Enhancement of the ECMA-368 UWB System by Means of Compatible Relaying Techniques

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Introduction

Ultra Wideband (UWB) Radio

- One of the strongest contenders for future **high-rate, short range** wireless communications
- Recently, first **technical standards** for UWB radio systems created
- **ECMA-368** standard currently receives **strong support** from industry

FCC Spectral Mask Limitation

- Protect existing **licensed** wireless services from excessive **interference**
- **Limits** permitted radiated **power levels** of UWB devices to very small values
- **Relaying techniques** very attractive for UWB systems to **improve** quality of service and coverage
- Available papers on the topic follow existing UWB standards rather **loosely**

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Objective of our Work

- Provide **realistic performance** results illustrating the **benefits** of relaying techniques for ECMA-368 UWB systems
- We closely follow current **system standard** and adopt IEEE 802.15.3a **channel models**
- Focus on **compatible** relaying techniques requiring a **minimum of change** to current specifications
  - Decode-and-forward (D&F) relaying
  - Amplify-and-forward (A&F) relaying
  - Combination of D&F/ A&F relaying with distributed version of cyclic delay diversity (CDD) across relays
- Investigate **impact** of path-loss effects, relay positions, and shadowing effects on overall system performance

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Overview

- **System Model and Relaying Techniques**
  - ECMA-368 Specifications
  - IEEE 802.15.3a Channel Models
  - Relaying Techniques
- **Numerical Performance Results**
- **Conclusions**

System Model and Relaying Techniques

ECMA-368 Specifications

- Multiband (MB) Orthogonal Frequency-Division Multiplexing (OFDM)
- Zero-padding (ZP) OFDM, overlap-and-add (O+A) processing at receiver
- Three 528 MHz subbands within 3.1-4.8 GHz band
- 128 orthogonal subcarriers per subband (100 available for data transmission)
- Optional frequency-hopping (FH) between subbands

- Focus on data-rate modes 53.3 Mb/s, 80 Mb/s, 106.7 Mb/s, 160 Mb/s
  - Quadrature phase-shift-keying (QPSK) modulation on each subcarrier
  - Convolutional code with puncturing (P) and interleaving (Π)
  - Time-domain spreading (TDS)/ frequency-domain spreading (FDS)
  - Outer cyclic-redundancy-check (CRC) code for error detection

- Receiver structure (not further specified)
  - TD/FD despreading via maximum-ratio combining (MRC)
  - Soft QPSK demapping
  - Convolutional decoding by means of Viterbi algorithm

