

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

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Agenda

- Multiband OFDM System model
- Proposed extensions
 - Capacity-approaching codes
 - Bit-loading
- Performance Measures
 - Channel capacity and cutoff rate
 - System error rate
- Results
- Conclusions



System model

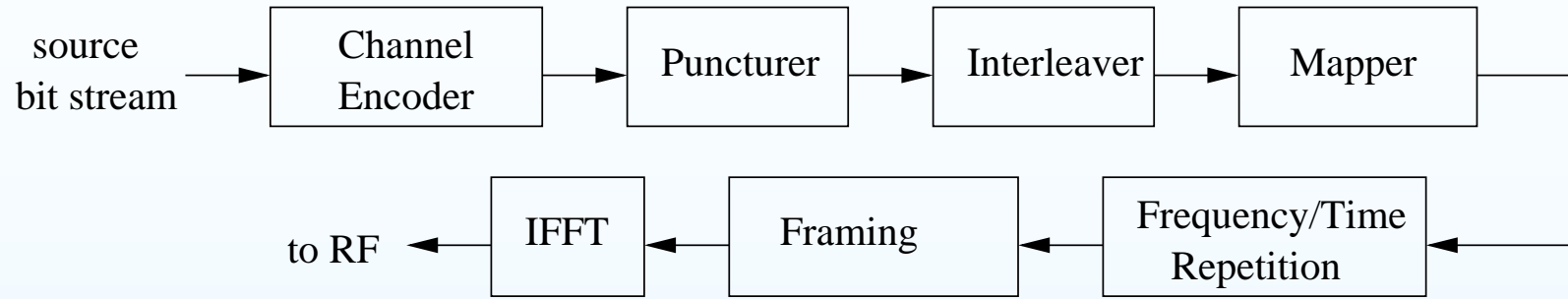


Figure 1: Transmitter

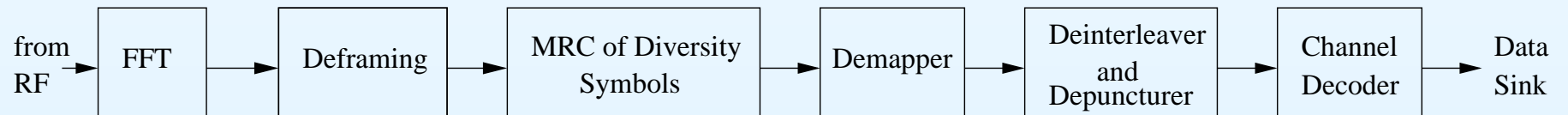


Figure 2: Receiver



Standard System & Channel

System:

- OFDM with 128 tones, QPSK modulation (100 tones carry data)
- Convolutional code ($k=7$, $R=1/3$ to $3/4$)
- Time and/or frequency spreading at low data rates
- MRC and soft-input Viterbi decoding

Channel:

- Channel model for UWB [*Molish, Foerster, Pendergrass '03*]
- Modified Saleh-Valenzuela model
- Four separate parameter sets, depending on environment (CM1,2,3,4)
- Impulse response assumed time invariant for at least several data packets



Extension: Coding

We consider two candidate coding schemes for enhanced performance:

1. Turbo Codes [*Berrou, Glavieux '96*]
 - Generator polynomials and interleavers from 3GPP
 - Code input lengths of 150, 300, 600 bits (depends on data rate)
 - Maintain time/frequency spreading from standard
 - 10 iterations of log-domain BCJR decoding
2. Repeat-Accumulate (RA) codes [*Divsalar, Jin, McEliece '98*]
 - Systematic, regular RA code
 - This is a simple serially-concatenated code
 - No time/frequency spreading, instead use $R=1/4$ or $1/8$ code
 - Randomly generated interleaver



Extension: Loading

- UWB channel slowly time varying, so use bit-loading (differing modulations on each tone)
- No power-loading (we assume operation at FCC power limit on each tone)
- Algorithms considered:
 - CCB [*Chow, Cioffi, Bingham '95*] — loads according to capacity
 - Piazzo [*Piazzo '99*] — loads according to expected BER
- Each tone can carry from 0 to 6 bits (using QAM modulations)
- To maintain same data rates: load a total of 200 bits onto 100 tones



Extension: Clustered Loading

- Since either channel state or loading information must be fed back to TX, we are interested in reducing the feedback requirements
- We calculate the loading at the RX and feed back the loading information
- Instead of calculating a per-tone loading, group the tones into *clusters* of D tones each, and do a per-cluster loading
- We can use a simple modification of the CCB algorithm: calculate the per-cluster number of bits as

