Enabling Techniques for Multiband OFDM-based UWB Communication

Ph.D. Proposal

Chris Snow

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

Organization of the Talk

1. Introduction
    - What is Ultra Wideband (UWB) radio?
    - Overview of Multiband OFDM proposal for UWB
    - Description of UWB channel models
2. Contributions
    - Analysis of UWB channel for OFDM systems
    - Study of channel estimation for Multiband OFDM
    - Performance of Multiband OFDM proposal
        - Information Theory: capacity and cutoff rate
        - Simulation: bit error-rate of Multiband OFDM
    - Conclusions
3. Future Work & Timetable

UWB & Multiband OFDM

Ultra-Wideband Radio

- "an intentional radiator that ... 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: short-range high-speed wireless

Multiband OFDM proposal for IEEE 802.15.3a (high-rate PANs)

- Split the 3.1–10.6 GHz band into 528 MHz sub-bands
- OFDM with QPSK on $N = 128$ subcarriers
- bit-interleaved coded modulation (BICM)
- 10 different data rates from 53.3 Mbps to 480 Mbps
- Frequency hop between bands every OFDM symbol

Channel Model developed by IEEE 802.15

The real-valued RF channel impulse response given by

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

- Multipath rays arrive in clusters (index l) of rays (index k)
- 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 and equiprobable $\pm$
- X a lognormal r.v.

Four sets of decay factors and mean interarrival times have been defined. We consider the two extreme cases:

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

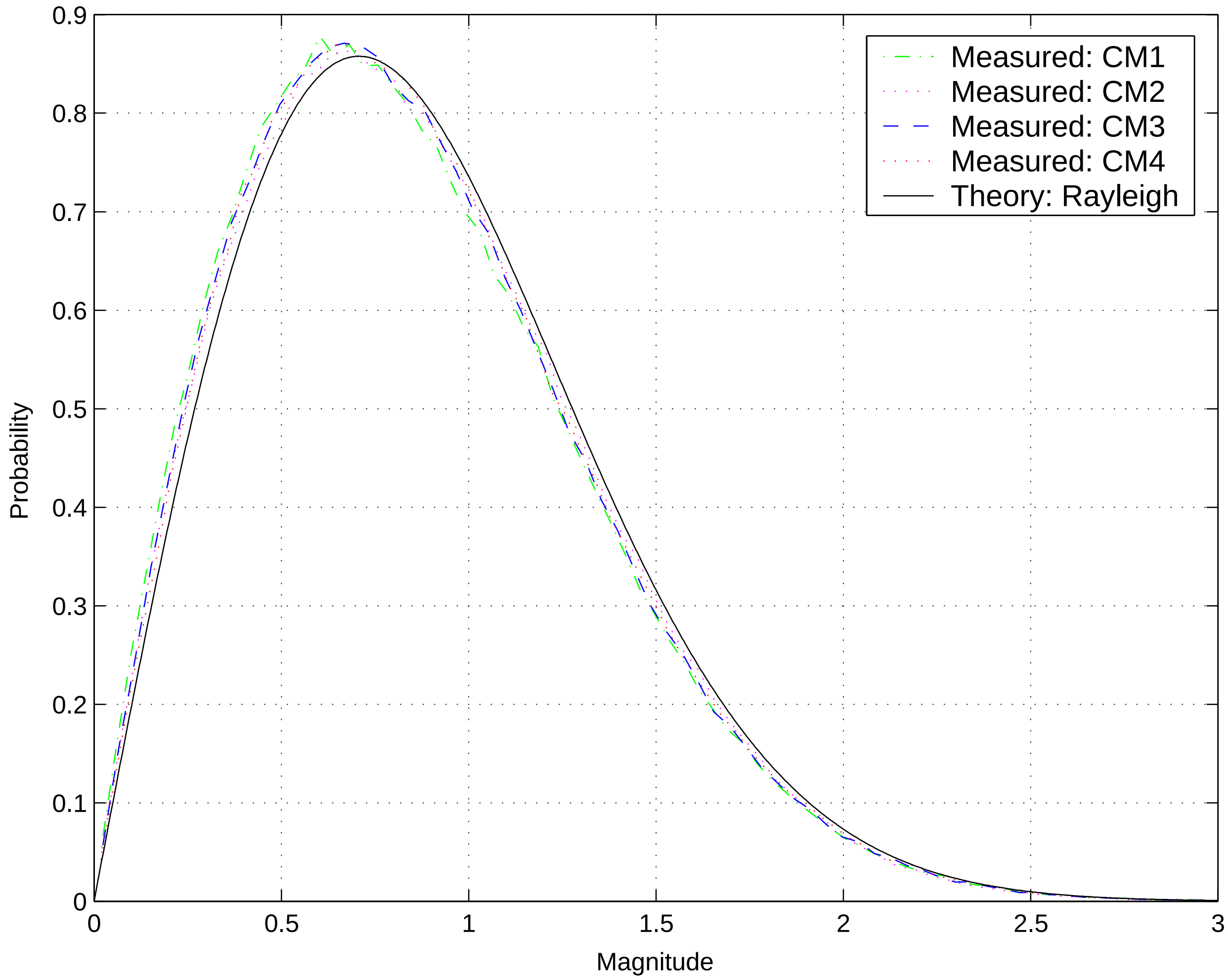
Contributions

Channel Model Analysis

We consider H_i, the frequency-domain channel responses of each carrier. We also ignore the "outer" lognormal term X. We study

