EXPERIMENTAL RESULTS FOR MULTI-SYMBOL DETECTION OF PCM/FM

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ABSTRACT

It has been previously shown, through computer simulations, that a multiple symbol detector can provide substantial gains in detection efficiency (nearly 3 dB) over traditional PCM/FM detectors. This is accomplished by performing correlations over multiple symbol intervals to take advantage of the memory inherent in the continuous phase PCM/FM signal. This paper presents measured hardware results, from a prototype developed for the Advanced Range Telemetry (ARTM) Project, that substantiate the previously published performance and sensitivity predictions. Furthermore, this work confirms the feasibility of applying this technology to high-speed commercial and military telemetry applications.

KEY WORDS

Multiple Symbol Demodulation, Binary PCM/FM, and Noncoherent Detection.

INTRODUCTION

There currently exists a large installed base of PCM/FM telemetry transmitter and receiver equipment. It was shown in [1] that the detection performance of PCM/FM could be improved by nearly 3 dB by using a multiple symbol demodulator instead of a traditional single symbol type detector. This paper presents measured results taken from high-speed prototype hardware, developed for the ARTM project, which implements the multiple symbol detection processing algorithms. Results characterizing the bit error probability, as well as the robustness of the detector to offsets in carrier frequency, symbol timing, and modulation index, are presented.

SYSTEM DESCRIPTION

A multi-symbol detection algorithm was shown to provide a significant gain in detection efficiency as compared to traditional single symbol recovery of PCM/FM. Figure 1 illustrates a conceptual diagram of a PCM/FM communication system in which the source data is filtered, modulated, corrupted by Additive White Gaussian Noise (AWGN), and processed by the multi-symbol demodulator to recover the data. While conceptually correct, this simplified model doesn't show the upconversion, downconversion, and IF filtering that is present in practical systems.

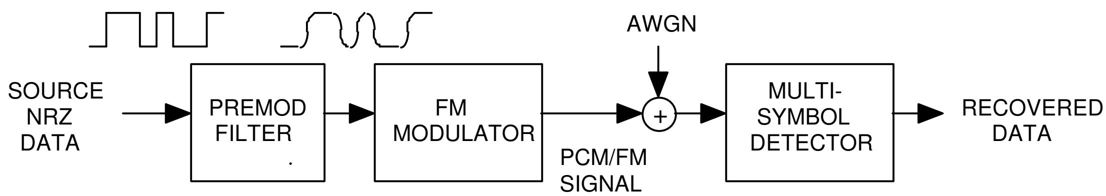

Figure 1. Conceptual Diagram of PCM/FM Communication System

Figure 2 illustrates the test setup used to evaluate the prototype multi-symbol demodulator under more realistic conditions. The data source (2047 test pattern), premodulation filter, modulation and upconversion functions were performed with a Rohde and Schwarz I/Q Modulation Generator and HP ESG-D4000A Digital Signal Generator. This combination of test equipment allows precise generation of the PCM/FM waveform with various offsets in frequency, timing, and modulation index and produces an L-band output signal suitable for RF testing. An external noise source corrupts the signal and produces a desired Signal-to-Noise Ratio (SNR) for measuring error rate performance. The resulting signal is filtered, gain controlled, and downconverted to a 70 MHz intermediate frequency (IF) by a Microdyne 700-MR receiver. The IF signal is processed by the Multi-Symbol demodulator and the recovered data is compared to the source data using a Fireberd 6000-A bit error rate tester.