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

- Result: loading according to mean capacity of the tones in the cluster



Constellation-Constrained Channel Capacity

Instantaneous capacity in bits per complex dimension of an N tone BICM-OFDM system with channel gains H_i using bit-loading is

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

- \bar{m} is the average number of bits/symbol ($\bar{m} = 2$ throughout)
- m_i and \mathcal{X}_i are the number of bits per symbol and the signal constellation for the i^{th} tone
- $p(Y_i | H_i, X_i)$ a Gaussian pdf: mean $H_i X_i$, 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



Constellation-Constrained Cutoff Rate

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

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

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

$$B(\mathbf{H}) = \frac{1}{N} \sum_{i=1}^N \sum_{\ell=1}^{m_i} \frac{1}{m_i} \mathbb{E}_{b, Y_i} \left\{ \sqrt{\frac{\sum_{X_i \in \mathcal{X}_{i, \bar{b}}^\ell} p(Y_i | H_i, X_i)}{\sum_{X_i \in \mathcal{X}_{i, b}^\ell} p(Y_i | H_i, X_i)}} \right\}$$



Outage Capacity and Cutoff Rate

- Since channel is slowly time-varying, we are interested in *outage capacity* and cutoff rate
- The X % outage capacity (cutoff rate) is the minimum capacity (cutoff rate) achieved by the best $(100-X)$ % of channel realizations
- We can obtain this by using previous formulas to calculate the capacity (cutoff rate) of many channel realizations, and using this information to obtain the corresponding X % outage capacity (cutoff rate) value

