LDPC CODING FOR FREQUENCY DIVERSITY IN MULTI-CHANNEL AIR-TO-GROUND TELEMETRY

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ABSTRACT

We consider the application of LDPC codes for improving performance in multi-channel (spectrum aggregation) for air-to-ground telemetry, by virtue of frequency diversity available on a wide-band frequency-selective multipath channel. Our particular interest is in use of multi-channel OFDM transmission on 'white spots' in the microwave spectrum. Each such channel is subject to frequency-selective fading over its bandwidth (typically a few MHz) due to multipath, for which typical OFDM equalization is standard. However, some subcarriers within this OFDM channel may experience deep fading at the output of the equalizer, rendering the symbol error probability poor relative to that on an AWGN channel at the same average SNR. We study simulated performance on a multipath channel described by the ETU fading model. Specific performance reported includes error rate of LDPC coding constrained to a single channel (effective diversity order roughly 2) and error rate of coding across eight channels (diversity order roughly 5). Further, performance on this dispersive fading channel is only about 3 dB worse than that on a no-multipath channel, at block error probability 0.01.

INTRODUCTION

The need for increased downlink transmission rate in test range telemetry, coupled with increased spectrum squeeze on legacy frequency allocations, has prompted the use of spectrum aggregation technology in microwave bands now allocated to other legacy services. Possible co-use of such bands on a non-interference basis has led to the design of a multichannel OFDM physical layer with up to eight simuataneous channels to provide downlink rates of 12 Mbps or higher. OFDM modulation on each channel has been suggested for its ease of equalizing for frequency-selective channel effects due to multipath, where the delay spread can be microseconds or longer.

Even though equalization is relatively straightforward in the frequency domain with OFDM [1], using pilot tones and interpolation for the entire channel frequency response, some OFDM subcarriers are left with relatively poor SNR, implying the error performance is still compromised by deep fades in the channel response.

One response to this is to employ strong error control coding (here high-rate LDPC codes) to diffuse the payload message across one or more OFDM carriers, and with decoding, obtaining the benefits of frequency-diversity. Use of a high-rate LDPC code [2] with coding across multiple OFDM symbols at the same frequency helps somewhat, but when the delay spread in the channel is significantly less than the reciprocal of the OFDM channel bandwidth, there is no diversity gain against fading, though performance improves relative to uncoded transmission. In such situations, we advocate LDPC coding across all the active channels, which may be well-separated in frequency. After each is equalized per OFDM methods, the output symbols seen by the decoder exhibit a higher degree of independence in terms of fading, and diversity gain is possible. We focus in particular on use of a rate 0.84 ($(n,k) = (6400, 5376)$) quasi-cyclic code whose code bits are spread across up to eight OFDM channels, with an OFDM symbol on one channel carrying 200 code bits when QPSK modulation is employed. In this case a codeword is conveyed by $6400/(8 \times 200) = 4$ consecutive vectors of OFDM transmissions. No codeword interleaving or permutation of the ordering is employed, as the LDPC code itself possesses natural interleaving. In either case, we assume the channel is quasi-stationary, or slow-fading, over this codeword transmission interval.

Results are presented for the ETU channel model [3] developed for cellular modeling. This model has two sets of three roughly equal power Rayleigh fading tap gains spanning a delay spread of 500 nanoseconds, plus four more lower power tap gains, spanning a delay spread range up to 5 microseconds. We simulate 1000 realizations from this model to provide selective fading across an eight-channel multiplex of OFDM channels, which in aggregate provide a throughput of about 14.3 Mbps after all OFDM pilot and guard-band overhead is accounted. Each such realization provides a distinct frequency-response across the adopted spectrum, due to the random tap gain model.

This approach is applicable to any so-called cognitive radio (or white-space) communication system, but in the remainder of the paper we consider an application that employs 2 MHz channel slots situated in the C-band region, around 6 GHz.

PHYSICAL LAYER DESCRIPTION

The aircraft terminal hardware supports eight parallel OFDM synchronized channels, with a channel width of 2 MHz. (This value was driven by decision that this would be a sensible smallest quantum of allocatable frequency spectrum.) On each OFDM subsystem, we use a $N = 128$-point FFT, coupled with a 22 sample cyclic prefix designed to be longer than anticipated multipath impulse response. These 150 samples per OFDM symbol are clocked out at rate 1.6 Msps, which with root-raised-cosine pulse shaping provides a spectrum essentially confined to 2 MHz. The duration of one OFDM symbol is 93.75 microseconds, so the OFDM symbol rate is $10.667(10^3)$ symbols per second.