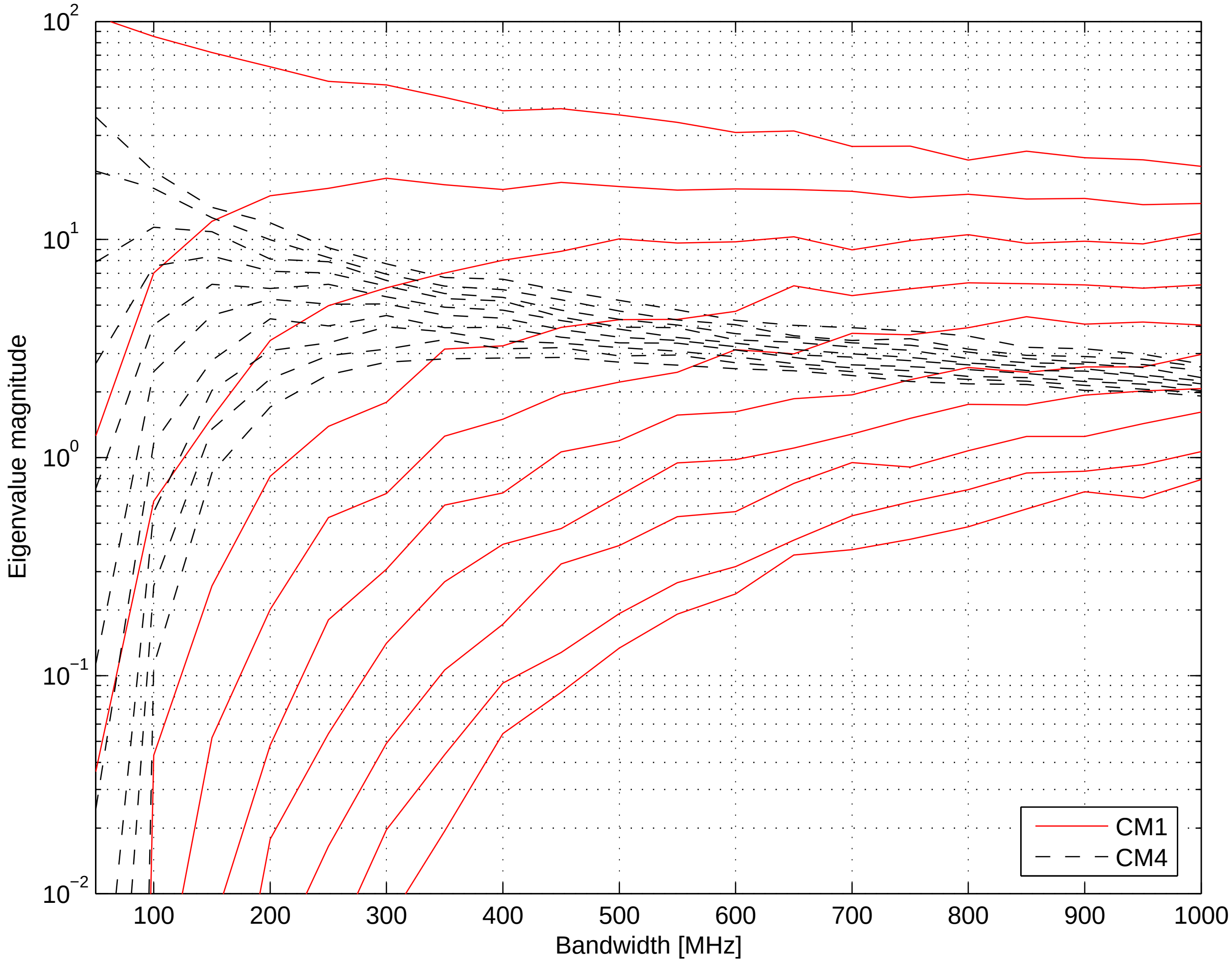
- Marginal distribution of $|H|$, i.e. $p(|H_i|)$
- Eigenvalues of subcarrier correlation matrix $\mathbf{R_{HH}}$
  - We are interested in diversity available on the UWB channel
    - Convolutional codes used in Multiband OFDM can exploit diversity order $d_{\text{free}} \leq 15$
  - # of "large" eigenvalues (≥ 1) is a measure of diversity
  - We will look at the sorted eigenvalue magnitudes

