Enhancing Multiband OFDM Performance: Capacity-Approaching Codes and Bit Loading

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***Abstract*— In this paper we consider Turbo and Repeat-Accumulate (RA) codes as well as bit-loading as methods of enhancing the performance of *Multiband OFDM,* a frequency-hopping orthogonal frequency-division multiplexing system which is a strong contender for the physical layer IEEE standard for high-rate wireless personal area networks (WPANs) based on ultra-wideband (UWB) transmission. Our methodology consists of (a) development and quantification of appropriate information-theoretic performance measures, and (b) comparison of these measures with simulation results for the Multiband OFDM standard proposal as well as our proposed extensions. We find that the current Multiband OFDM standard proposal sufficiently exploits the frequency selectivity of the UWB channel, and that the system performs in the vicinity of the channel cutoff rate. By applying Turbo codes and a reduced-complexity clustered bit-loading algorithm the system power efficiency can be improved by over 6 dB at a data rate of 480 Mbps.**

I. Introduction

Ultra-wideband (UWB) radio has recently been popularized as a technology for short-range, high data rate communication and locationing applications (cf. e.g. [1]), and the IEEE 802.15 wireless personal area networks (WPANs) standardization group has organized task group 3a to develop an alternative physical layer based on UWB signaling [2]. Currently there are two main contenders for this standard: a frequency-hopping orthogonal frequency-division multiplexing (OFDM) proposal known as *Multiband OFDM* and a code-division multiple access (CDMA) based technique.

In this paper, we consider the proposed Multiband OFDM standard [3]. Multiband OFDM is a conventional OFDM system [4] combined with bit-interleaved coded modulation (BICM) [5] for error prevention and frequency hopping for multiple access and improved diversity. The signal bandwidth is 528 MHz, which makes it a UWB signal according to the definition of the US Federal Communications Commission (FCC) [1], and hopping between three adjacent frequency bands is employed for first generation devices [3]. Thus, the Multiband OFDM proposal is a rather pragmatic approach for UWB transmission, which builds upon the proven BICM-OFDM concept.[1]

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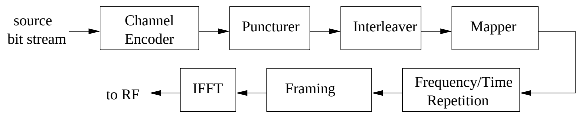
[1]Throughout this paper, the term "Multiband OFDM" refers to the particular standard proposal [3], whereas "BICM-OFDM" refers to the general concept of combining BICM and OFDM.

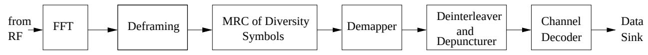
The objective of this paper is to study methods of enhancing the performance of Multiband OFDM for UWB transmission. We propose system extensions by applying capacity-approaching Turbo and Repeat-Accumulate (RA) codes and by using OFDM bit-loading. These specific techniques were chosen because of their potential for improved system performance without requiring substantial changes to other portions of the Multiband OFDM system, nor requiring major increases in complexity. As appropriate performance measures for coded communication systems, we discuss the capacity and cutoff rate limits of BICM-OFDM systems for UWB channels. The information-theoretic performance limits are compared with simulated bit-error rate (BER) results for the Multiband OFDM proposal and the extensions introduced herein.

The literature on Multiband OFDM systems and performance is surprisingly sparse. In [6] the authors present an overview of the Multiband OFDM system as well as performance results, but no comparison with information-theoretic limits is made. As an extension to the standard proposal, simplified Low-Density Parity-Check (LDPC) codes are considered in [7] in order to improve the power efficiency of the Multiband OFDM system for a subset of the proposed data rates. Again, no information-theoretic analysis or comparisons are attempted. The authors of [8] consider the application of a clustered power allocation scheme to Multiband OFDM. However, this scheme attempts to maximize throughput and therefore does not provide fixed data rates compatible with the Multiband OFDM standard proposal. Furthermore, no information-theoretic measures are considered. In [9] the authors present a space-time-frequency coding scheme for Multiband OFDM, but they do not consider any information-theoretic comparisons. A subband and power allocation strategy for a multiuser Multiband OFDM system is given in [10], but each user in the system uses a fixed modulation (i.e. no per-user bit allocation is performed).