Each OFDM symbol carries 100 QAM data symbols of payload, leaving 8 guard tones on either edge of the spectrum, a DC null subcarrier, and 11 pilot subcarriers space uniformly across the spectrum. Though larger data constellation symbols are possible, depending on link SNR, we focus on QPSK transmission in this paper. With uncoded QSPK, the net throughput is $R_b = 100(2)(10667) = 2.13$ Mbps, per channel. Eight such carriers in parallel provides an uncoded throughput in excess of 17 Mbps.

To improve performance, especially providing increased immunity to frequency-selective fading on isolated OFDM subcarriers, we consider the use of high-rate LDPC outer codes with parameters $(n, k) = (6400, 5376)$, having rate 0.84. Code bits are played out over 32 OFDM symbols if coding is confined to one OFDM channel. Alternatively, code bits could be interleaved across all 8 OFDM subchannels, meaning a code block would be sent in four (vector) OFDM symbols. The latter choice requires more careful bit packing at the transmitter and receiver terminals. The block diagram of the transmitter an OFDM system using LDPC codes is shown in Figure (1). The receiver will perform reverse operations to recover the transmitted source data (k bits).

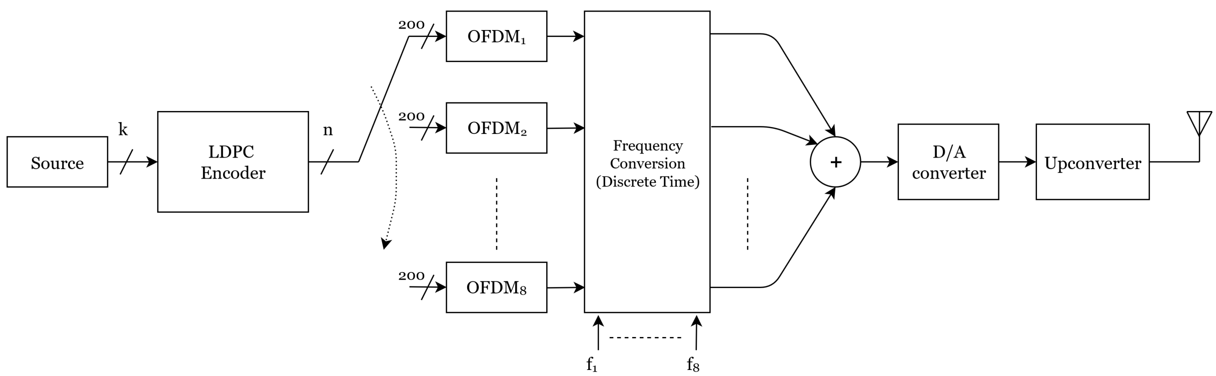

Figure 1: Transmitter of the coded OFDM system.

The specific code construction is a quasi-cyclic LDPC code, as described in [4], that offers some simplification in encoding and decoding relative to more general LDPC codes. However, other LDPC codes with similar rate and blocklength can be expected to perform in similar fashion.

While coding onto one OFDM channel will provide some diversity protection, assuming the delay spread does not exceed $5\mu s$, we expect a larger amount of frequency diversity if coding is spread over multiple channels. The degree of independence of the frequency responses will depend on where the channels are placed in the frequency domain, but we should always expect some gain over single-channel coding.

Our assumption is that the channel impulse response (or frequency response) remains essentially static over the duration of a codeword transmission, so that the encoder/decoder tandem sees a fixed (but variable over time) frequency-selective fading channel due to time-varying multipath. In the design described above, the transmission interval for an LDPC codeword is 3 milliseconds for a single channel (or 0.375 milliseconds), depending on whether code bits are multiplexed over one or eight OFDM channels.

No explicit interleaving of code bits is employed, except sequentially across frequency. The LDPC graph structure embodies natural interleaving anyway, and further interleaving was found to offer no additional gain.

CHANNEL MODEL

For simulation purposes, we select the Extended Typical Urban (ETU) fading model [3], which prescribes Rayleigh fading on up to 9 taps, spanning a delay range from 0 to 5 microseconds. The power profile across taps is tabulated in Table 1, and we normalize this average power to 1 so that E_b/N_0 below represents average received energy per information bit.