$p(|H_i|)$ Measurements



- For a particular lognormal fading X, $\mathbf{H}$ is well approximated by a Rayleigh fading channel

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



- The 528 MHz bandwidth of MB-OFDM has sufficient diversity to fully exploit the coding gain of the codes we are using

Channel Estimation with MB-OFDM

- 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 math, just note that performance depends only on the SNR and a parameter defined as

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

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

Equivalent SNR with Channel Estimation

We can represent the system with estimation operating at SNR γ_t as a system with perfect CSI at some equivalent SNR γ_e given by

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

Note:

- as $\gamma_t \to \infty$, SNR loss due to estimation goes to $1/(\eta + 1)$
- as $\eta \to 0$, the equivalent SNR $\gamma_e \to \gamma_t$ (i.e. the estimates become perfect)
- for $\eta = 0.125$ (as in proposed standard) we expect SNR loss of 0.5–0.7 dB in the region of interest

Performance Measures: Introduction

We are interested in the performance limits of Multiband OFDM as well as the practical performance of the currently-defined proposal.

We take two approaches:

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

We consider both perfect CSI as well as channel estimation using our proposed method

BICM-OFDM Capacity

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

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

- 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

BICM-OFDM Cutoff Rate

Instantaneous cutoff rate in bits per complex dimension

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

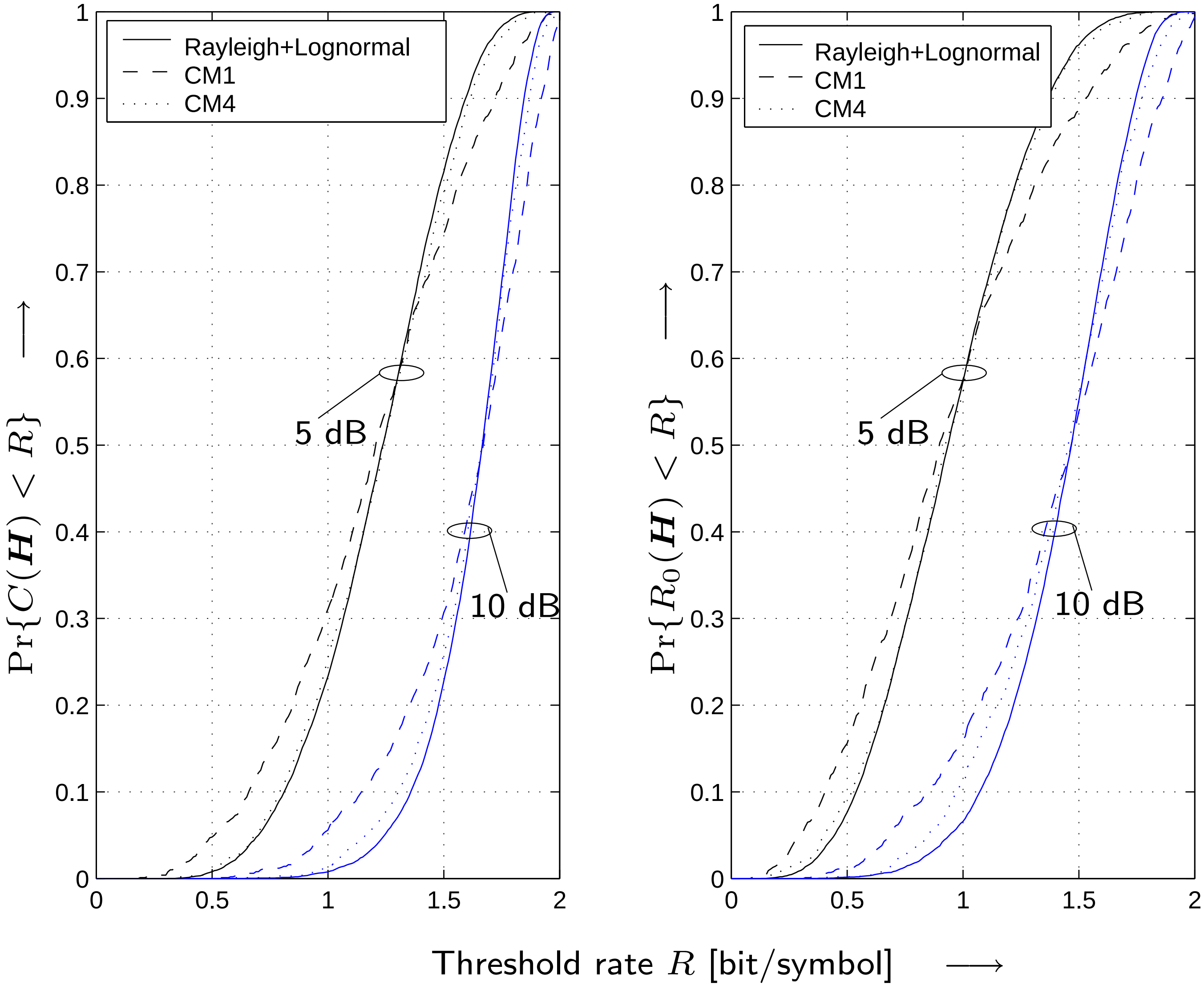
with the instantaneous Bhattacharya parameter ($\bar{b}$ denotes the complement of b)

