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

Submission Title: [NICT PHY Proposal]
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Re: [In response to call for technical contributions TG8]

Abstract: [ ]

Purpose: [Material for discussion in 802.15.8 TG]

Outline

- Physical Channels
- PHY Frame Structure
- Data Formatting
  - FEC coding, scrambling, interleaving, modulations
- Multicarrier Modulation Parameters
- Multiple Antenna Procedures
- Discovery Signal
- Random Access Procedure during Peering

DCN documents proposal

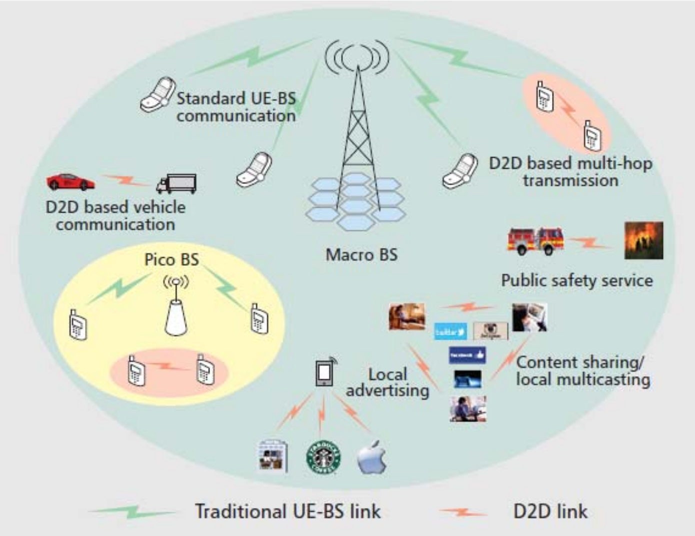
- The core NICT PHY proposal has already been presented since the July 2013 meeting in Geneva, Switzerland.
  - DCN 13-0639r1 and 13-0670r0.
- An updated version was presented in the last meeting January 2014, in Beijing, China.
  - DCN 14-114r0.
- Specification text
  - DCN 14-248r1

MIMO technologies

- Now a days MIMO technologies are incorporated in mass market commercial wireless networks.
- We want to incorporate it for IEEE802.15 family of Standards.
- We propose mature technologies that can help PAC systems to deliver high throughput and increased robustness.
- Regarding implementation, we envision PDs in mobile devices mostly, but also fixed PDs in malls, stadiums, shops, museums, etc.

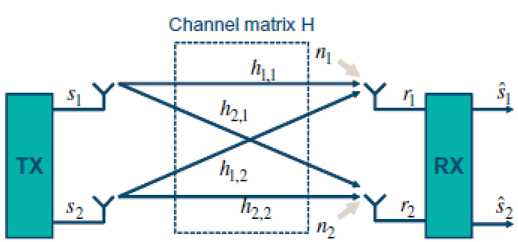
MIMO technologies

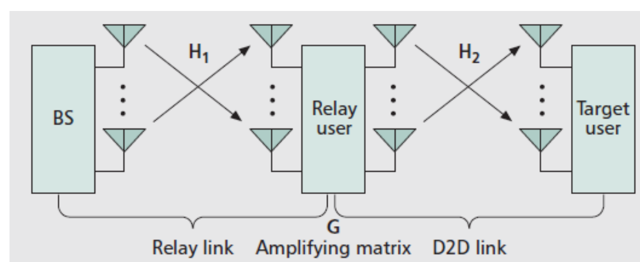
- Modern mobile devices can integrate 2 antennas (handheld) or 4 antennas (tablets) with power constrains.
- Fixed PDs can integrate 4 antennas in malls, stadiums, shops, museums, etc., without power constrains.



Spatial multiplexing

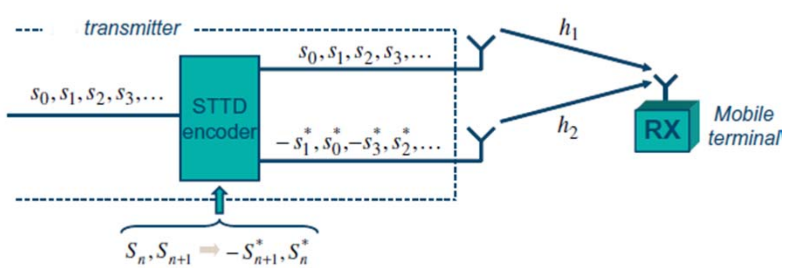
- We propose to use open loop spatial multiplexing (increase capacity) and space-time/transmit diversity, STBC, (increase performance).
- Spatial multiplexing can increase the capacity twice (2x2) or 4-times (4x4).
  - without a corresponding reduction in power efficiency or, in other words, the possibility for very high data rates within a limited bandwidth without a disproportionately large degradation in terms of coverage

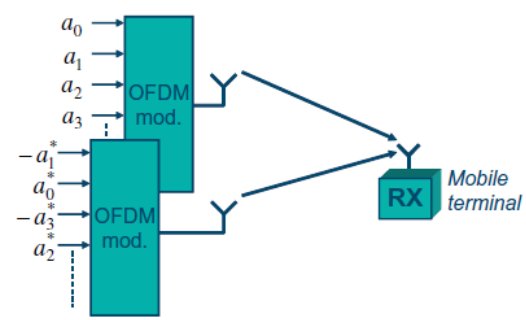




Transmit diversity

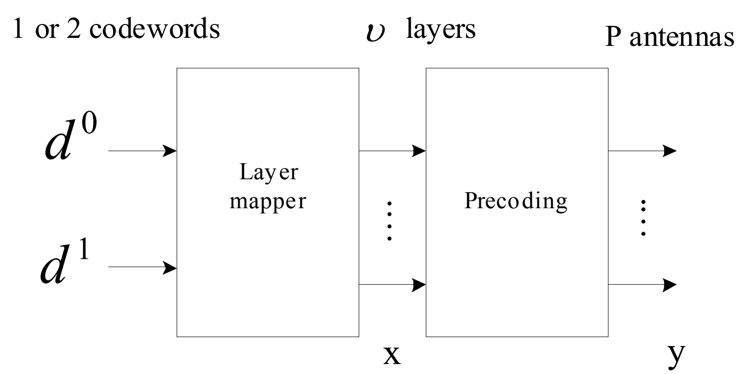
- Case of 2 antennas
  - STBC (Alamouti scheme) for DTF-Spread OFDM
  - SFBC (equivalent of STBC) for OFDM
- Case of 4 antennas
  - It is a combination of SFBC (2 antennas) with frequency switch transmission diversity





MIMO technologies

- Moreover, by introducing precoding, the system performance can be increased.
- Precoding is introduced by feeding back the channel's rank.
  - We propose a codebook for 2 and 4 antennas.
  - It can be seen as a form of beamforming.



Spatial multiplexing scenarios

- Open-loop spatial multiplexing can increase the capacity and performance of PAC systems.
  - Highly attractive in expected high PAC traffic scenarios, like in malls, arenas, etc.
  - However, transceivers' complexity increases.
  - More attractive for fixed PAC terminals in malls, museums, etc.

Transmit diversity scenarios

- Space-time (transmit) diversity is supported for 2 or 4 antennas
  - It is aimed to increase robustness in scenarios with low SNR, low delay tolerance or no feedback to the transmitter is available or reliable.
  - It means that the radio links can work at larger distances or lower SNR operation, saving power.
  - More attractive for PAC mobile terminals (simple and proof technology).

Summary

- Fixed PAC terminals can handle MIMO as spatial multiplexing or transmit diversity without major implementation issues.
- Mobile PAC terminals due to limited battery and space can handle transmit diversity (simple, effective and proof technology).

