A PERFORMANCE COMPARISON OF TURBO, TCM AND CONVOLUTIONAL CODES FOR A SERIAL-TONE AND OFDM 2400 BPS HF MODEM

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ABSTRACT

This paper compares the performance of Turbo, Trellis-Coded Modulation (TCM) and Convolutional codes on some characteristic HF channels. These Forward-Error Correction (FEC) techniques are applied to two signaling methods: serial-tone and OFDM (i.e. Multicarrier modulation), which have been designed specifically for the HF channel to provide protection against several milliseconds of multi-path and several Hertz of fading (conditions commonly encountered on HF channels [1]). These waveforms provide a user data rate of 2400 bps in a 3 kHz bandwidth.

1 INTRODUCTION

Since the introduction of Turbo-codes in 1993 [2], much research has been devoted to applying these codes to different communications systems where some delay due to interleaving can be tolerated. Their large hamming distance makes them an attractive FEC scheme for use on both Additive White Gaussian Noise (AWGN) and independent Rayleigh fading channels [2][3][4] [5].

This paper examines the performance of Turbo-codes, TCM and convolutional codes for use on an AWGN and a CCIR Poor [6][7][8] HF channel. The organization of the paper is as follows: First, a brief overview of the HF Channel is provided. Following this, a short discussion on coding techniques for fading channels is given. Then, a description of the waveforms and FEC techniques used are provided proceeded by bit error rate (BER) simulation results. The paper concludes with a discussion on the possible use of turbo-codes on HF channels.

2 HF CHANNEL

The HF channel can be characterized as a multi-path time-varying environment producing time and frequency spreads. These characteristics limit the rate at which data can be sent without the use of complex waveforms and demodulation techniques.

For mid-latitude HF circuits, the amount of multipath (often called delay spread) can range up to 6 ms and the fading rate (often called Doppler spread) can be as high as 5 Hz. However, more typical values are 2 ms and 1 Hz respectively which are the basic parameters of the standardized CCIR Poor channel [6][7][8].

Adaptive equalization (serial-tone, OFDM) and guard-time protection (OFDM) are common techniques used to combat the effects of Inter-Symbol Interference (ISI) [1][8][9][10][11].

To combat the effects of fading, an FEC scheme combined with an interleaver is typically used. For best performance, the size of the interleaver is chosen to be inversely proportional to the fading rate. Unfortunately, some HF channel conditions (CCIR Good [6][7][8]) suffer from very slow fade rates which require interleavers spanning between 1 to 2 minutes. If an interleaver is not long enough, the fading process becomes correlated and the expected coding gains of the FEC schemes can degrade significantly when compared to expected performance on an independent Rayleigh fading channel. Since long interleaver sizes cause large latencies at the receiver, a trade-off between latency and performance is unavoidable. For the NATO Standard Stanag 4285 Serial-Tone (ST) HF waveform [8], a latency of about 10 seconds was selected using a convolutional interleaver. Similarly, for the US MIL-STD-188-110A serial-tone HF waveform [9], a latency of 9.8 secs was chosen by means of a 4.8 second block interleaver. Given such small interleaver sizes (when compared to possible fading rates over HF), an interesting question arises as to which of the available FEC techniques offers the best performance when the independence of the fading process is not achieved.

3 Coding for Fading Channels

In recent years, much research has focused in the area of coding for fading channels [3][4][12][13][14][15][16][17][18][19][20]. Although opinions differ as to which approach works best on a fading channel, the three most promising techniques are

1) TCM codes optimized for fading channels combined with symbol interleavers and/or code interlacers [12] [15][18][19][20][21]
2) Convolutional Codes combined with bit interleavers [13][14][16][17]
3) Turbo codes [3][4]

Performance is usually compared by assuming an independent Rayleigh fading channel and perfect channel-state information. The independent Rayleigh fading channel assumption is a good model to measure the codes resistance to random symbol/bit fading while perfect channel state information allows decoder metrics to be scaled by the relative confidence of the received data (i.e. allowing for erasures when deep fades occur). Although in practice neither assumption is completely valid, this test is nevertheless a useful indication of the codes performance in a fading environment.