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

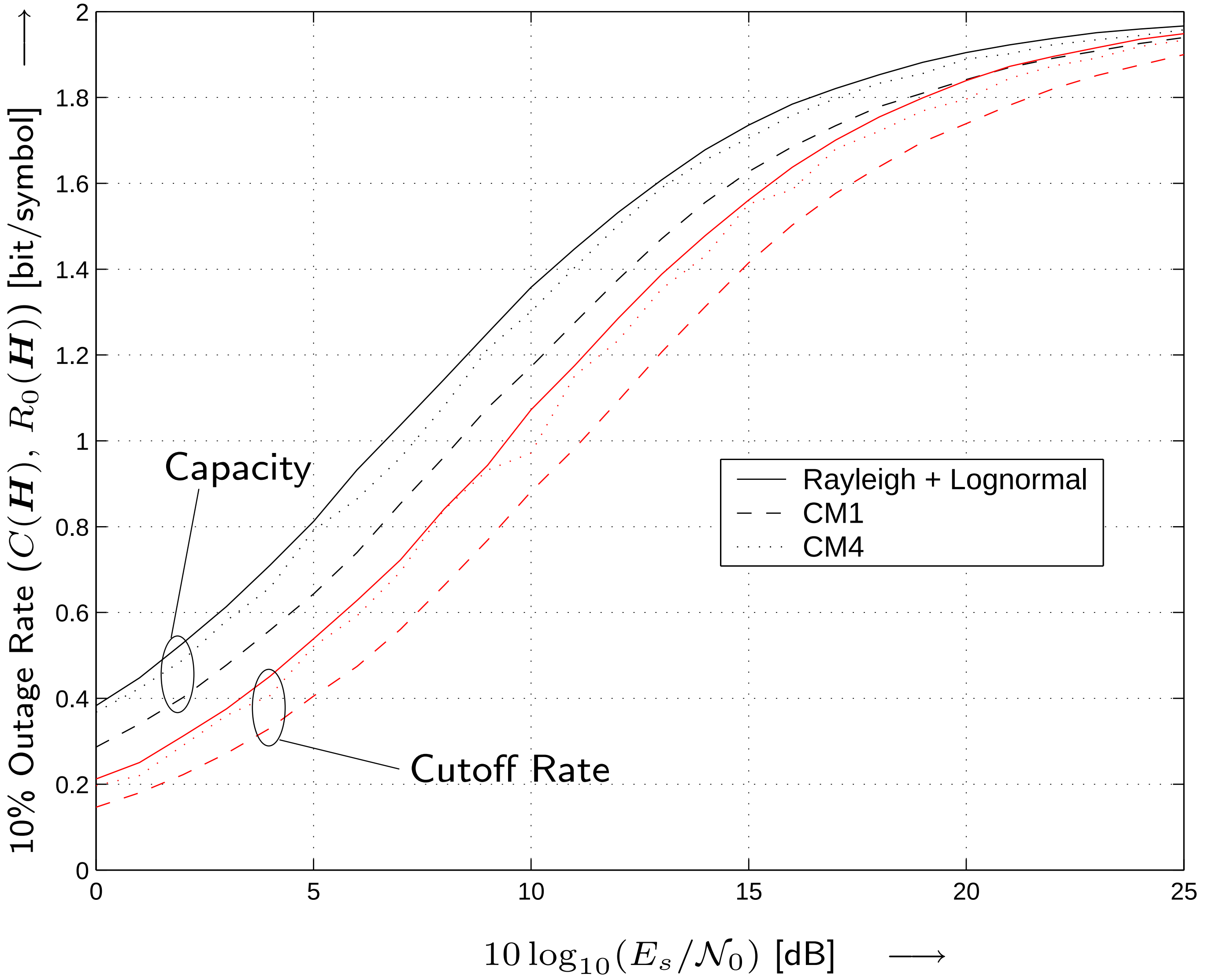
Results — Parameters

- Show as comparison “Rayleigh+Lognormal” (i.i.d Rayleigh fading on each carrier with an outer lognormal as with UWB)
- We only show CM1 and CM4 as they are the extreme cases
- 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