Table 1: ETU Delay Profile

Excess Tap Delay	Relative Power (dB)
0	-1.0
50	-1.0
120	-1.0
200	0.0
230	0.0
500	0.0
1600	-3.0
2300	-5.0
5000	-7.0

The model is applied in the simulations by drawing one realization for each symbol. The impulse response of this simulation is convoluted with time domain transmission after adding the cyclic prefix. During equalization at the receiver, we assume that the channel conditions are known.

Figure (2) shows the absolute values of the channel frequency responses of eight channel realizations which are also next to each other. The null values between different realizations are the guard bands in the frequency domain.

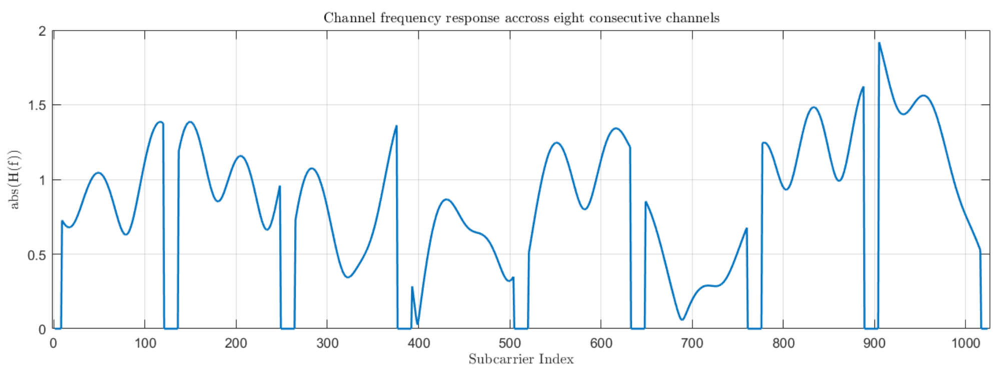

Figure 2: Absolute value of the ETU channel frequency response over eight OFDM contiguous channels, with guard bands evident.

NUMERICAL RESULTS

For calibration and as a performance baseline, we first simulated the BER and BLER performance for a non-fading (ideal) AWGN channel. The waterfall curves show the precipitous drop at around 4.5 dB on an E_b/N_0 basis, as shown in Figure (3). Channel capacity for this code rate 0.84 is about $E_b/N_0 = 2.5$ dB assuming QPSK signaling, so the performance is within 2 dB of capacity, reasonable for the modest blocklength adopted here.

Next we present results for coding across one OFDM channel. In Figure (4), we show decoder performances over an ensemble of block fading conditions. Clearly the randomness of the chan-

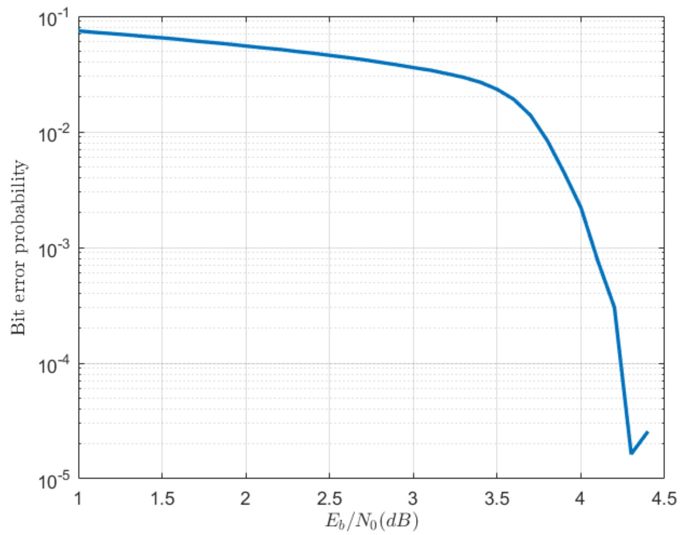

Figure 3: BER performance with LDPC coding for a flat-fading AWGN channel.

nel makes some channel realizations poorer than others, though all exhibit the expected waterfall behavior if SNR is sufficiently high. These relatively infrequent poor channels are what limits the averaged error performance. Figure (4) plots BER for an ensemble of 1000 blocks, versus E_b/N_0. The colored curves are conditional BER curves for different channel realizations; clearly some channel realizations supply better mutual information than others, but all exhibit the typical LDPC threshold behavior for BER. The black curve is the ensemble average versus SNR for these 1000 realizations. Two features are evident in the ensemble average. First there is an expected penalty relative to the non-fading case, and second, we find a slower decrease in BER with SNR, typical of fading channels and due to dominance of 'bad' realizations. The slope of log BER versus log SNR can be interpreted as the effective diversity order that coding extracts on this random frequency-selective channel. For single channel coding, this diversity order is roughly two.

