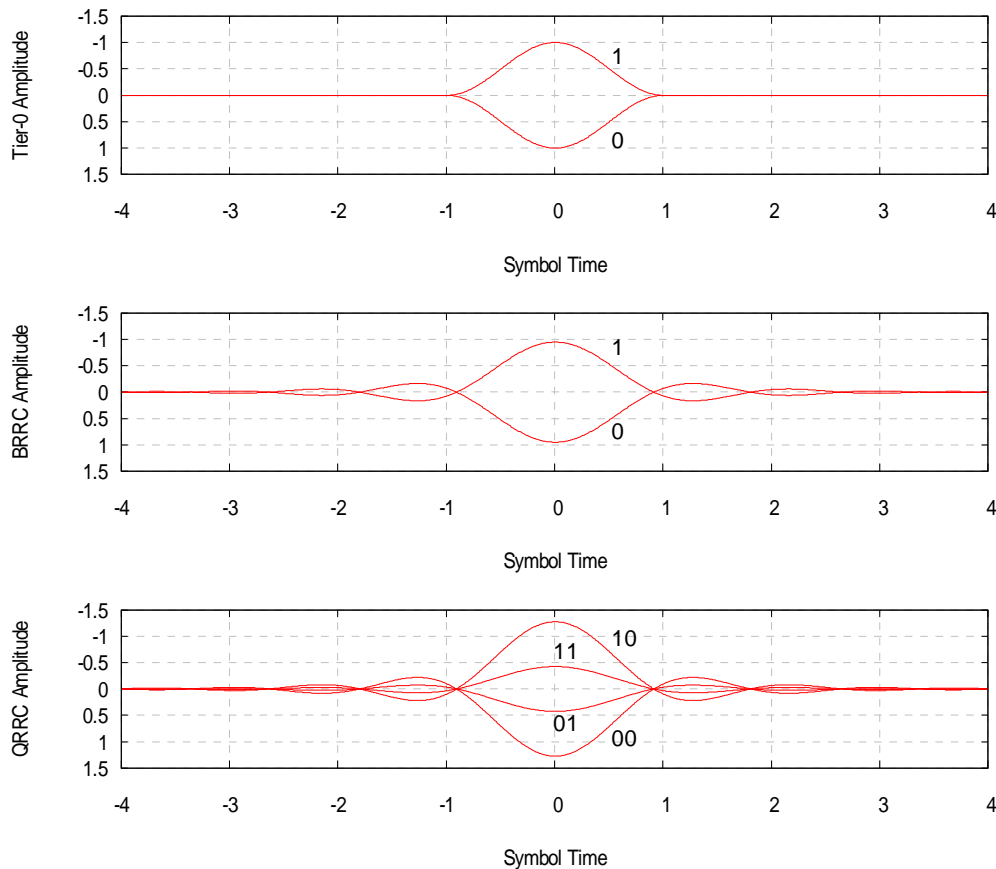


Figure 3 : Pulse shapes for Tier-0, BRRC and QRRC showing each possible pulse variation.

3.3 Forward Error Correction (FEC)

There are a variety of FEC codes in use in wireless communications systems today, including many variants of convolutional codes, turbo codes and low density parity check (LDPC) codes. All of these techniques rely on adding some redundancy to a stream of data so that the receiver can detect and correct a proportion of the errors that occur during transmission.

The code used for this paper is a half-rate convolutional code with $k=7$ which is widely used in telemetry products today. This code type has the advantage of using a very simple encoder (thus reducing airborne hardware complexity) and is a streaming code so that no framing is required. This allows resynchronization to occur rapidly after a reception outage.

4 RESULTS AND ANALYSIS

4.1 Pulse Shape Analysis

An identical sequence of bits filtered by the three pulse shapes is shown in Figure 4 below. The amplitudes are normalized to equalize the bit energy for each pulse type.