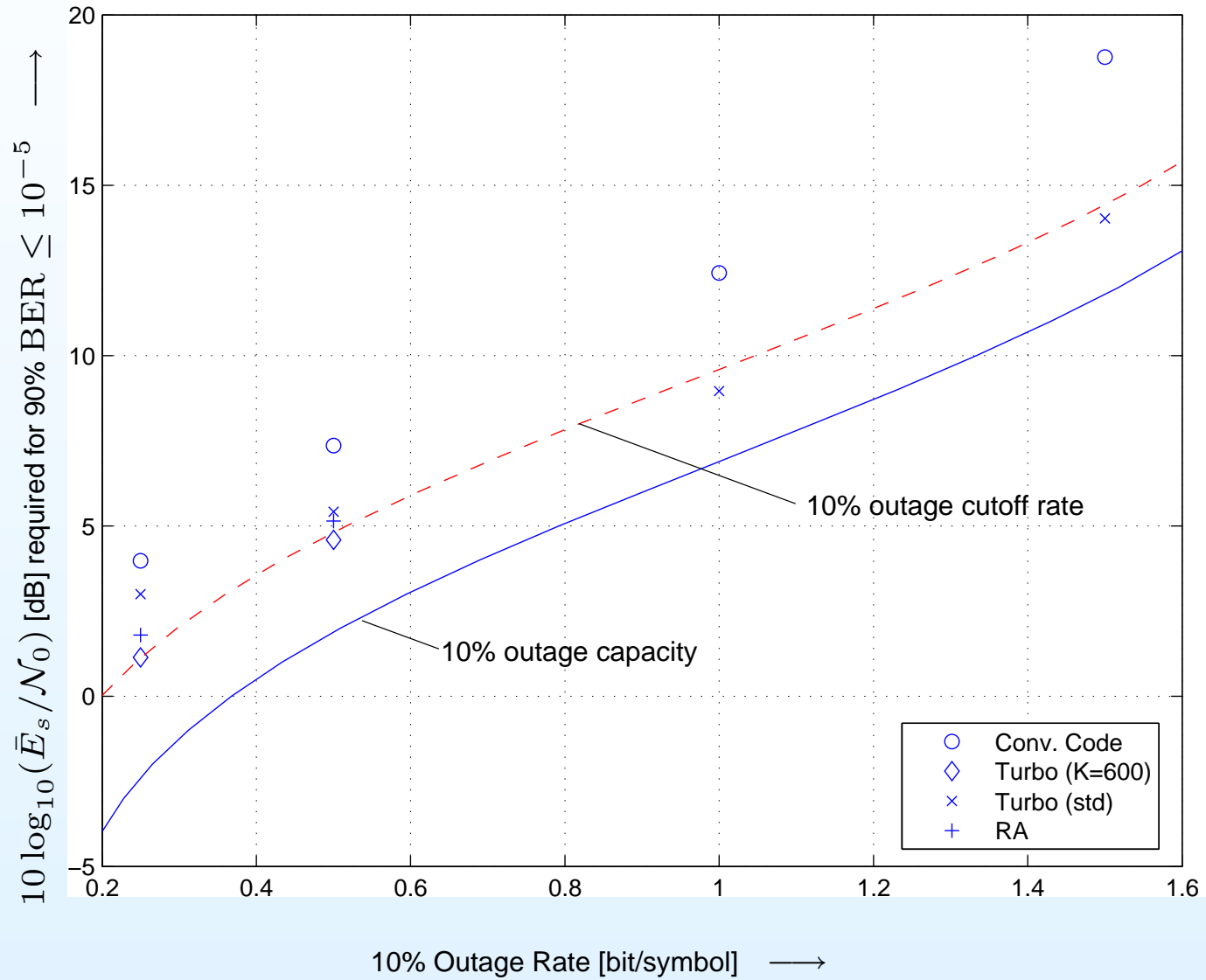


Error Rate Results

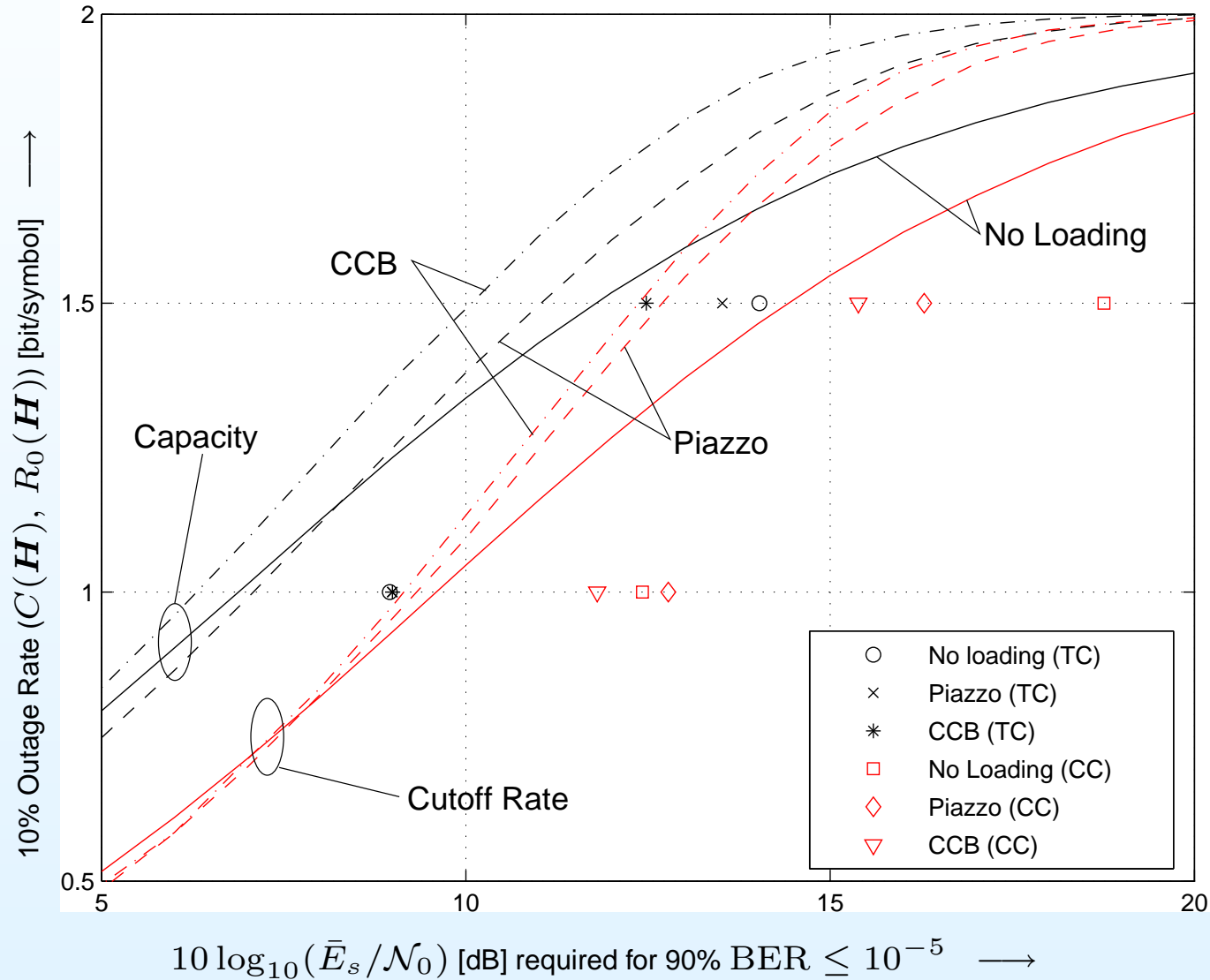
- Interested in error rate performance to compare with outage capacity/cutoff rate
- Simulations are done over the same 100 channel realizations
- The error rate results presented here are the $10 \log_{10}(\bar{E}_s/\mathcal{N}_0)$ required to achieve $\text{BER} \leq 10^{-5}$ for the 90% best channel realizations
- This corresponds to “reliable” communication with a 10 % outage
- These points denoted by markers on the plots



