

Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Title: [First Principles Analysis of UWB DS-CDMA and UWB OFDM In Multipath]

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Abstract: DS-CDMA applies FEC to the output of a UWB correlator that is sampling the UWB channel with a signal that is coherent across the whole of the bandwidth and therefore has little fading. OFDM, on the other hand, applies FEC to the output of a large number of narrowband filters, each of which has a random “flat fade” due to the frequency selective fading of the UWB multipath channel. In the receiver the statistics of the fading for OFDM carriers are Rayleigh with long tails and a negative median, while the statistics of the UWB DS-CDMA signal are Gaussian with relatively small variance and zero median. As a result the ability of the FEC in each to render an effective radio is drastically different.

Purpose: [Information to help the TG3A voters understand what fundamental principles drive the relative performance of UWB DS-CDMA and UWB OFDM systems]

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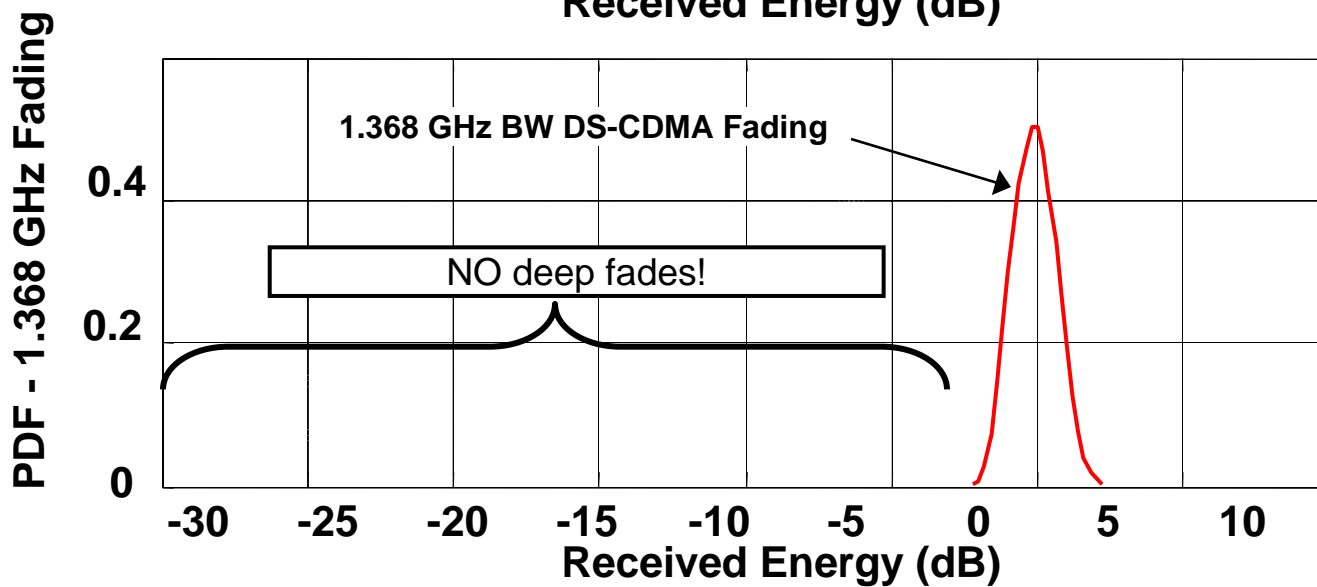
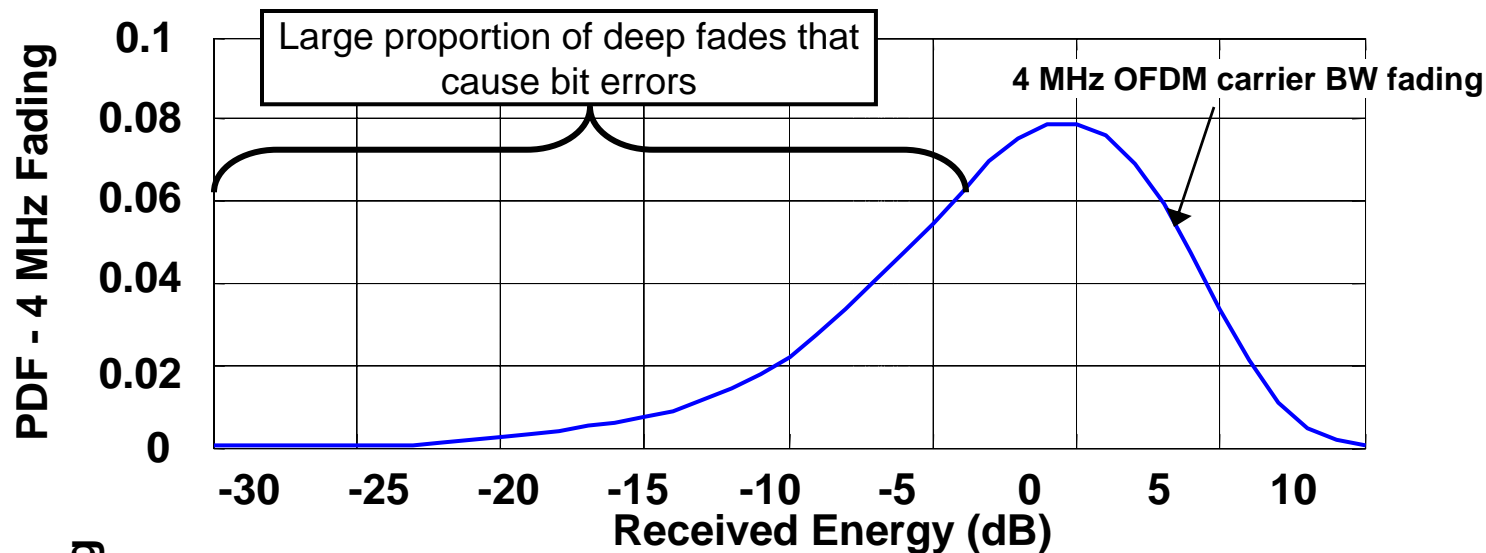
First Principles Analysis of UWB DS-CDMA and UWB OFDM Performance In Multipath

- Only difference between OFDM and DS-CDMA in this analysis is the fading statistics of wideband pulses and narrowband OFDM carriers
- This initial analysis shows the fundamental loss associated with non-coherent FEC processing given the fading statistics across the carriers
- Assumptions
 - Ideal interleaver performance
 - Randomizes the bit error distribution
 - Ideal energy capture (no cyclic prefix over-run, ideal RAKE)
 - Ideal equalization (perfect pilot tones and training)
 - OFDM and DS-CDMA have same energy per bit
 - Same bandwidth, Same total power, Same data rate
 - No system loss – everything is perfect
 - No cyclic prefix SNR degradation
 - Ignores transmitted energy that carries no information
 - OFDM given small advantage by ignoring power loss in cyclic prefix
 - DS-CDMA given a little advantage due to imperfect RAKE
- Initial Test Configuration
 - $\frac{1}{2}$ rate $k=7$ convolutional code

