EXPERIMENTAL RESULTS FOR PCM/FM, TIER 1 SOQPSK, AND TIER II MULTI-H CPM WITH CMA EQUALIZATION

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ABSTRACT

It is widely recognized that telemetry channels, particularly airborne channels, are afflicted by multipath propagation effects. It has also been shown that adaptive equalization can be highly effective in mitigating these effects. However, numerous other factors influence the behavior of adaptive equalization, and the type of modulation employed is certainly one of these factors. This is particularly true on modulations that exhibit different operating bandwidths. Computer simulations using the Constant Modulus Algorithm (CMA) have recently been reported for PCM/FM, ARTM Tier 1 SOQPSK, and Tier II SOQPSK. These encouraging results have led to a hardware implementation of a CMA equalizer. This paper presents the latest results from this work.

KEY WORDS

Adaptive Equalization, CMA, PCM/FM, Tier 1, SOQPSK, Tier II, Multi-h CPM

INTRODUCTION

The objective of this effort is to evaluate the benefit of adding adaptive equalization to three telemetry waveforms, namely legacy PCM/FM, Tier 1 SOQPSK, and Tier II Multi-h CPM. In particular, this paper investigates the performance gains attainable with a constant modulus algorithm (CMA) equalizer. Since CMA bases its adaptation solely on the modulus (or envelope) of the signal, it is particularly attractive because it is applicable to all three waveforms. Simulation results from [1] with static multipath showed that a dramatic reduction in signal distortion, typical of air-to-ground telemetry links, was attainable with adaptive equalization. This improvement was quantified in terms of the mean squared error (MSE) as compared to an uncorrupted signal. Improvements on the order of 10 to 20 dB were typical depending on the modulation type, data rate, time delay, and notch position. To evaluate the equalizer's effectiveness with real-time signals, a programmable hardware implementation was embedded into Nova's MMD44 multi-mode demodulator. At the time of this submission, only the PCM/FM and Tier 1 SOQPSK modes have been integrated with the equalizer. Therefore, results for the Tier II Multi-h CPM are not yet available.

Measurements of the performance with and without equalization will be presented to determine, 1) loss due to having the equalizer activated if no multipath is present, 2) performance improvement in static and dynamic multipath environments typical of airborne telemetry channels, 3) relationship between improvements in MSE (mean squared error) and bit error probability (BEP).

MULTIPATH CHANNEL CHARACTERISTICS

Based on channel sounding results from [2], it has been determined that the wideband aeronautical telemetry channel is dominated by a line of sight path plus a strong specular reflection with a relative amplitude of 70% to 96% and a delay of 10-80 ns. Therefore, a two-ray model consisting of a signal, reflection, and noise ($r(t) = s(t) + \Gamma s(t-\tau) + n(t)$) will be used in the hardware evaluation of the equalizer. Figure 1 (reprinted with permission from [3]) shows the magnitude of the frequency response H(f) for this channel. Frequency selective notches occur at intervals equal to the reciprocal of the time delay τ with the depth and offset being determined by the magnitude $|\Gamma|$ and phase θ of the reflection coefficient. Multipath testing was conducted with both strong-short delays ($\Gamma=0.9, \tau=0.2T_b$) and weak-long delays ($\Gamma=0.9, \tau=2T_b$). However, since the weak-long delay condition only caused a very small amount of degradation, with or without the equalizer, it was not tested further. All the following results are for channels with a strong specular reflection ($\Gamma=0.9$).

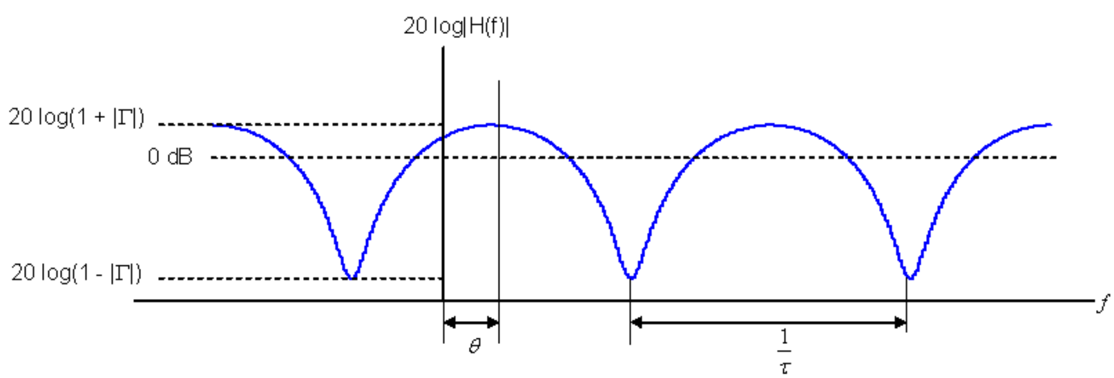

Figure 1. Frequency Response of Multipath Channel.

WAVEFORM DESCRIPTIONS

Several recent papers have been published describing these particular modulations [4] [5] [6], so they will only be briefly described here. The objective of the Tier 1 and Tier II waveforms was to improve the spectral efficiency as compared to legacy PCM/FM while maintaining similar detection efficiency. Figure 2 shows the measured BEP performance of the three modes and demonstrates that PCM/FM (with traditional detection), SOQPSK, and Multi-h CPM all require around 13 dB Eb/No to achieve an error rate of 10^{-6}. However, if a more sophisticated multi-symbol detector is used with PCM/FM, the performance can be improved by roughly 3 dB.