Receivers

- As it is well known, receivers are not part of the final specification standard.
  - However, we provide some highlights and results to address concerns about implementation.
- MIMO detection techniques (spatial multiplexing)
  - There are many techniques that can be found in the literature.
  - From those techniques that are implementable: equalization-based detection, nulling and cancelling and sphere decoding.
  - The received signal can be expressed as:

$$\boldsymbol{r} = \boldsymbol{H}\boldsymbol{d} + \boldsymbol{n}$$

Receivers

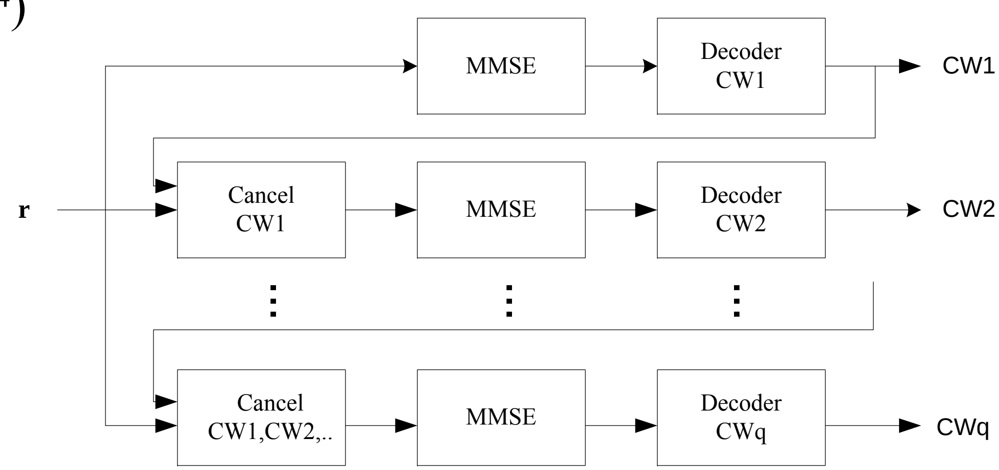
- The optimal detection is ML:
  - All vectors are equally likely and fully exploits available diversity:

$$\hat{\boldsymbol{d}}_{ML} = \arg\min_{d \in D} \left\{ \left\| \boldsymbol{r} - \boldsymbol{H}\boldsymbol{d} \right\|^2 \right\}$$

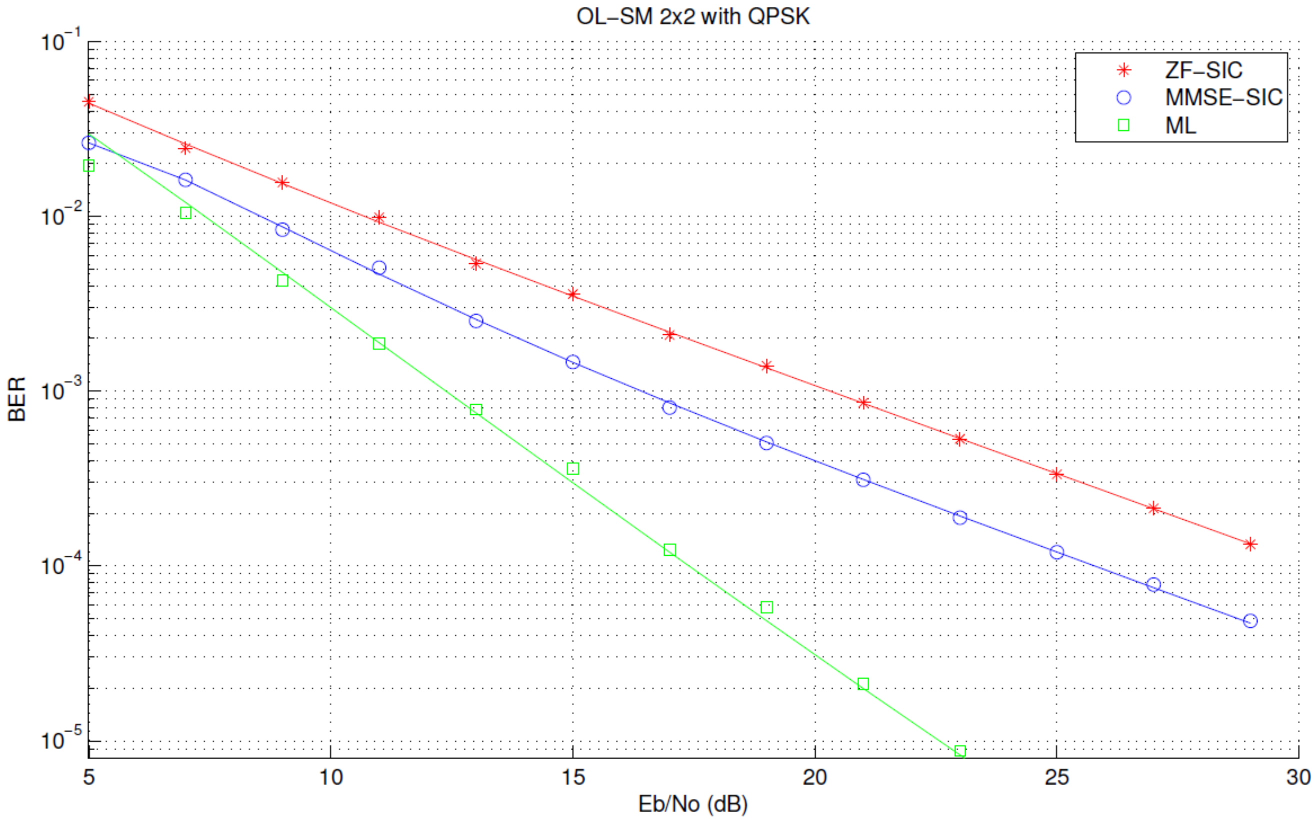
  - $D=A^{Nt}$ set of all possible data vectors. Constrained LS problem known to be nondeterministic polynomial-time NP hard (complexity $O(|A|^{Nt})$).
  - It is too complex, thus suboptimal approaches have been proposed.
- Equalization-based detection
  - Estimate of Tx data vector is formed as $\boldsymbol{y} = \boldsymbol{G}\boldsymbol{r}$
  - Zero forcing equalization $\boldsymbol{y}_{ZF} = (\boldsymbol{H}\boldsymbol{H}^H)^{-1}\boldsymbol{H}^H\boldsymbol{r}$
  - MMSE equalization $\boldsymbol{y}_{MMSE} = (\boldsymbol{H}^H\boldsymbol{H} + \sigma_n^2\boldsymbol{I})^{-1}\boldsymbol{H}^H\boldsymbol{r}$
  - $\boldsymbol{H}$ must be full rank. Complexity $O(Nt^3)$
  - Some other equalization and variants have been proposed.

Receivers

- Nulling and cancelling (inspired from CDMA multiuser detection)
  - Recursive detection in which each step, a single data vector is detected and subtracted from receive vector ***r***. Other components that have not been detected yet, are nulled out using equalization.
- MMSE-SIC detection
  - Complexity $O(Nt^4)$



Suboptimum Receivers



Receivers

- Sphere decoding
  - It is an efficient determination of all data vectors $\boldsymbol{d} \epsilon D$ for which $\boldsymbol{Hd}$ lies within a hyper-sphere of radios r_a around $\boldsymbol{r}$

$$\|\boldsymbol{r} - \boldsymbol{Hd}\|^2 < r_a$$

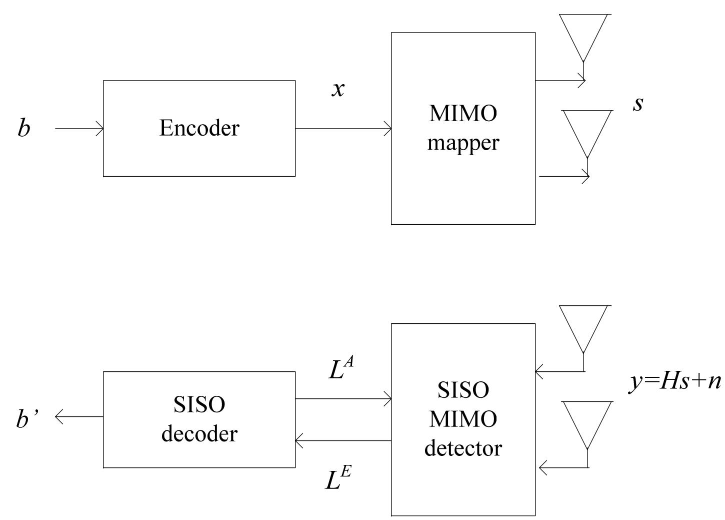
  - It then suffices to minimize $\|\boldsymbol{r} - \boldsymbol{Hd}\|^2$ for data vectors produced by the SD.
  - It implies a substantial reduction of complexity.
  - However, the complexity depends on channel realization and SNR (as high as exponential to Nt and low as polynomial in Nt).