The remainder of this paper is organized as follows. Section II describes the Multiband OFDM system and the performance enhancements we propose, as well as the UWB channel model under consideration. Section III presents the capacity and cutoff rate analysis and numerical results. Simulation results for the Multiband OFDM system and the proposed extensions are presented and compared with the theoretical benchmark measures in Section IV, and conclusions are given in Section V.



(a) Transmitter



(b) Receiver

Fig. 1. Block diagram of Multiband OFDM transmission system.

II. Multiband OFDM System, Extensions, and UWB Channel Model

In this section, the transmission system and channel model are introduced. We describe the transmitter of the proposed Multiband OFDM standard [3] as well as extensions to channel coding and to modulation. For the receiver we adopt a conventional state-of-the-art architecture. We assume perfect channel state information (CSI) throughout this paper (cf. [11] for a discussion of channel estimation for Multiband OFDM).

The block diagram of the Multiband OFDM transmitter is shown in Fig 1a). A total of ten data rates (from 53.3 Mbps to 480 Mbps) are supported by the use of different code puncturing patterns as well as time and/or frequency repetition. We present a description of the Multiband OFDM standard proposal [3] in parallel with our extensions to channel coding and to modulation.

A. Transmitter: Channel Coding and Spreading

Multiband OFDM Standard Proposal: Channel coding in the proposed standard consists of classical BICM [5] with a punctured maximum free distance rate $1/3$ constraint length 7 convolutional encoder. A multi-stage block-based channel interleaver is used (see [3] for details). After modulation (described below), modulated symbols are optionally repeated in time (in two consecutive OFDM symbols) and/or frequency (two tones within the same OFDM symbol), reducing the effective code rate by a factor of 2 or 4 and providing an additional spreading gain for low data rate modes. The channel interleaver length (300, 600 or 1200 coded bits) depends on the spreading factor.

Extension — Turbo Codes: We propose the use of Turbo codes [12] in order to improve the system power efficiency and more closely approach the channel capacity. We examined generator polynomials of constraint length 3, 4 and 5 as well as various interleavers (including s-rand [13] and dithered relative prime [14] designs). Due to their excellent performance for the code lengths considered as well as reasonable interleaver memory storage requirements, we decided to adopt the generator polynomials and interleaver design developed by the 3rd Generation Partnership Project (3GPP) [15]. For low data rates, the time/frequency spreading technique of the Multiband OFDM proposal is retained. We would like to maintain compatibility with the Multiband OFDM channel interleaver by having each coded block fit into one channel interleaver frame.[2] However, to maintain compatibility at the lowest data rates would require a Turbo code interleaver length of only 150 or 300 bits. Due to the poor distance properties and resultant performance degradation associated with short-length Turbo codes, at low data rates we consider both Multiband OFDM-compliant block lengths and longer blocks of 600 input bits (the same length as used without spreading).

Extension — RA Codes: The limited length of the Multiband OFDM channel interleaver motivates the consideration of serially-concatenated codes, where the interleaver is positioned between the constituent encoders and thus has a longer length. We consider nonsystematic regular RA codes [16] due to their simplicity and good performance for the required code lengths. The time/frequency spreading mechanism described above is discarded, and low-rate RA codes ($R = 1/4$ or $1/8$) are used. The interleaver between the repeater and accumulator is randomly generated (no attempt is made to optimize its performance).

B. Transmitter: Modulation

Multiband OFDM Standard Proposal: In the proposed standard, the interleaved coded bits are mapped to quaternary phase-shift keying (QPSK) symbols using Gray labeling. After the optional spreading described above, groups of 100 data symbols are used to form OFDM symbols with $N = 128$ tones.