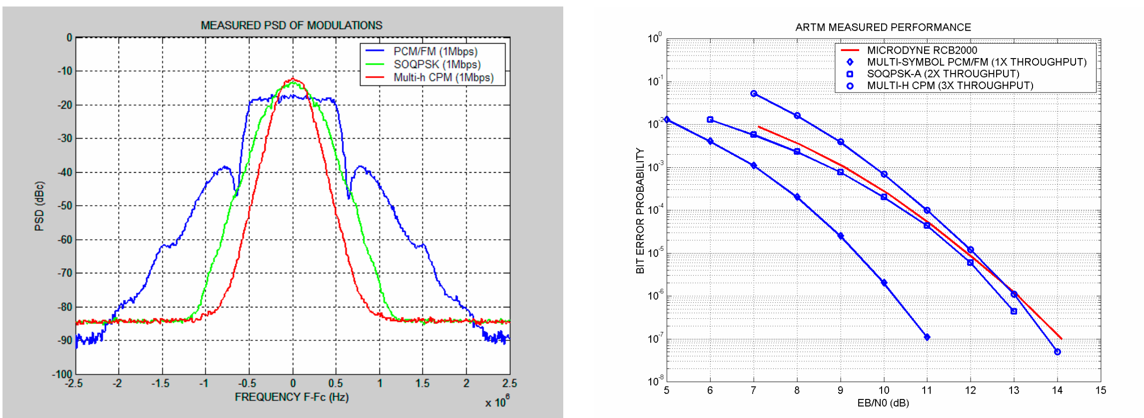

Figure 2. PSD and BEP performance of the modulations.

HARDWARE SETUP

The equalizer performance was evaluated using real-time hardware measurements. A modified digital processing board (from a MMT28) was used to generate a 5 Mbps multipath corrupted signal at an IF frequency of 70 MHz. This circuitry synthesizes the modulated signal (line-of-site path) plus a time-shifted, scaled, and complex rotated version (reflection) to produce the desired multipath test signal. Noise was then added using an analog noise source and passed to a MMD44 Hypermod demodulator with embedded CMA equalizer. Measurements were taken with the equalizer enabled and disabled and the performance was evaluated using bit error rate statistics along with analysis of the waveform samples at various points within the demodulator. A Fireberd 6000A bit error rate tester and logic analyzer were used to collect the data. A diagram of the hardware setup is shown in Figure 3.

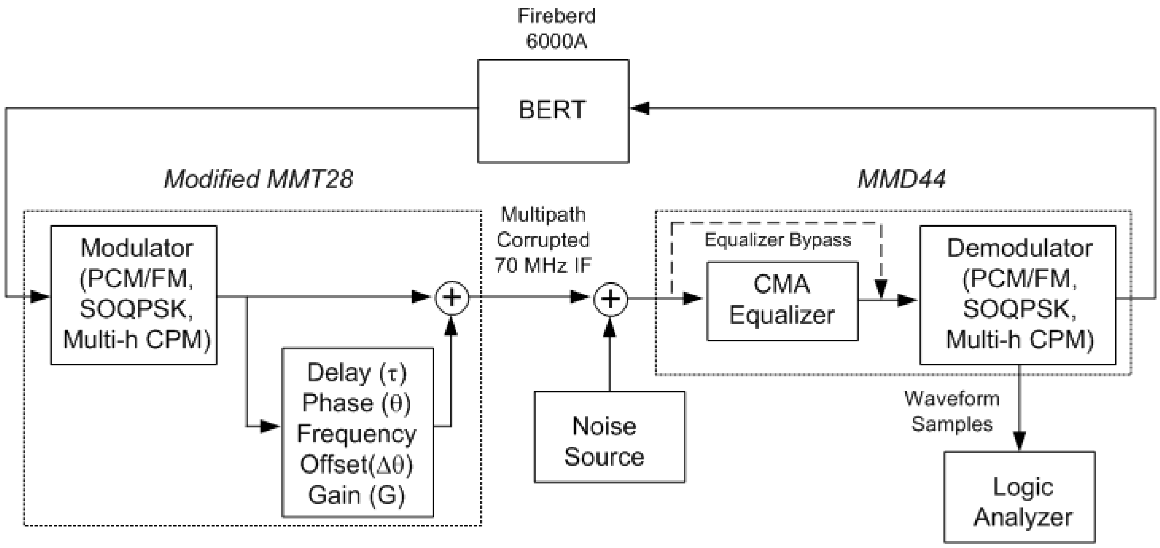

Figure 3. Configuration for Hardware Measurements

BASELINE PERFORMANCE WITH NO MULTIPATH

To establish a performance baseline, BEP curves of PCM/FM and SOQPSK without multipath were measured and are shown in Figures 4 and 6. They show that when no multipath is present, having the equalizer turned on costs less than 0.5 dB, as compared to the case when the equalizer is off. This is a reasonable trade since it will be shown in later sections that the equalizer can outperform the unequalized case by 10's of dB when severe multipath is present. A single set of equalizer parameters was used for all testing (no multipath, static and dynamic multipath) since it is envisioned that equalizer would be enabled all the time. Figures 3 and 5 show a typical PCM/FM eye diagram and a SOQPSK constellation for reference purposes.