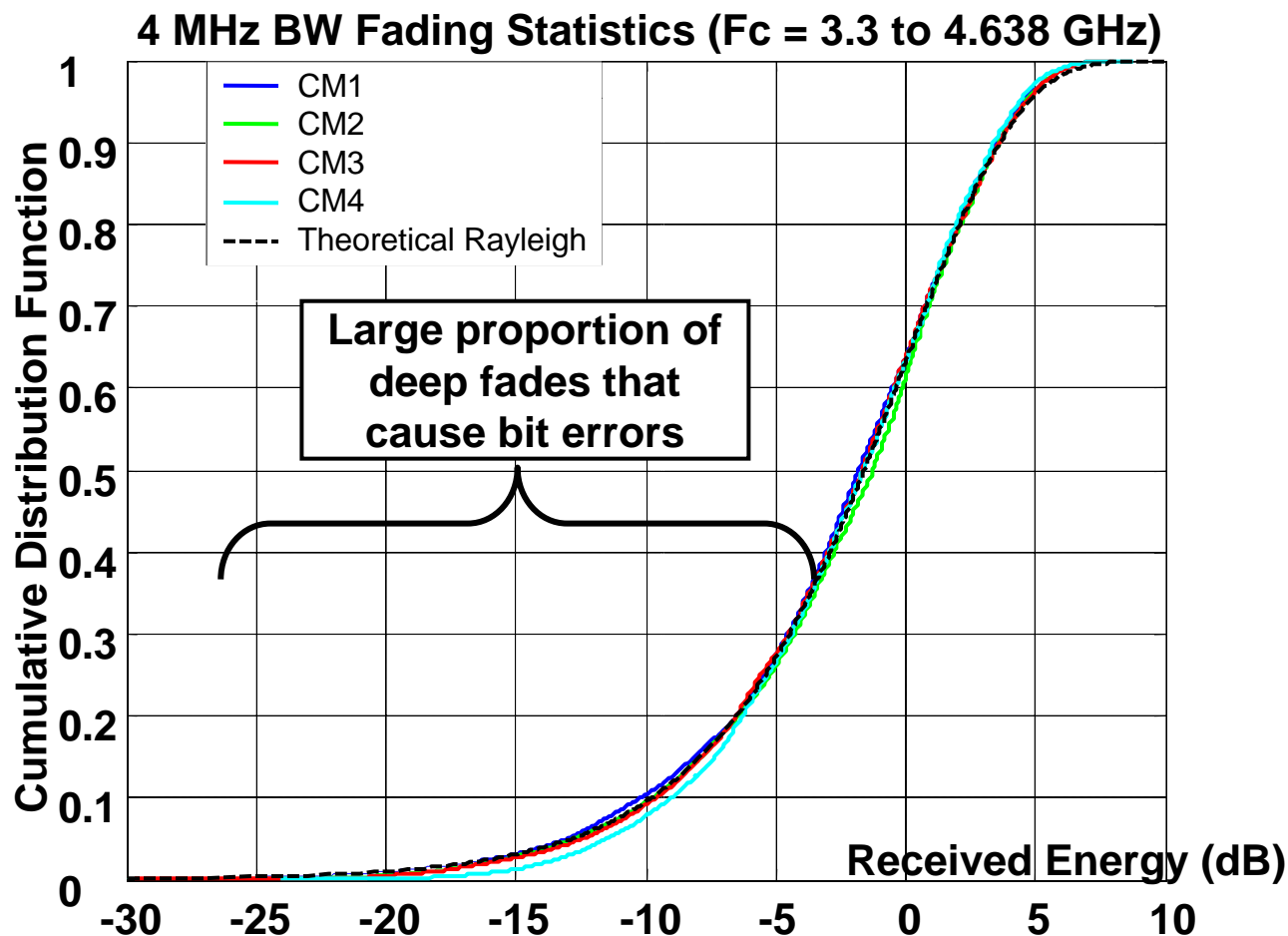
Multipath and OFDM

- UWB OFDM uses 4 MHz bandwidth carriers
 - Long symbol reduces ISI, but
- Each carrier experiences a flat fade
 - Every carrier reaches receiver with a different amplitude
 - Data is lost in these fades (i.e. bit errors in the receiver)
 - Even if perfect phase compensation (equalization) is assumed
- Fading across 4 MHz BW carriers has Rayleigh statistics
 - Tails (percentage of carriers with higher attenuation) follow a Rayleigh distribution
- Energy in the large percentage of carriers with low SNR cannot be recovered by FEC processing
 - FEC is sub-optimal non-coherent processing across the band
- OFDM is a sub-optimal approach to addressing multipath
 - Illustrated in OFDM by the difference in performance between AWGN and CM-1,2,3,4
- OFDM solves the energy capture problem and swaps it for another
 - It introduces Rayleigh fading in the carriers
 - High complexity codes are required to work on the Rayleigh statistics