Extension — Bit-Loading: The UWB channel (see Section II-D) is considered time-invariant for the duration of many packet transmissions. For that reason, it is feasible to consider bit-loading algorithms to assign unequal numbers of bits to each OFDM subcarrier [4]. Channel state information is obtained at the transmitter, either by (a) exploiting channel reciprocity (if the same frequency band is used in the uplink and downlink as in the standard proposal), or (b) some form of feedback (which may be required even if the same frequency band is used, since reciprocity may not apply due to different interference scenarios for transmitter and receiver). We consider loading for higher data rates (without time or frequency spreading) using two different OFDM bit-loading schemes. We selected the algorithm of Piazzo [17] (which loads according to the uncoded BER) due to its low computational complexity, and the algorithm of Chow, Cioffi and Bingham (CCB) [18] because it loads according to the information-theoretic capacity criterion, as well as for its moderate computational complexity.

The data rates and OFDM symbol structure of the Multiband OFDM proposal are maintained by loading each OFDM symbol with 200 bits. Each tone carries from 0 to 6 bits using Quadrature Amplitude Modulation (QAM) signal constellations with Gray or quasi-Gray labeling (note that 6 bit/symbol corresponds to 64-QAM, which is a reasonable

[2] Note that keeping the block lengths short also reduces the memory requirements and decoding delay at the receiver.

upper limit for modulation on a wireless channel). Due to FCC restrictions on the transmitted power spectral density, power loading is not used (all tones carry the same power). The target uncoded BER for the Piazzo algorithm is chosen as 10^{-5} (cf. [17] for details), but we found that performance is quite insensitive to this parameter. For the CCB algorithm, the signal-to-noise ratio (SNR) gap parameter Γ is either 6 dB (when convolutional codes are used) or 3 dB (for Turbo codes). When the algorithm is unable to determine a suitable loading, an all-QPSK loading is used, cf. [18] for details.

Extension — Clustered Bit-Loading: One potential feedback-based method of bit-loading is for the receiver to determine the appropriate modulation for each tone and feed the loading information back to the transmitter. To lower the feedback transmission requirements and significantly reduce the loading algorithm's computational complexity, we propose a clustered loading scheme where clusters are formed by considering groups of D adjacent tones. As we found the CCB algorithm superior to the Piazzo algorithm in terms of achievable power efficiency (see Sections III-B.1 and IV-B), we make the following modification to the CCB algorithm. We substitute Eq. (1) of [18] with:

$$b(i) = \frac{1}{D}\sum_{k=1}^{D}\log_2\left(1+\frac{SNR(i,k)}{\Gamma+\gamma_{margin}(dB)}\right) \tag{1}$$

where $SNR(i,k)$ is the signal-to-noise ratio of the k^{th} tone in the i^{th} cluster, γ_{margin} is the system performance margin (iteratively calculated by the CCB algorithm), and $b(i)$ is the (possibly non-integer) number of bits allocated for each tone in cluster i. Using the modified algorithm to load $200/D$ bits on $100/D$ clusters provides the final integer-valued loadings $\hat{b}(i)$ for each cluster. Finally, all tones in cluster i are assigned $\hat{b}(i)$ bits (i.e. the loading inside each cluster is constant). This modification causes the CCB algorithm to load according to the mean capacity of the tones in each cluster.

C. Transmitter: Framing and Transmission

The time domain signal is generated via an inverse fast Fourier transform (IFFT) and a cyclic prefix of 32 symbols is inserted. The radio frequency (RF) transmit signal hops after each OFDM symbol between three 528 MHz frequency bands with center frequencies at 3.432, 3.960, and 4.448 GHz (see [3] for more details).

D. UWB Channel Model

For a meaningful performance analysis of the Multiband OFDM proposal, we consider the channel model developed under IEEE 802.15 for UWB systems [19] (a Saleh-Valenzuela model [20] modified to fit the properties of measured UWB channels). Four separate channel models (CM1-CM4) are available for UWB system modeling, each with arrival rates and decay factors chosen to match a different usage scenario. The channel impulse response is assumed time invariant during the transmission period of several packets (see [19] for a detailed description).