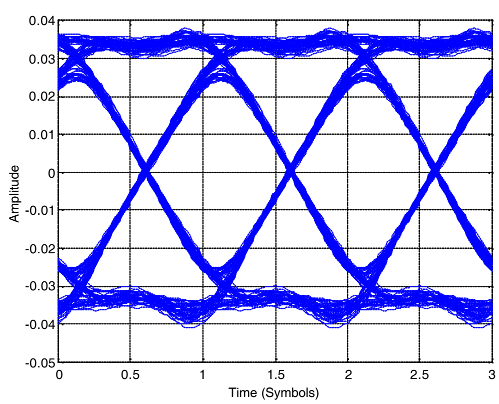

Figure 3. Measured PCM/FM Eye Pattern (No Multipath)

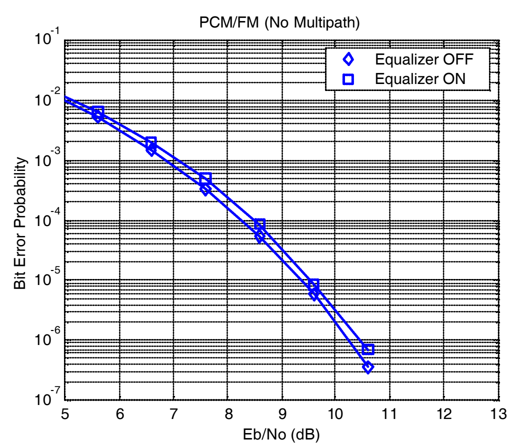

Figure 4. Measured 5 Mbps PCM/FM BEP curve (No Multipath)

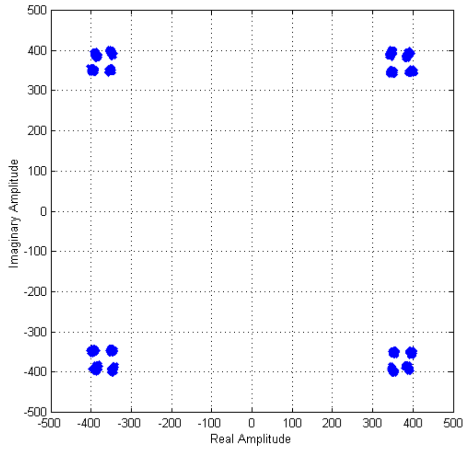

Figure 5. Measured 5 Mbps SOQPSK Constellation (No Multipath)

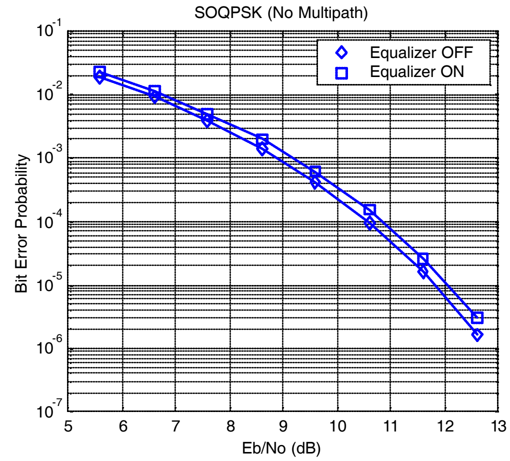

Figure 6. Measured 5 Mbps SOQPSK BEP curve (No Multipath)

PCM/FM WITH STATIC MULTIPATH

This section examines the behavior of PCM/FM in a static multipath channel. The magnitude of the reflection coefficient is $|\Gamma| = 0.9$ and its angle θ is varied to set the position of the notch. Figure 7 shows measured spectra of PCM/FM without multipath, the channel response, and the resulting multipath signal. Significant distortion is seen in the unequalized eye pattern at the top of Figure 8 which is completely eliminated when the equalizer is turned on. This improvement will be measured in two ways: 1) difference in mean squared error (MSE) relative to an ideal signal with and without the equalizer, and 2) the difference in the additive noise level that produces a BEP of 10^{-5}.

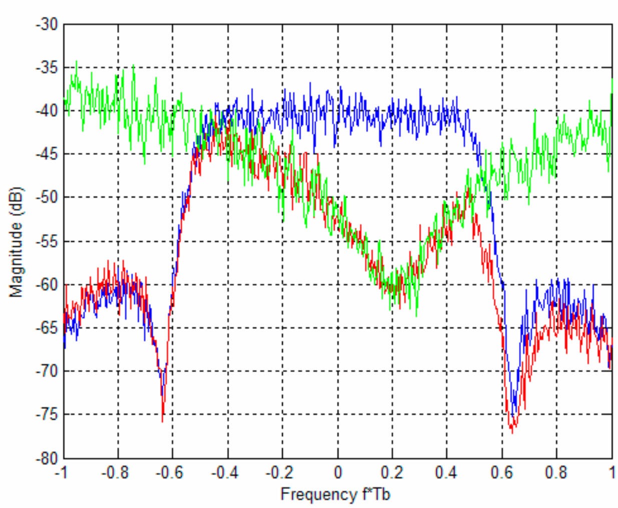

Figure 7. 5 Mbps PCM/FM PSD with Multipath ($|\Gamma| = 0.9, \tau = 40$ ns, Notch at 0.2 bit rates)