Fading PDF Statistics of OFDM carriers versus DS-CDMA

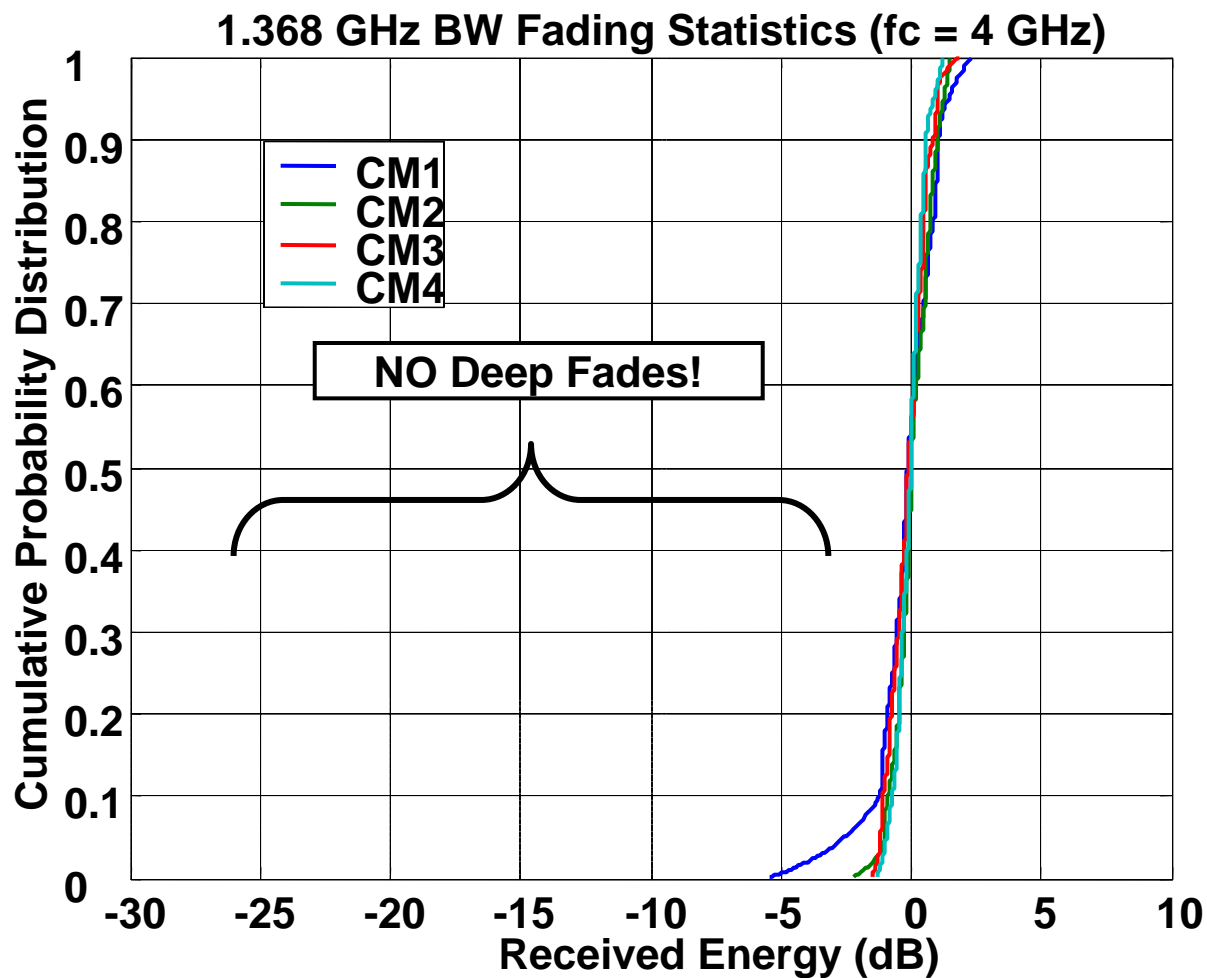


Cumulative Probability Distribution of Fading for OFDM Carriers



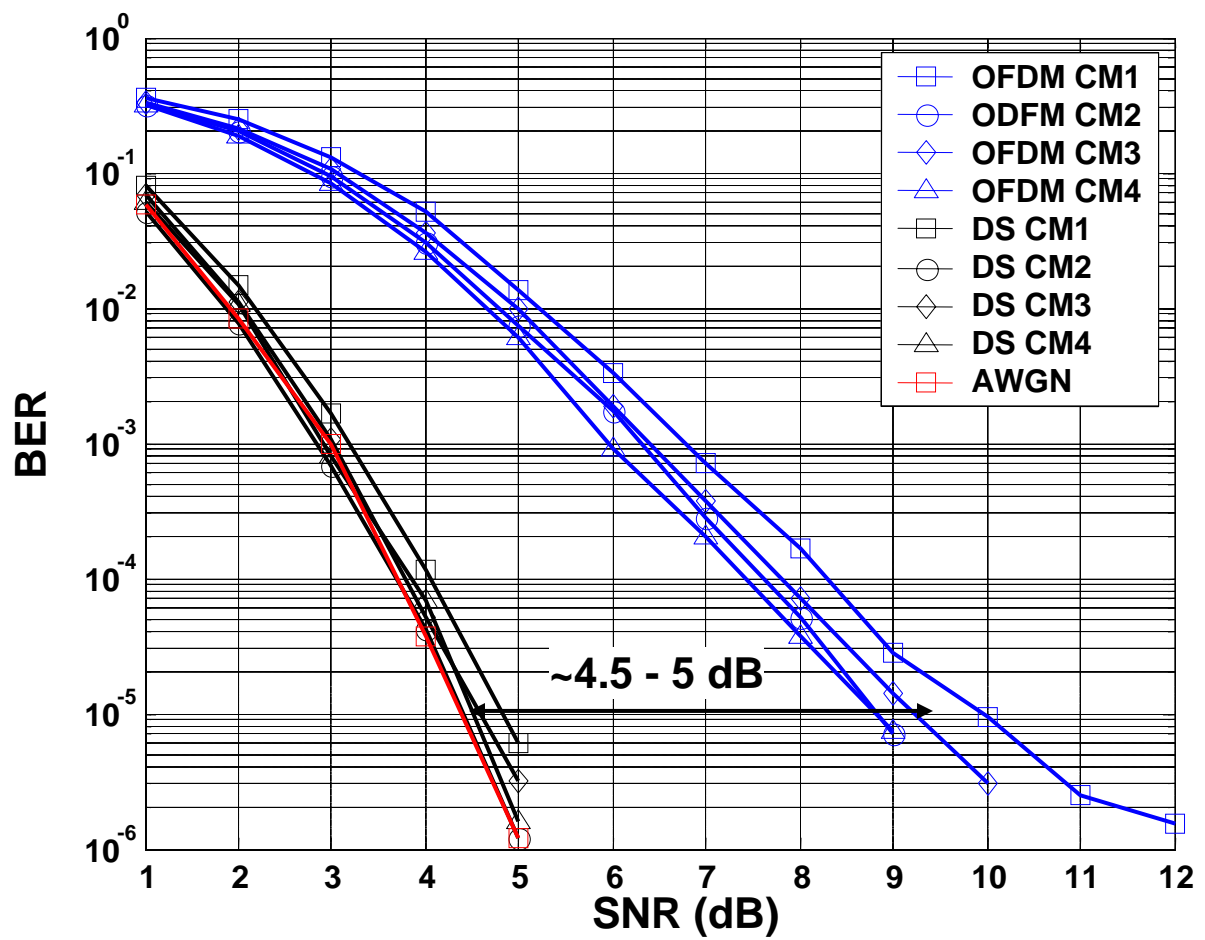
- Amplitude of received power follows a Rayleigh distribution
- Large proportion of OFDM carriers have of deep fades