E. Receiver

The block diagram of the receiver considered in this paper is depicted in Fig 1b). We assume perfect timing and frequency synchronization. Furthermore, for the system parameters and UWB channel model outlined above, the cyclic prefix can safely be assumed longer than the delay spread of the channel impulse response. Thus, after FFT we see an equivalent N dimensional frequency non-selective vector channel, expressed as [4],

$$\boldsymbol{Y}[k] = \boldsymbol{X}_d[k]\boldsymbol{H} + \boldsymbol{N}[k] \;, \tag{2}$$

where the vector notation $\boldsymbol{Z}[k] = [Z_1[k]\dots Z_N[k]]^T$ is used ($\cdot^T$ denotes transpose) and $\boldsymbol{X}_d[k]$ is the $N\times N$ diagonal matrix with elements $X_i[k]$ at its main diagonal. $Y_i[k]$, $X_i[k]$, and $N_i[k]$ are the received symbol, the transmitted symbol, and the additive white Gaussian noise (AWGN) sample on frequency tone $i = 1\dots N$ of the kth OFDM symbol, respectively. The vector $\boldsymbol{H}$ contains the frequency domain samples of the channel transfer function on tones $i = 1\dots N$ and is assumed constant over the considered time span (see Section II-D).

Maximum-ratio combining (MRC) [21] in the case of time and/or frequency spreading (see Section II-A and [3]) and demapping in the standard BICM fashion [5] are performed, and the resulting "soft" bit metrics are deinterleaved and depunctured.

Convolutionally coded schemes use a soft-input Viterbi decoder to restore the original bit stream, requiring a decoding complexity of 64 trellis states searched per information bit. Turbo-coded schemes are decoded with 10 iterations of a conventional Turbo decoder using the log-domain BCJR algorithm [22], with a complexity of roughly $10{\cdot}2{\cdot}2{\cdot}8 = 320$ trellis states searched per information bit (i.e. 10 iterations of two 8-state component codes, and assuming that the BCJR algorithm is roughly twice as complex as the Viterbi algorithm due to the forward-backward recursion). RA decoding is performed by a turbo-like iterative decoder, using a maximum of 60 iterations and an early-exit criterion which, at relevant values of SNR, reduces the average number of decoder iterations to less than ten [23]. We note that the per-iteration decoding complexity of the RA code is less than that of the Turbo code (since only a 2-state accumulator and a repetition code are used), making the total RA decoder complexity slightly more than the convolutional code but less than the Turbo code. The increased decoder complexities of the Turbo and RA codes, compared to the convolutional code, are reasonable considering the performance gains they provide (see Section IV).

III. Capacity and Cutoff Rate Analysis

The purpose of this section is to quantify potential data rates and power efficiencies of OFDM-based UWB transmission. Of particular interest here are the channel capacity and cutoff rate, which are widely accepted performance measures for coded transmission using powerful concatenated codes and convolutional codes, respectively. Since coding and interleaving are limited to single realizations of lognormal shadowing (see [19]), we focus on the notion of *outage probability*, i.e., the probability that the instantaneous capacity and cutoff rate for a given channel realization $\boldsymbol{H}$ fall below a certain threshold. These theoretical performance measures will be compared with simulation results for the Multiband OFDM system in Section IV.

In Section III-A, we present the capacity and cutoff rate expressions for BICM-OFDM with bit-loading. Section III-B contains the numerical results.