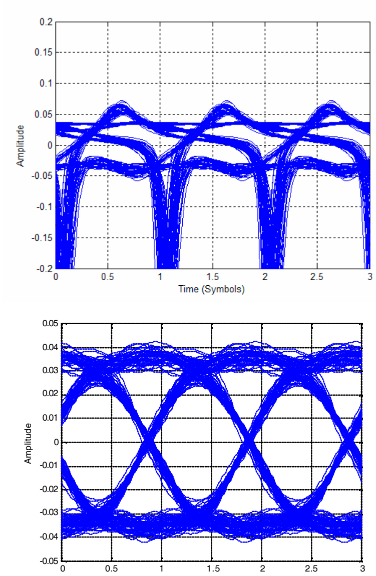

Figure 8. Equalizer OFF (top) & ON (bottom)

By analyzing waveform samples from the demodulator, the difference in MSE (relative to an ideal signal) with and without the equalizer can be computed as a function of notch position. The additive noise was turned off for this measurement and the results are illustrated in Figure 9. The improvement is seen to increase as the notch moves towards the center of the signal and decreases as the notch moves away. This seems reasonable and is typical of the simulation results from [1].

The second test consists of first establishing the noise level to achieve a BEP of 10^{-5} without multipath, turning on the multipath component, and recording the amount that the noise has to be attenuated to achieve the same reference BEP. This test is performed with and without the equalizer over a range of notch offsets. Generally speaking, this test measures the amount of additional SNR required to overcome the multipath distortion.

Figure 10 shows the measured results with the equalizer on and off as well as the difference. In general, as the notch approaches the center of the signal it takes more SNR (or less noise) to maintain the reference BEP. At a notch position of 0.2, the desired BEP could not be reached with the equalizer off regardless of the SNR level. This is due to fact that the multipath induced distortion completely closed the eye pattern causing data recovery to fail. The equalized case always outperformed the unequalized case and was symmetric and well behaved. The advantage is small when the notch is far away (very little distortion) and very large towards the center (significant distortion).

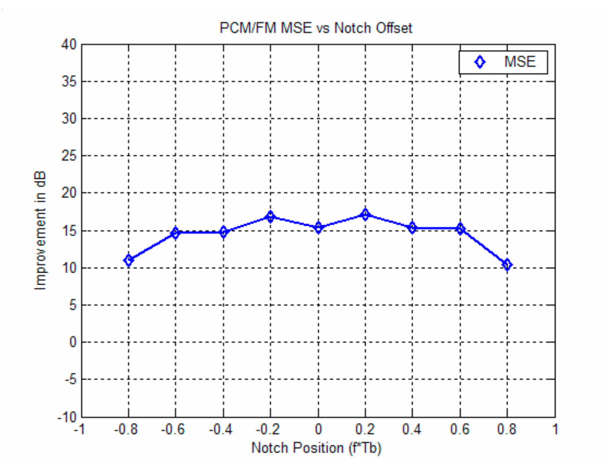

Figure 9. MSE Improvement due to equalizer vs Notch Offset $(|\Gamma| = 0.9, \tau = 40 \text{ ns})$

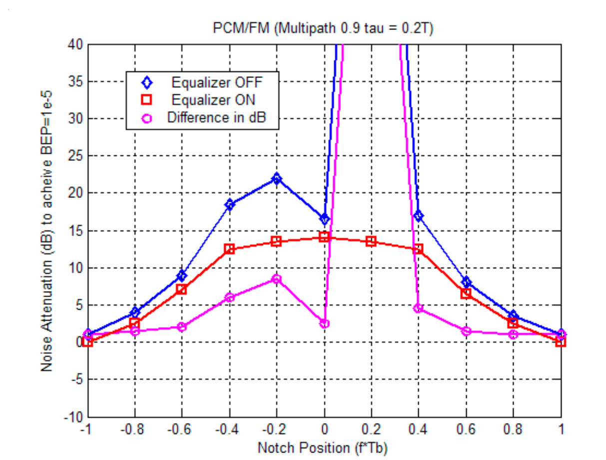

Figure 10. 5 Mbps PCM/FM - Noise reduction required to achieve 10^{-5} BEP vs Notch Offset

Figure 11 plots the MSE improvement, additional SNR required, and difference between equalizer on and off. Notice the strong correlation between the MSE improvement and the additional SNR required. One interpretation is that if the equalizer can provide 15 dB of MSE improvement, roughly 15 dB of additional link margin (SNR) is required to take full advantage of the equalizer capability. From a spectral perspective, if the multipath causes a 15 dB fade relative to a fixed noise floor, the equalizer must have an additional 15 dB in SNR to achieve the same BEP as the non-multipath case. From an equalizer perspective, the adaptive filter will only invert the channel response to the point at which the cost of accentuating the noise doesn't outweigh the improvement in distortion. Although this seems reasonable in hind-sight, it was a surprising that the MSE and Noise tests correlated so well. Last but not least, the difference between the equalized and unequalized case is quite dramatic. As mentioned previously, the reference BEP cannot be met without the equalizer at a notch offset of 0.2 regardless of the SNR.