Additional factors which must be considered when selecting modulation/coding schemes for fading channels are:

- Peak to Average of coded waveform
- Constellation vulnerability to imperfect channel state information (i. e. M-QAM is more susceptible to imperfect channel state information than M-PSK)

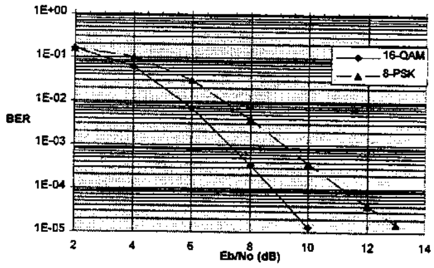

Figure 1 Performance on Rayleigh Fading Channel

For example, Figure 1 compares the performance of a rate 1/2 4-AM TCM code on the I and Q channels (i. e. 16-QAM rate 2/4 code similar to approaches described in [13][14]) and a rate 2/3 8-PSK TCM code optimized for a fading channel [12]. The computational complexity of the codes is the same (256 states). Comparing only Eb/No, the rate 2/4 16-QAM approach is better by about 3 dB at a BER of 10^{-5} . If we then consider the difference in Peak to Average ratio (unfiltered 16-QAM = 2.55 dB, unfiltered 8-PSK = 0.00 dB), the gain drops from 3.0 dB to 0.45 dB. This performance assumed perfect channel state information. Since all constellation points of 8-PSK have the same amplitude, it is reasonable to expect 8-PSK to be less susceptible to incorrect channel state information than 16-QAM, Therefore, taking all factors into account, it can be concluded that 8-PSK would perform as well (if not better) than 16-QAM on an actual HF channel.

4 Waveform and FEC Description

The 2400 bps ST waveform selected was the MIL-STD-188-110A [9]. It is used extensively throughout the world for HF communication and provides a meaningful reference for performance comparisons.

Candidate FEC techniques for ST waveform:

- Rate 1/2 k=7 convolutional code (as described in MIL-STD-188-110A [9])
- Rate 2/3 256-state 8-PSK TCM code [10], the symbol rate is adjusted to provide 2400 bps
- Rate 1/2 Turbo-block-code [5], where the block length is 11520 bits

The 2400 bps OFDM waveform selected was a waveform developed in-house using DQPSK and providing 5 ms of multi-path protection (25 ms frames). Additionally, the waveform has been clipped to 5.6 dB peak-to-average ratio for fair comparisons with the serial-tone waveform.

Candidate FEC techniques for OFDM waveform:

- Rate 1/2 k=9 convolutional code [10] and 4.8 seconds block interleaver [9]
- Rate 1/2 256-state 4-PSK TCM code optimized for fading (TCM code generated by in-house computer search program) and utilizing code interlacing [19][20][21] (latency close to 9.6 seconds)
- Rate 1/2 Turbo-block-code [5], with a block length of 11520

5 Performance Results

Figures 2 and 3 compare the performance of the three FEC schemes which will be used for the ST waveform on a Gaussian channel and Rayleigh channel. The turbo-block-code performance is for 6 iterations. As can be seen for a BER of 10^{-5}, the turbo-block-code provides a gain of at least 2.5 dB on a Gaussian channel and between 5-7 dB on a Rayleigh channel.

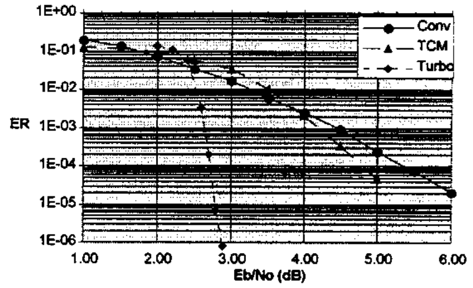

Figure 2 Performance of FEC Schemes for ST Waveform on a Gaussian Channel

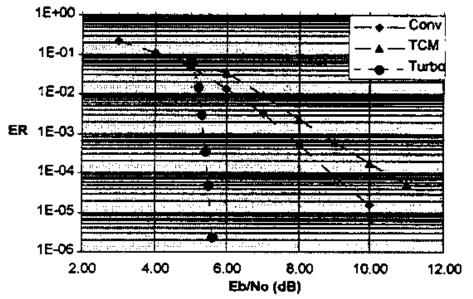

Figure 3 Performance of FEC Schemes for ST Waveform on a Rayleigh Channel

Figures 4 and 5 compare the performance of the three FEC schemes which will be used for the OFDM waveform on a Gaussian channel and a Rayleigh channel (with QPSK instead of DQPSK). Turbo-block-codes offer an improvement of over 1 dB on a Gaussian channel and a little over 2 dB on a Rayleigh channel.