A. Capacity and Cutoff Rate Expressions

The instantaneous capacity in bits per complex dimension of an N tone BICM-OFDM system using bit-loading can be found by extending the results of [24] (following the methodology of [5]) as

$$C(\boldsymbol{H}) = \bar{m} - \frac{1}{N}\sum_{i=1}^{N}\sum_{\ell=1}^{m_i} \mathsf{E}_{b,Y_i}\left\{ \log_2\left(\frac{\sum\limits_{X_i \in \mathcal{X}_i} p(Y_i|H_i, X_i)}{\sum\limits_{X_i \in \mathcal{X}_{i,b}^{\ell}} p(Y_i|H_i, X_i)} \right) \right\}. \tag{3}$$

In (3), $\bar{m}$ is the average number of bits/symbol ($\bar{m} = 2$ throughout this paper), m_i and $\mathcal{X}_i$ are the number of bits per symbol and the signal constellation for the i^{th} tone, respectively, $p(Y_i|H_i, X_i)$ is the probability density function (pdf) of the channel output Y_i for given input X_i (a Gaussian pdf with mean $H_i X_i$ and variance σ_N^2), $\mathcal{X}_{i,b}^{\ell}$ is the set of all constellation points $X \in \mathcal{X}_i$ whose label has the value $b \in \{0, 1\}$ in position ℓ, and $\mathsf{E}_z\{\cdot\}$ denotes expectation with respect to z.

Similarly, we can express the instantaneous cutoff rate for bit-loading systems in bits per complex dimension as

$$R_0(\boldsymbol{H}) = \bar{m}(1 - \log_2(B(\boldsymbol{H}) + 1)) \tag{4}$$

with the instantaneous Bhattacharya parameter ($\bar{b}$ denotes the complement of b)

$$B(\boldsymbol{H}) = \frac{1}{N}\sum_{i=1}^{N}\sum_{\ell=1}^{m_i}\frac{1}{m_i}\mathsf{E}_{b,Y_i}\left\{ \sqrt{\frac{\sum\limits_{X_i \in \mathcal{X}_{i,\bar{b}}^{\ell}} p(Y_i|H_i, X_i)}{\sum\limits_{X_i \in \mathcal{X}_{i,b}^{\ell}} p(Y_i|H_i, X_i)}} \right\}. \tag{5}$$

B. Numerical Results

In this section we examine the capacity and cutoff rate of systems employing the Piazzo and CCB loading algorithms. We evaluated expressions (3) and (4) via Monte Carlo simulation using 1000 channel realizations.

1) No Clustering: Figure 2 (lines) shows the 10% outage capacity and cutoff rates for the CM1 channel using the Piazzo and CCB loading algorithms. (The markers in this figure will be discussed in Section IV-B). It should be noted that $\bar{E}_s$ is not adjusted to account for tones carrying 0 bits. This is because we assume operation at FCC transmit power limits, precluding the re-allocation of power from unused tones to other subcarriers (which would put the transmit power spectral density beyond the allowed limits). For high rates, both the CCB and the Piazzo loading algorithms provide a gain of several dB in capacity and in cutoff rate compared to the unloaded case, and this gain grows with increasing rate and $\bar{E}_s/\mathcal{N}_0$. The Piazzo algorithm is sub-optimal because it considers only the relative SNR between tones, and loads according to BER using a power minimization criterion. This loading strategy is not guaranteed to produce an increased channel capacity (or cutoff rate). On the other hand, the CCB algorithm requires knowledge of the actual SNR values of each tone and loads according to their approximate capacities, resulting in an increased channel capacity for all SNR values and an improved performance compared to Piazzo loading.

