Performance Analysis of Multiband OFDM for UWB Communication

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1. System and Channel

2. Analysis of UWB channel

3. Performance of Multiband OFDM

   - Information Theory: capacity & cutoff rate

   - Simulation: bit error rate

4. Conclusions

Multiband OFDM proposal for Ultra Wideband communications (IEEE 802.15)

- Use 3.1–10.6 GHz spectrum (where FCC permits full-power UWB)
- Split the spectrum into 528 MHz sub-bands (frequency hop over 3+ bands)
- OFDM with QPSK on $N = 128$ subcarriers
- bit-interleaved coded modulation (BICM)
- 10 data rates (53.3 Mbps to 480 Mbps)

- UWB channel is slowly time varying $\Rightarrow$ use pilot symbols in the packet header
- Least-squares error (LSE) channel impulse response estimator allows us to exploit fact that impulse response length $L \leq N$
- Performance depends only on SNR and parameter

$$\eta = \frac{L}{NP}$$

L impulse response length, N number of carriers, P number of pilot OFDM symbols (for proposed standard, $L = 32$, $N = 128$, $P = 2$, $\eta = 0.125$)

We will come back to this later...

The real-valued RF channel impulse response given by *[Molisch et al.'03]*

$$h(t) = X \sum_{l \geq 0} \sum_{k \geq 0} \alpha_{k,l} \delta(t - T_l - \tau_{k,l})$$

- Multipath arrivals in clusters of rays
- Arrival times (T_l and $\tau_{k,l}$) are conditionally exponentially distributed
- Magnitudes ($\alpha_{k,l}$) exponentially decaying, *lognormal* and equiprobable $\pm$
- X a lognormal r.v.

Four channels have been defined. We consider extreme cases:

- CM1: 0–4 meters, line-of-sight (LOS) channel
- CM4: 4–10 meters, "extreme non-LOS multipath channel"