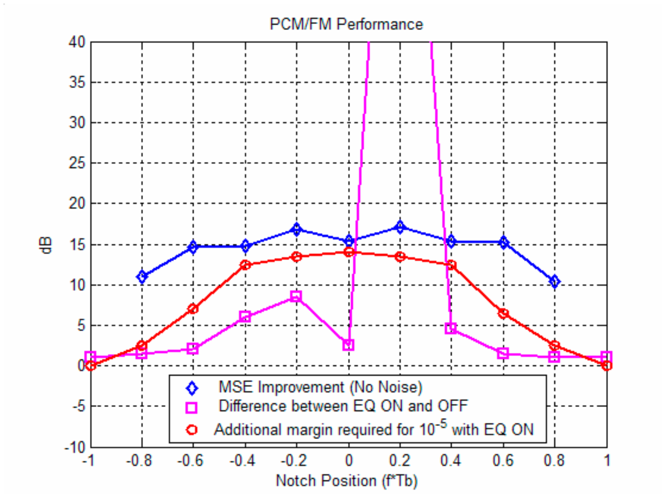

Figure 11. Comparison of MSE and Eb/No Improvement with PCM/FM

SOQPSK WITH STATIC MULTIPATH

The same static testing was performed with SOQPSK. Figure 12 shows measured spectra of SOQPSK without multipath, the channel response, and the resulting multipath signal. Significant distortion is seen in the unequalized constellation at the top of Figure 13 which is completely eliminated when the equalizer is turned on.

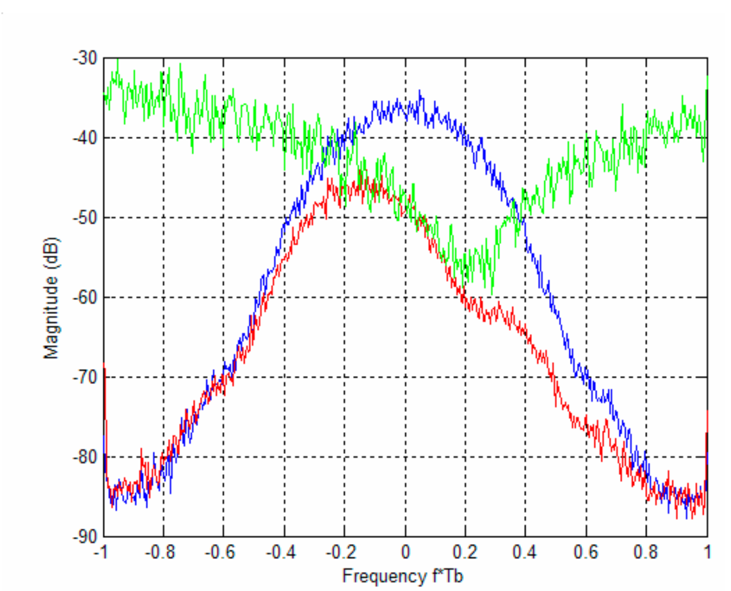

Figure 12. 5 Mbps SOQPSK PSD with Multipath ($|\Gamma| = 0.9, \tau = 40$ ns)

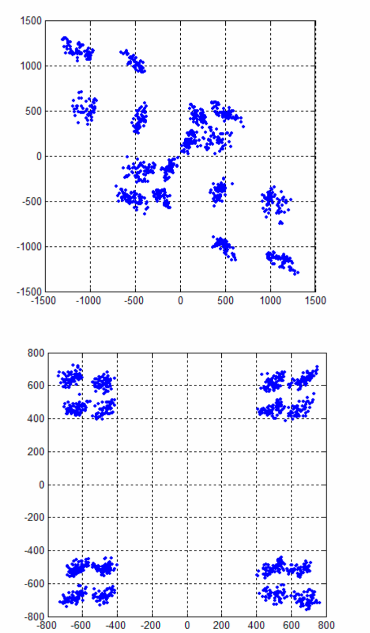

Figure 13. Equalizer OFF (top) & ON (bottom)

Figure 16 shows the improvement in MSE (relative to an ideal signal) with and without the equalizer as a function of notch position. As with PCM/FM, the improvement is seen to increase as the notch moves towards the center of the signal and decreases as the notch moves away. However, note that the plateau is narrower as compared to PCM/FM due to narrower spectrum of SOQPSK.

Figure 17 shows the measured results from the noise level test with the equalizer on and off. As before, when the notch approaches the center of the signal it takes more SNR (or less noise) to maintain the reference BEP. At a notch position of -0.2, the desired BEP could not be reached with the equalizer off regardless of the SNR level. With the notch in the middle, the equalizer improved the situation by 30 dB. Again, the advantage is small when the notch is far away (very little distortion) and very large towards the center (significant distortion). It is apparent that without equalization, SOQPSK is more susceptible to multipath than PCM/FM, but it is affected over a narrower range. Again, the equalized case was symmetric and well behaved.