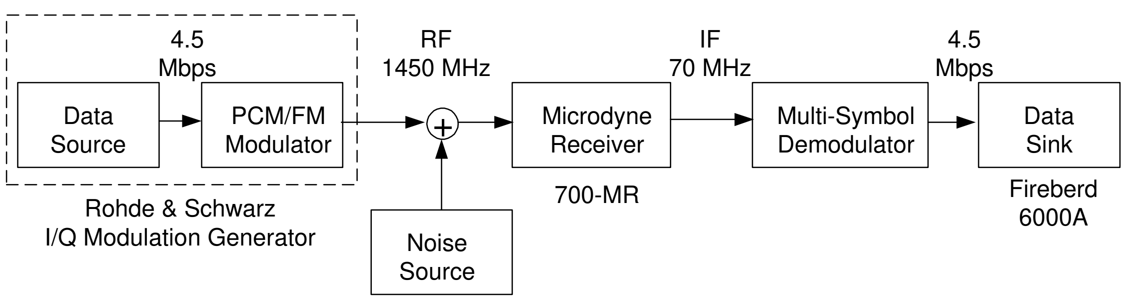

Figure 2. Test Setup for Evaluating the Multiple-Symbol Demodulator Hardware

For testing, a 4.5 Mbps PCM/FM waveform was generated using a fourth order Bessel pre-modulation filter with a 3 dB cutoff frequency at 0.7 bit rates, a peak deviation equal to 0.35 times the bit rate, and a modulation index of h = 0.7as per the current recommendation for PCM/FM telemetry systems.

MULTI-SYMBOL DEMODULATOR HARDWARE

A hardware prototype of the multi-symbol demodulator, developed for the Advanced Range Telemetry (ARTM) Project, was used for all performance testing and is shown in Figure 3. It consists of a single circuit card housed in a 19 inch rack with various analog, digital, and control connections. It accepts a 70 MHz IF input signal (typically from a receiver), performs filtering and gain control, converts the signal from analog to digital, and implements the digital processing algorithms necessary to recover the PCM/FM data. The recovered clock and data outputs are coaxial and are electrically compatible with commercial bit error rate testers and other data collection equipment. Although the unit was originally designed to process other, more complex, continuous phase waveforms, the hardware platform is also ideally suited for hosting the PCM/FM mode of operation.

The demodulator currently handles variable data rates from 0.5 to 11 Mbps in PCM/FM mode with rates up to 15 Mbps being supported in future versions. The analog section has the circuitry necessary to accept the range of IF levels typically available from commercial receivers and also features a set of IF filters that are automatically selected based on data rate. For diagnostic purposes, the unit has analog test outputs for displaying constellation and eye diagrams.

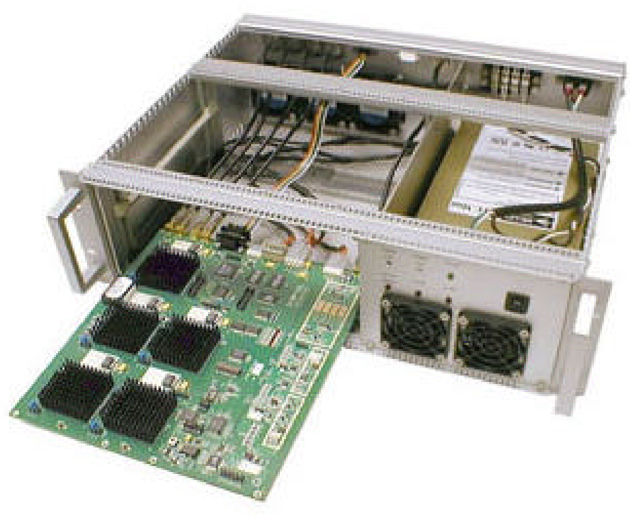

Figure 3. Multi-Symbol Demodulator Prototype (Up to 11 Mbps in PCM/FM mode)

MEASURED BIT ERROR PROBABILITY (BEP)

Figure 4 shows the measured BEP performance of the multi-symbol demodulator at 4.5 Mbps versus a traditional single symbol detector. For reference purposes, results from a Microdyne RCB2000 are also included that were taken at 5 Mbps and graciously provided by Eugene Law of NAWCWD, Point Mugu, CA. For testing, a 15 MHz IF filter was used in the MR-700 and the RCB2000 used IF and Video bandwidths of 6 MHz, a max rate/max deviation set to 10 MHz/4.5MHz, and its internal bit synchronizer. Since the 'matched' filtering is performed digitally in the multi-symbol demodulator, the analog IF filter selection is not as critical as for the single symbol detector. The first observation is that the measured data from the multi-symbol demodulator is very close to what was previously predicted. Although one might be skeptical of these results, it makes sense that the measured and predicted performance are very close since the SNR is set using an external noise source, the demodulator is digital signal processing based with many bits of resolution, and the only synchronization required is symbol timing. In other words, one should not expect much loss in this implementation.