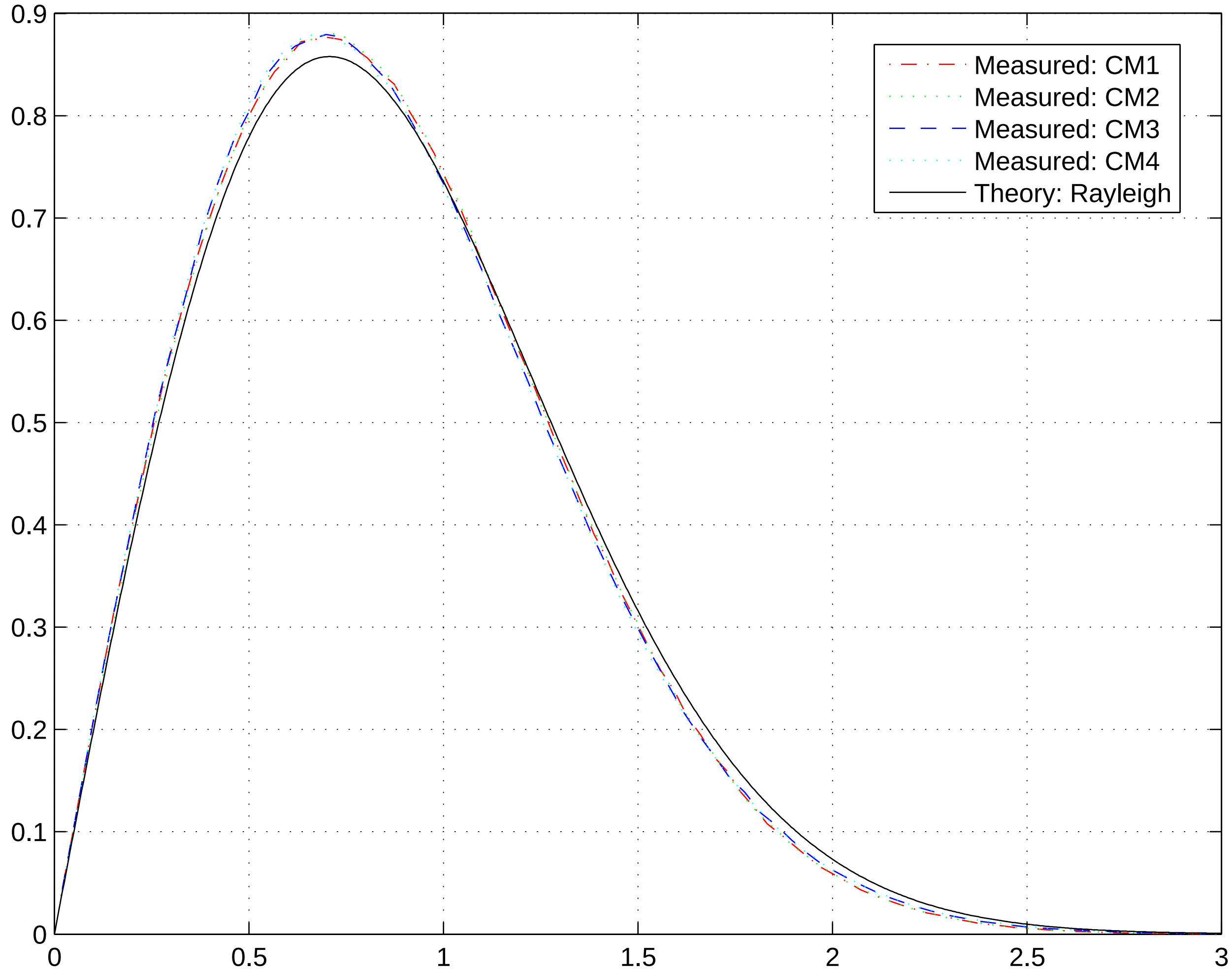
CHANNEL MODEL ANALYSIS

Examine H_i (frequency domain channel responses of each carrier). Ignore the "outer" lognormal term X.

- Marginal distribution of $|H|$, i.e. $p(|H_i|)$
  - What kind of fading do we see?

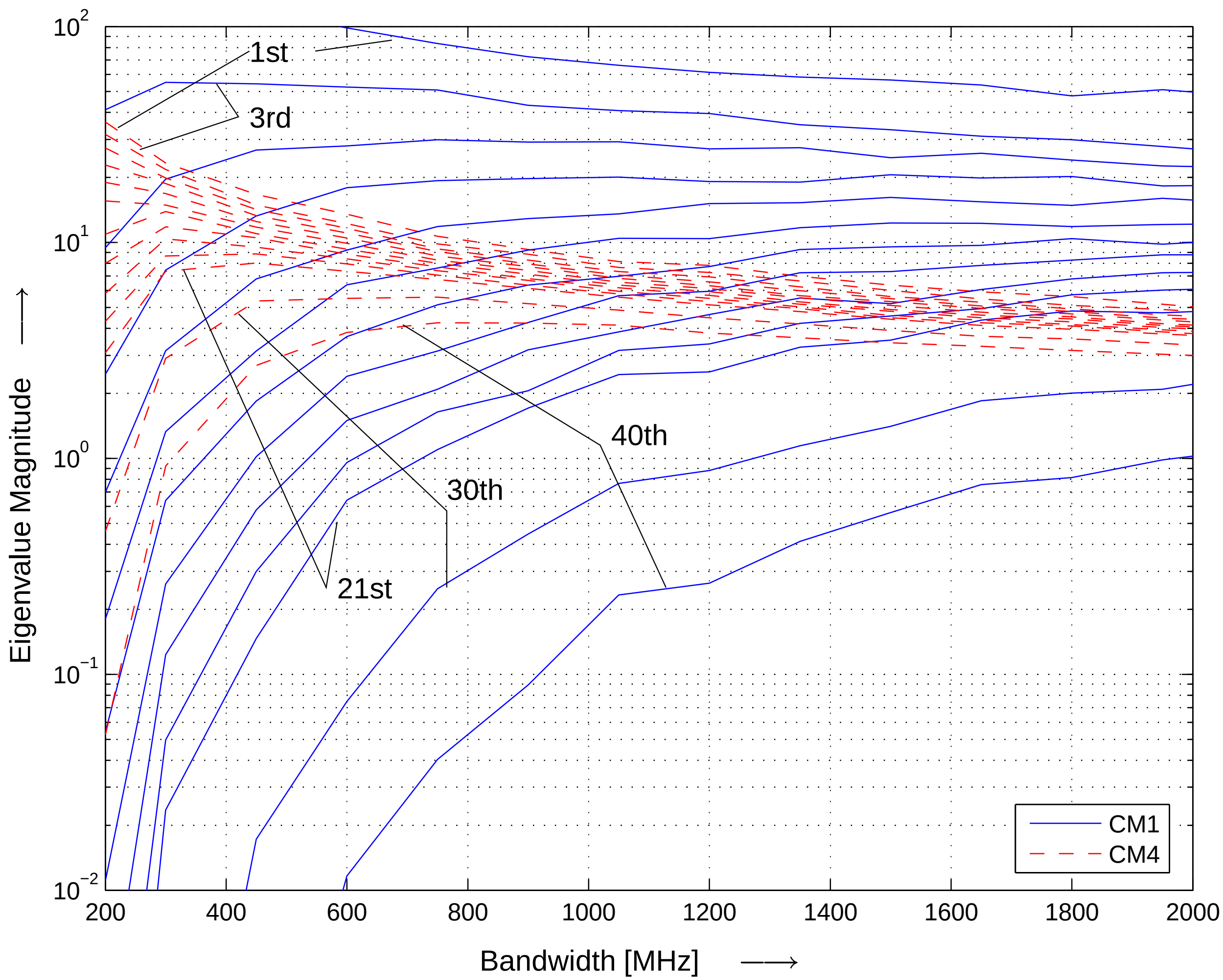
- Eigenvalues of subcarrier correlation matrix $\mathbf{R_{HH}}$
  - What diversity is available on the UWB channel?
    - MB-OFDM Convolutional codes can exploit diversity order $d_{\text{free}} \leq 15$
  - # of "large" eigenvalues (≥ 1) is a measure of diversity

