Enabling Techniques for Multiband OFDM-based UWB Communication

Ph.D. Proposal

Chris Snow

Advisors: L. Lampe and R. Schober (joint)

Organization of the Talk

- Overview of Ultra Wideband (UWB) and Multiband OFDM
- UWB channel models
- Channel Estimation for Multiband OFDM
- Performance Measures
  - Information Theory: capacity and cutoff rate
  - Simulation: bit error-rates
- Results
- Conclusions
- Future Work & Timetable

Ultra-Wideband Radio

- "an intentional radiator that, at any point in time ... has a bandwidth equal to or greater than 500 MHz" (US FCC)
- Max -41.3 dBm/MHz over allocated spectrum (3.1–10.6 GHz)
- Application: low-power, short-range, high-speed wireless

Multiband OFDM proposal for IEEE 802.15.3a (PANs)

- Split the 3.1–10.6 GHz band into 528 MHz sub-bands
- OFDM with QPSK on $N = 128$ subcarriers (100 carry data)
- bit-interleaved coded modulation (BICM)
- 10 different data rates from 53.3 Mbps to 480 Mbps, via code puncturing and optional repetition in time/frequency
- Frequency hop between bands every OFDM symbol

Channel Model developed by IEEE 802.15

The real-valued RF channel impulse response given by

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

- Cluster and ray arrival times (T_l and $\tau_{k,l}$) are conditionally exponentially distributed
- Ray magnitudes ($\alpha_{k,l}$) are exponentially decaying, lognormally distributed ($\therefore$ a random number of rays)
- X a lognormal r.v.

Four separate sets of parameters available, depending on scenario. We consider the two extreme cases:

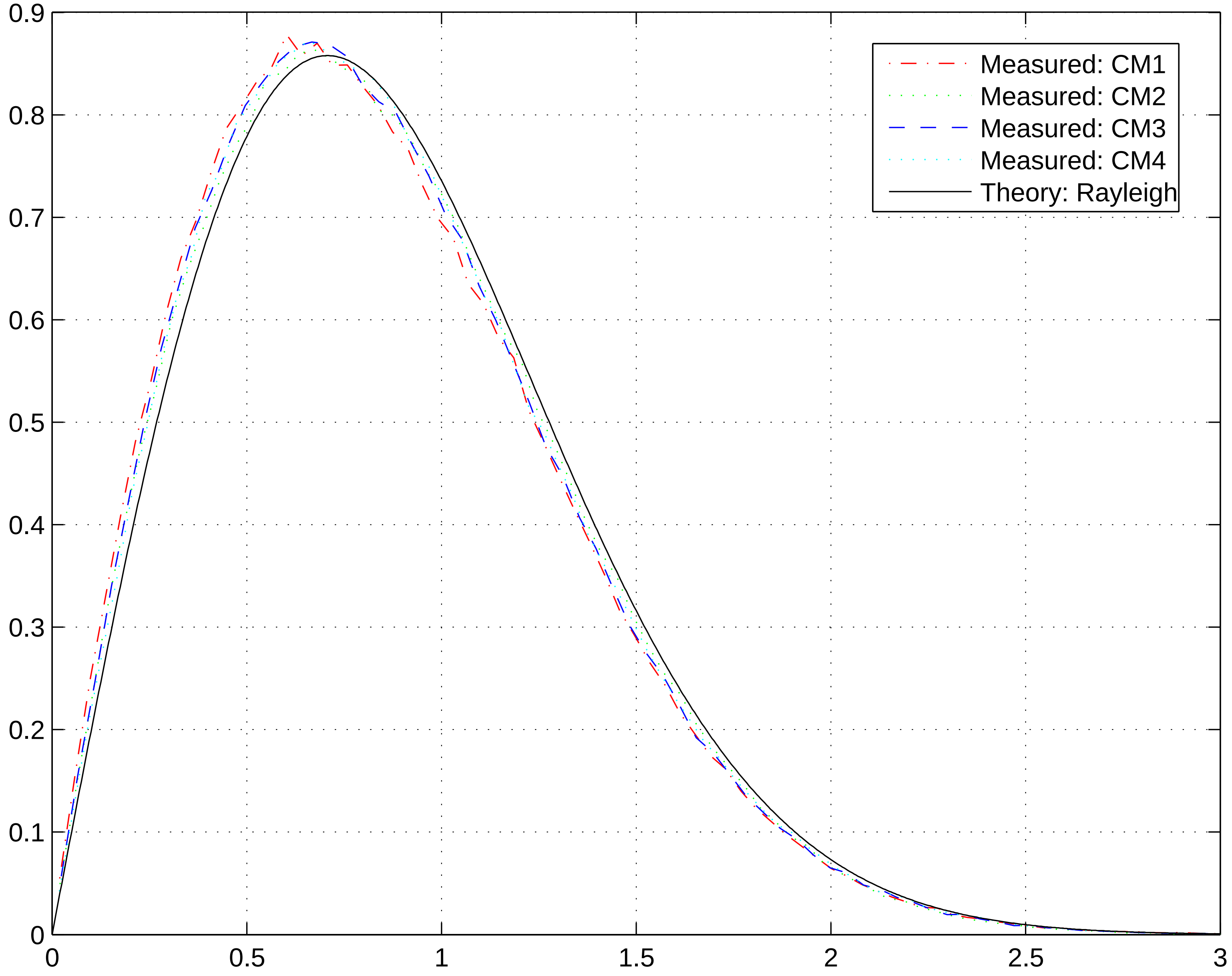
- CM1: 0–4 meters, line-of-sight (LOS) channel
- CM4: "extreme non-LOS multipath channel"