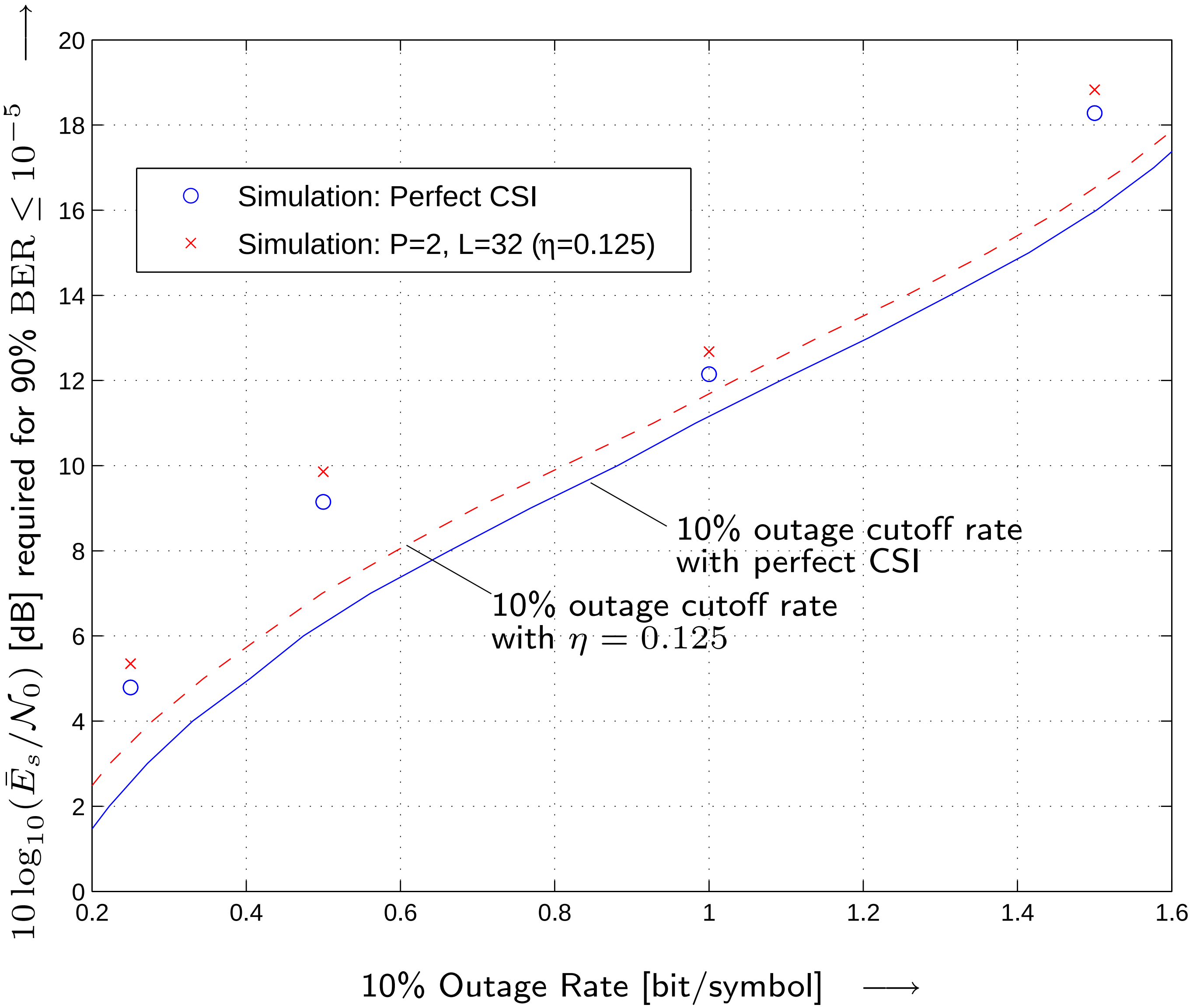
Capacity and Cutoff CDFs — Perfect CSI



10% Outage Capacity and Cutoff Rate — Perfect CSI



10% Outage Cutoff Rate vs Simulations



Conclusions of our work thus far

- 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+Lognormal channel
- 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

We have a framework from which to base our future studies

Future Work

We consider enhancements to Multiband OFDM by applying:

- 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

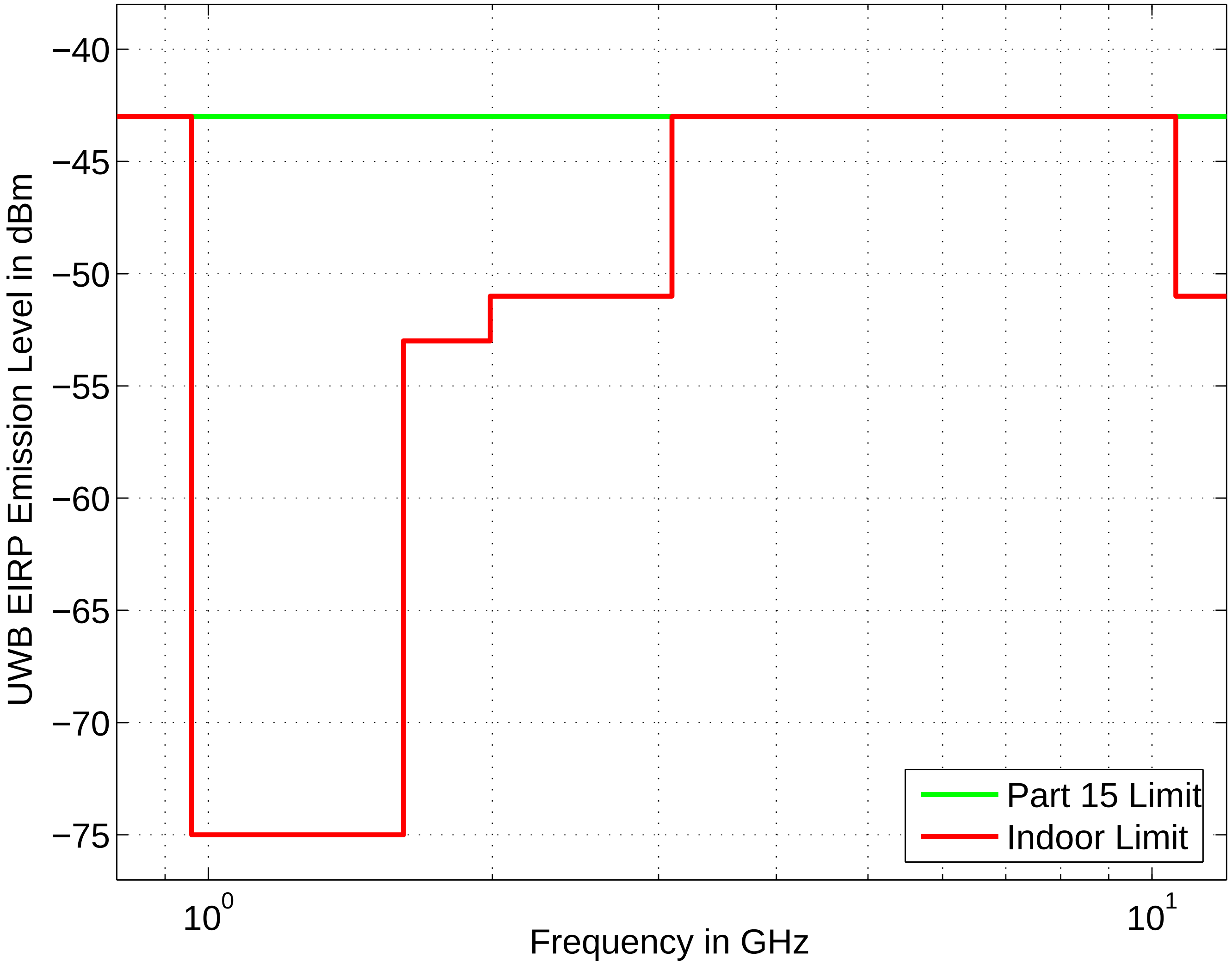
Tentative Timetable for Completion

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

Questions?

Extra Slides

UWB Spectral Mask



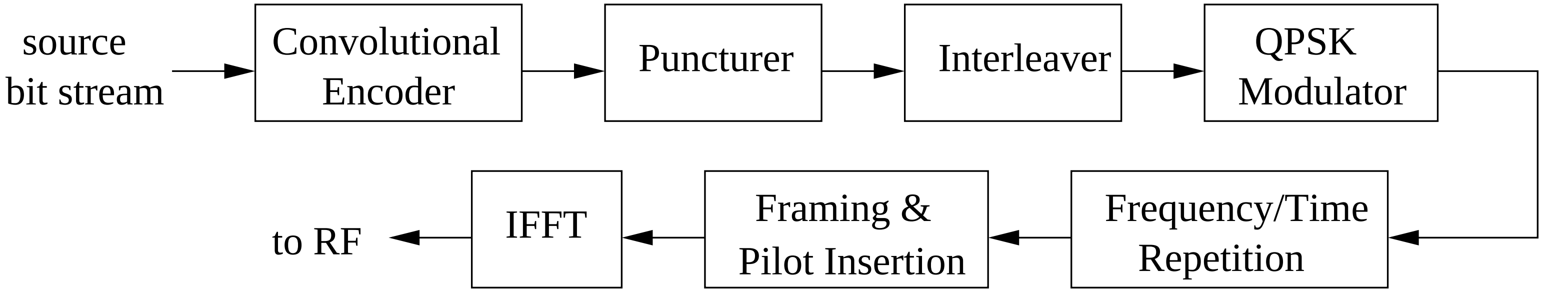
Adapted from G.R. Aiello and G.D. Rogerson "Ultra-Wideband Wireless Systems", *IEEE Microwave Mag.*, June 2003