Furthermore, the performance of the Microdyne RCB2000 is also as expected and is nearly 3 dB worse that the multi-symbol demodulator. The conclusion from this data is that the enhanced detection algorithm works as advertised and is suitable for implementation in high-speed commercial hardware applications.

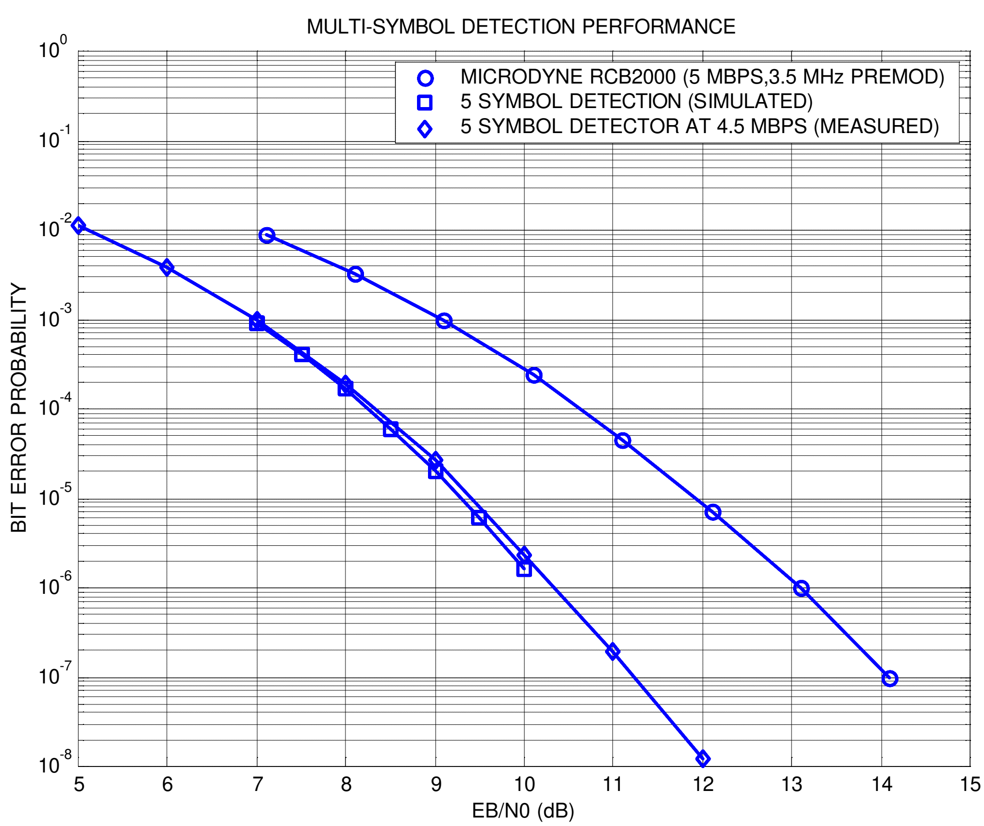

Figure 4. Measured BEP Performance of Multi-Symbol versus Traditional Detector

MEASURED SENSITIVITY TO FREQUENCY OFFSET

The previous section showed that the detection performance of the multi-symbol detector in AWGN is excellent. However, the transmitter equipment may not be precisely aligned with the demodulator in carrier frequency, data rate, or modulation index. This section presents measured hardware results for the degradation caused by carrier frequency offset. To take these measurements, the Automatic Frequency Control loop (AFC) in the demodulator was disabled. Although the AFC would normally be operating, the objective is to characterize the multi-symbol demodulator without it for comparison purposes to the previous performance predictions.