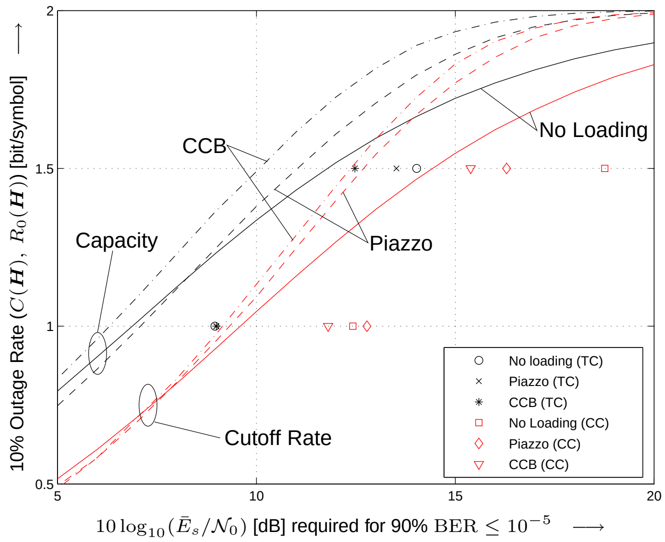


Fig. 2. 10% outage capacity and cutoff rate with and without loading for CM1 (lines). $10\log_{10}(\bar{E}_s/\mathcal{N}_0)$ required to achieve BER $\leq 10^{-5}$ for the 90% best channel realizations using convolutional codes (CC) and Turbo codes (TC), with and without loading (markers).

2) Clustering: We next consider the application of clustered loading using the modified CCB algorithm as described in Section II-B. Figure 3 shows the 10% outage capacity (solid lines) and cutoff rate (dashed lines) for various values of cluster size D, for channels CM1 and CM3. Also included for comparison are the non-clustered loading ($D = 1$) and unloaded (all-QPSK) curves. As the cluster size D increases the attainable rates decrease because the modulation scheme chosen for each cluster is not optimal for all tones in the cluster. This loss is slightly more pronounced for the cutoff rate than for the capacity, which indicates that when using clustered loading we should expect more performance degradation with convolutional codes than with Turbo codes (see also Section IV-B). The performance degradation with increasing cluster size is higher for CM3 than for CM1, because the frequency responses of adjacent subcarriers are less correlated for CM3 than for CM1 (cf. [11] for a discussion of the UWB channel properties relevant to OFDM-based systems). The less correlated the tones of a cluster are, the higher the average mismatch between the optimal modulation for each tone (i.e. that chosen by the non-clustered loading algorithm) and the fixed modulation chosen for the cluster. The higher

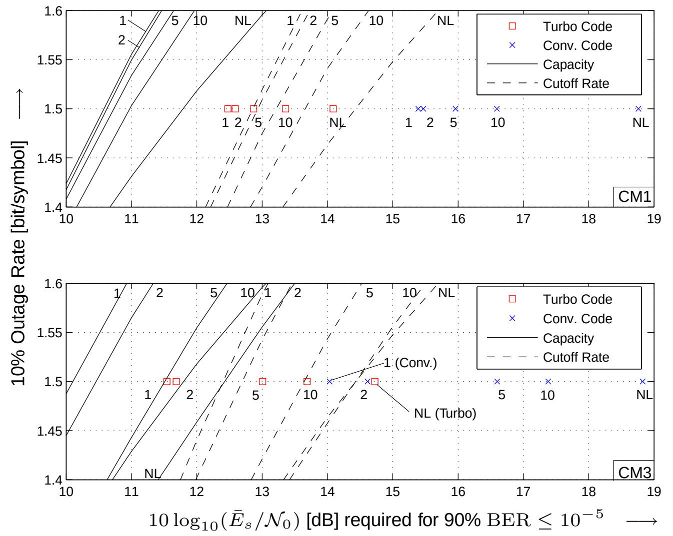


Fig. 3. Lines: 10% outage capacity (solid) and cutoff rate (dashed) for clustered CCB loading (cluster sizes $D \in \{1, 2, 5, 10\}$) and for non-loaded QPSK ("NL"). Markers: $10\log_{10}(\bar{E}_s/\mathcal{N}_0)$ required to achieve $\text{BER} \leq 10^{-5}$ for the 90% best channel realizations using Turbo codes (☐ markers) and convolutional codes (x markers). Channels CM1 (top) and CM3 (bottom).