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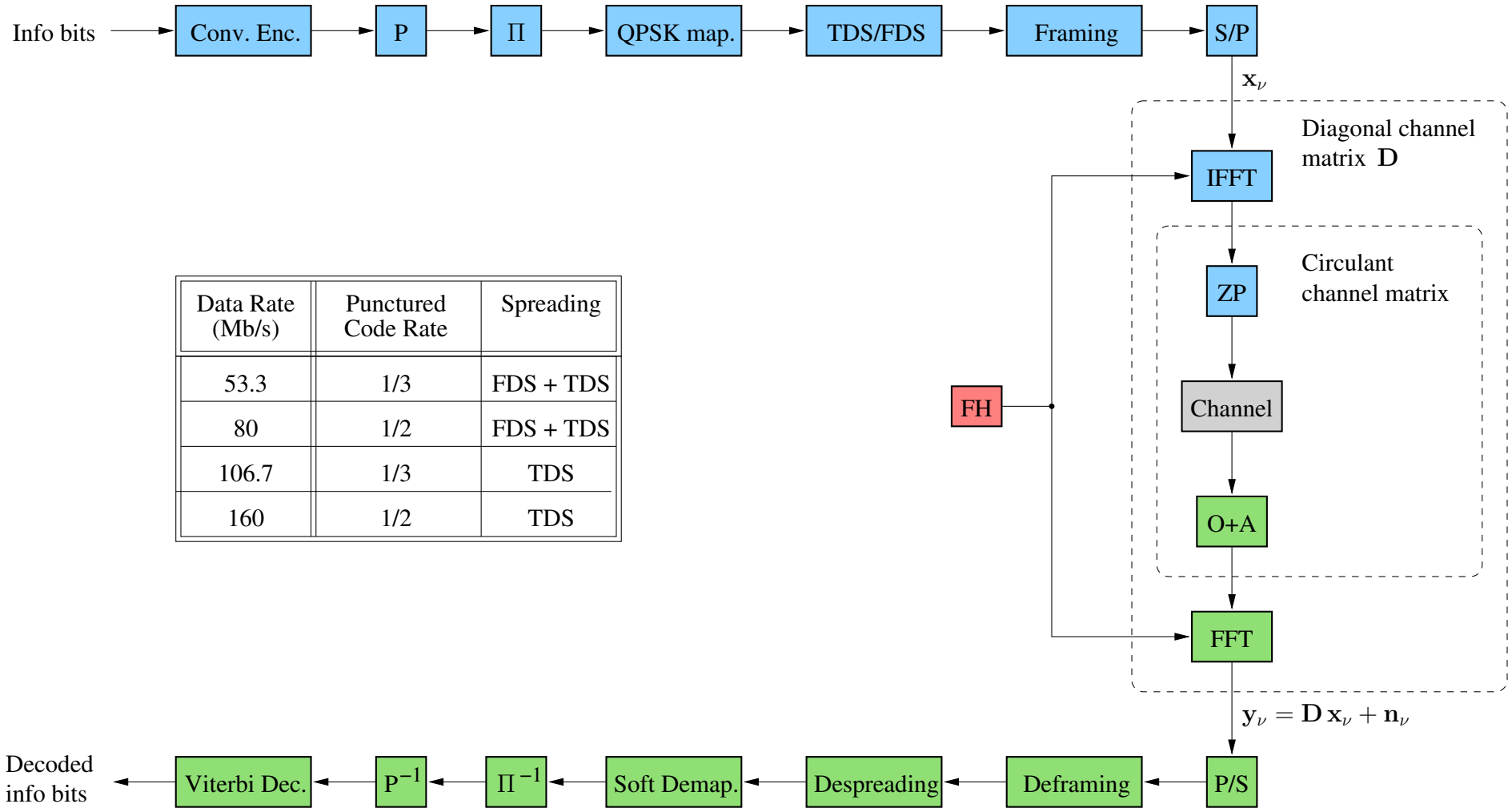

Data Rate (Mb/s)	Punctured Code Rate	Spreading
53.3	1/3	FDS + TDS
80	1/2	FDS + TDS
106.7	1/3	TDS
160	1/2	TDS

System Model and Relaying Techniques

IEEE 802.15.3a Channel Models CM1 – CM4

- Include typical **clustering behavior** of multipath arrivals, log-normal **shadowing** effects, and realistic **path-loss** modeling
- Passband channel impulse response (CIR) of link i modeled as

$$h_i(t) = X_i \sum_{l=1}^{L_c} \sum_{k=1}^{L_r} \alpha_{i,k,l}\, \delta(t - T_{i,l} - \tau_{i,k,l})$$

  - L_c number of clusters, $T_{i,l}$ random delay of lth cluster
  - L_r number of rays per cluster, $\tau_{i,k,l}$ random delay of kth ray within lth cluster
  - $\alpha_{i,k,l}$ random multipath gain of kth ray within lth cluster
  - X_i outer log-normal shadowing term
- Path-loss exponent p: CM1 (line-of-sight) $\rightarrow p = 1.7$
  CM2–CM4 (non-line-of-sight) $\rightarrow p = 3.5$
- Parameters $\alpha_{i,k,l}$, $T_{i,l}$, $\tau_{i,k,l}$ typically **uncorrelated** across links
- Shadowing terms X_i can be **correlated**, e.g., if shadowing object is close to common transmitter/ receiver