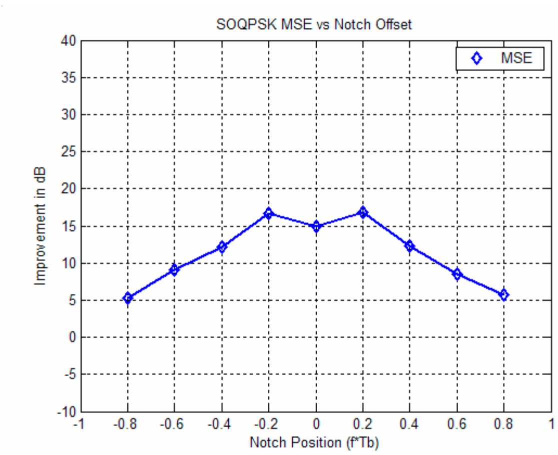

Figure 16. 5 Mbps SOQPSK MSE Improvement vs Notch Offset (G = 0.9)

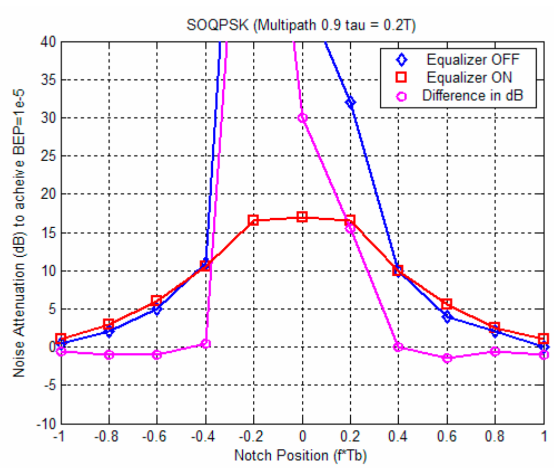

Figure 17. 5 Mbps SOQPSK AWGN Improvement vs Notch Offset (G = 0.9)

Figure 11 plots the MSE improvement, additional SNR required, and difference between equalizer on and off for SOQPSK. Again, the correlation is almost perfect between the MSE improvement and the additional SNR required. The difference between the equalized and unequalized case is quite dramatic especially with the notch near the center requiring many dB's of additional SNR to match the performance with the equalizer. As mentioned previously, the reference BEP cannot be met without the equalizer at a notch offset of -0.2 regardless of the SNR.

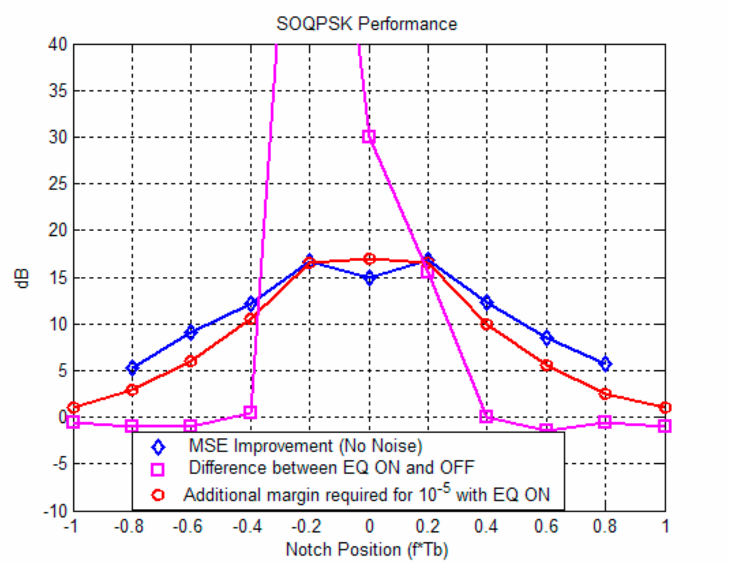

Figure 18. Comparison of MSE and Eb/No Improvement with PCM/FM

PCM/FM WITH DYNAMIC MULTIPATH

In addition to the static testing, dynamic multipath testing was also conducted. Typically, the notch does not stay in a stationary position, but sweeps through the signal as the vehicle moves. In contrast to the static case, the phase angle of the reflection is rotated at a constant rate to produce the desired dynamic test signal. A rotation rate of 2 Hz (period of 0.5 seconds) is typical of notch sweep rates seen in recordings of the IF during flight tests and was used for all dynamic testing.

Two delays were tested, 40 ns and 200 ns, with a 5 Mbps PCM/FM signal. The frequency response of the two channels along with their relationship to the modulated signal is shown in figures 19 and 20. For τ = 40 ns ($0.2T_b$), the notch period is 5 times the bit rate resulting in a fairly flat fade as the notch sweeps through the signal. In contrast, with τ = 200 ns (T_b), the nulls are spaced at the bit rate causing the signal to be distorted throughout the entire range of notch positions.