OFDM Refresher

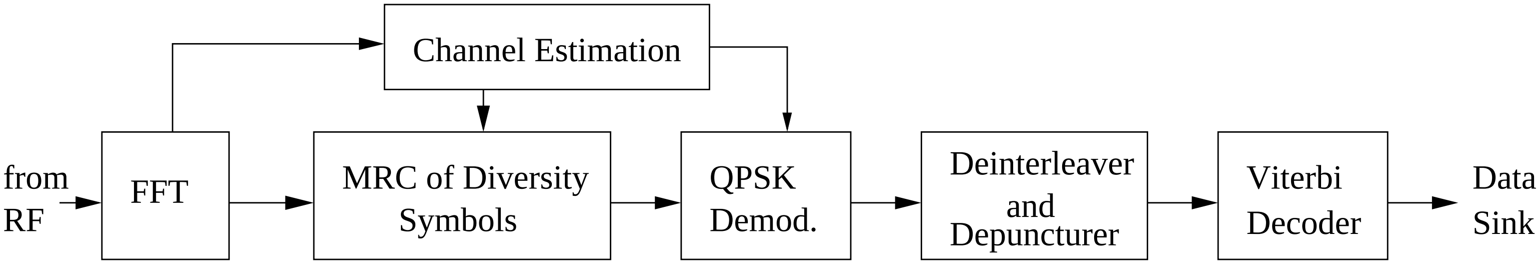
- OFDM = “Orthogonal Frequency Division Multiplexing”
- Alternative to single-carrier modulation for high data rates
- Use N narrowband carriers, each at a fraction of total data rate
- Implementation: IFFT/FFT to combine/separate carriers
- Cyclic prefix prevents inter OFDM-symbol interference, result is N non-interfering channels (in frequency domain)
- Proven technology — used in (for example):
  - WLAN standards (eg 802.11g, HiperLAN/2)
  - DSL modems (wireline people call it DMT)

Frequency-selective fading channel → N flat fading channels

Multiband OFDM Transmitter



Multiband OFDM Receiver



$p(|H_i|)$ **Conclusions**

- H_i are almost Rayleigh distributed! (neglecting X)
- This is expected — H_i is a superposition of relatively many mutually-independent time-domain multipath components
- For a particular lognormal fading X, **$\mathbf{H}$** is well approximated by a Rayleigh fading channel

Eigenvalues of $\mathbf{R_{HH}}$ — Conclusions

Diversity order is (roughly) the number of “useful” (ie not small) eigenvalues

- Diversity order is increasing with bandwidth
- At 500 MHz, have diversity order ≥ 20 for CM4, ≥ 10 for CM1
- Our code ($R = 1/3, k = 7, d_{free} = 15$) can only exploit at most diversity order 15, so bandwidth higher than 500 MHz not useful except with low-rate time/freq repetition modes
- 528 MHz bandwidth of MB-OFDM a good tradeoff between complexity and achievable diversity order
- CM1 advantageous for high-rate modes (lots of puncturing, therefore cannot exploit a large diversity order) due to larger dominating eigenvalues

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 $1/(\eta+1)$

Information Theory Refresher

Channel Capacity C:

- For any transmission rate $R < C$, it is possible to drive the error rate $\varepsilon \to 0$
- May require very long decoding delay / high complexity
- Practical capacity-approaching codes have been developed (eg Turbo codes, LDPC codes)

Cutoff Rate R_0:

- Bound for the attainable performance of convolutional codes
- Relates attainable code rate R, word error probability (reliability), and codeword length n as