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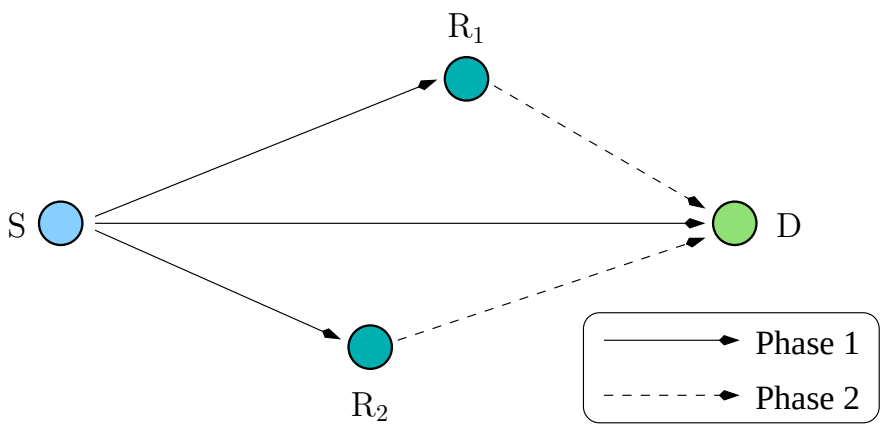
System Model and Relaying Techniques

Basic Relaying Scenario

- Two-hop scenario
- Single-antenna nodes
- Two-phase transmission protocol
- Relaying of complete OFDM frames
- Active relays transmit simultaneously
- Destination node performs MRC of source signal and relayed signals



Fair comparison with direct transmission

- SNR at destination **normalized** w.r.t. number of available relays
- Consider higher data-rate modes for relaying case (106.7 Mb/s, 160 Mb/s) and lower data-rate modes for direct transmission (53.3 Mb/s, 80 Mb/s)
  $\Rightarrow$ **Compensate** for rate-loss 1/2 due to employed relaying protocol

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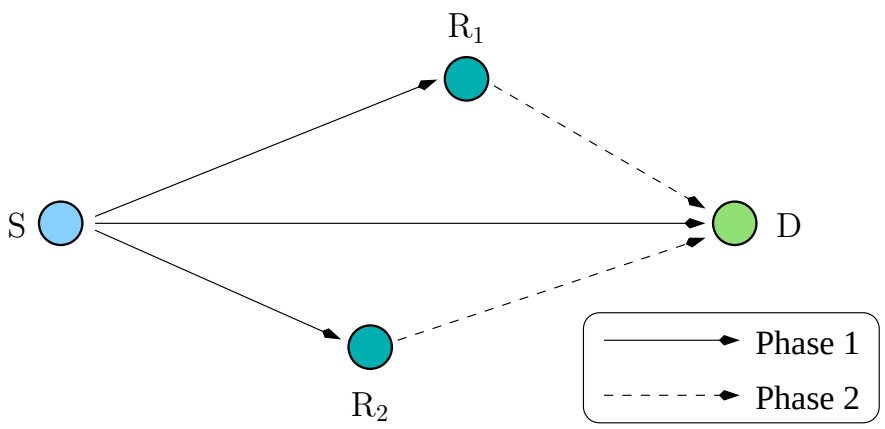

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Relaying Techniques

- D&F relaying
  - Relays decode entire OFDM frame and detect errors using CRC code
  - Only if no errors detected relays re-encode and re-transmit frame
    $\Rightarrow$ **no error propagation** at expense of **high relay complexity**
- A&F relaying
  - All available relays active; relays normalize received signal and re-transmit it (no FFT/IFFT or O+A processing required)
    $\Rightarrow$ **Low relay complexity** at expense of **noise propagation**
- Distributed CDD
  - CDD originally for cyclic-prefix OFDM systems with co-located Tx antennas
  - Each Tx antenna applies unique cyclic shift to transmitted OFDM symbol
    $\Rightarrow$ **Increases** effective frequency diversity; **transparent** to receiver
  - **Here:** Distributed CDD across relays using **random** cyclic shifts at relays

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- **Numerical Performance Results**
  - Comparison of Relaying Techniques
  - Impact of Shadowing
- **Conclusions**