Receivers

- However, iterative MIMO decoding is the most promising approach for low complexity and close optimum performance.
  - Core idea: independent MIMO detection and channel decoding.
- We present 2 promising iterative systems for spatial multiplexing:
  - SISO MMSE PIC and sphere decoding.

Receivers

- Iterative MIMO decoding
  - Reliability information of coded bits (LLRs) is iteratively exchange between SISO MIMO detector and SISO decoder to improve error-rate.



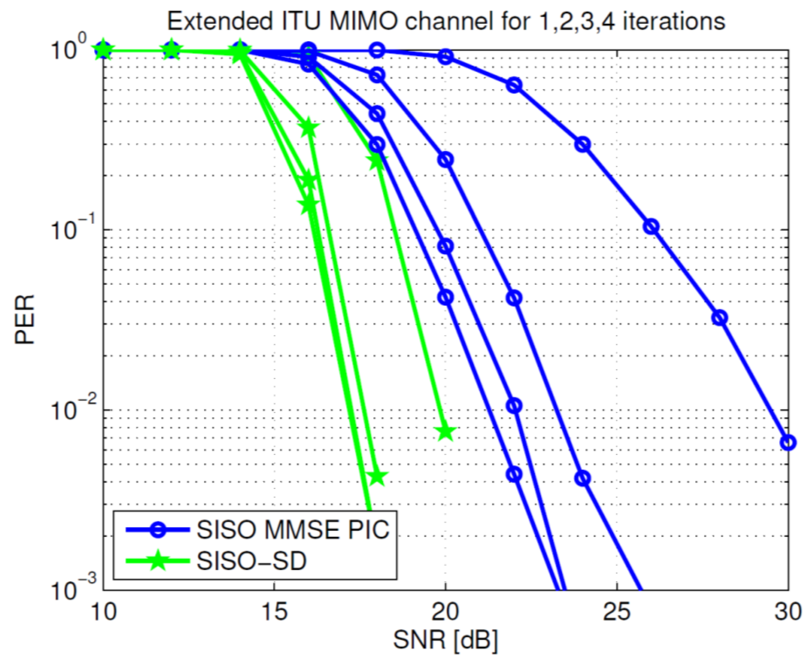
$$L^{\mathrm{E}} = \log\left(\frac{\mathrm{P}[x_{i,b} = 1 \mid \mathbf{y}]}{\mathrm{P}[x_{i,b} = 0 \mid \mathbf{y}]}\right) - L^{\mathrm{A}}$$

Receivers

- SISO MMSE PIC is a suboptimum algorithm to compute LLRs
  - Compute soft-symbols: $\hat{s}_i$. PIC: $\hat{y}_i = y - \sum_{j \neq i} h_j \, \hat{s}_i$. MMSE filtering: $z_i = w^H \hat{y}_i$. Intrinsic LLR: $L^D(z_i)$. Extrinsic LLR: $L^E = L^D = L^A$.

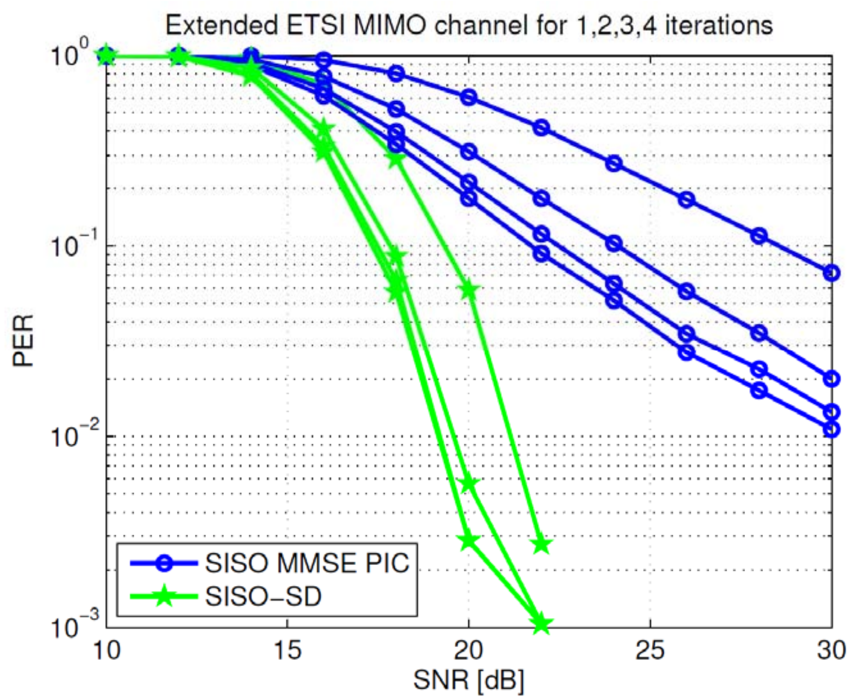
- SISO sphere decoding allows near-optimum performance with low complexity
  - Computes intrinsic LLR: $L = \log\left(\sum_{\mathbf{s} \in \chi^{+1}} p(\mathbf{y} \mid \mathbf{sH}) \, P(\mathbf{s})\right) - \log\left(\sum_{\mathbf{s} \in \chi^{-1}} p(\mathbf{y} \mid \mathbf{sH}) \, P(\mathbf{s})\right)$
  - Extrinsic LLR: $L^E = L - L^A$
  - Use max-log approximation in L
  - LLR is reformulated as a weighted tree search problem that is solved efficiently by the SD algorithm