$p(|H_i|)$ MEASUREMENTS



$\mathbf{H}$ is $\approx$ a Rayleigh fading channel for a particular lognormal X

40 LARGEST EIGS OF $\mathbf{R_{HH}}$ (NOT ALL SHOWN)



3 * 528 MHz bandwidth ⇒ sufficient diversity to fully exploit coding gain of the codes

Where are we?

1. Studying Multiband OFDM and the 802.15 channel model for UWB
2. We have a simple, practical channel estimation scheme
3. Examined UWB channel in frequency domain
   - Channel gains $\Rightarrow$ “Rayleigh + Lognormal”
   - Available diversity? $\Rightarrow$ sufficient for codes used

Performance Analysis

Two approaches:

1. Information-theoretic analysis
   - Channel capacity (ultimate limits)
   - Cutoff rate (practical limit of convolutional codes)
2. Simulations of proposed system

We will:

- Compare results with "Rayleigh+Lognormal" channel
- Consider perfect CSI as well as channel estimation

Instantaneous capacity in bits per complex dimension of an N tone BICM-OFDM system is given by *[Ekbal et al.'03]*

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

- m is the number of bits per symbol (2 in our case)
- $\mathcal{X}$ is the signal constellation (QPSK in our case)
- $\mathcal{X}_b^\ell$ is the set of all constellation points $X \in \mathcal{X}$ whose label has the value $b \in \{0,1\}$ in position ℓ
- $p(Y_i|\hat{H}_i, X_i)$ is the pdf of the channel output Y_i for given input X_i and channel estimate $\hat{H}_i$
- $\mathsf{E}_z\{\cdot\}$ denotes expectation with respect to z