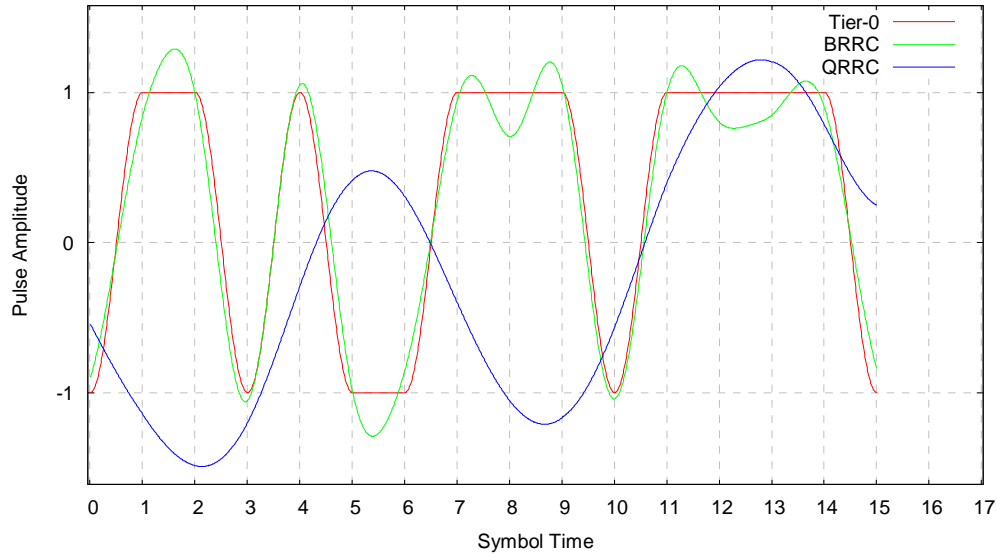


Figure 4 : Sequences of filtered data for Tier-0, BRRC and QRRC filter types.

Note that because the QRRC pulses have four levels, two bits are encoded for each symbol. This means that for a given transmission bit rate, the symbol rate for QRRC pulses is half that for Tier-0 or BRRC pulse shaping. Conversely, it is possible to double the transmission bit rate for QRRC by making the symbol rate equal to that of the binary signalling methods. This is the approach we shall use for the remainder of the paper.

The principle advantage of QRRC pulse shaping is that the transmitted bit rate can be doubled without increasing the spectral occupancy. In order to demonstrate this a simulated plot of Tier-0, BRRC and QRRC modulation for a 4 Msymbol/s data stream is shown in Figure 5 below. For Tier-0 and BRRC this equates to a 4 Mb/s data rate. For QRRC, the data rate is 8 Mb/s.

Note that it was necessary to tailor the modulation index in order to achieve an optimal combination of bandwidth and peak power for both BRRC and QRRC. This is a straightforward task with a programmable pre-modulation filter that has variable output amplitude.

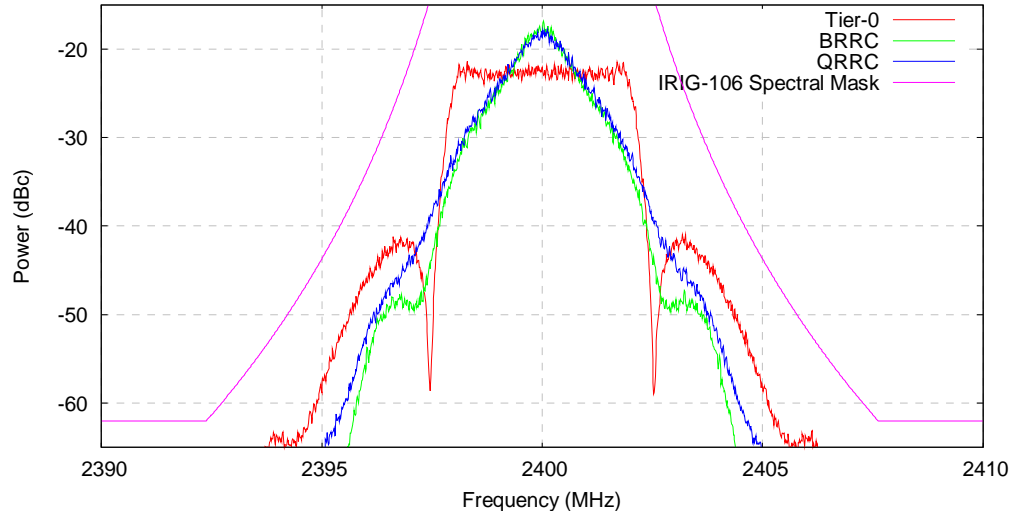


Figure 5 : PCM/FM modulated RF spectra for Tier-0, BRRC and QRRC modulation types.
Note that the raw bit rate for QRRC is double that of the other pulse shapes.

Measured 99% bandwidths for the spectral plots are as follows:

- Tier-0: 4.51 MHz
- BRRC: 4.01 MHz
- QRRC: 4.49 MHz

Note that spectral occupancy is roughly the same for Tier-0 and QRRC modulation types (although the peak power is somewhat higher for the latter), even though the raw bit rate for QRRC is double that of the other two pulse shapes.