Figure 5 illustrates the BEP curves for various offsets in carrier frequency with the AFC disabled. The data rate is 4.5 Mbps for all cases and the offsets range from 0 to 300 KHz. Since the Microdyne 700-MR receiver tunes in 100 kHz steps, most applications only require operation over a +/- 100 KHz range. However, since the data is taken primarily to illustrate the characteristic behavior of the multi-symbol detector, an extended range of offsets was investigated. It is evident that offsetting the carrier frequency (with no AFC) can result in significant performance degradation. Figure 6 shows the simulated degradation as well as the measured performance that is slightly worse than predicted. This may be due to the fact that if the signal is offset, the symbol tracking does not maintain optimal alignment as it does in the computer simulation. It is important to keep in mind that no loss in detection performance is experienced when the AFC enabled (as is the normal case). The 'no loss' curve was added to Figure 6 to emphasize this point.

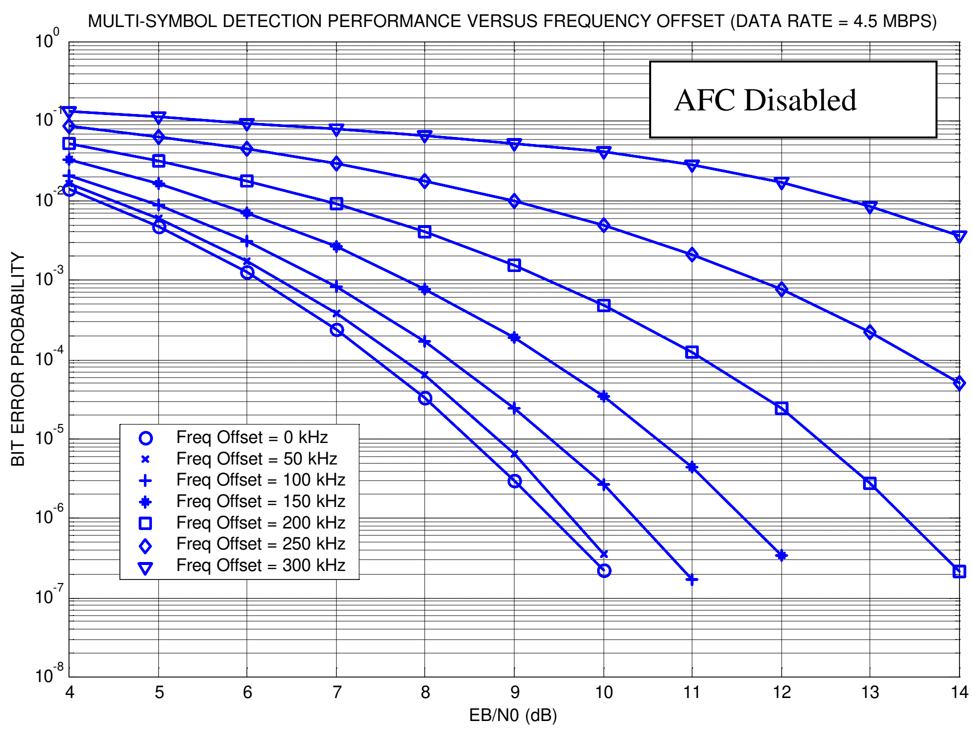

Figure 5. Multi-Symbol Demodulator BEP Curves with Frequency Offset (AFC Off)