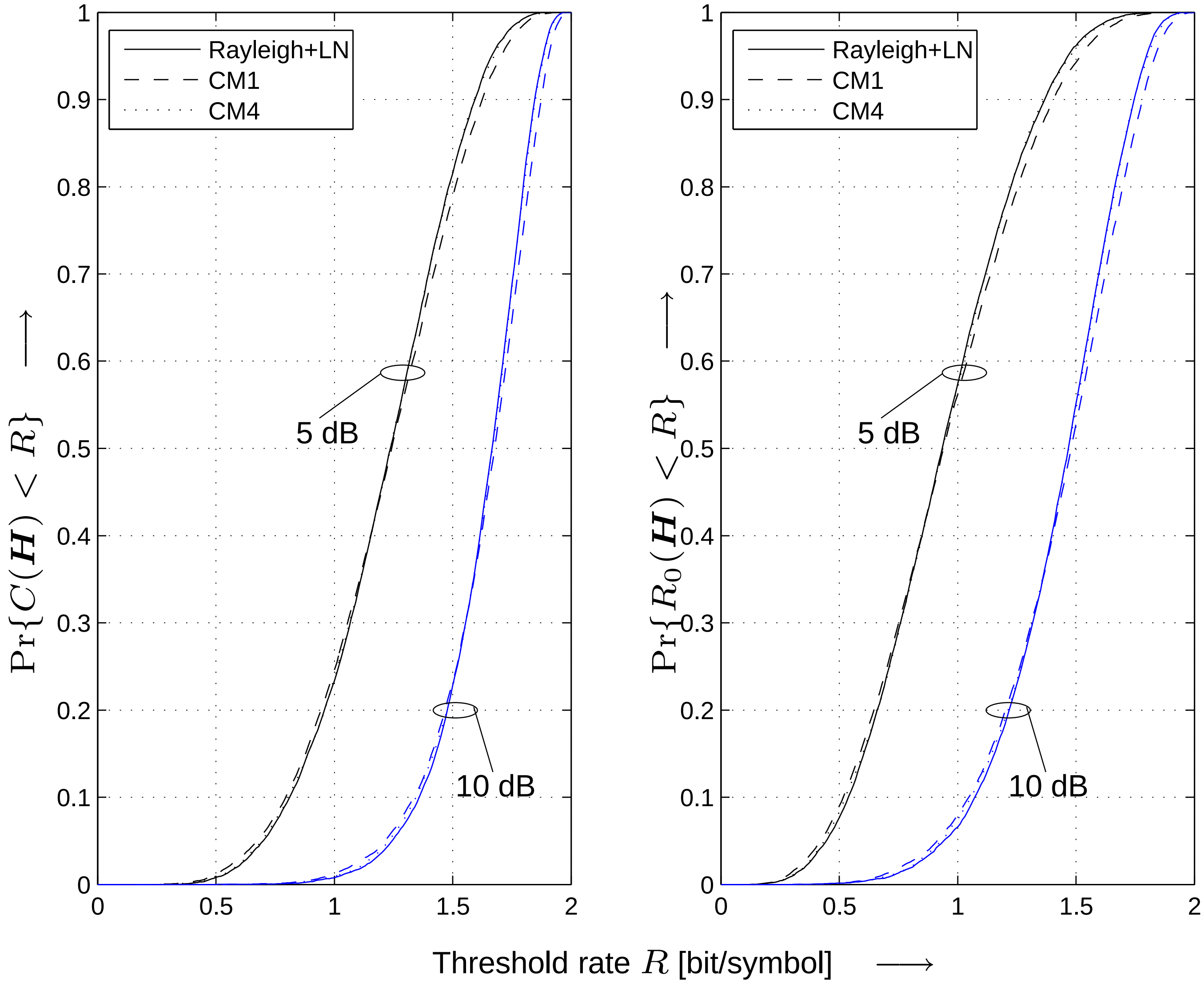
Instantaneous cutoff rate in bits per complex dimension *[Ekbal et al.'03]*