Numerical Performance Results

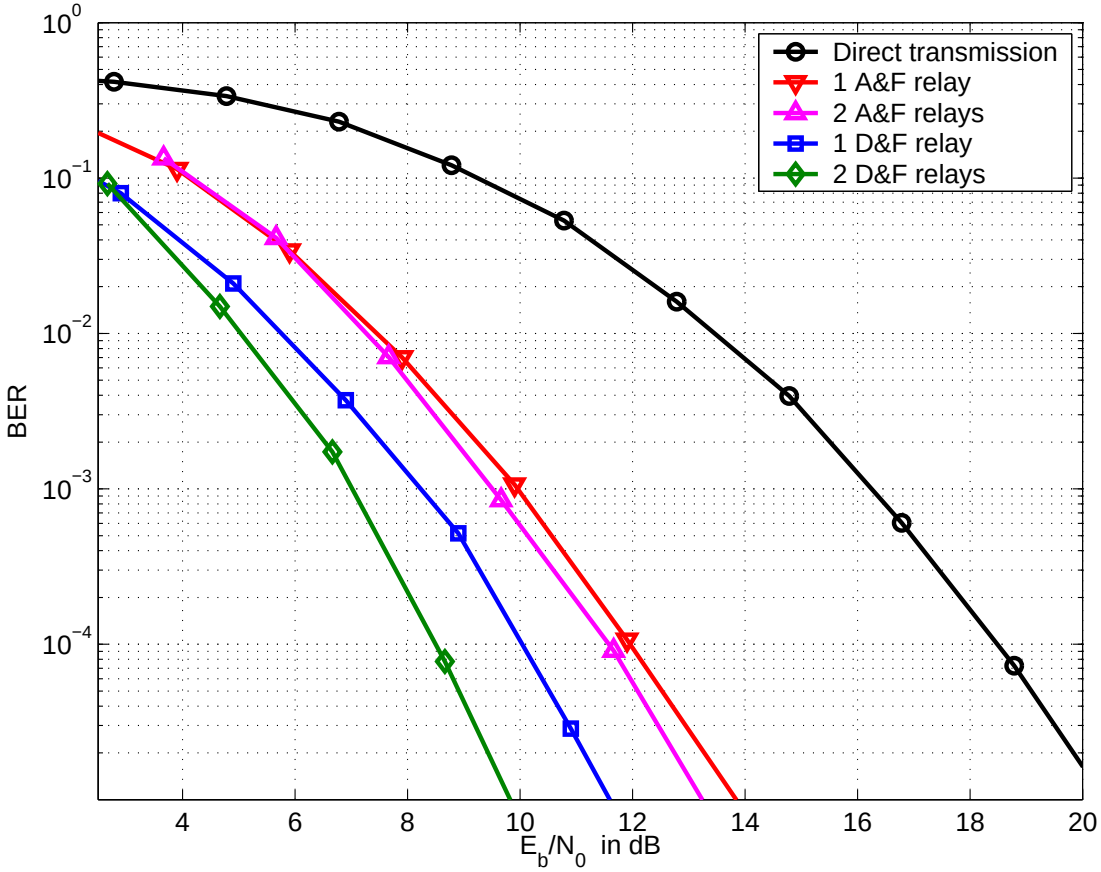
D&F vs. A&F relaying

$N_{\mathrm{r}} = 1, 2$ relays

Data-rate mode 160 Mb/s

Channel model CM2 ($p = 3.5$)

uncorrelated shadowing, no FH



Significant performance improvements over direct transmission, e.g.,
1 D&F relay: 8.5 dB gain $\hat{=}$ 75% range extension
1 A&F relay: 6.5 dB gain $\hat{=}$ 53% range extension