Results



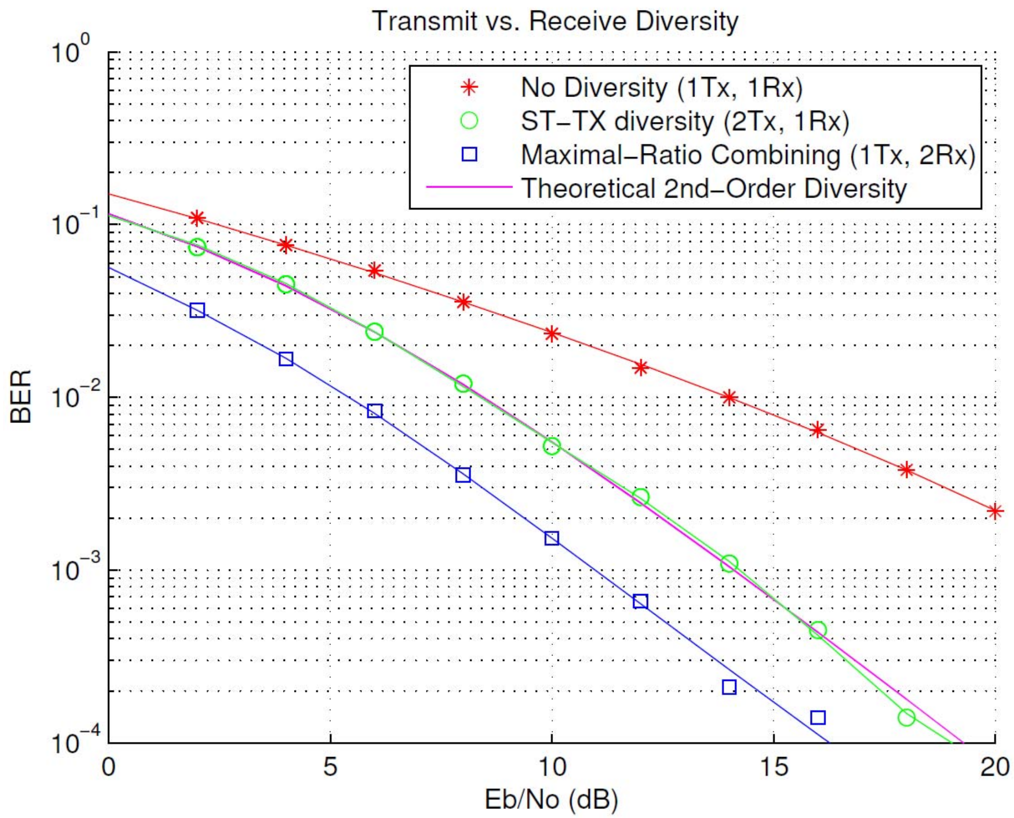
– PER performance, ½ rate CC, OFDM (1 MHz) with 16QAM symbols in the form of spatial multiplexing for 4x4 antennas with ITU MIMO channel, low correlation and pedestrian.

Results

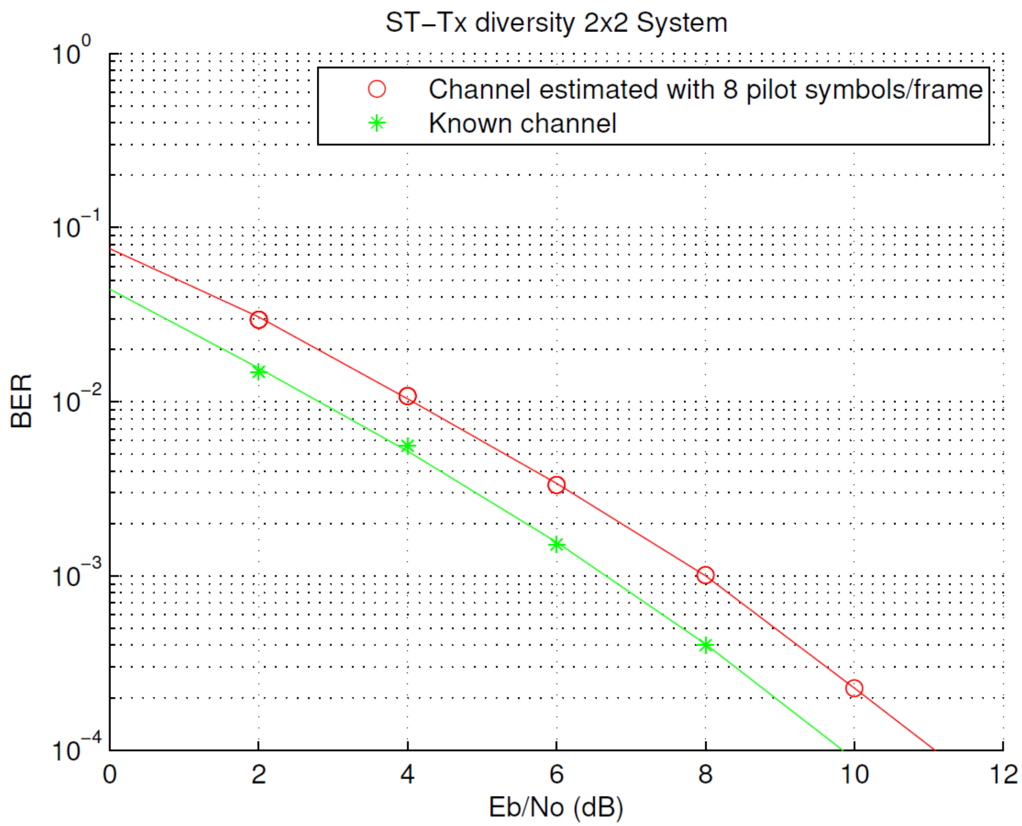


– PER performance, ½ rate CC, OFDM (1 MHz) with 16QAM symbols in the form of spatial multiplexing for 4x4 antennas with ETSI MIMO channel, low correlation and model A.

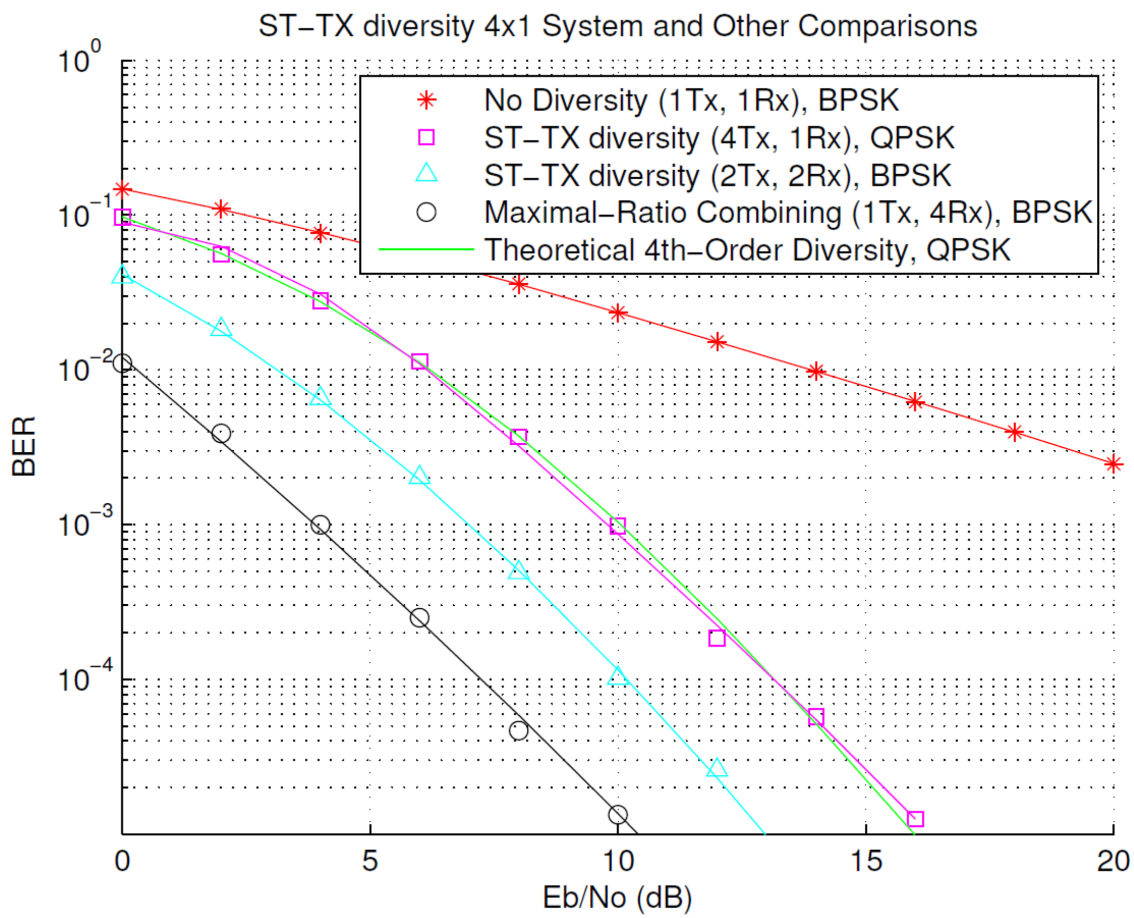
Transmit diversity results



Results


ST−Tx diversity 2x2 System
Channel estimated with 8 pilot symbols/frame
Known channel
BER
Eb/No (dB)
10^0
10^−1
10^−2
10^−3
10^−4
0
2
4
6
8
10
12