Channel Model Analysis

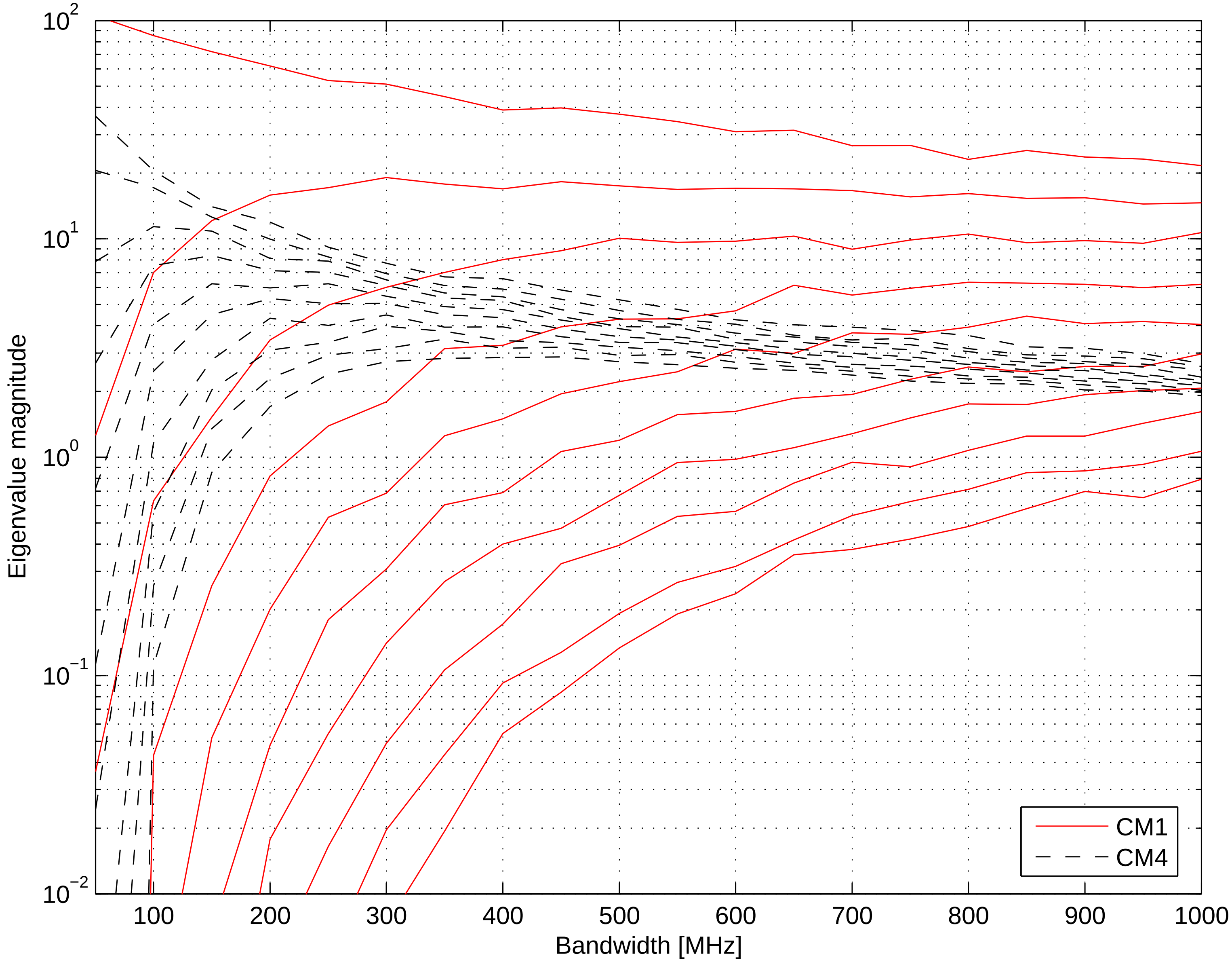
We will exclusively consider H_i, the frequency-domain channel responses of each carrier — sample $h(t)$ at 528Msps and take Fourier transform. We also ignore the "outer" lognormal term X. We study