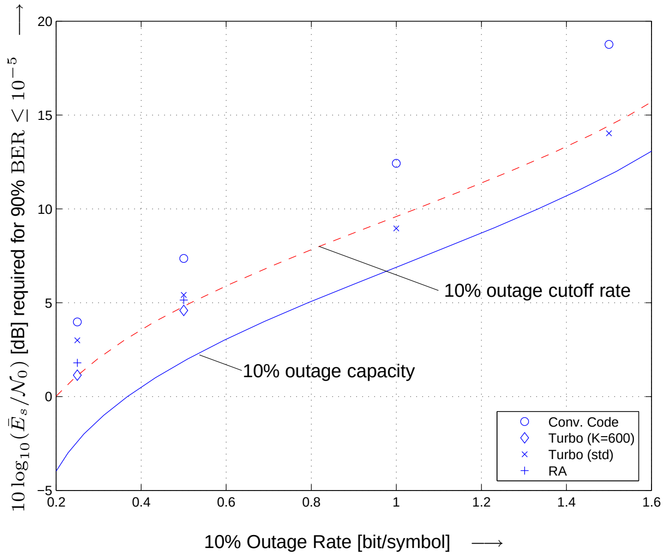


Fig. 4. $10\log_{10}(\bar{E}_s/\mathcal{N}_0)$ required to achieve $\text{BER} \leq 10^{-5}$ for the 90% best channel realizations using Turbo Codes, RA codes, and convolutional codes (markers). For comparison: 10% outage capacity and cutoff rate (lines). Channel model CM1.

average mismatch on CM3 results in lower performance when clustered loading is applied.

IV. Simulation Results

In Section IV-A, we study Turbo, RA, and convolutional coding without bit-loading. We examine channel CM1 with four different transmission modes with data rates of 80, 160, 320, and 480 Mbps corresponding to 0.25, 0.50, 1.00, and 1.50 bit/symbol, respectively. We then turn to the performance of systems with loading in Section IV-B. Based on the results of the information-theoretic analysis of Section III-B, we restrict our attention to rates ≥ 1.00 bit/symbol, where we expect loading algorithms to yield performance gains. We concentrate on Turbo and convolutional codes for this section. The simulation results presented in these two sections are the worst-case $10\log_{10}(\bar{E}_s/\mathcal{N}_0)$ values required to achieve $\text{BER}{\leq}10^{-5}$ for the best 90% of channel realizations over a set of 100 channels (i.e. they are simulation results corresponding to 10% outage).

In Section IV-C, we briefly summarize the power efficiency gains and attendant range improvements expected from the application of the system extensions we have proposed.

A. No Loading

Figure 4 (markers) shows the simulation results for Turbo and RA codes on channel CM1, as well as the convolutional code results for comparison. We also show the corresponding 10% outage capacity and cutoff rate curves. We observe that the SNR points for convolutional codes are approximately 3 dB to 4 dB from the cutoff-rate curves, which is reasonable for the channel model and coding scheme under consideration. These results (a) justify the relevance of the information-theoretic measure and (b) confirm the coding approach used in Multiband OFDM. More specifically, the diversity provided by the UWB channel is effectively exploited by the chosen convolutional coding and interleaving scheme. We can also see that Turbo codes give a performance gain of up to 5 dB over convolutional codes, and perform within 2.5 dB of the channel capacity, depending on the rate. At rates of 0.25 and 0.50 bit/symbol, Turbo code interleaver sizes compatible with the channel interleaver design of the Multiband OFDM proposal (the "std" points) incur a performance penalty of 1–2 dB compared with the longer block length ($K = 600$) points. Repeat-accumulate codes have a performance roughly 1 dB worse than the long block-length Turbo codes, but the RA codes are both (a) compatible with the Multiband OFDM channel interleaver, and (b) less complex to decode. They are thus a good candidate for low-rate Multiband OFDM transmission.