Results


ST–TX diversity 4x1 System and Other Comparisons
No Diversity (1Tx, 1Rx), BPSK
ST–TX diversity (4Tx, 1Rx), QPSK
ST–TX diversity (2Tx, 2Rx), BPSK
Maximal–Ratio Combining (1Tx, 4Rx), BPSK
Theoretical 4th–Order Diversity, QPSK
BER
Eb/No (dB)
0
5
10
15
20

Data rates

- Data rates depend on the employed spectrum (number of subcarriers and carrier aggregation), modulation scheme, coding rate, MIMO scheme and overhead (control information, etc.).
  - Data rate:

$$R_b = \frac{nN_{sc}^{RB} N_{sym} \operatorname{Log}_2(M)}{0.5\text{ msec}} C_R C_A C_M (1 - C_O)$$

  - The number of subcarriers is $nN_{sc}^{RB} N_{sym}$, where $N_{sc}^{RB} = 6$, $N_{sym} = 7$, $12 \leq n \leq 111$
  - The number of bits per symbol is $\operatorname{Log}_2(M)$
  - The coding rate C_R
  - The carrier aggregation C_A
  - Open loop spatial multiplexing scheme C_M
  - Overhead percentage C_O

Data rates

- The data rate parameters:

n	$Log_2(M)$	Modulation	C_A	C_A mode	C_R	C_M	C_M mode
12	1	BPSK	1	disable	1/2	1	disable
	2	QPSK	2	enable	2/3	2	2x2
	4	16QAM			3/4	4	4x4
111	6	64QAM			5/6		

- Example: the peak data rate given by using all RBs, n=111, carrier aggregation enable, 64QAM, coding rate of 5/6 and 4x4 MIMO is $\boldsymbol{R_b}$**=372.96** Mbps (without overhead).

QC-LDPC

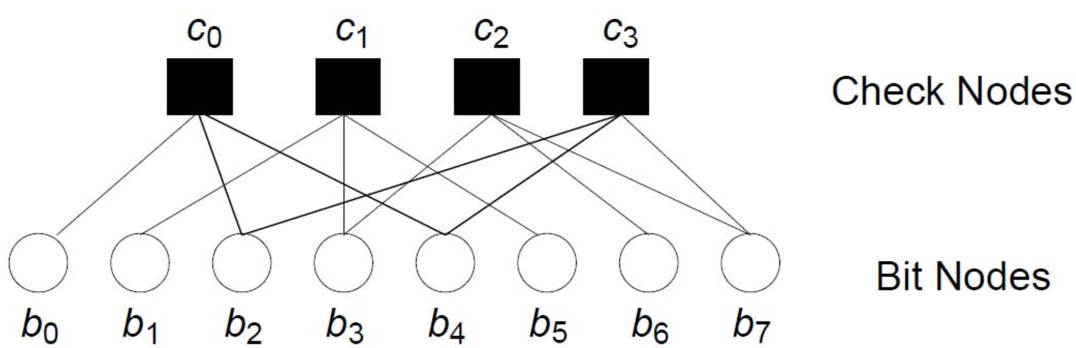
- General LDPCs have implementation issues:
  - Long randomly constructed LDPC codes have very good performance (very close to the Shannon's limit) but are hard to implement.
  - Encoding complexity and area/memory consumption.
- Analytic codes
  - Systematically designed LDPCs using algebra, geometry or non-random algorithms.
  - Idea: create codes with good performance, but simplify implementation.
  - In this area **quasi-cyclic LDPC** codes have been investigated.
  - Trade-off between loss in performance compared to long random codes and complexity of implementation.

Advantages of QC-LDPC

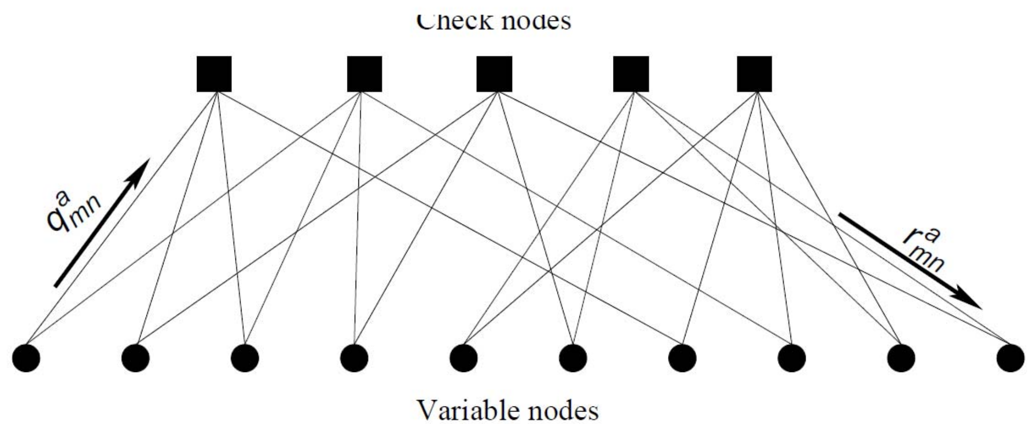
- Encoding
  - The complexity of the encoding process scales with $O(n)$
  - Really efficient hardware implementation
- Decoding
  - Implementation benefits from the analytic structure: decoding can be tweaked further to reduce complexity.
  - No need to store full ***H*** matrix

FEC decoding

- There are several techniques for decoding of QC-LDPC codes.
- LDPC decoding is represented as a message passing (MP) algorithm in a factor graph with N_pZ variable nodes and M_pZ check nodes.
  - Variable nodes are associated to information bits. The *m*th parity check node is connected to the *n*th variable node if $[\mathbf{H}]_{m,n}=1$



FEC decoding

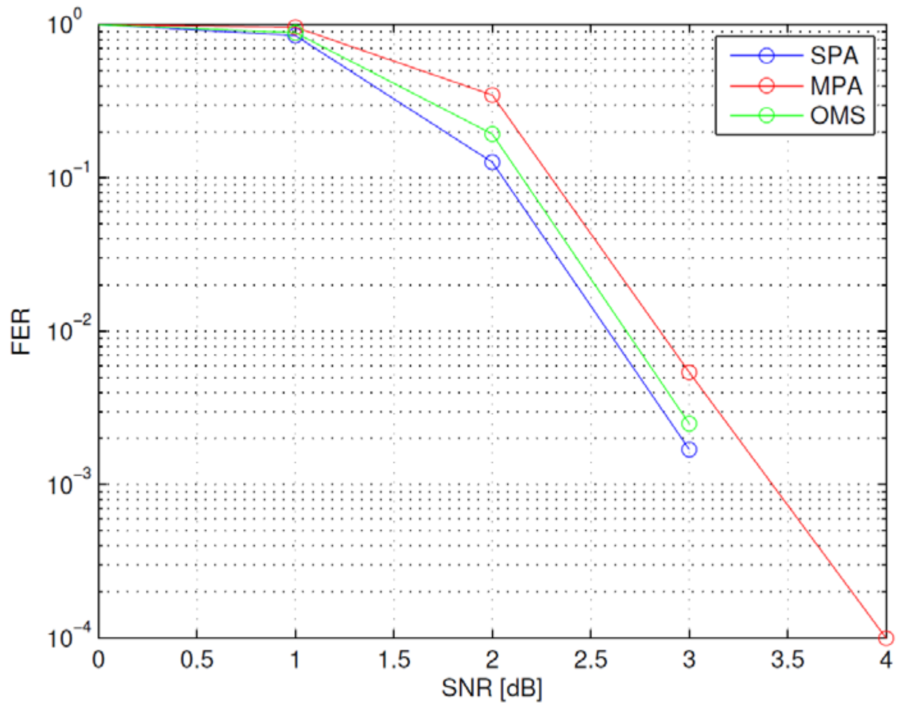


– The decoding employing the message passage algorithm can be tweaked to simplify implementation.