- Marginal distribution of $|H|$, i.e. $p(|H_i|)$
- Eigenvalues of subcarrier correlation matrix $\mathbf{R_{HH}}$
  - Diversity from subcarriers having independent fading
  - # of "large" eigenvalues (≥ 1) is measure of diversity

$p(|H_i|)$ Measurements



First 20 eigs of $\mathbf{R_{HH}}$ (every 2nd shown)



Channel model — Take-home message

- For a particular lognormal fading X, $\mathbf{H}$ is well approximated by a Rayleigh fading channel
- The 528 MHz bandwidth of MB-OFDM has sufficient diversity to fully exploit the coding gain of the codes we are using

- Effects of imperfect channel state information (CSI)?
- Because the UWB channel is slowly time varying, we will use pilot symbols in the packet header
- Least-squares error (LSE) channel impulse response estimator allows us to exploit fact that impulse response length $L \leq N$ (in fact, L should be less than the cyclic prefix length)

We skip maths here, just note that performance depends only SNR and

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

where

- L impulse response length, N number of carriers, P number of pilot OFDM symbols

(for proposed standard, $L = 32, N = 128, P = 2 \quad \rightarrow \quad \eta = 0.125$)

Equivalent SNR with Channel Estimation

With estimator as described, we can derive the conditional pdf at the receiver

$$p(Y_i|\hat{H}_i, X_i) = \frac{1}{\pi(\sigma_N^2(\eta\mu^2+1))} \exp\left(-\frac{|Y_i - X_i\hat{H}_i\mu^2|^2}{\sigma_N^2(\eta\mu^2+1)}\right)$$

where $\hat{H}_i$ is the channel estimate and μ is the correlation between the true channel H_i and the estimate $\hat{H}_i$.

This is a Gaussian density — we can represent the system with estimation operating at γ_t as a system with perfect CSI at some γ_e

$$\gamma_e = \frac{\gamma_t}{\eta\left(1+\frac{1}{\gamma_t}\right)+1}$$

Note as $\gamma_t \to \infty$, SNR loss due to estimation goes to $1/(\eta+1)$

MB-OFDM Channel Estimation — Take-home message

- Estimate slowly time-varying UWB channel using OFDM pilot symbols in the packet header
- LSE estimator, performance depends on SNR and η
- We can consider the system with estimation operating at SNR γ_t as a system with perfect CSI at some equivalent SNR γ_e

Performance Measures

We take two approaches:

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

For both approaches we consider perfect CSI as well as imperfect CSI due to channel estimation using OFDM pilot symbols

Instantaneous capacity in bits per complex dimension of an N tone BICM-OFDM system is given by