4.2 BER Results

In order to evaluate the link improvements introduced in previous sections a series of tests was performed across a range of noise conditions. Software was developed on a PC platform to generate simulator data with additive white Gaussian noise (AWGN). This data was sampled and streamed into the bitsync on the board, bypassing the frontend ADC. decommutated frames were sent to PC memory and checked for errors in software.

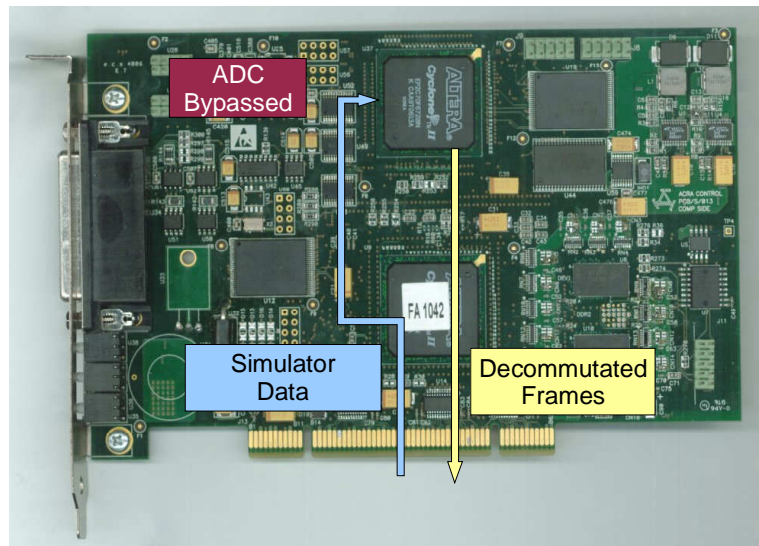


Figure 6 : GTS/DEC/003 showing simulator data paths

4.2.1 Tier-0 and BRRC with MRC

The plot below shows the BER performance of the bitsync for Tier-0 and BRRC pulse shapes with and without maximal ratio combining. The bit rate in each case was 4 Mb/s.

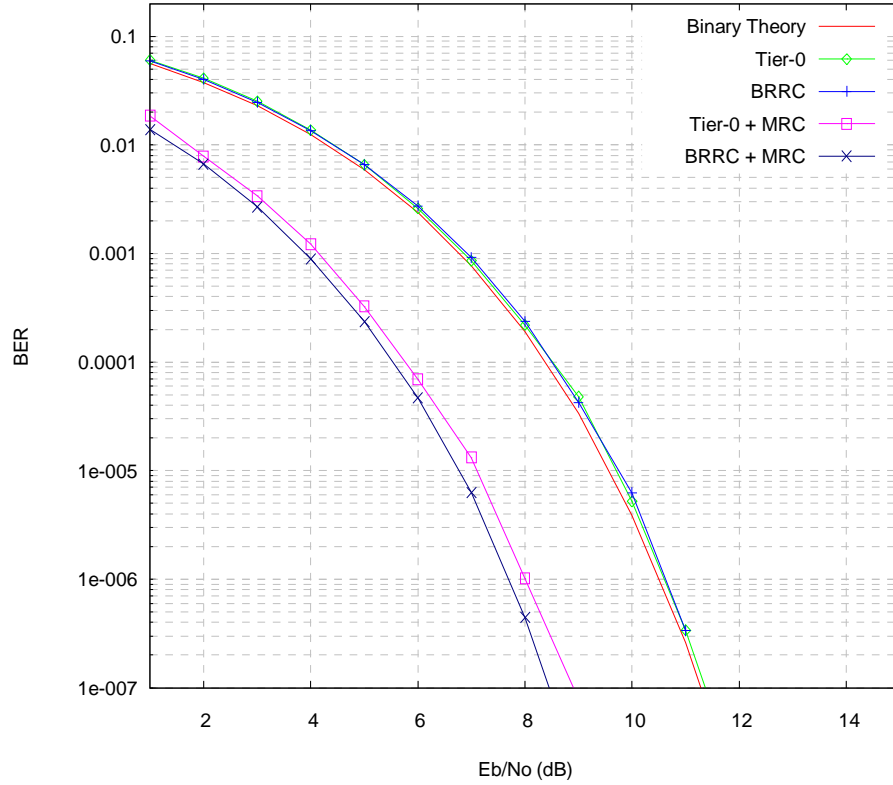


Figure 7 : BER performance for Tier-0 and BRRC pulse shapes with and without MRC

It is observed that performance of the Tier-0 and BRRC pulse shapes are both within 0.1 dB of binary theory in the absence of MRC. With MRC, the performance is improved by between 2.5 dB and 3 dB. Note that the MRC improvement exists down to an E_b/N_0 of 1 dB, demonstrating that the MRC stream synchronization functions well even in very noisy conditions.