FEC decoding

- For lack of space and not being part of the standard, details of receivers are omitted. We present core ideas and results.
  - An efficient decoding implementation is based on Layered LDPC decoding with offset min-sum (OMS) algorithm.
  - Efficient and low complex implementation in VLSI architectures.
  - Details can be found in the literature.

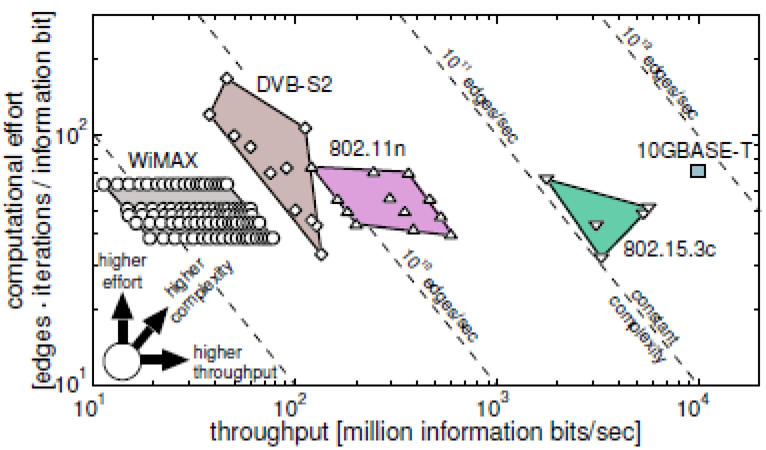
FEC decoding results



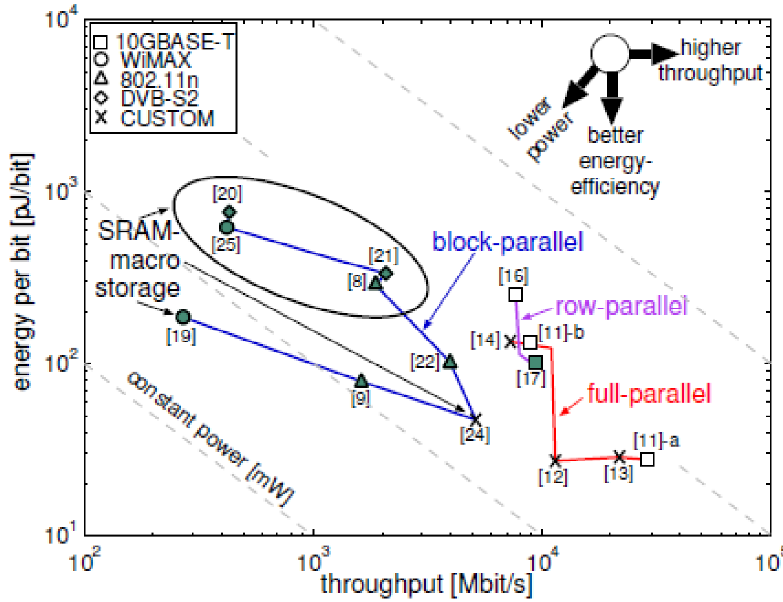
- PER performance, QC-LDPC(324,648), R=1/2, OFDM (1 MHz) with BPSK symbols for 1x1 antennas with ITU channel pedestrian. SPA=sum-product algorithm. MPA=message passing algorithm. OMS=offset min-sum algorithm.

VLSI implementation

State of the art implementations of products of popular standards.



Decoding complexity: No of edges in the graph and number of iterations to achieve a target error-rate per information bit.



Energy per bit to achievable throughput.