Cumulative Probability Distribution of Fading for OFDM Carriers versus DS-CDMA

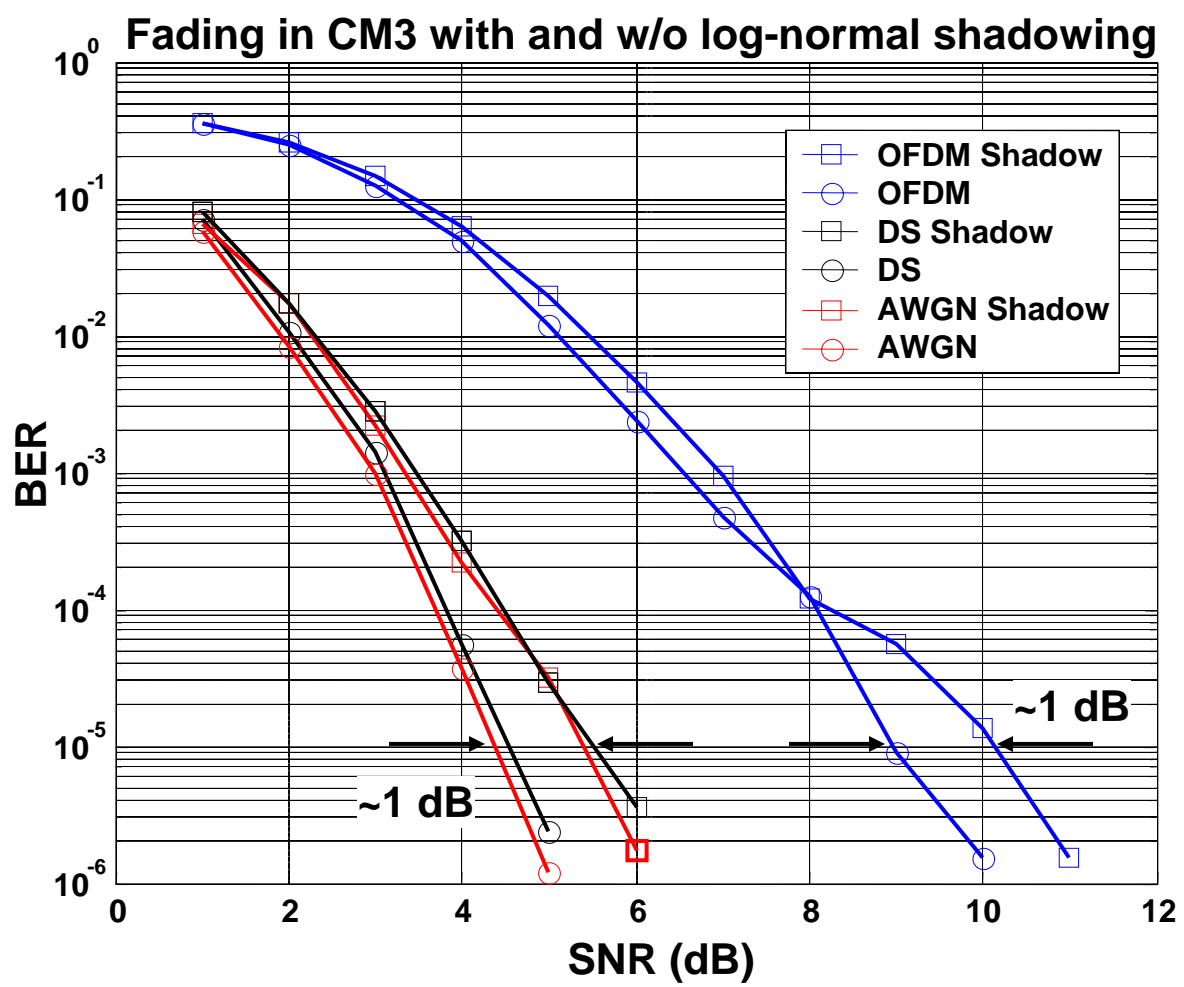


OFDM versus DS-CDMA with Rate $\frac{1}{2}$ k=7 Code

Performance Differential for 4 MHz OFDM vs. 1.368 GHz DS-CDMA

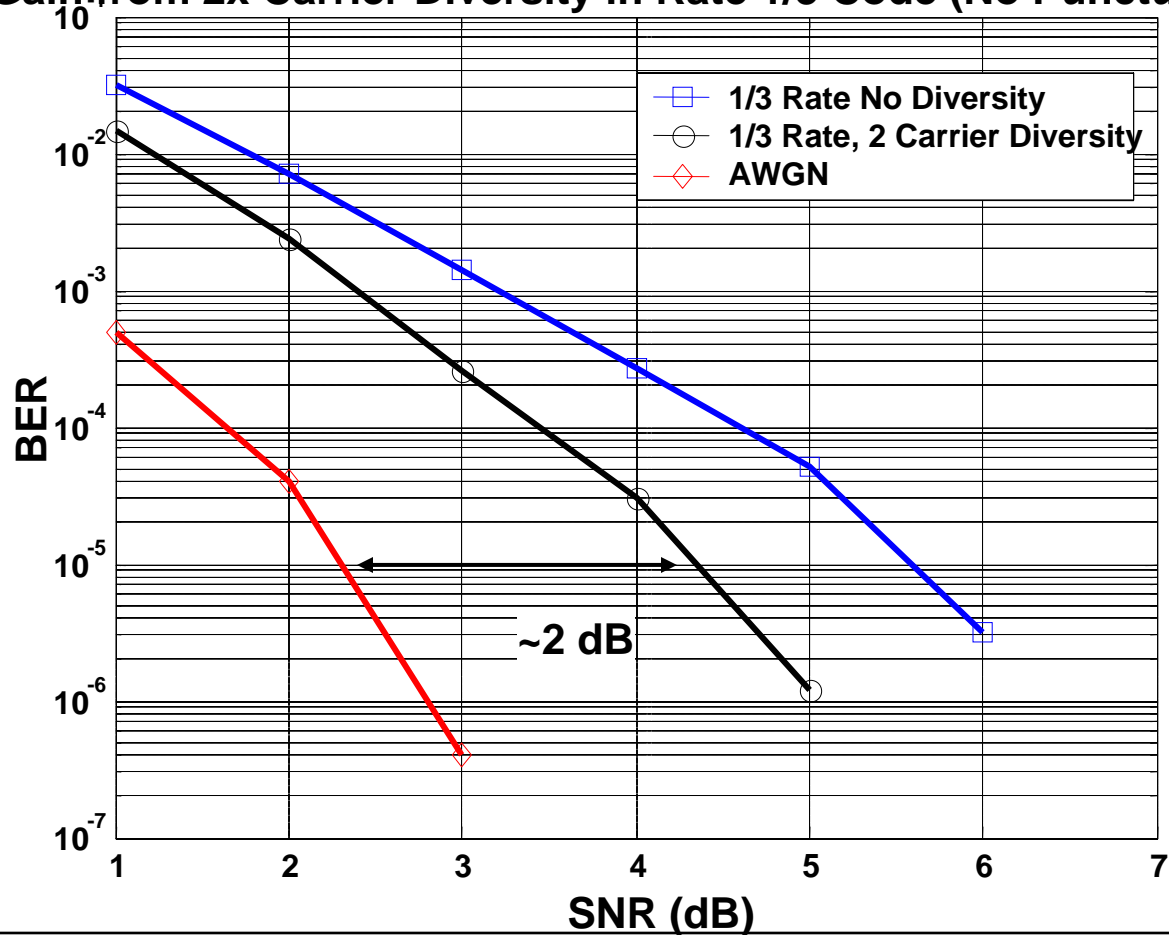


Effects of Log-Normal Shadowing



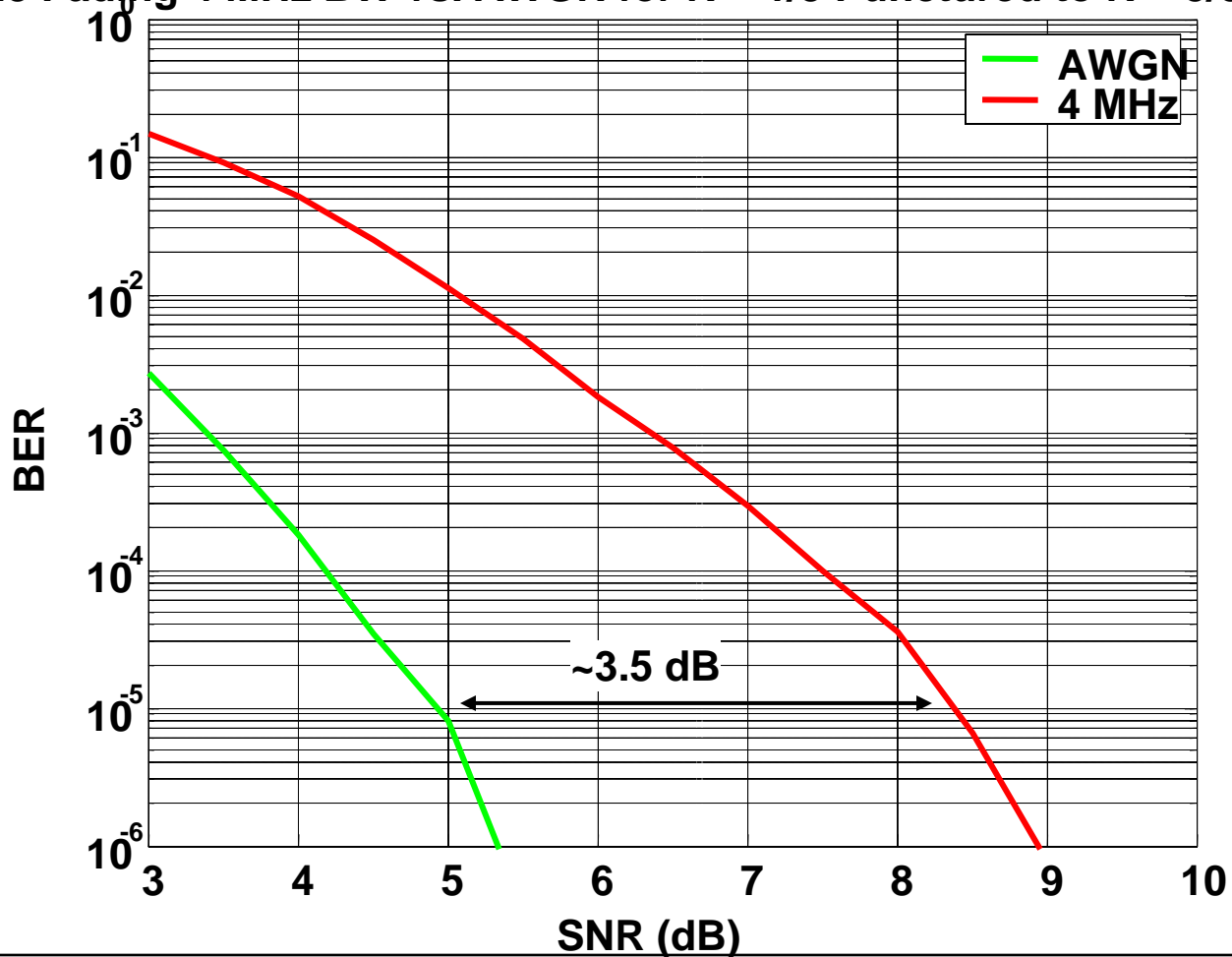
Rate-1/3 k=7 Code for AWGN & Rayleigh Fading (with Diversity)

Gain from 2x Carrier Diversity in Rate 1/3 Code (No Puncturing)



Rate-5/8 (Punctured 1/3) k=7 Code for AWGN & Rayleigh Fading (with Diversity)

CM3 Fading 4 MHz BW vs. AWGN for R = 1/3 Punctured to R = 5/8, K=7



Fundament Results of the OFDM “Gap to AWGN”

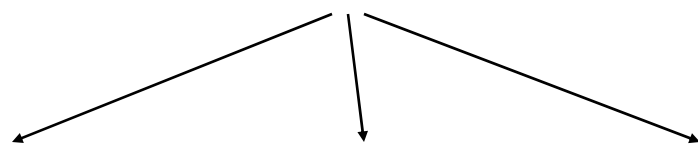
- The OFDM “gap to AWGN” that is caused by Rayleigh fading has three fundamental results on UWB OFDM
 - 1) **Performance**: OFDM requires a higher SNR to achieve the same BER. For equivalent systems (similar error coding and energy capture), DS-CDMA will always deliver better performance (lower BER) for a given channel.
 - 2) **System Capacity**: The ability to achieve high spatial capacity (Bits/second/meter²) is fundamentally related to required SNR. With it's lower SNR requirements, DS-CDMA can achieve higher aggregate data rates for any given coverage area.
 - 3) **Interference**: For any given link, an equivalent OFDM system transmits more power for the same performance & range. More power in the air results in a higher interference potential.

Poor Scaling to Higher Rates at Shorter Ranges

- Primary tools used by MB-OFDM to overcome effect of Rayleigh fading are (1) frequency diversity and (2) FEC
 - 1) Spreading bits over multiple carriers mitigates deepest fades (although this also reduces effective bit rate)
 - 2) Strong, low-rate FEC is effective at limiting BER degradation
- To achieve higher rates, MB-OFDM gives up both
 - 1) No frequency diversity used for 320 or 480 Mbps modes
 - 2) Rate 1/3 FEC is punctured to 5/8 & 3/4 rates for higher data rates
- Result: SNR requirements are much higher for highest rates
 - “Gap to AWGN” rises from 2 dB (for 110 Mbps mode) to over 6 dB (for 480 Mbps mode)
- Scaling to even higher rates using M-PSK or QAM will further degrade the efficiency of the MB-OFDM proposal
- More bands? Mode 2 link margins (7-bands) are even worse than Mode 1 (3-bands)!