Numerical Performance Results

D&F vs. A&F relaying

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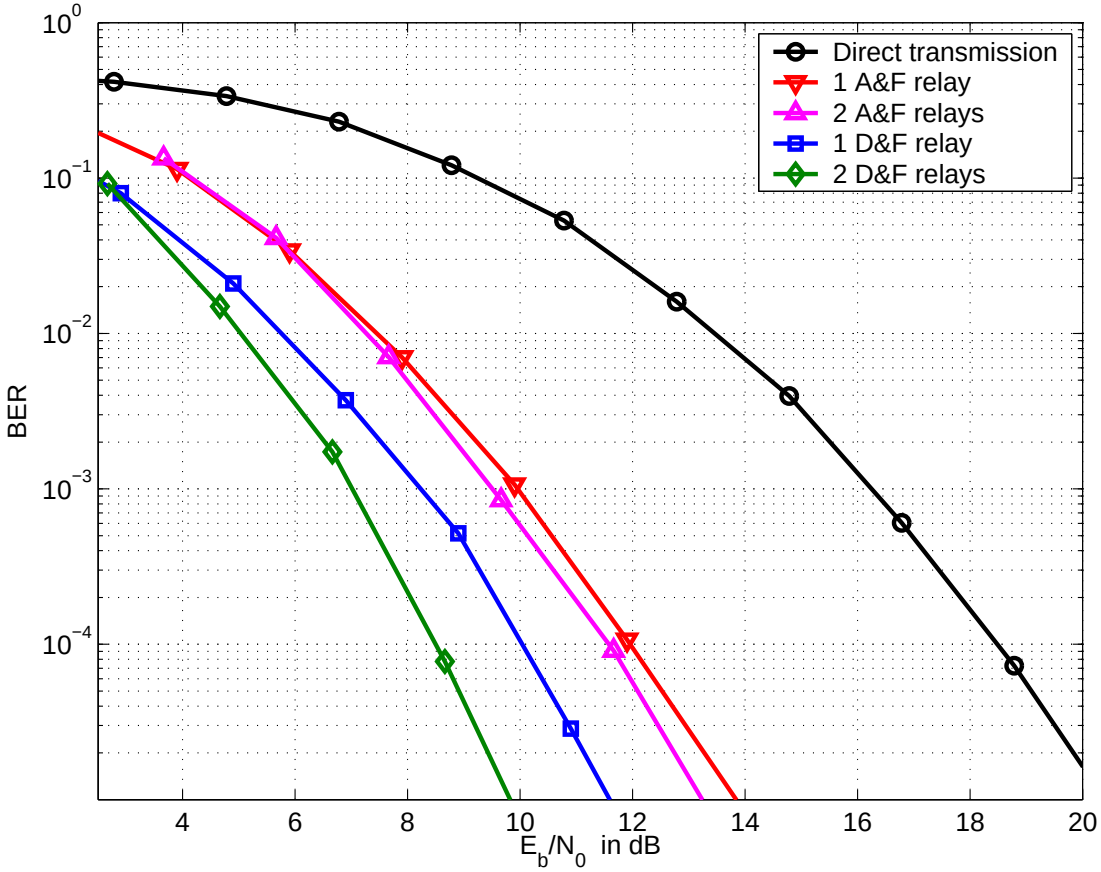

D&F outperforms A&F relaying, as it effectively utilizes channel coding scheme (along with frequency diversity) for error correction at relays; A&F relaying captures mainly path-loss gains and macrodiversity

Numerical Performance Results

FH and Distributed CDD

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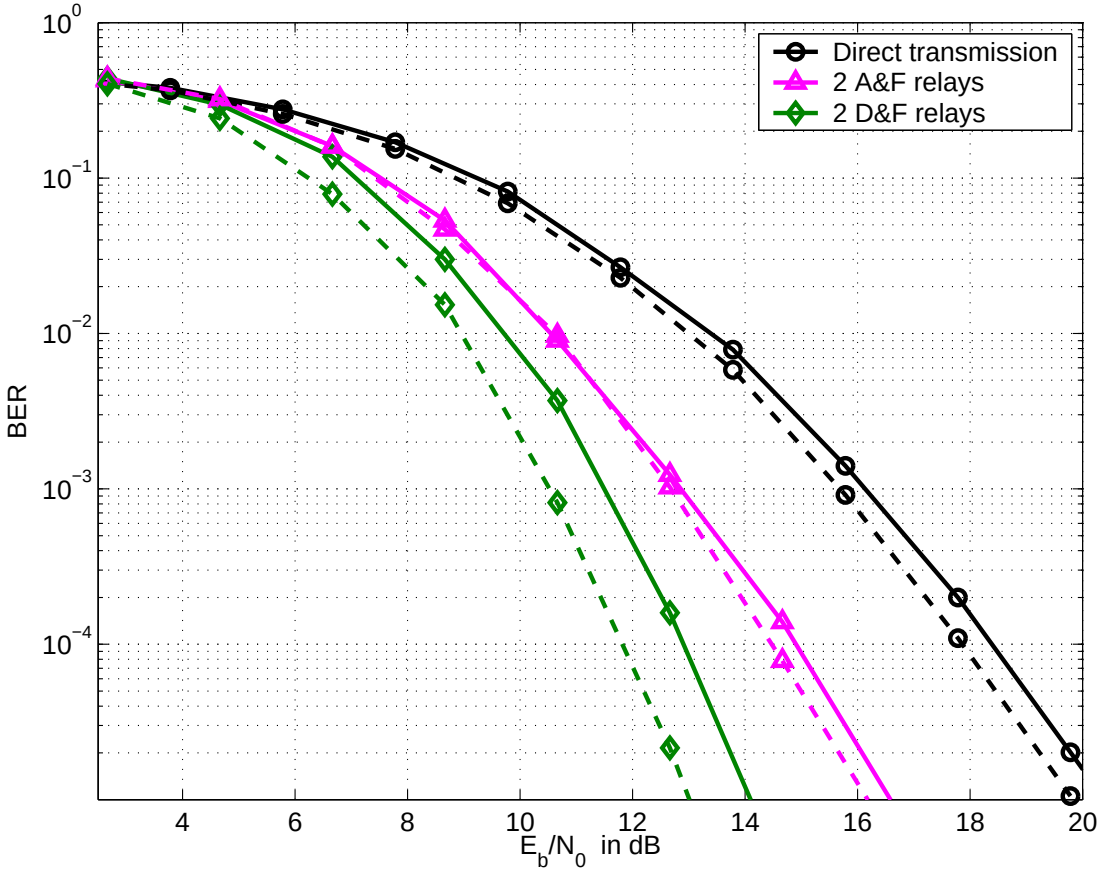
no FH ———, FH - - - -