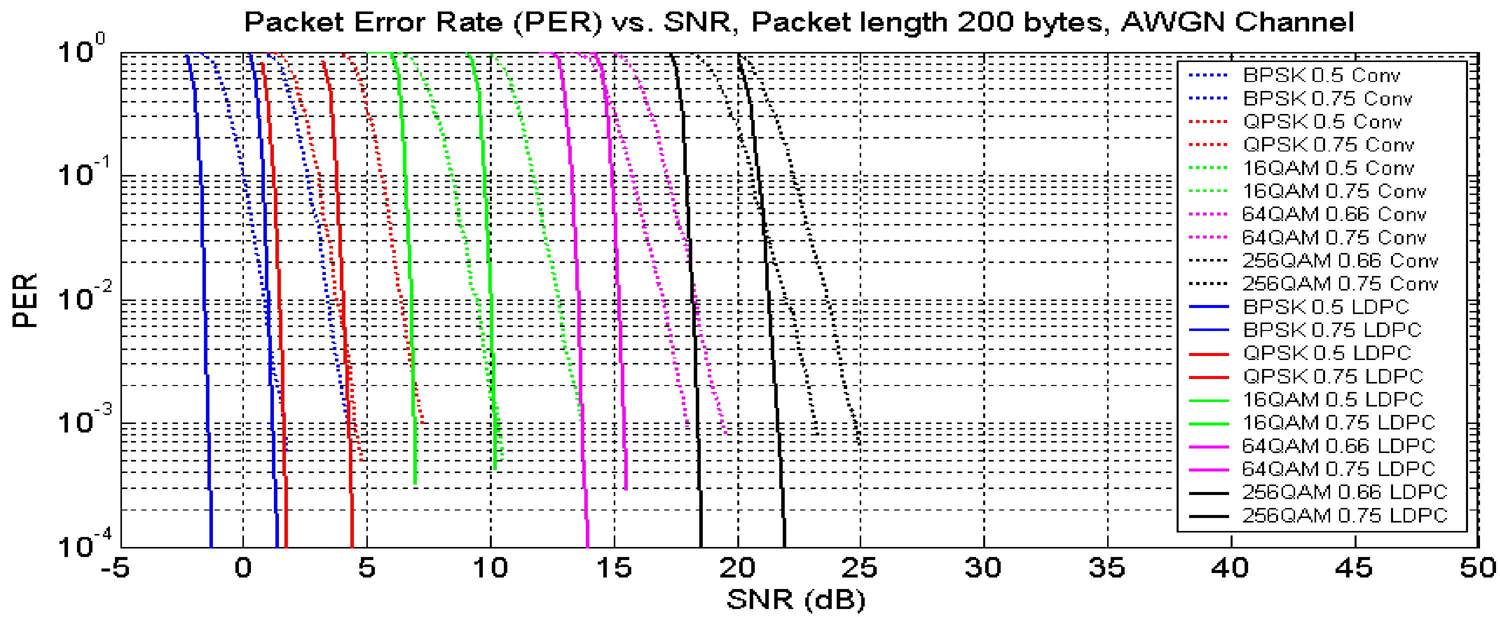
Comparison

- Comparison between QC-LDPC and convolutional codes
  - Based on 802.11 PHY

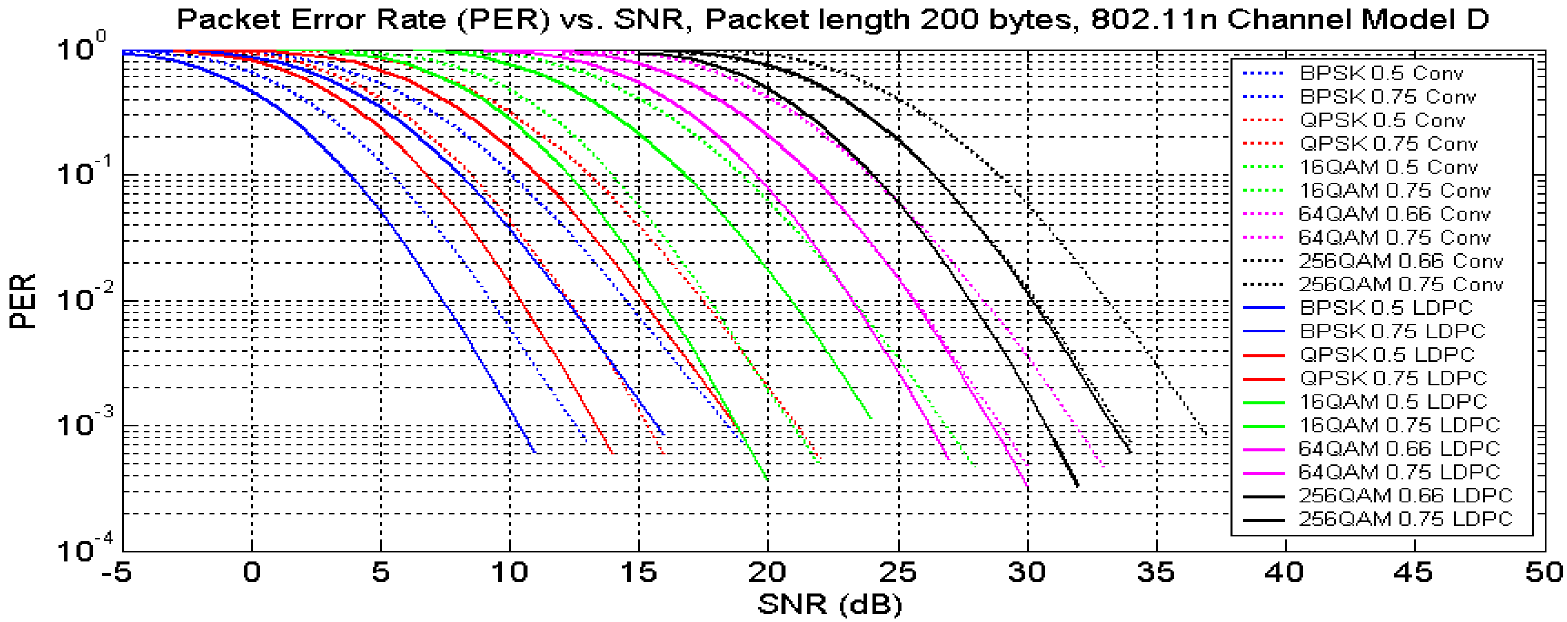
Data Rate (Mbits/s)	6	9	12	18	24	36	48	54	64	72
Modulation	BPSK	BPSK	QPSK	QPSK	16QAM	16QAM	64QAM	64QAM	256QAM	256QAM
Coding Rate (R)	1/2	3/4	1/2	3/4	1/2	3/4	2/3	3/4	2/3	3/4

  - Viterbi decoding for CC and sum-product algorithm for LDPC.

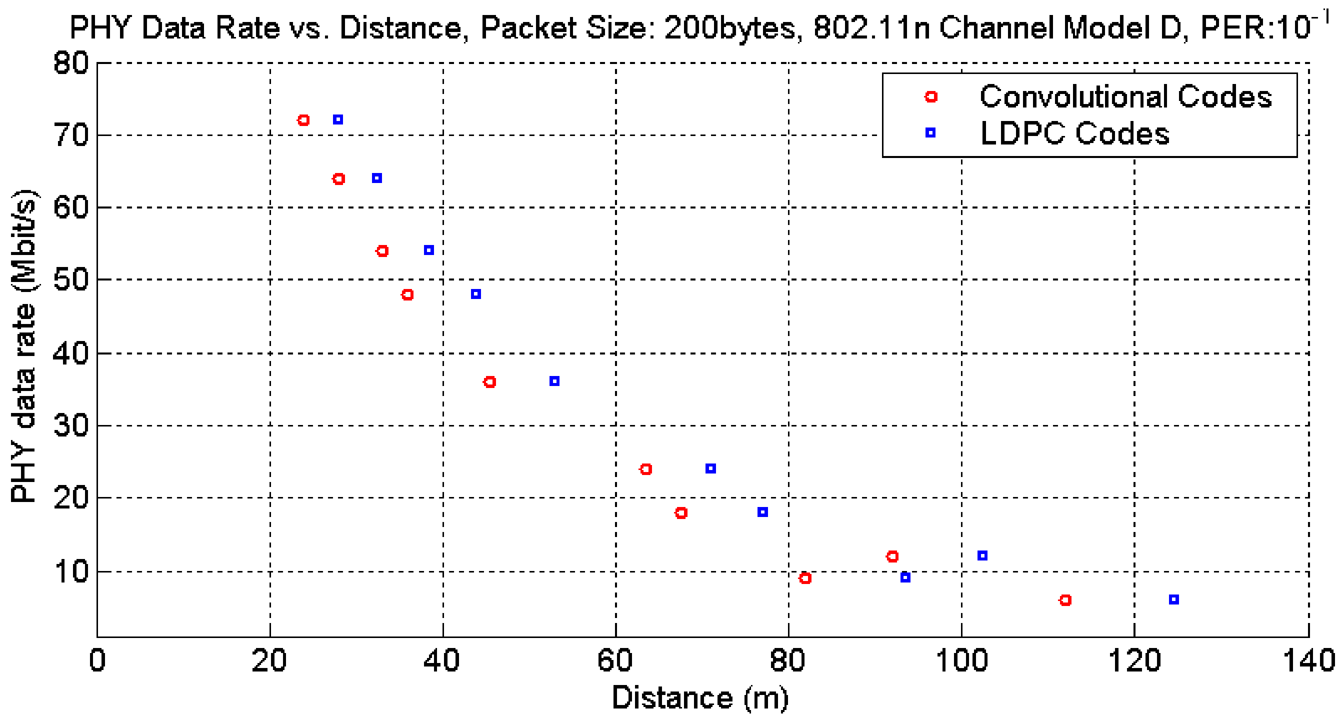
Comparison


Packet Error Rate (PER) vs. SNR, Packet length 200 bytes, AWGN Channel
PER
SNR (dB)
10^0
10^-1
10^-2
10^-3
10^-4
-5
0
5
10
15
20
25
30
35
40
45
50
BPSK 0.5 Conv
BPSK 0.75 Conv
QPSK 0.5 Conv
QPSK 0.75 Conv
16QAM 0.5 Conv
16QAM 0.75 Conv
64QAM 0.66 Conv
64QAM 0.75 Conv
256QAM 0.66 Conv
256QAM 0.75 Conv
BPSK 0.5 LDPC
BPSK 0.75 LDPC
QPSK 0.5 LDPC
QPSK 0.75 LDPC
16QAM 0.5 LDPC
16QAM 0.75 LDPC
64QAM 0.66 LDPC
64QAM 0.75 LDPC
256QAM 0.66 LDPC
256QAM 0.75 LDPC

Comparison


Packet Error Rate (PER) vs. SNR, Packet length 200 bytes, 802.11n Channel Model D
PER
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
-5
0
5
10
15
20
25
30
35
40
45
50
SNR (dB)
BPSK 0.5 Conv
BPSK 0.75 Conv
QPSK 0.5 Conv
QPSK 0.75 Conv
16QAM 0.5 Conv
16QAM 0.75 Conv
64QAM 0.66 Conv
64QAM 0.75 Conv
256QAM 0.66 Conv
256QAM 0.75 Conv
BPSK 0.5 LDPC
BPSK 0.75 LDPC
QPSK 0.5 LDPC
QPSK 0.75 LDPC
16QAM 0.5 LDPC
16QAM 0.75 LDPC
64QAM 0.66 LDPC
64QAM 0.75 LDPC
256QAM 0.66 LDPC
256QAM 0.75 LDPC