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

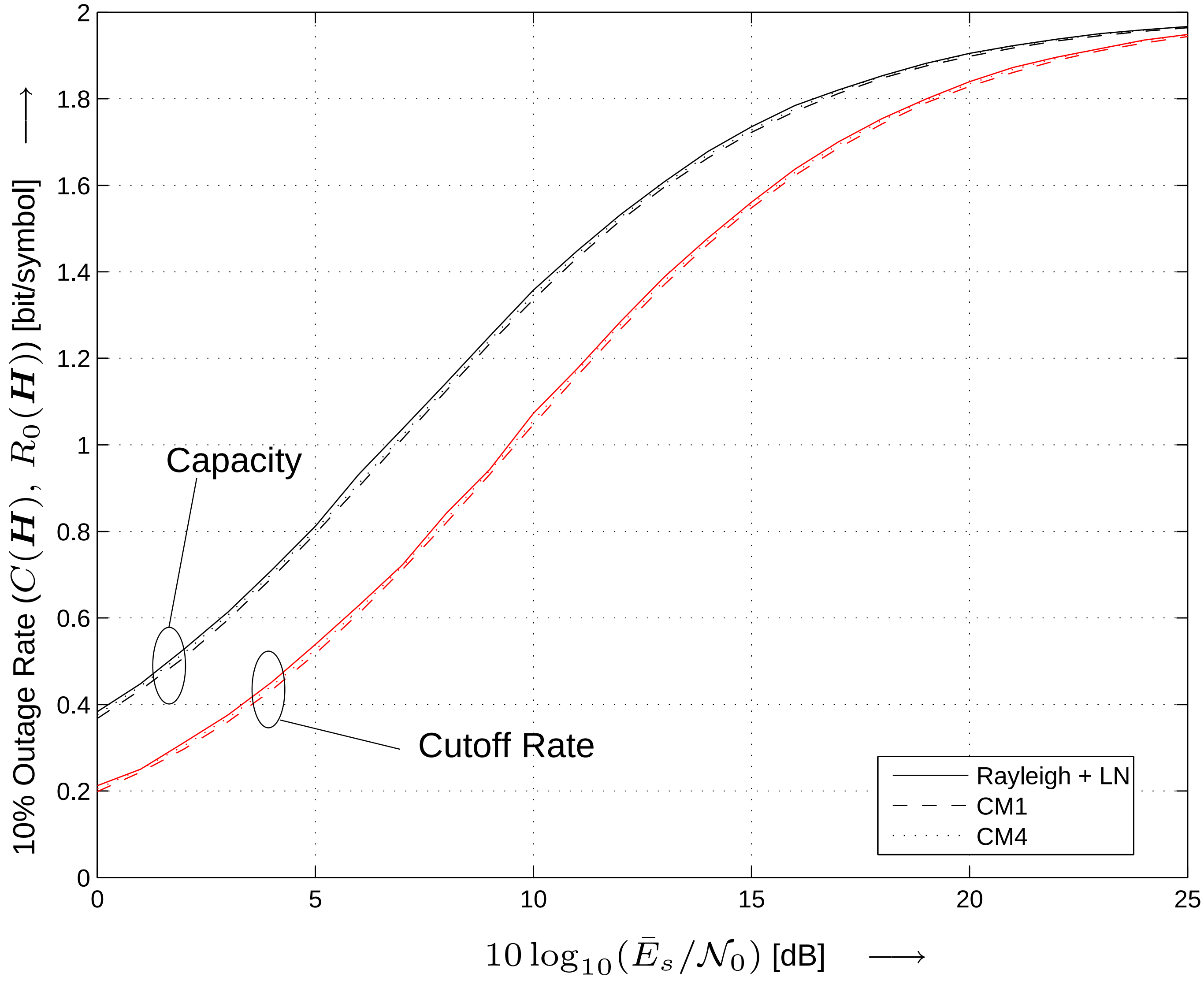
with the instantaneous Bhattacharya parameter ($\bar{b}$ denotes the complement of b)