4.2.2 QRRC with MRC

The plot below shows the BER performance of the QRRC pulse shape with and without maximal ratio combining. The bit rate for this pulse shape was 8 Mb/s, even though the spectral occupancy is the same as for the 4 Mb/s Tier-0 and BRRC pulse shapes in the previous section.

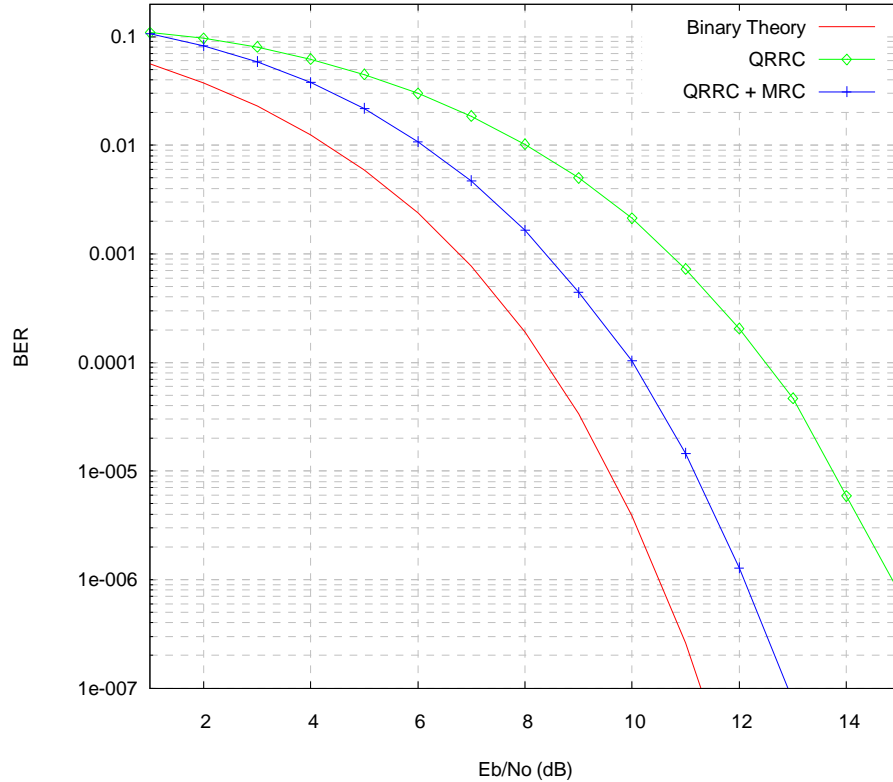


Figure 8 : BER performance for QRRC pulse shape with and without MRC

As predicted by M-ary PAM theory the Quaternary RRC pulse shape incurs a degradation of just over 4 dB. However using MRC more than halves this degradation to just under 2dB at a bit error probability of 10^{-6} . Note however that in contrast to the binary pulse shapes (Tier-0 and BRRC above), the BER performance converges at lower values of E_b/N_0 . This reflects the difficulty in synchronizing the two data streams.

Note that although the BER performance is degraded somewhat, QRRC pulse shaping allows twice the data to be transmitted for the same degree of RF spectral efficiency. Thus QRRC pulse shaping is ideal for relatively low noise environments where there already exists a large RF link budget excess.

4.2.3 QRRC with MRC and CFEC

The plot below shows the BER performance with a combination of maximal ratio combining and convolutional forward error correction. In this set of simulations a half-rate convolutional code was used to encode the data. Although the raw data rate remained at 8 Mb/s, the net information rate was 4 Mb/s due to the encoding overhead.