The results here are tied to the ETU model to some extent. If the delay spread were made very small, with the same power profile as above, then the channel will not exhibit frequency selectivity, hence no diversity for coded OFDM.

Finally, we turn to coding across eight contiguous OFDM channels, other parameters held constant. It is expected that the decoder sees within its codeblock more 'independent' realizations of fading on the various code bits. Figure (5) indeed confirms this fact, with a performance curve that is slightly shifted to the left, but more notably having steeper slope, implying larger effective diversity. Slope of the mean BER curve here is roughly five. The larger diversity is correlated with a smaller density of 'bad' channels as seen in the colored ensemble.

CONCLUSIONS

We have presented results for LDPC-coded multi-channel OFDM transmission on multipath channels for two cases: single channel and eight channel coding. Fading imposes an expected BER

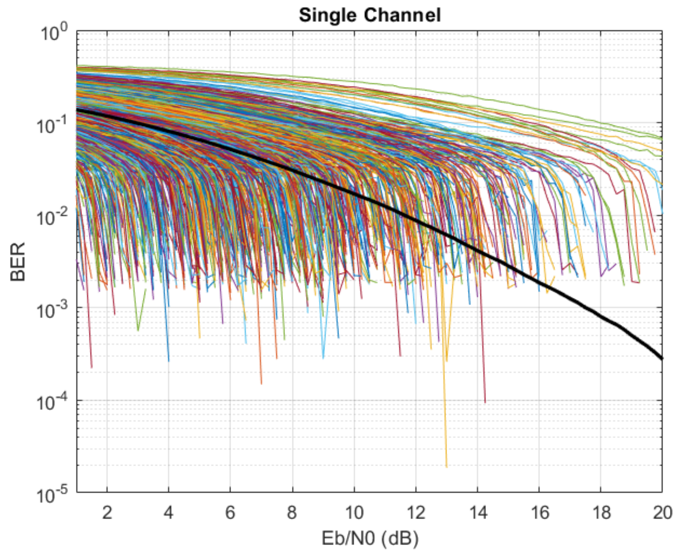

Figure 4: BER performance with LDPC coding for an ensemble of 1000 blocks over a single channel. ETU channel model is used here and the black curve is the mean.

penalty with expected diversity about 2 for single channel and 5 for eight channel case (as expected from higher number of degrees of freedom). These all depend on the ETU channel model, and though the channel model has nine independent fading coefficients, the delay spread relative to the adopted channel bandwidth in this design makes prediction of the actual diversity order difficult

Channel equalization in this work is assumed perfect, i.e. the demodulation processing has access to the true channel frequency response. In actuality, this must be estimated from pilot signals, and the performance will degrade slightly, dependent on channel estimation technique, [5].

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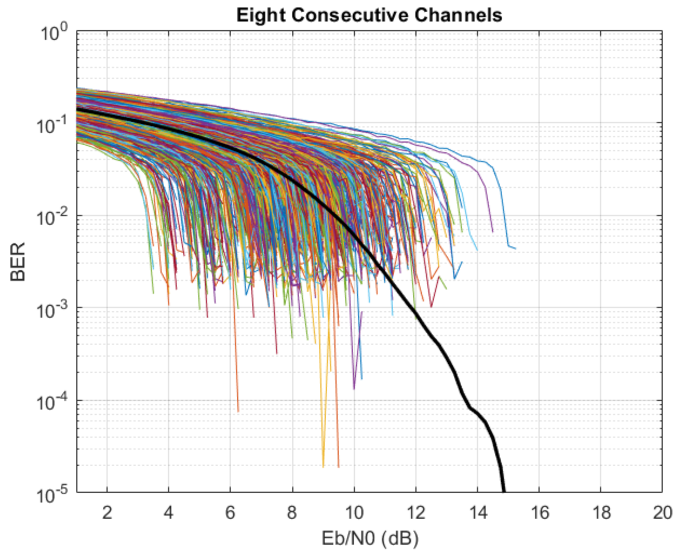

Figure 5: BER performance with LDPC coding for an ensemble of 1000 blocks over eight channels. ETU channel model is used here and the black curve is the mean.

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