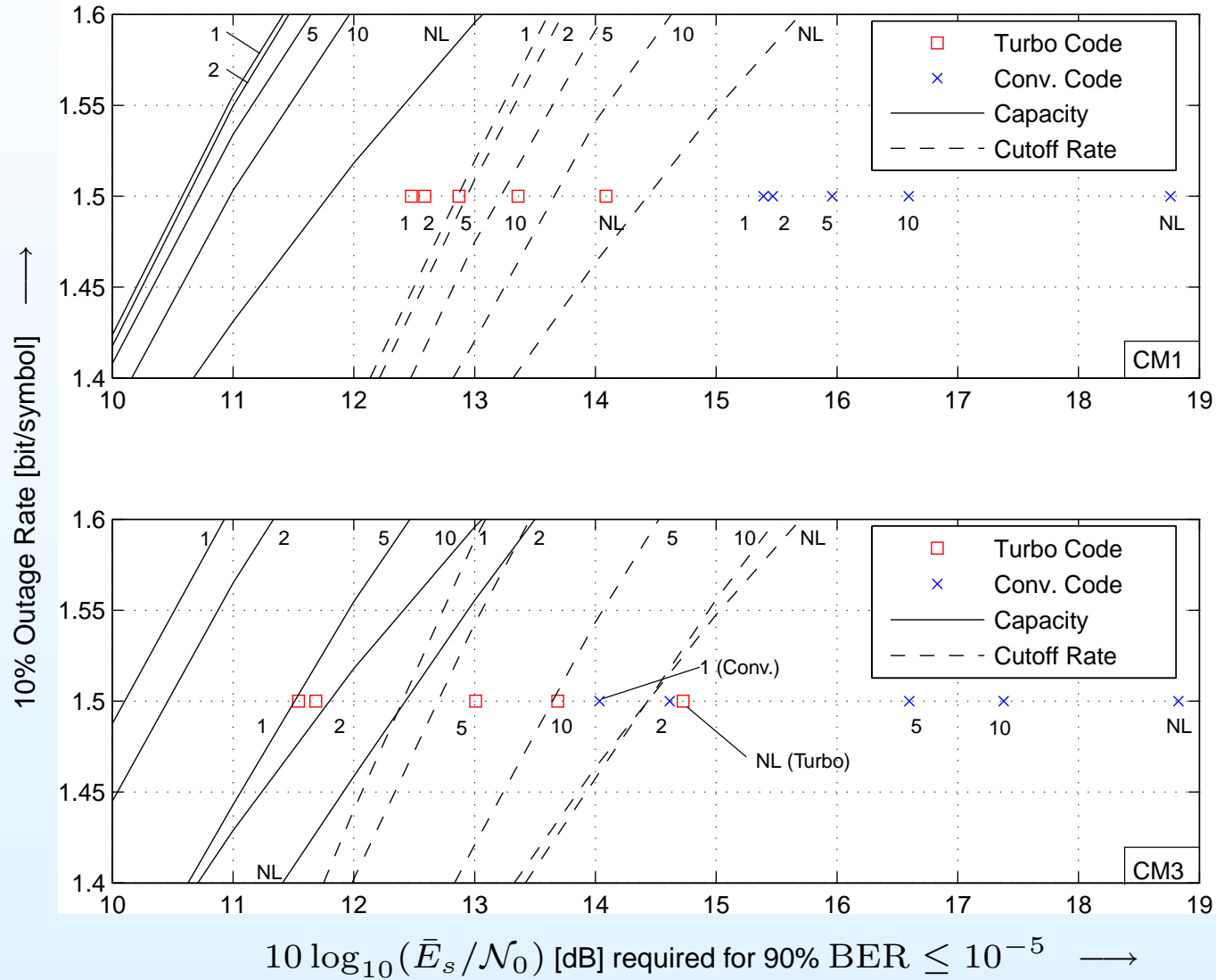
Results: No Loading



Results: Loading



Results: Clustered Loading



Results: Range Improvements

Increases in range and power efficiency using proposed extensions.
Channel CM1, rate 1.50 bit/symbol (480 Mbps), path loss exponent $d = 2$. [Batra et al. '04]

| 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 % |



Conclusions

- Standard BICM-OFDM performs close to the cutoff rate
- Application of stronger codes (Turbo, RA) improves power efficiency by up to 5 dB, depending on the data rate
- Bit-loading provides additional performance gains for high data rate modes
- Simple clustered loading scheme allows for reduced rate feedback of loading information with minimal performance degradation