Performance improvements over direct transmission:
2 D&F relays: 5.5 dB gain $\hat{=}$ 110% range extension
2 A&F relays: 3.5 dB gain $\hat{=}$ 61% range extension

Numerical Performance Results

FH and Distributed CDD

$N_{\mathrm{r}} = 2$ relays

Data-rate mode 160 Mb/s

Channel model CM1 ($p = 1.7$)

uncorrelated shadowing

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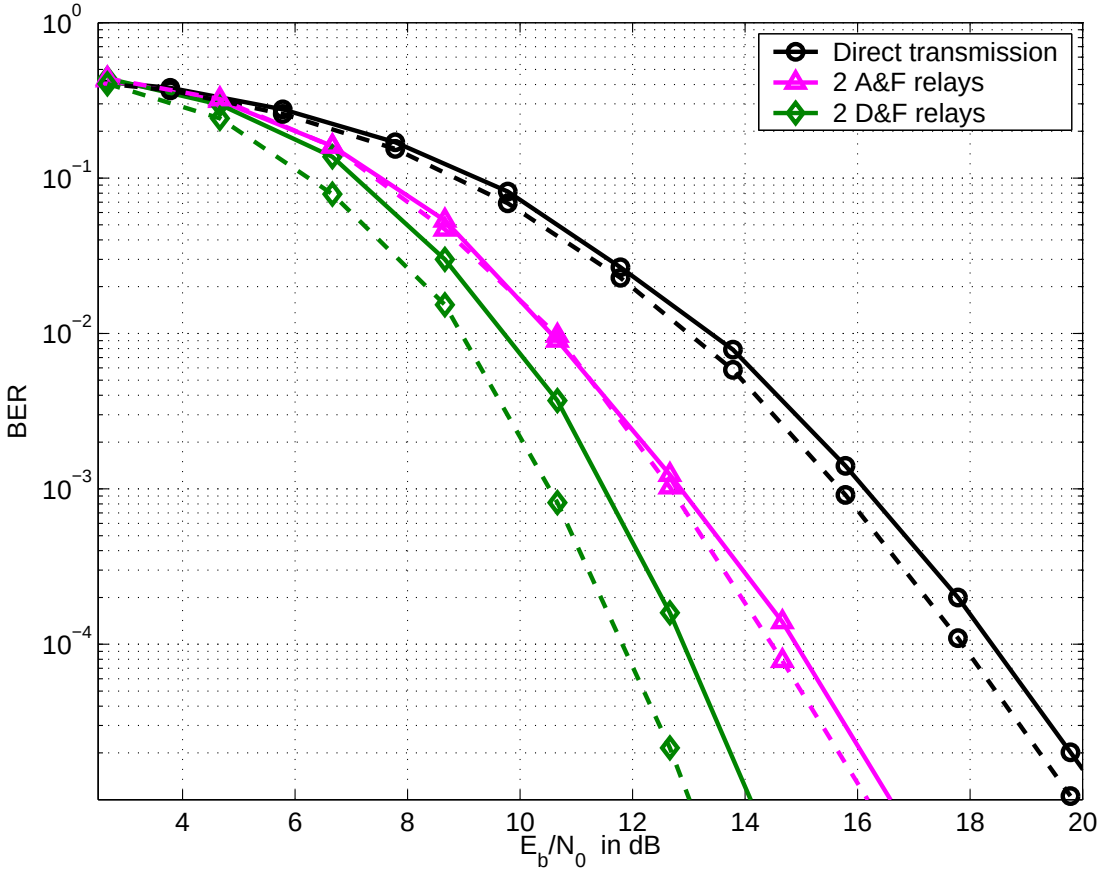