Multipath Link Margin Degradation (Mode 1: 3-band)

Loss from AWGN represents degradation from Rayleigh fading and other losses
More loss at 480Mbps is due to less capable FEC and no carrier pre-sum diversity



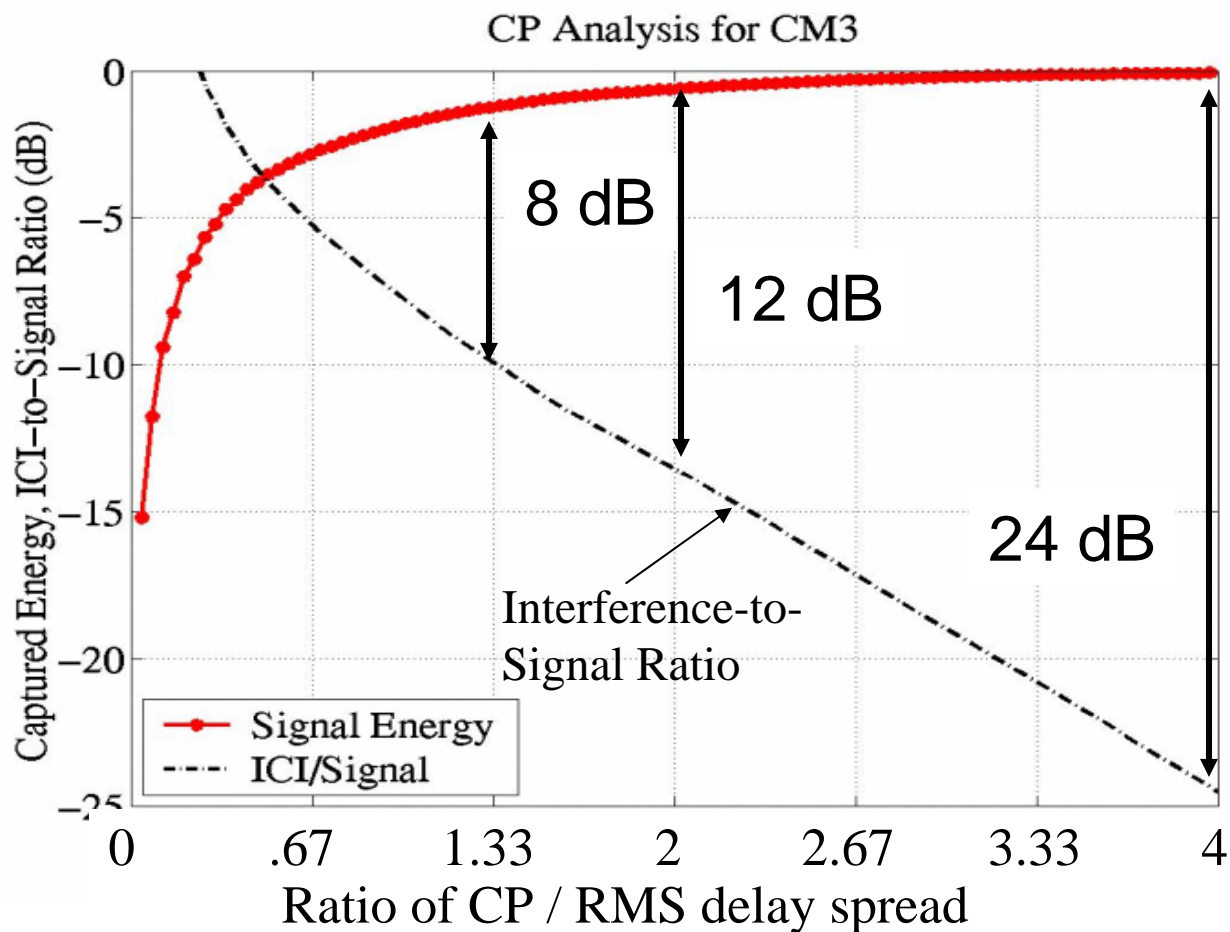
Range and Margin	AWGN Range	CM1 Range	CM1 WRT AWGN	CM2 Range	CM2 WRT AWGN	CM3 Range	CM3 WRT AWGN
110 Mbps	20.5 m	11.5 m	-5.0 dB	10.9 m	-5.5 dB	11.6 m	-4.9 dB
200 Mbps	14.1m	6.9 m	-6.2 dB	6.3 m	-7.0 dB	6.8 m	-6.2 dB
480 Mbps	7.8 m	2.9 m	-8.6 dB	2.6 m	-9.5 dB	N/A	N/A

- Link margin degradation is based on 1/R² path loss used for original simulations

OFDM Scales Poorly To Longer Ranges

- Primary design parameter of OFDM is the length of the cyclic prefix
 - Longer prefix needed for larger delay spread
- But longer cyclic prefix also causes degraded SNR performance
 - CP is transmitted energy that carries no information
 - Not accounted for in the first principles analysis
- RMS delay spread grows as $\sqrt{\text{range}}$
 - At 40 m, 2x longer and at 90 m, 3x longer relative to 10m
 - Also longer in adverse channels e.g. factories, containers, etc.
- MBOA CP length is too short to extend the range
 - Length chosen for TG3a proposal is 60.5 ns
 - ~20m multipath bounces over a 10m line-of-site link
 - For comparison, 802.11a uses a cyclic prefix of 800 ns to cover 100m paths
 - Lowering the rate does not fix the problem
- Analysis does not show this problem
 - Proposal was “tuned” to 4-10 meters channels (CM-3)