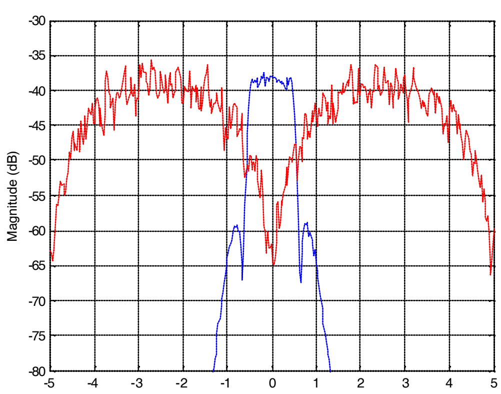

Figure 19. Frequency Response (| Γ | = 0.9,τ = 40 ns) and 5 Mbps PCM/FM

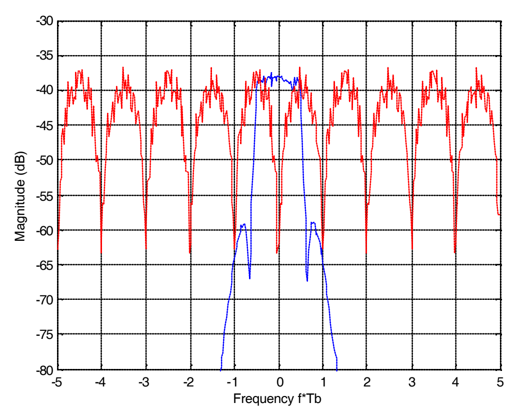

Figure 20. Frequency Response (| Γ | = 0.9,τ = 200 ns) and 5 Mbps PCM/FM

The resulting BEP curves for no multipath and dynamic multipath, with the equalizer on and off, are shown in Figures 21 and 22. The first observation is that with τ = 40 ns, PCM/FM without equalization hits an average error rate floor due to the fact that it produces errors regardless of the SNR when the notch sweeps through the center of the signal. Conversely, the shape of BER curve with the equalizer is the same as the baseline case (no multipath), but it needs about 14 dB of additional SNR to make up for the signal fade. For the τ = 200 ns case, PCM/FM without equalization is not viable regardless of the SNR. With the equalizer, the curve moves out another 5 dB or so from the τ = 40 ns case, but it still allows reliable communication over the link.

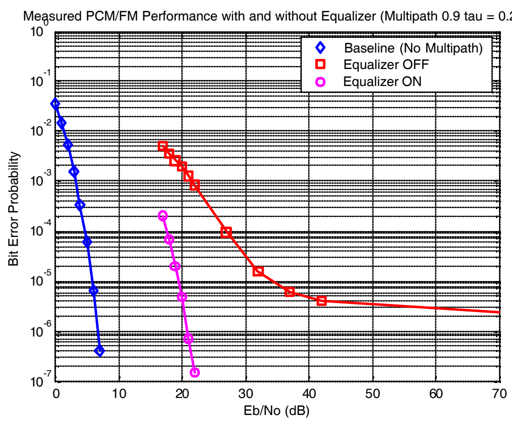

Figure 21. BEP Performance with and without Equalizer (| Γ | = 0.9, τ = 40 ns, 2 Hz sweep rate)

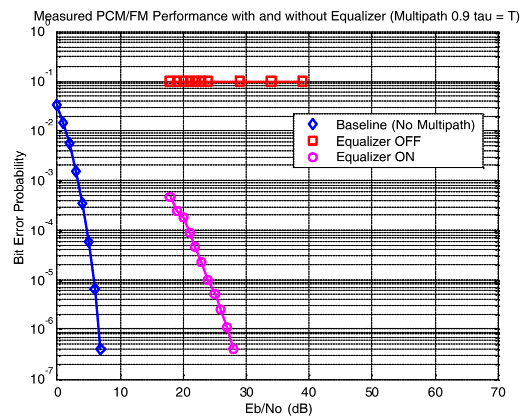

Figure 22. BEP Performance with and without Equalizer (| Γ | = 0.9, τ = 200 ns, 2 Hz sweep rate)

SOQPSK WITH DYNAMIC MULTIPATH

The same two delays, 40 ns and 200 ns, were tested with a 5 Mbps SOQPSK signal. The frequency response of the two channels along with their relationship to the modulated signal is shown in figures 23 and 24. Since SOQPSK is narrower than PCM/FM, the τ = 40 ns ($0.2T_b$) channel looks even more like a flat fade as the notch sweeps through the signal. The τ = 200 ns (T_b) still causes the signal to be distorted throughout the majority of notch positions.

The resulting BEP curves for no multipath and dynamic multipath with the equalizer on and off are shown in Figures 25 and 26. With τ = 40 ns, SOQPSK without equalization has a much higher average error rate floor than does PCM/FM. However, when the equalizer is turned on, the BEP curve has the same shape of the baseline BEP curve (no multipath) but it needs about the same 14 dB of additional SNR to make up for the signal fade. For the τ = 200 ns case, SOQPSK without equalization is not viable regardless of the SNR. Interestingly enough, the equalized SOQPSK at τ = 200 ns outperforms the τ = 40 ns case by about 4 dB. Only 10 dB of additional SNR is required to match the no multipath case. It may be that the signal doesn't experience as much of a loss in signal power with the narrower notches.