FH yields additional improvements, especially for D&F relaying

Numerical Performance Results

FH and Distributed CDD

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Channel model CM1 ($p = 1.7$)

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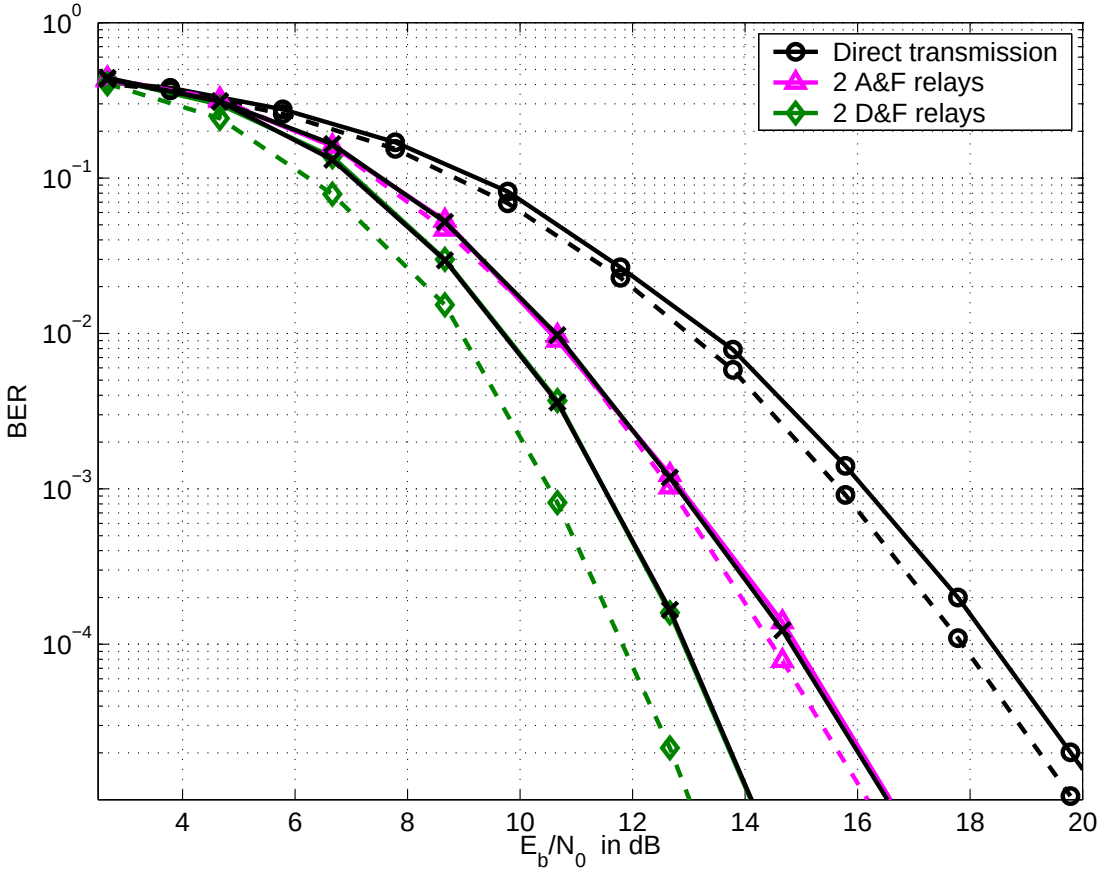


Distributed CDD offers virtually no additional gains, as channel coding scheme already picks up a large amount of frequency diversity