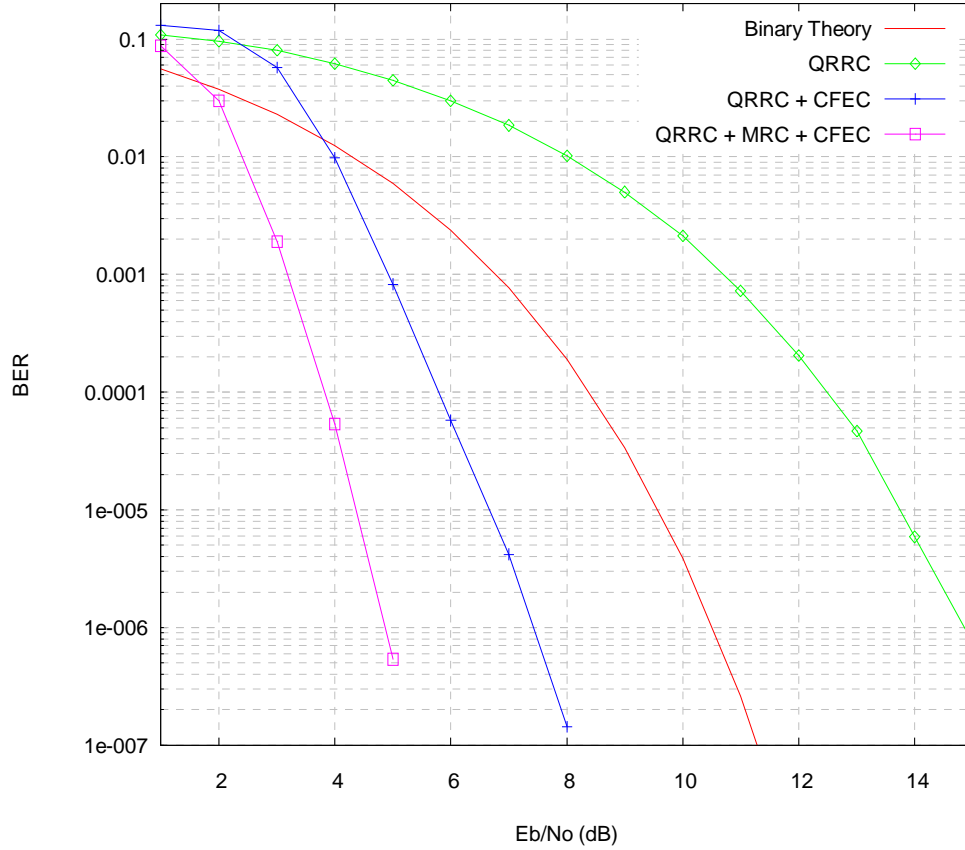


Figure 9 : BER plots for QRRC pulse shaping with MRC and CFEC.

It is observed that by using QRRC to double the raw bit rate and then using the additional throughput for forward error correction, BER performance can be improved by more than 3 dB at a bit error probability of 10^{-6} . This improvement is increased to 6 dB when using maximal ratio combining. It should be noted however that these improvements are not consistent down to low E_b/N_0 values, again due to the difficulty of synchronizing the two streams when they contain a large proportion of bit errors.

5 FURTHER WORK

The results shown in this paper represent the first phase in an evaluation of PCM/FM link improvement techniques. In order to quantify these improvements in context, future work will include series of comparisons against ACRA CONTROL's ARTM Tier-I demodulator in the following areas:

- BER Performance
- Spectral Occupancy
- Link budget requirements
- Resynchronization time & link availability
- Performance with distortion (e.g. multipath fading)

6 CONCLUSIONS

This paper illustrates a number of techniques designed to improve the PCM/FM link. Using a combination of a quaternary root-raised cosine pulse shape, maximal ratio combining and forward error correction it is possible to vary aspects of throughput and bit error rate performance according to the operating environment.

A summary of the system setup may be described as follows:

- Identical Infrastructure
The RF link can use the same transmitter, the same receiver and the same antenna setup both on the aircraft and at the groundstation.
- Identical RF Spectrum
As illustrated in section 4.1 the spectral occupancy of the QRRC pulse shape is slightly less than that of Tier-0 pulse shaping for double the raw bit rate.
- Inherently Interoperable
The bitsync and pre-modulation filter used were designed for Tier-0 pulse shaping and remain unchanged for BRRC and QRRC except for new filtering coefficients. Thus the hardware remains inherently backward-compatible with Tier-0 operation.

A system operator may use QRRC pulse shaping and choose from the following operating scenarios:

- a) Data rate remains the same
 - A BER improvement of 3 dB is achieved for a bit error probability of 10^{-6} , or 6 dB in the case that MRC is used.
 - This scenario is useful for noise-prone environments
- b) Data rate is doubled
 - A degradation of 4 dB is observed, reduced to 2 dB when MRC is used.
 - This operating scenario is useful for low-noise environments where spectral occupancy and data rate must be optimized.

7 REFERENCES

- [1] Proakis, John G., "Digital Communications", Fourth Edition, McGraw Hill, 2001, pp 264-267.
- [2] Range Commanders Council Telemetry Group, "IRIG Standard 106-04: Telemetry Standards", Range Commanders Council, White Sands Missile Range, New Mexico, 2004, Appendix A (Available on-line at <http://www.ntia.doc.gov/osmhome/106.pdf>).