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

- 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

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

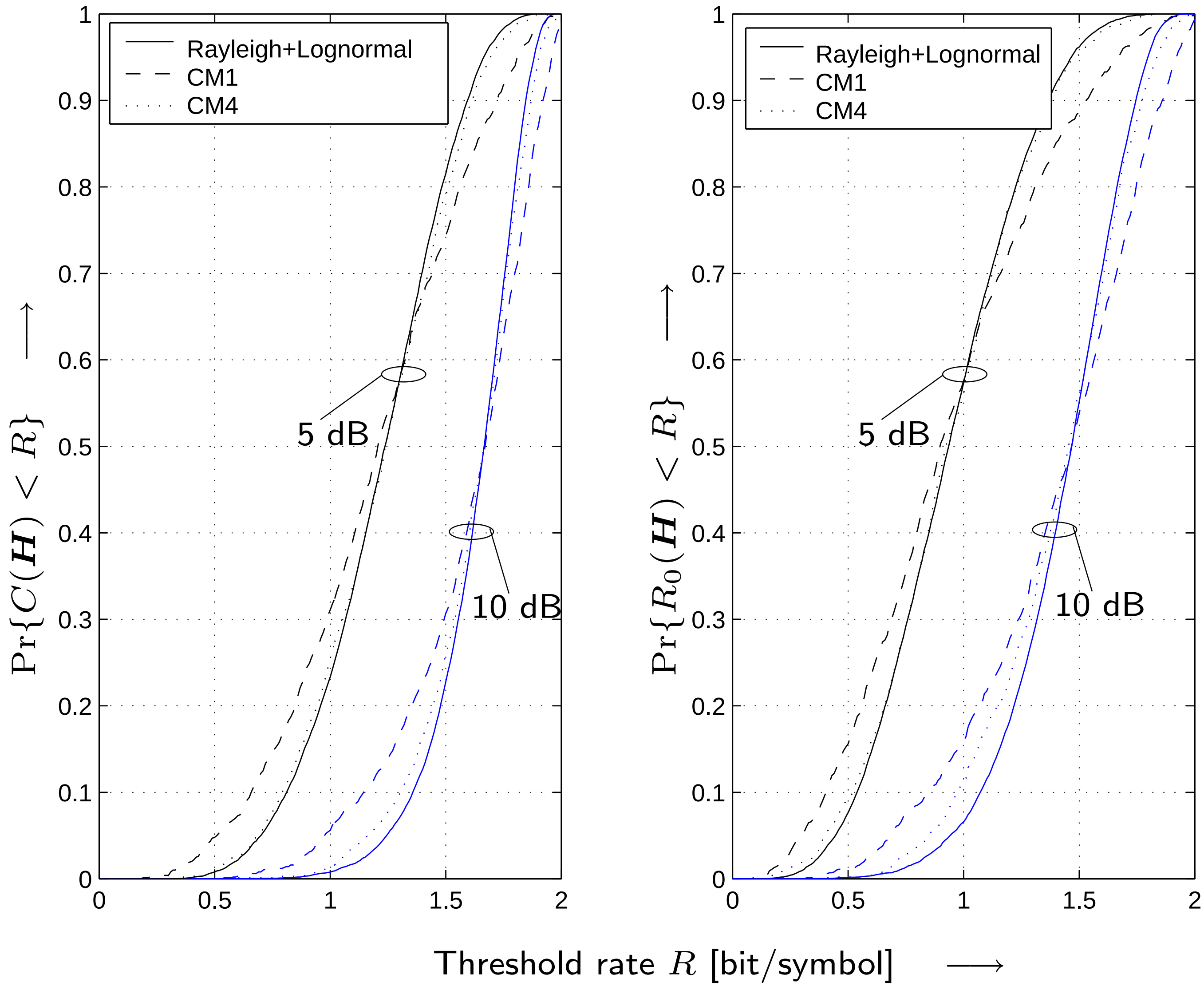
with the instantaneous Bhattacharya parameter ($\bar{b}$ denotes the complement of b)