OFDM Degrades By Ratio of CP-length to RMS Delay Spread



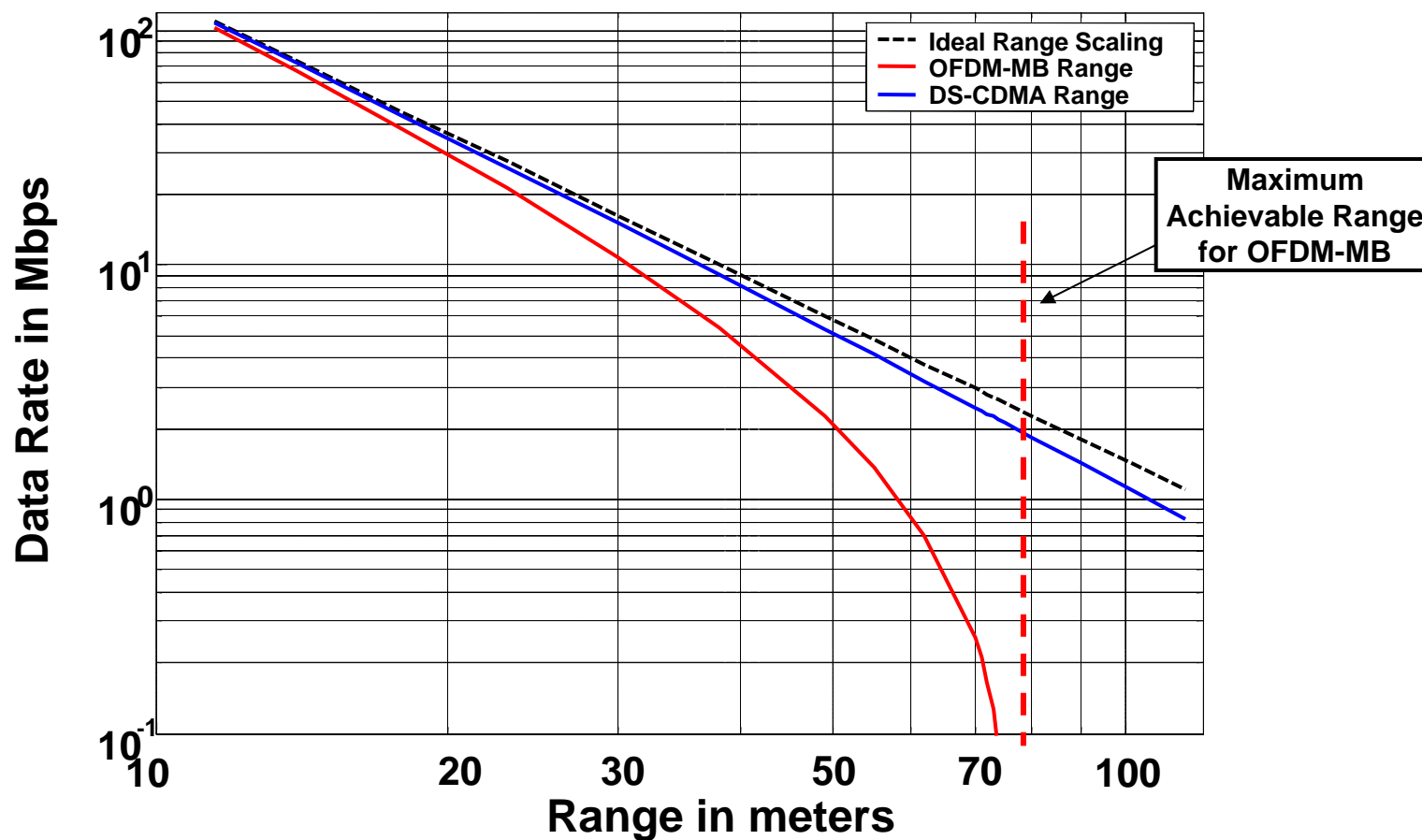
Scalability in Multipath Channels

- Cyclic prefix provides 24 dB ratio of ICI to signal
 - About 18 dB below noise at 6.5 dB Eb/No
- For longer delay spreads, the same plot shows the effect of a 60 ns prefix by using the *ratio* of the delay spread to prefix length
- For example, if the delay spread is 2x longer, then ICI/signal is ~12 dB
 - So about 1 dB rise in effective noise floor
- If delay spread is 3x longer, then ICI/signal is ~8 dB
 - So about 2.5 dB rise in effective noise floor
- *Fundamental result.* OFDM performance gets increasingly degraded by ICI at longer ranges or in worse channels

Fundamental Range Limits due to Length of Cyclic Prefix

- Many standards are designed to trade-off data-rate for range to handle longer ranges or adverse channels
 - Lower rates often acceptable for long range or adverse channels
 - E.g. for TG3a, a PHY with 110 Mbps @ 10m could scale to 7 Mbps @ 40m and 1.7 Mbps @ 80m (in $1/R^2$)
- OFDM performance is increasingly degraded by ICI as delay spreads increase
 - ICI degrades effective SNR, limiting data throughput
 - OFDM is fundamentally range limited by ICI (self-interference)
- In contrast, DS-CDMA systems scale very well to longer ranges or worse channels
 - Simple integration scales to long ranges & delays
 - ISI conditions actually get better as the system trades data rate for range (equalizer requirements are relaxed)

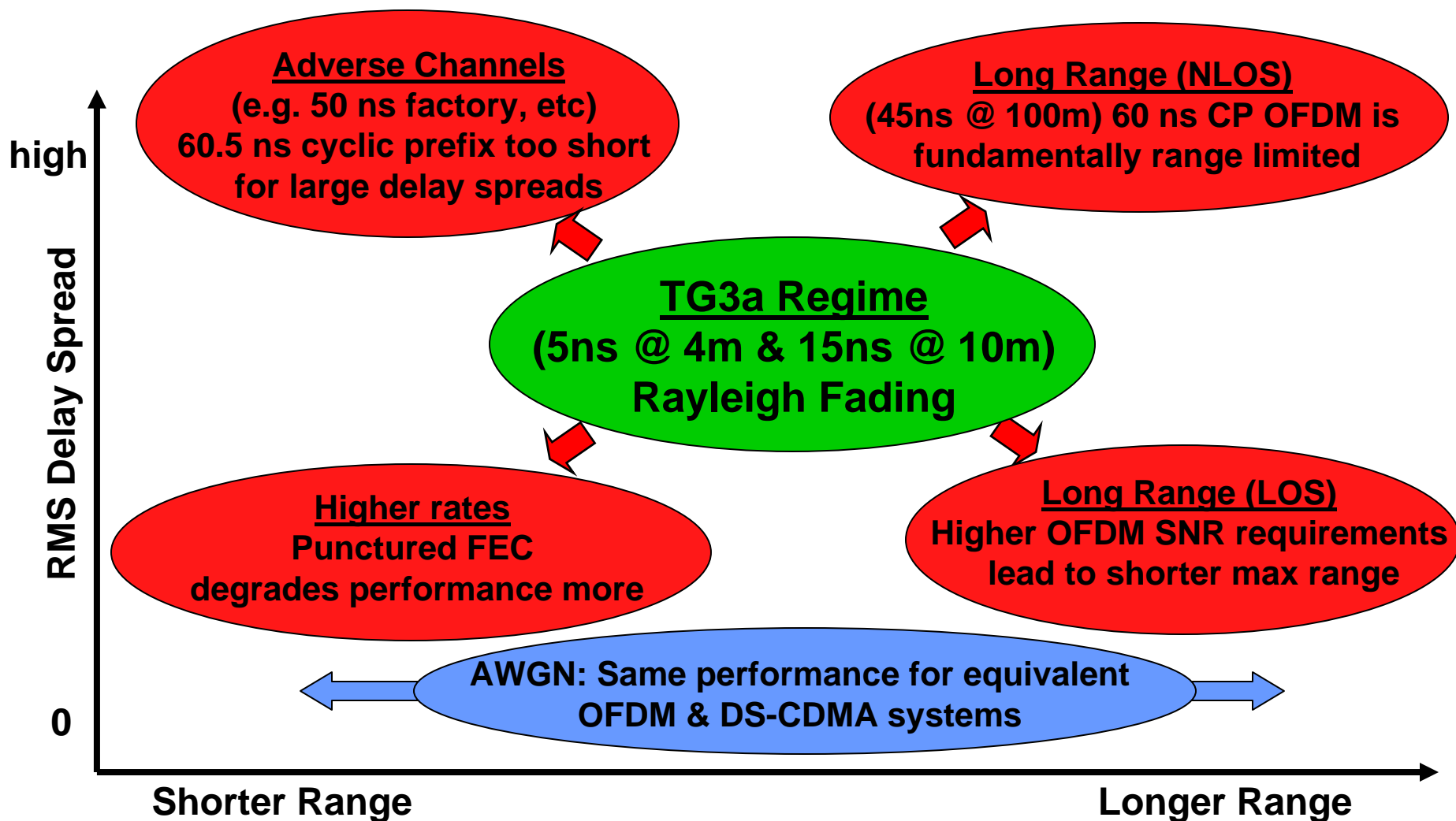
Range vs. Data Rate Scaling for DS-CDMA and MBOA-OFDM (60ns CP)