B. With Loading

Figure 2 (markers) shows the simulation results for Turbo codes and for convolutional codes, using both the CCB and Piazzo loading algorithms on channel CM1. At 1.00 bit/symbol and using convolutional codes, we see a performance gain of less than 1 dB using CCB loading, and a slight performance degradation using Piazzo loading. Performance using Turbo codes at 1.00 bit/symbol is relatively constant regardless of loading. However, at 1.50 bit/symbol we see gains of approximately 1.5 dB for Turbo codes and almost 4 dB for convolutional codes when CCB loading is used. The gains using the Piazzo algorithm are approximately 1 dB less, as predicted by the capacity analysis of Section III-B. Finally, we note that at 1.50 bit/symbol the system employing CCB loading and Turbo codes is approximately 6 dB better than the unloaded convolutionally coded system, and performs within approximately 2.5 dB of the channel capacity.

In Figure 3 (markers) we consider the performance of clustered loading with Turbo codes and with convolutional

TABLE I

INCREASES IN RANGE AND POWER EFFICIENCY USING PROPOSED EXTENSIONS, COMPARED TO THE MULTIBAND OFDM STANDARD PROPOSAL. CHANNEL CM1, RATE 1.50 BIT/SYMBOL (480 MBPS), PATH LOSS EXPONENT $d=2$. $10\log_{10}(\bar{E}_s/\mathcal{N}_0)$ VALUES ARE THOSE REQUIRED TO ACHIEVE $\mathrm{BER} \leq 10^{-5}$ FOR THE 90% BEST CHANNELS. (CC: CONVOLUTIONAL CODE, TC: TURBO CODE).

System	$10\log_{10}(\bar{E}_s/\mathcal{N}_0)$	Gain (dB)	% range increase
CC, no loading (Standard Proposal)	18.76	–	–
CC, CCB loading	15.38	3.38	47 %
CC, $D=2$ clust. load.	15.47	3.29	46 %
TC, no loading	14.09	4.67	71 %
TC, CCB loading	12.48	6.28	106 %
TC, $D=2$ clust. load.	12.58	6.18	103 %

codes for 1.50 bit/symbol on the CM1 and CM3 channels. As predicted by information-theoretic analysis, clustered loading incurs a performance penalty with increasing cluster size D. We note that Turbo codes suffer a smaller performance degradation (relative to $D=1$) than convolutional codes, because the more powerful Turbo code is better suited to handle the mismatched modulation (as discussed in Section III-B.2). The performance degradation is larger for CM3 due to that channel model's lower correlation between adjacent subcarrier frequency responses and resultant larger loading mismatch. However even $D=10$ loading provides performance gains for both channels and code types. Cluster size $D=2$ is a good tradeoff point for both Turbo and convolutional codes, allowing for feedback reduction by a factor of 2 with losses of approximately 0.1 dB for CM1 and 0.4 dB for CM3. Cluster sizes as large as $D=5$ could be used with Turbo codes, depending on the required power efficiency and expected channel conditions.

C. Range Improvements from Turbo Codes and Loading

Table I lists the gains in required $10\log_{10}(\bar{E}_s/\mathcal{N}_0)$ and percentage range increases on channel CM1 for various combinations of the extensions we have proposed. We assume a path loss exponent of $d=2$, as in [6]. We can see that bit loading alone provides up to 47% increase in range, Turbo codes without loading provide a 71% increase, and the combination of Turbo codes and loading allows for a 106% increase in range. Furthermore, the use of clustered loading with $D=2$ only reduces these range improvements by 1% to 3% over the non-clustered case, while providing reduced-rate feedback and lower computational complexity.

V. CONCLUSIONS

In this paper, the application of Multiband OFDM for UWB communication has been analyzed. The BICM-OFDM scheme proposed for Multiband OFDM performs close to the outage cutoff-rate measure and is thus well suited to exploit the available diversity. The application of stronger coding, such as Turbo codes or Repeat-Accumulate codes, improves power efficiency by up to 5 dB, depending on the data rate. Bit-loading algorithms provide additional performance gains for high data rates, and a simple clustering scheme allows for reduced-rate feedback of loading information depending on the channel conditions and required power efficiency.

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