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

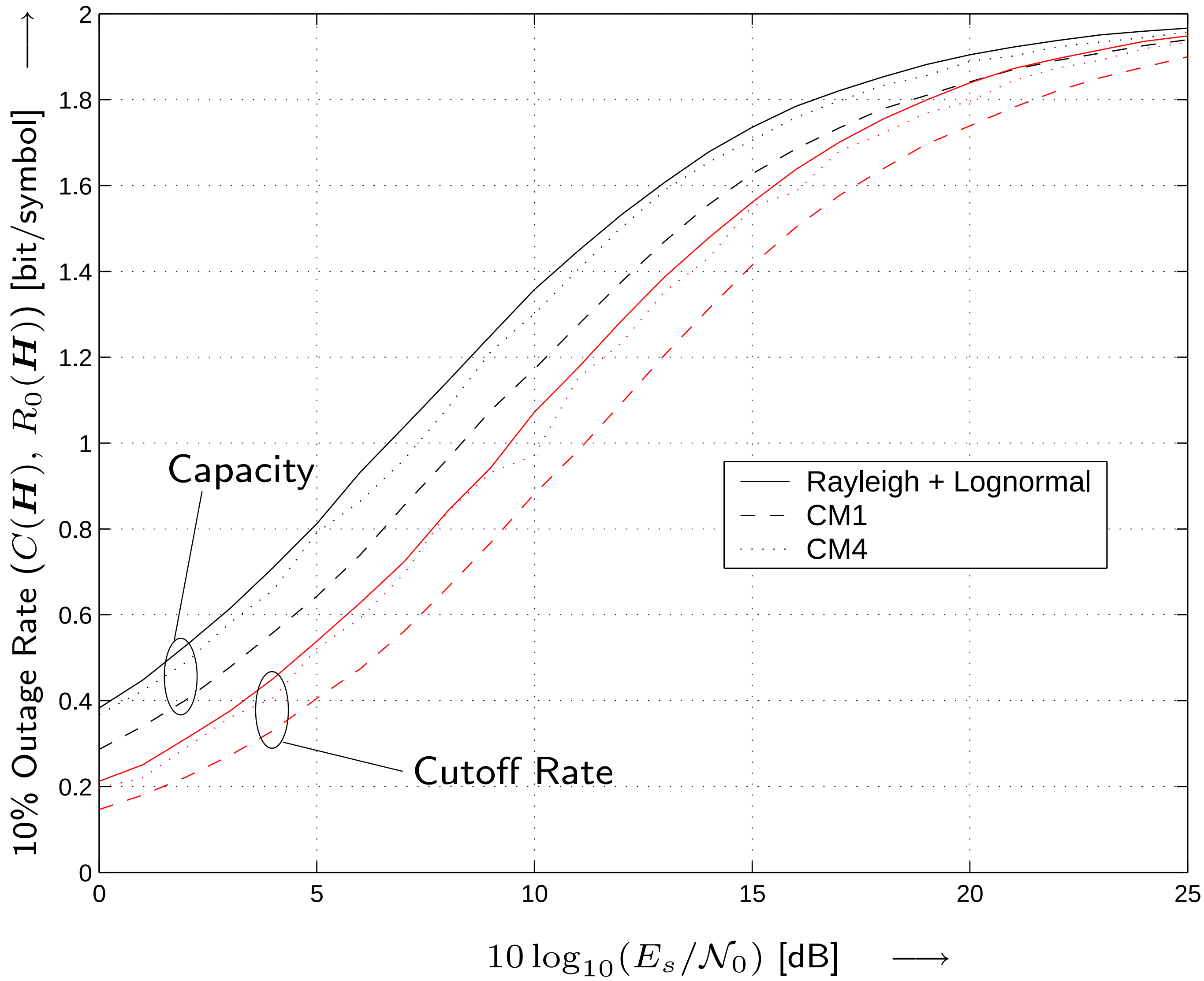
Results — Parameters

- Capacities and cutoff rates evaluated by Monte Carlo simulation using 1000 realizations of each channel model
- Simulation results using 100 realizations of each channel model
- Simulation results for 4 of the 10 modes of MB-OFDM proposal
- We only show CM1 and CM4 as they are the extreme cases
- Show as comparison "Rayleigh+Lognormal" (i.i.d Rayleigh fading on each carrier with an outer lognormal as with UWB)
- Channel estimation factor $\eta = 0.125$ for imperfect CSI simulations