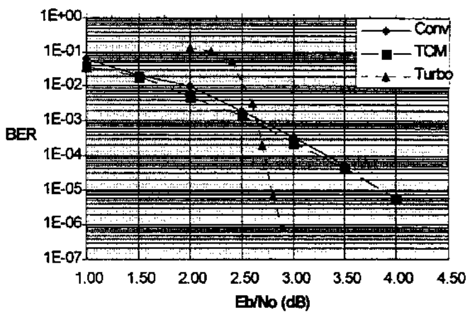

Figure 4 Performance of FEC Schemes for OFDM Waveform on a Gaussian Channel

Figures 6,7, 8 and 9 are the actual performances of the ST and OFDM waveforms on a Gaussian channel and a CCIR Poor HF channel. As can be seen, the performance of the Turbo-block-code is over 2 dB better than the other approaches for a Gaussian channel. On the Poor channel, the interleaver is not long enough for the Turbo-block-code to offer a significant improvement in performance over the current coding approach.

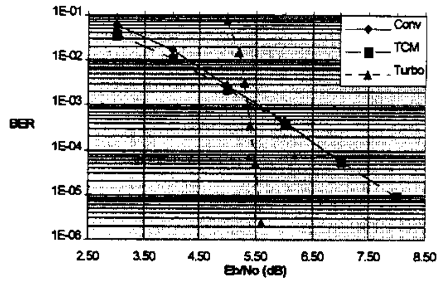

Figure 5 Performance of FEC Schemes for OFDM Waveform on a Rayleigh Channel

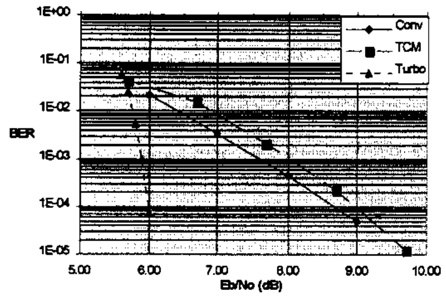

Figure 6 Performance of ST Waveform on a Gaussian Channel

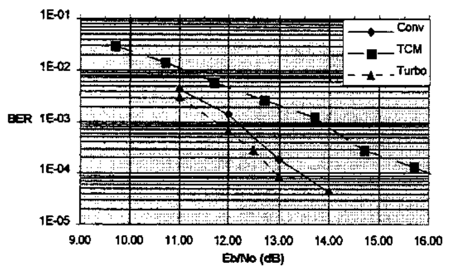

Figure 7 Performance of ST Waveform on a CCIR Poor Channel

One final comment on the simulation results provided is that the Turbo-block-code had very few blocks in error on the Poor channel, but when a block was received in error, it had a large amount of bit errors. For example, for the ST waveform, at an Eb/No of 13 dB, the simulation ran 13.5 hrs error free and then had one block with errors (2130 errors out of 11520).

6 CONCLUSION

This paper has compared the performance of Turbo-codes, TCM and Convolutional codes on an AWGN and CCIR Poor HF channel. Turbo-codes provided a gain of over 2 dB on a Gaussian channel but minimal improvements on a Poor channel. Although at first this might suggest that Turbo-codes may not provide much improvement on HF channels, it is believed that the bursty nature of Turbo-codes makes them an attractive scheme for an ARQ system. Future work will be focused on increasing interleaver sizes, improving the equalization process, and comparing ARQ performance of FEC schemes in conjunction with BER performance.

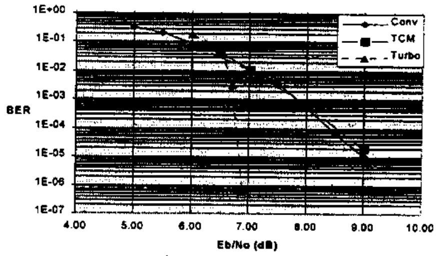

Figure 8 Performance of OFDM Waveform on a Gaussian Channel

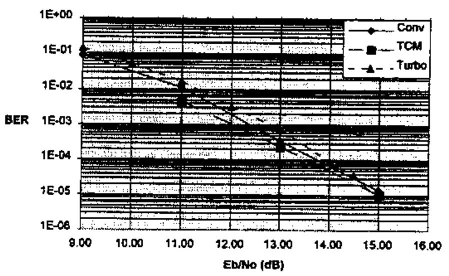

Figure 9 Performance of OFDM Waveform on a CCIR Poor Channel

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