$$\mathrm{WER} < 2^{-n(R_0 - R)}$$

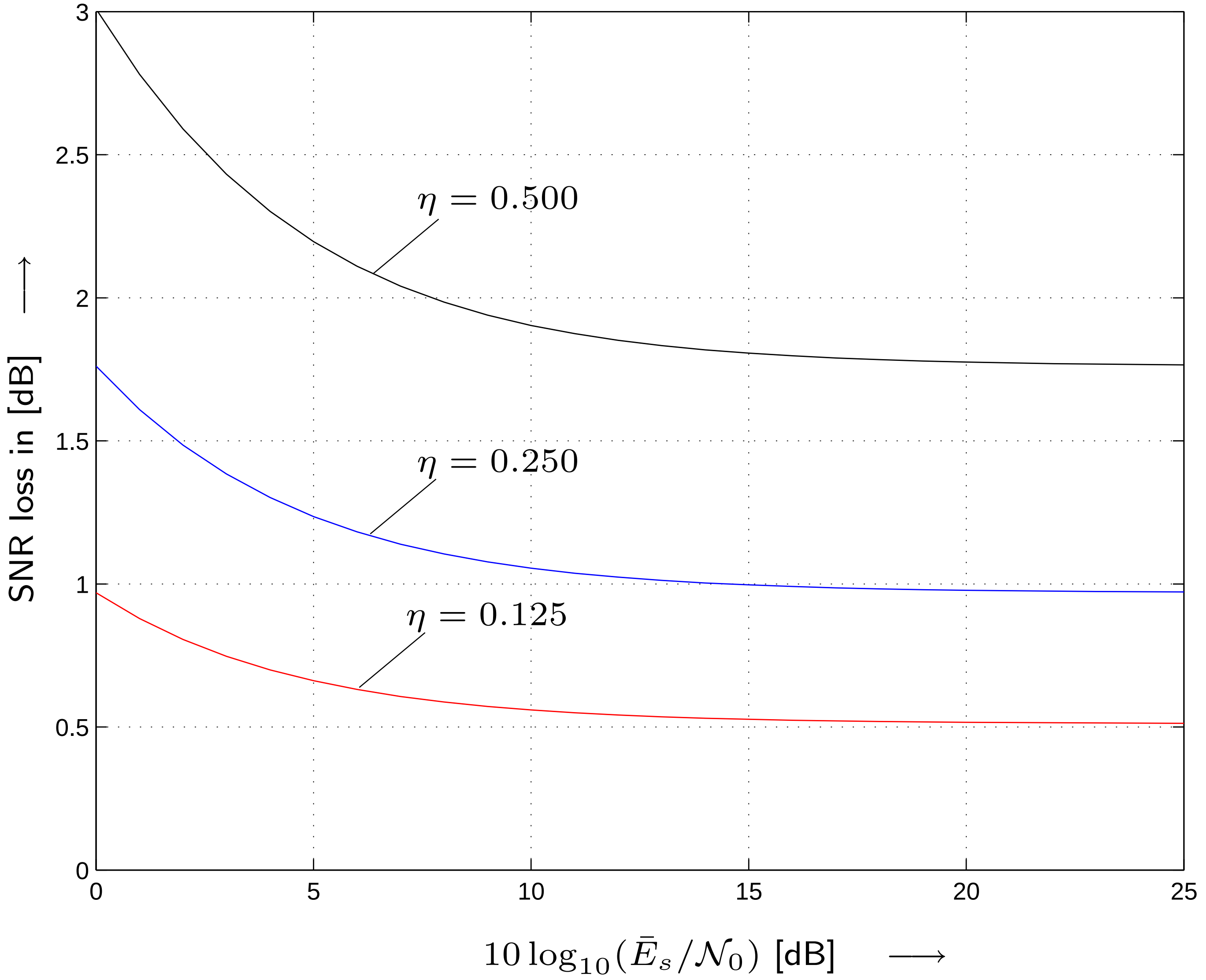
Capacity and Cutoff CDFs — Analysis

- Capacity and cutoff rate for UWB channel similar to i.i.d. Rayleigh fading channel with additional shadowing
- High diversity provided by UWB channel results in relatively steep outage curves → reliability can be considerably improved by deliberately introducing coding redundancy (slightly more so for capacity i.e. powerful codes)
- Shadowing, which cannot be averaged out by coding, causes a flattening towards low outage probabilities ≤ 0.1
- In high outage probability range CM1 is superior to CM4, which corresponds to the large dominant eigenvalues

10% Outage Capacity and Cutoff Rate — Analysis

- Differences of 1-2 dB in power efficiency due to different UWB channel types, with CM4 providing basically the same performance as Rayleigh+Lognormal
- Comparison of capacity with cutoff rate curves → gains of 2.5 dB to 3 dB can be anticipated by the application of more powerful capacity approaching codes (eg: Turbo codes, LDPC codes)

Loss in SNR due to Imperfect CSI



Loss in SNR – Analysis

- Penalty due to imperfect CSI about 0.5 dB in the range of interest for the Multiband OFDM system.
- Reducing channel estimation overhead to $P = 1$ ($\eta = 0.25$) could be an interesting alternative for short packets, as the additional loss is only about 0.5 dB in $\bar{E}_s/\mathcal{N}_0$
- Further reduction of pilot tones is not advisable as the gains in throughput are outweighed by the losses in power efficiency.

10% Outage Cutoff Rate vs Simulations — Analysis

- Simulated SNR points well approach the cutoff-rate curves, which
  - justifies the relevance of the information-theoretic measure
  - confirms the coding approach used in Multiband OFDM
- Diversity provided by the UWB channel effectively exploited by the convolutional coding and interleaving scheme
- System with LSE channel estimation performs within 0.5 dB of the perfect CSI case (as expected from the cutoff-rate analysis)