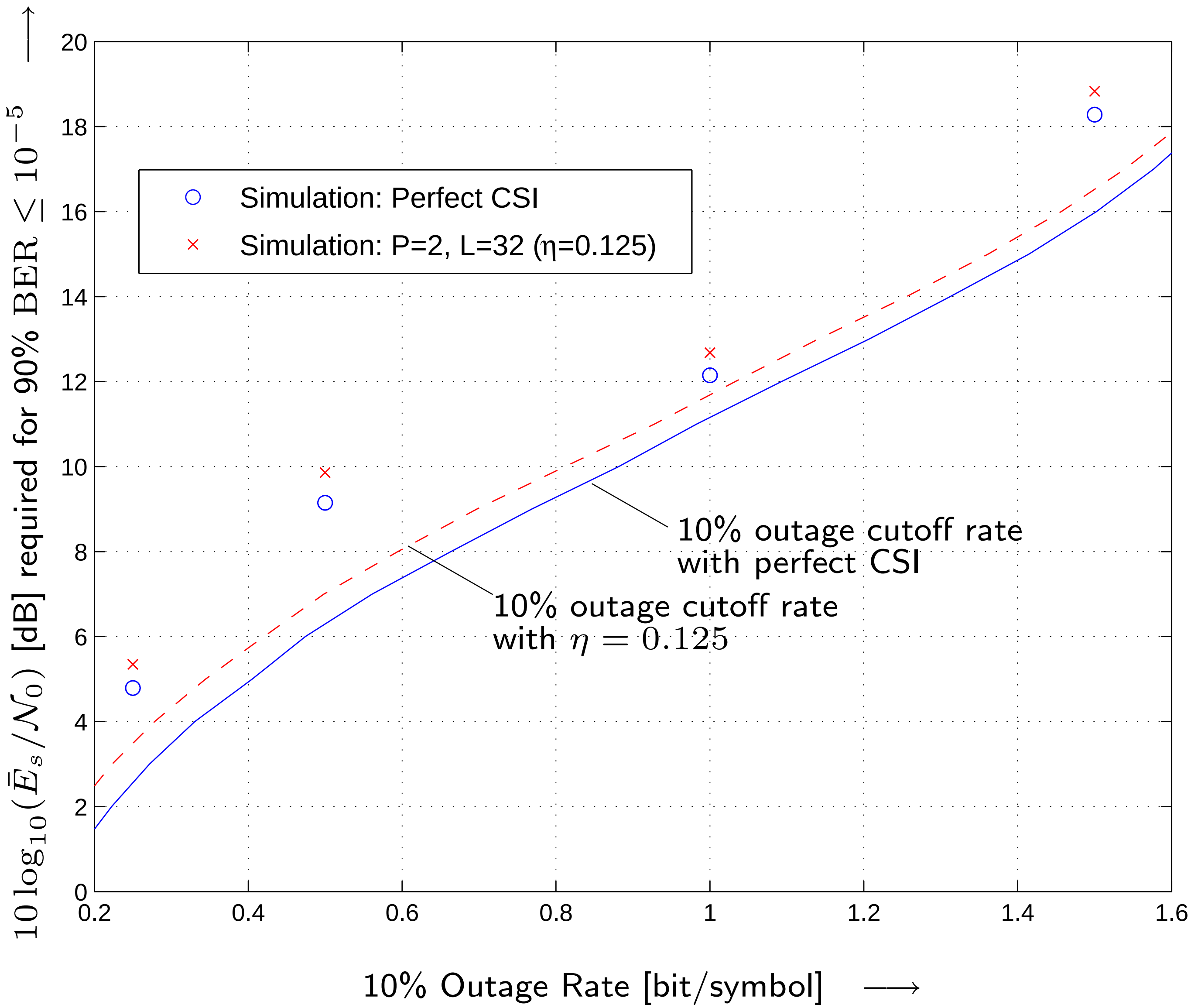
Capacity and Cutoff CDFs — Perfect CSI



10% Outage Capacity and Cutoff Rate — Perfect CSI



10% Outage Cutoff Rate vs Simulations



Conclusions

- UWB channel seen by OFDM systems as “fast” Rayleigh fading, with additional shadowing
- Codes used in Multiband OFDM capture all the diversity they can use with the 528 MHz bandwidth
- Information-theoretic limits of UWB channel similar to those of a perfectly-interleaved Rayleigh channel plus log-normal shadowing
- BICM-OFDM scheme proposed in Multiband OFDM performs close to the cutoff rate — well suited to exploit the available diversity
- LSE estimation performs within 0.5 dB of perfect CSI

Future Work

We will consider application of these advanced communication techniques to Multiband OFDM

- Capacity-approaching codes (Turbo and LDPC)
  - Higher data rates with same signal constellation
  - Short block lengths required due to delay constraints
- Higher-order modulation schemes
  - Increase of data rate by moving to e.g. 8-PSK or 16-QAM
- Modulation diversity
  - Multidimensional signal constellations give diversity gain
  - Tradeoff is the increased decoding complexity
- Multiple-input multiple-output (MIMO) schemes
  - Promise of large increases in data rate and/or reliability
  - No work so far on MIMO-OFDM for UWB channels

Tentative Timetable for Completion

Description	**Months**	**Tentative Period**
Capacity-approaching Codes	8	Sep. 2004 – Apr. 2005
Alternative Modulations	2	May 2005 – June 2005
Modulation Diversity	6	July 2005 – Dec. 2005
MIMO-OFDM	6	Jan. 2006 – June 2006
Preparation of dissertation	6	July 2006 – Dec. 2006