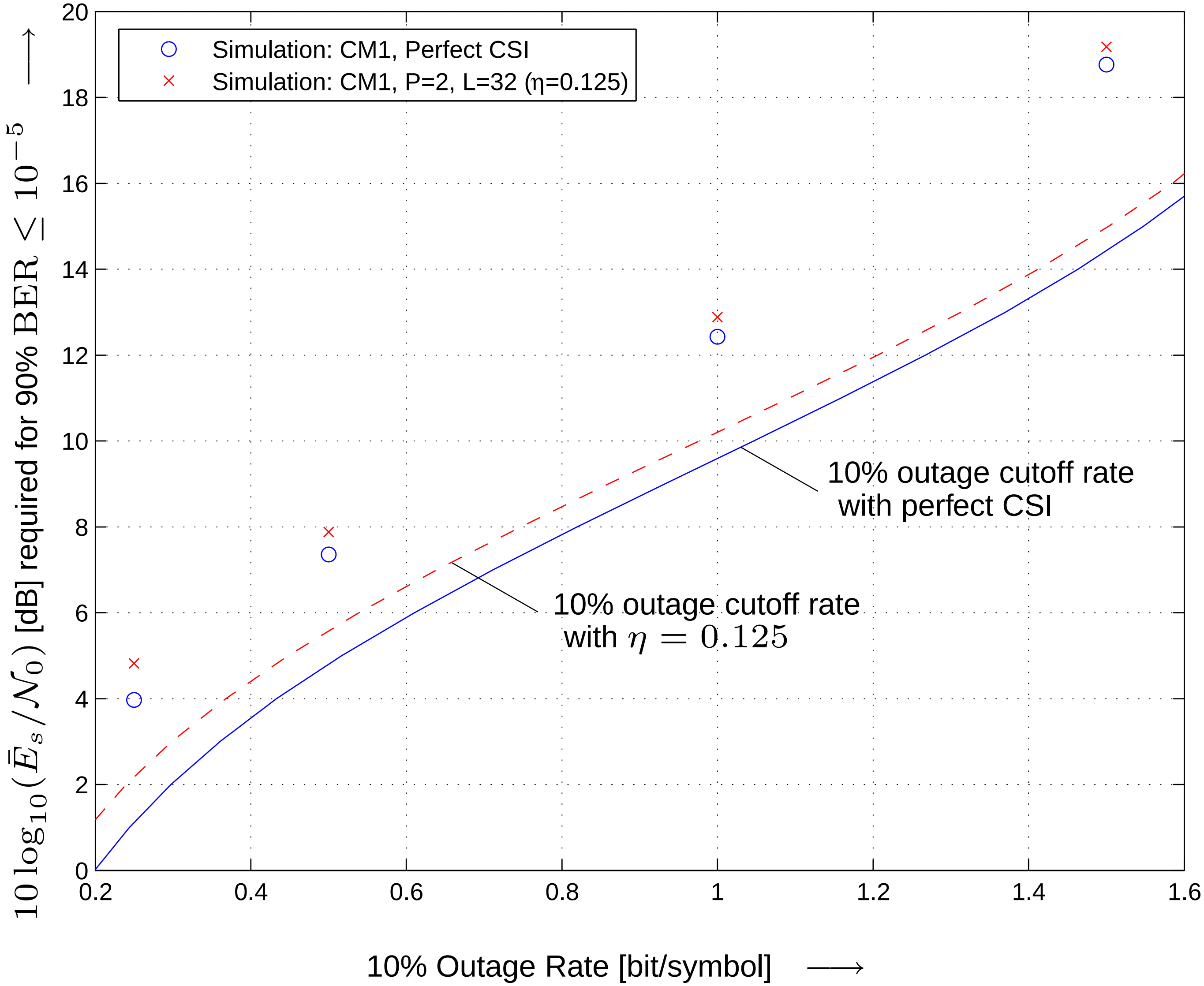
$$B(\boldsymbol{H}) = \frac{1}{mN} \sum_{\ell=1}^{m} \sum_{i=1}^{N} \mathsf{E}_{b,Y_i} \left\{ \sqrt{\frac{\sum_{X_i \in \mathcal{X}_{\bar{b}}^{\ell}} p(Y_i|\hat{H}_i, X_i)}{\sum_{X_i \in \mathcal{X}_{b}^{\ell}} p(Y_i|\hat{H}_i, X_i)}} \right\}$$

Evaluate C and R_0 by Monte Carlo methods


1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Rayleigh+LN
CM1
CM4
5 dB
10 dB
$\Pr\{C(\boldsymbol{H}) < R\}$ ⟶
$\Pr\{R_0(\boldsymbol{H}) < R\}$ ⟶
0
0.5
1
1.5
2
Threshold rate R [bit/symbol] ⟶

10% Outage Capacity and Cutoff Rate — Perfect CSI





Simulation: CM1, Perfect CSI
Simulation: CM1, P=2, L=32 (η=0.125)
10% outage cutoff rate with perfect CSI
10% outage cutoff rate with $\eta = 0.125$
$10\log_{10}(\bar{E}_s/\mathcal{N}_0)$ [dB] required for 90% BER $\leq 10^{-5}$ ⟶
10% Outage Rate [bit/symbol] ⟶
0
2
4
6
8
10
12
14
16
18
20
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

- UWB channel seen by OFDM as Rayleigh fading, with additional shadowing
- Multiband OFDM codes capture sufficient diversity with $3 * 528$ MHz bandwidth

- IT limits of UWB channel similar to perfectly-interleaved Rayleigh+Lognormal
- BICM-OFDM scheme performs close to cutoff rate — well suited to exploit the available diversity
- LSE estimation performs within 0.5 dB of perfect CSI