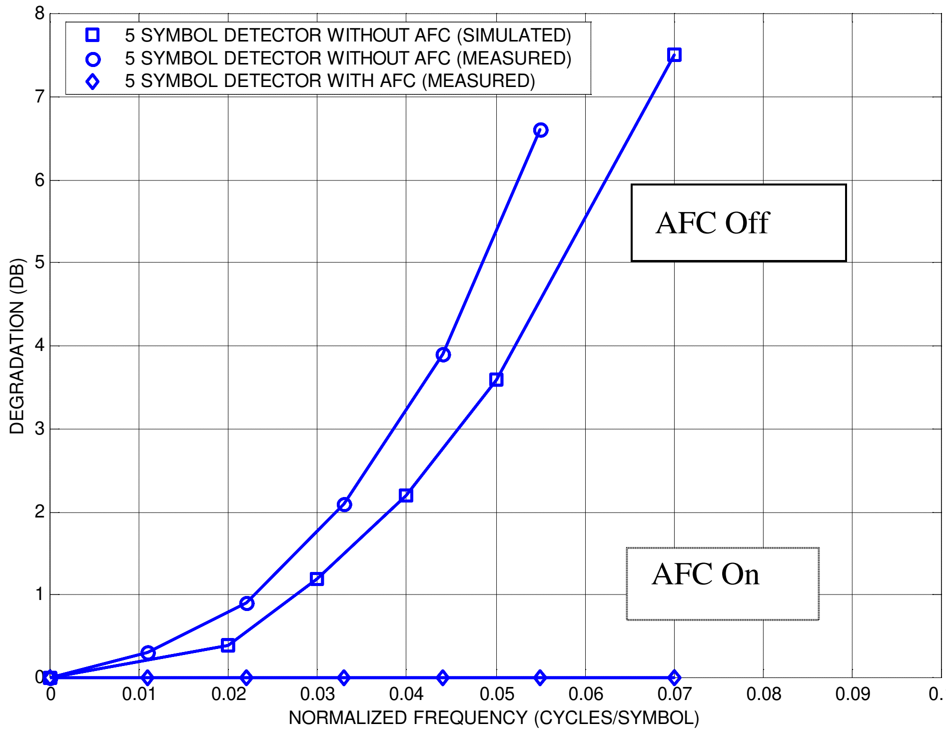

Figure 6. Multi-Symbol Demodulator Degradation with Frequency Offset (AFC Off/On)

MEASURED SENSITIVITY TO TIMING RATE

The effect of timing error on the performance of the multi-symbol demodulator was also investigated. Although the previous simulation results characterized the performance with a static timing offset, a more meaningful test is to offset the timing rate (i.e., data rate). This was accomplished by simply changing the sampling rate on the Rohde and Schwarz modulation generator. Several BEP curves were taken at timing offsets ranging from 0 to 500 parts per million and the resulting degradation was negligible for all timing offsets tested. As long as the bit synchronizer maintains the correct symbol boundary alignment, there is virtually no loss when the data rates are within reasonable tolerances.

MEASURED SENSITIVITY TO MODULATION INDEX

A parameter that does affect the BEP performance of the demodulator is modulation index and it is characterized in Figure 7. Note that modulation indices from 0.675 to 0.725 cause little loss since the detector is designed for h=0.7 while the larger offsets (h=0.6 or 0.8) experience large penalties in detection performance. Figure 8 illustrates the amount of degradation in dB as a function of the percent offset in modulation index for the original computer simulations and the hardware measurements. The measured data is slightly worse than predicted for higher h values and may be function of where the bit synchronizer chooses to sample the offset waveform. In addition to these results, a curve representing a prediction of what the performance would be if the modulation index was tracked is presented. If the demodulator knew how the modulation index of the signal was offset from the ideal 0.7, it could easily compensate by using slightly different set of correlation look-up tables. Consequently, the receiver would be closely matched to the transmitter and the loss would negligible. Therefore, if the modulation index can be tracked, this sensitivity can be virtually eliminated.