Assumptions on Range Limits

- Assumptions:
 - 11.5 m range at 110 Mbps for both systems in CM3
 - Multipath response dilates in time at longer ranges (RMS delay spread increase as square root of range)
 - $1/R^2$ total energy in multipath channel response
 - OFDM determines optimal timing (initial non-zero multipath arrivals are at beginning of cyclic prefix)
 - OFDM system uses integration to achieve required SNR (4.0 dB Eb/No + 2.5 dB implementation loss)
 - Multipath responses averaged over 100 realizations at each range
 - Cyclic prefix length of 60 ns
 - DS-CDMA system only collects energy over first 60 ns of response, even in longer channels

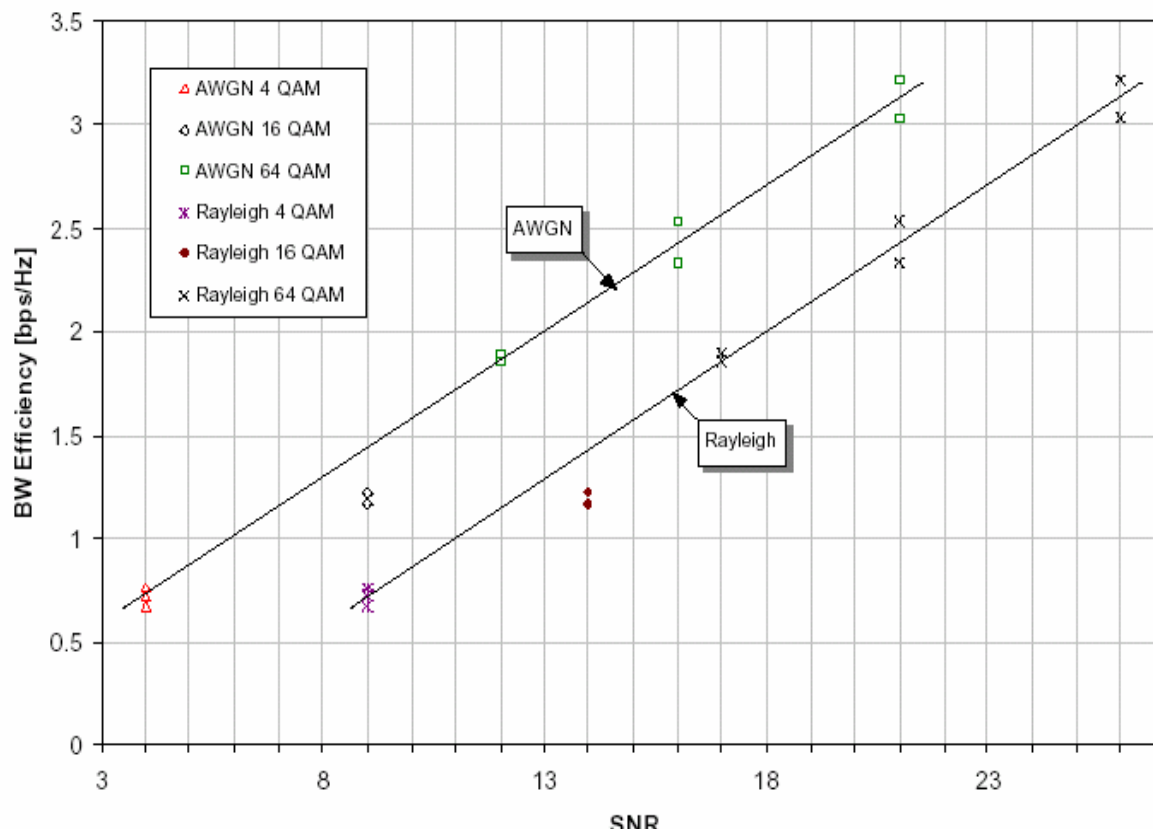
MB-OFDM Scales Poorly In Multipath



Effects of Rayleigh Fading On OFDM is Well Known

Upstream BW Efficiency vs SNR PHY w/FEC, AWGN & Rayleigh, CER = 1e-7

- Consider this analysis of OFDM in WMAN applications shows that Rayleigh fading results in 5 dB performance loss regardless of symbol constellation size



Source:

Non-LOS Wireless Challenges and the BWIF Solution, David Hartman, 2/06/2002

Conclusions

- DS-CDMA has first principle advantages over OFDM
 - OFDM provides good energy capture at the expense of introducing deep Rayleigh fading across carriers
 - Proposed FEC does not resolve Rayleigh fading, so...
 - OFDM needs higher SNR in multipath than AWGN
 - DS operates in multipath with about the same SNR as in AWGN
- DS produces less interference to others than OFDM
 - Since OFDM transmits more power for the same performance & range, it necessarily has more potential to interfere
- DS has higher system capacity
 - High spatial capacity is fundamentally related to required SNR.
 - DS-CDMA can achieve higher aggregate data rates for any given coverage area
- DS scales to higher and lower data rates better than OFDM
 - OFDM scaling to longer ranges with adverse channels is fundamentally limited by choice of cyclic prefix length
 - OFDM scaling to higher rates at shorter ranges is limited by higher SNR requirements due punctured FEC and lack of carrier diversity