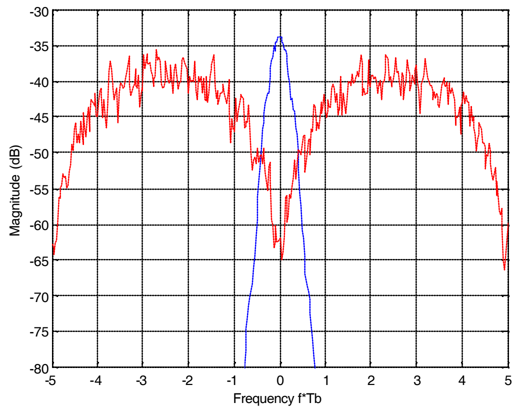

Figure 23. Frequency Response (| Γ | = 0.9,τ = 40 ns) and 5 Mbps SOQPSK

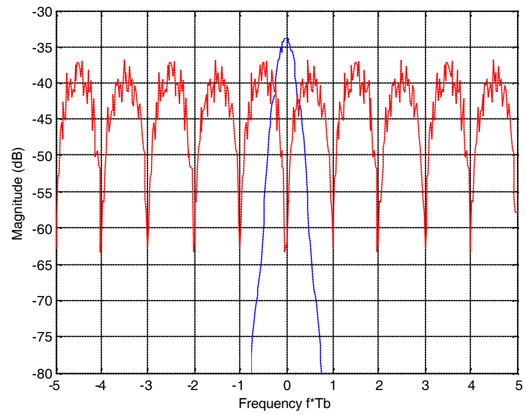

Figure 24. Frequency Response (| Γ | = 0.9,τ = 200 ns) and 5 Mbps SOQPSK

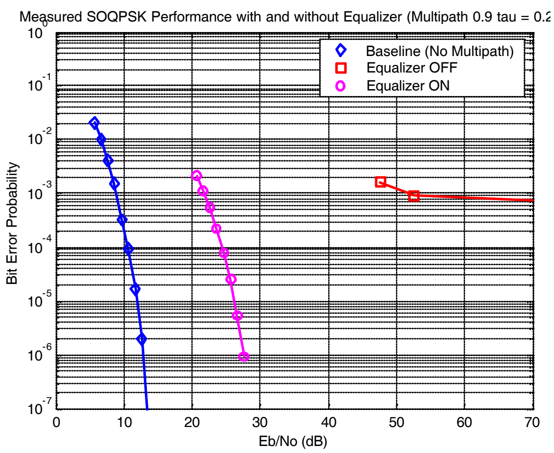

Figure 25. BEP Performance with and without Equalizer (| Γ | = 0.9,τ = 40 ns)

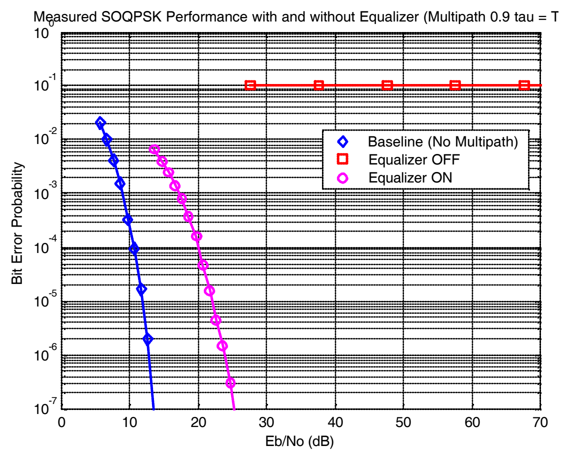

Figure 26. BEP Performance with and without Equalizer (| Γ | = 0.9,τ = 200 ns)

CONCLUSIONS

Measured hardware results for PCM/FM and SOQPSK with a CMA equalizer in static and dynamic multipath typical of airborne telemetry channels have been presented. For both modes, the penalty incurred for leaving the equalizer on was seen to small (0.5 dB or less) in an AWGN environment without multipath. Testing with static multipath was performed using two different methods: 1) calculation of the MSE based on the waveform samples and 2) the amount of additional SNR that was required to overcome the multipath distortion. For both tests, the distortion increased as the notch moved towards the center of the signal as did the performance difference between the equalized and unequalized cases. For example, at a notch position of 0.2, unequalized PCM/FM could not meet the reference BEP regardless of SNR while the equalized version performed well. Similar results were seen with unequalized SOQPSK at a notch offset of -0.2. It was shown that the equalizer can significantly improve the communication ability of a link with moderate or severe multipath. SOQPSK was more sensitive to multipath, as compared to PCM/FM , but was affected over a smaller frequency span due to its narrower spectrum.

An interesting correlation was noted between MSE improvement and the amount of additional SNR required to maintain the reference BEP. For both PCM/FM and SOQPSK, the two curves were very similar. The results indicate that the equalizer needs additional link margin of roughly the amount of MSE distortion it has to correct to achieve the same performance of a signal without multipath.

Dynamic multipath using a sweep rate of 2 Hz and time delays of 40 and 200 ns were investigated. The equalizer was shown to provide signficant benefit as compared to the unequalized case. Somewhat surprising was the fact that equalized SOQPSK performed slightly better with τ = 200 ns as compared to τ = 40 ns.

This work proves the feasibility of applying this technology in airborne telemetry equipment. Although more lab and flight testing remain, it appears that adaptive equalization has the potential to provide significant improvements in data quality over telemetry links with multipath fading.

ACKNOWLEDGEMENTS

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REFERENCES

1. Hill T., Geoghegan M.S., "A comparison of adaptively equalized PCM/FM, SOQPSK, and multi-h CPM in a multipath environment", Proceedings of the International Telemetering Conference, October 2002.
2. Rice M., Davis A., Bettwieser C., "A wideband channel model for aeronautical telemetry – part 2: modeling results", Proceedings of the International Telemetering Conference, October 2002.
3. Rice M., Jefferis R.,"Modulation Techniques for Telemetry Applications", Short course ITC 2001.
4. Geoghegan M.S., "Description and Performance Results for the Advanced Range Telemetry (ARTM) Tier II Waveform", Proceedings of the International Telemetering Conference, October 2000.
5. Hill T., "An Enhanced, Constant Envelope, Interoperable Shaped Offset QPSK (SOQPSK) Waveform for Improved Spectral Efficiency", Proceedings of the International Telemetering Conference, San Diego, CA, October 2000.