Numerical Performance Results

Correlated Shadowing

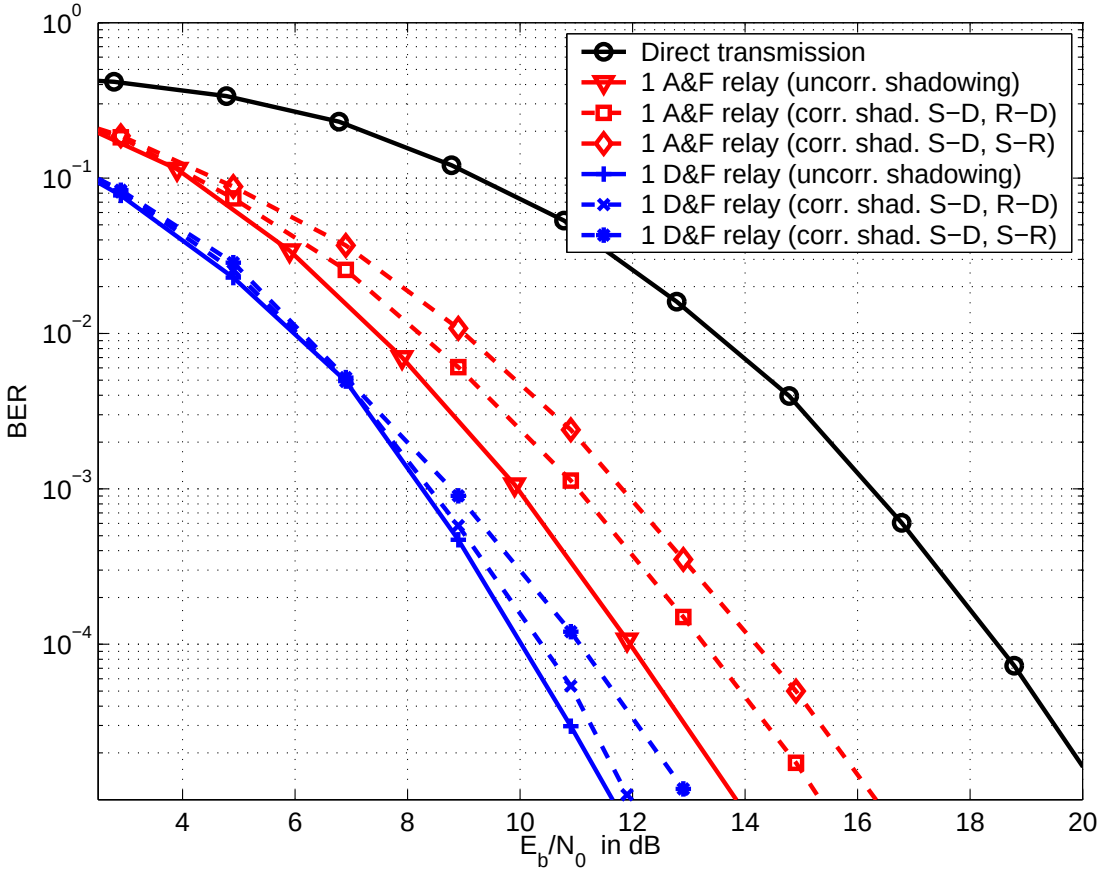
$N_{\mathrm{r}} = 1$ relay

Data-rate mode 160 Mb/s

Channel model CM2 ($p = 3.5$)

Correlation 0.9

no FH



Uncorrelated shadowing leads to best performance;
Correlation between S–D link & R–D link or between
S–D link & S–R link entails some performance degradation

Conclusions

- Benefits of **relaying techniques** for ECMA-368 UWB systems investigated; focus on techniques that require **little change** to current specifications
- D&F and A&F relaying offer significant **performance improvements** over direct transmission, even in the case of correlated shadowing
- Distributed CDD yields **little** additional gains

- D&F relaying **more efficient** than A&F relaying, but higher relay **complexity**
- A&F relaying increases effective **CIR length** of S–R–D link, which can be critical for long CIRs (e.g., CM3, CM4)
- A&F relaying might require some power back-off at the relays to make sure that relays comply with **FCC spectral mask**

$\Rightarrow$ Future work might focus on more **efficient**, yet **simple** relaying techniques

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