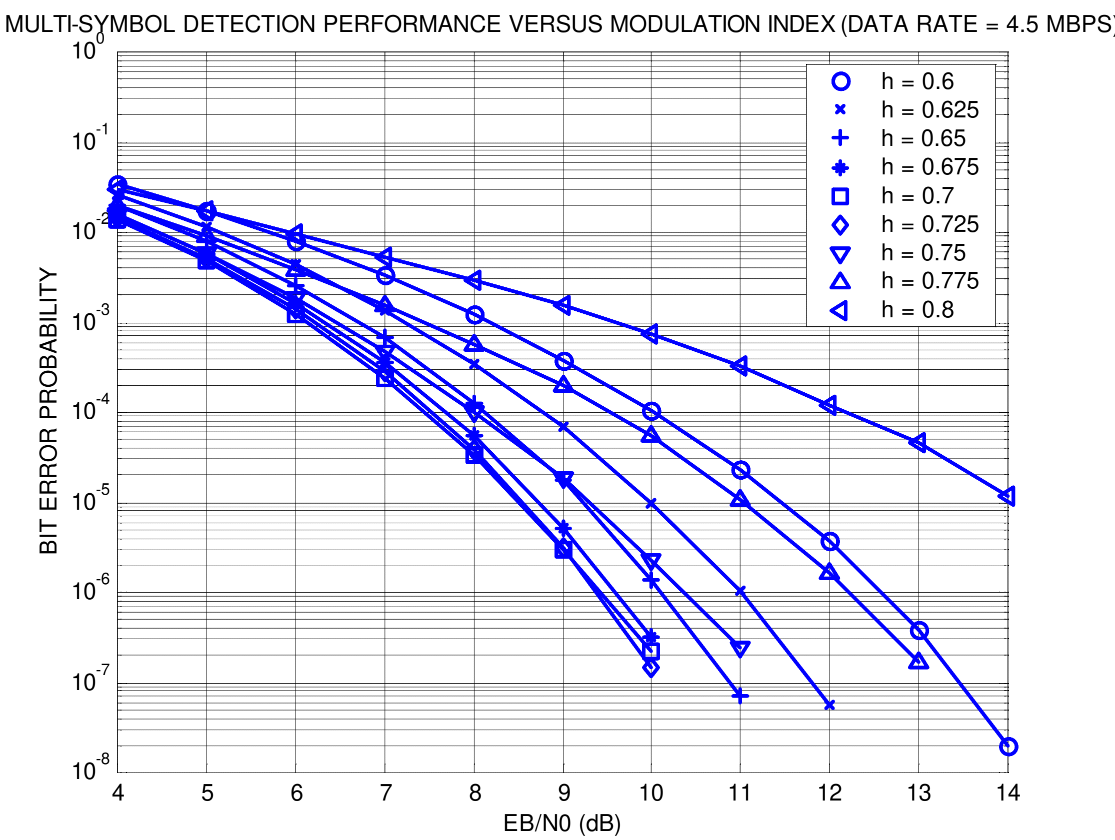

Figure 7. Measured Results of Sensitivity to Modulation Index

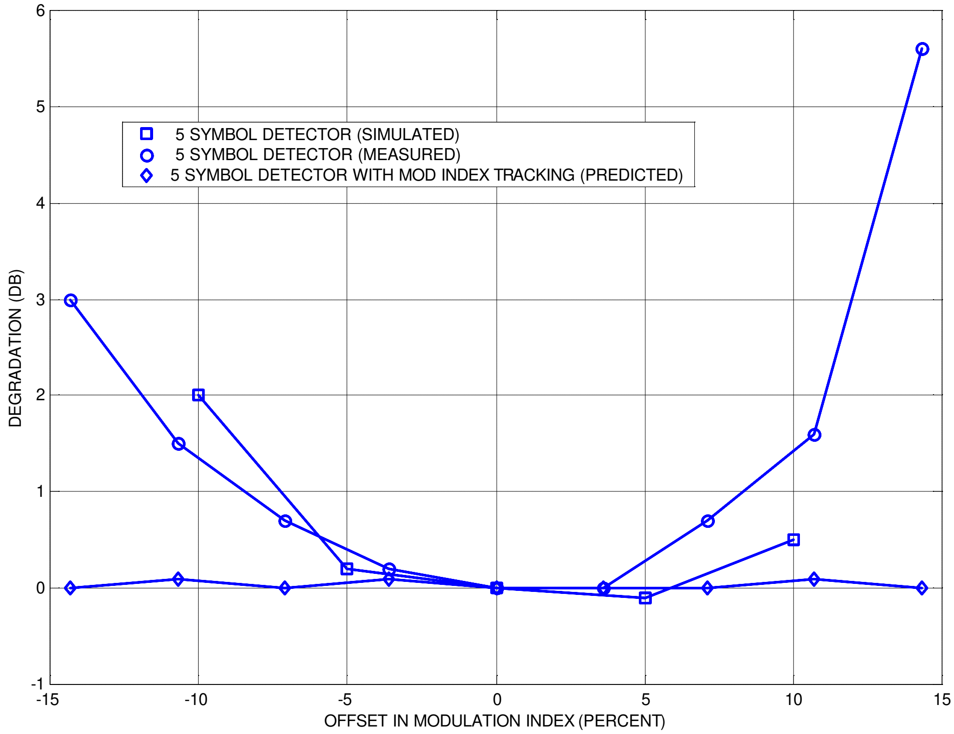

Figure 8. Degradation with Offset in Modulation Index

Although the current prototype does not track the modulation index of the received signal, any of several candidate implementations could easily be added to accomplish this function. Figure 9 illustrates one possibility in which the coefficients for the detector are selected by comparing the outputs of three candidate filters. Once the winning filter is declared, correlations at each modulation index are performed and the value that consistently produces the largest output is used in the multi-symbol detector. The resolution (number of tables and step sizes) can be tailored as desired to meet a particular application.

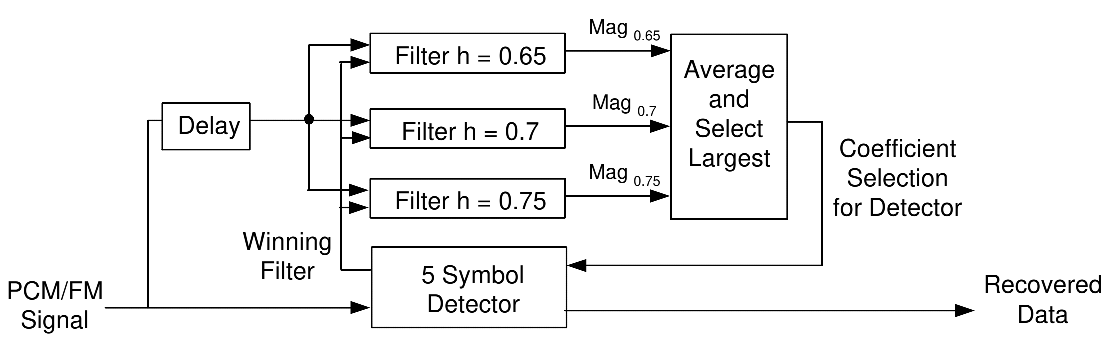

Figure 9. Architecture for Tracking Modulation Index

CONCLUSIONS

Performance results from a high-speed hardware prototype have verified that the detection performance of PCM/FM can be improved by nearly 3 dB by using a multiple symbol demodulator instead of a traditional single symbol type detector. The measured BEP data closely matched the performance predicted by previously published simulation results. Furthermore, sensitivity to errors in frequency, timing, and modulation index were characterized.

The sensitivity to carrier frequency offset was measured with and without the AFC loop and the results showed a loss similar to that predicted by simulation. It was also shown that this degradation can be completely eliminated by turning on the AFC loop that tracks out the gross frequency offset. Offsets in timing rate were also investigated and were found to be negligible over a range sufficient for typical telemetry applications. Finally, various offsets in modulation index were examined and the degradation was quantified. For small offsets of 5 percent or less, the loss is minimal. However, for offsets that approach 10 percent, over 1 dB of degradation in detection efficiency can occur. In order to mitigate this loss, a simple method of tracking the modulation index was presented.

ACKNOWLEDGEMENTS

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REFERENCES

1. Geoghegan M.S., “Improving the Detection Efficiency of Conventional PCM/FM Telemetry by using a Multi-Symbol Demodulator”, Proceedings of the 2000 International Telemetry Conference, Volume XXXVI,675-682, San Diego CA, October 2000.