Comparison

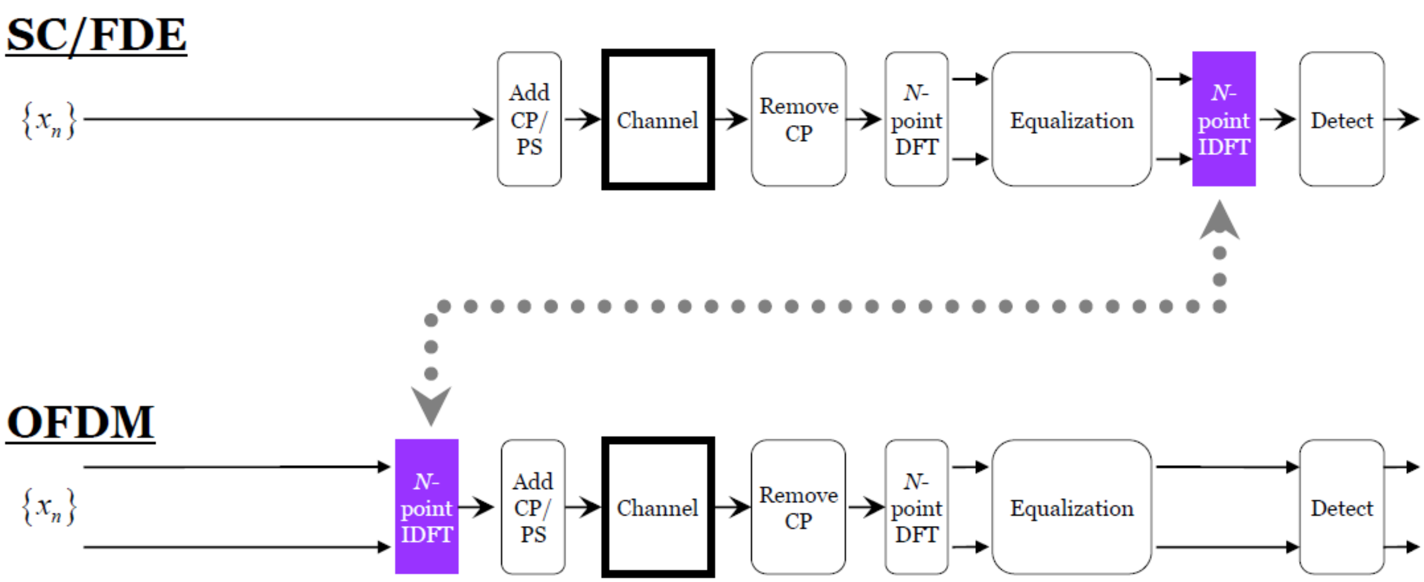

PHY Data Rate vs. Distance, Packet Size: 200bytes, 802.11n Channel Model D, PER:10^-1
Convolutional Codes
LDPC Codes
PHY data rate (Mbit/s)
Distance (m)
80
70
60
50
40
30
20
10
0
20
40
60
80
100
120
140

OFDM issues

- High peak-to-average power ratio (PAPR):
  - Since the transmitted signal is a composition of multiple subcarriers, high peaks occur.
- Carrier frequency offset:
  - Frequency offset breaks the orthogonality between subcarriers and causes inter-carrier interference.
- Adaptive scheme or channel coding is required to overcome the spectral null in the channel.
- There are many techniques to mitigate these isues.
- We focus on single carrier with frequency domain equalization (DFE)

Single Carrier with FDE

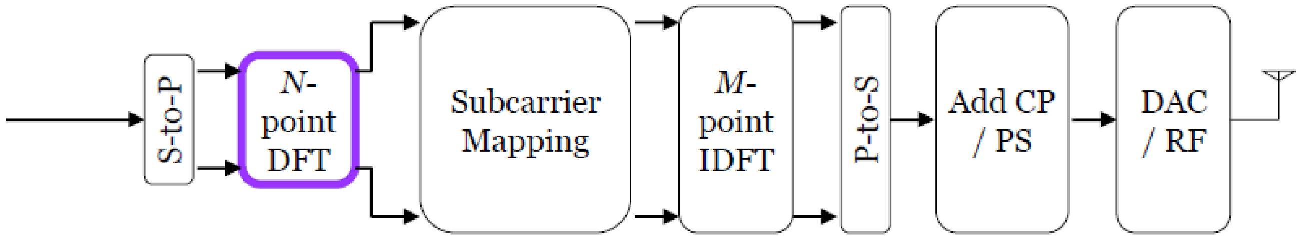
- SC/FDE as a form of OFDM



Single Carrier with FDE

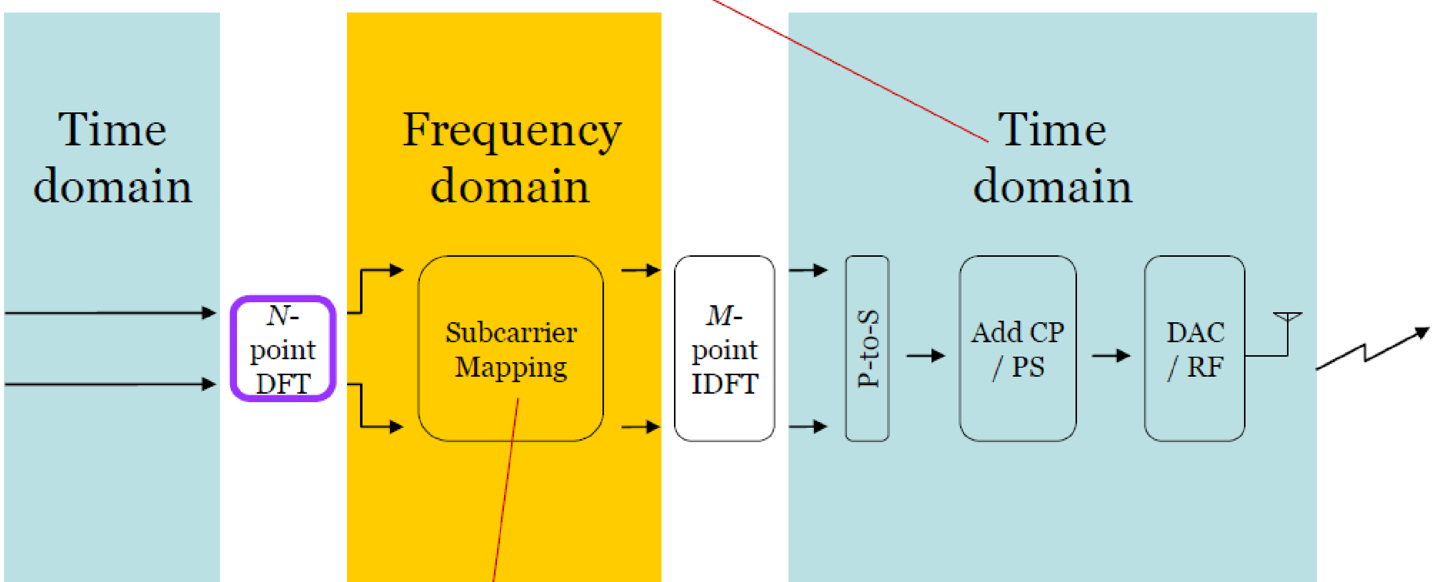
- SC/FDE delivers performance similar to OFDM with essentially the same overall complexity, even for long delay spread channels.
- SC/FDE has advantages over OFDM in terms of:
  - Low peak to average power ratio (PAPR).
  - Robustness to spectral null.
  - Less sensitivity to carrier frequency offset.
  - Frequency-domain-generated SC-FDMA is simply a pre-coded OFDM scheme known as **DFT-Spread OFDM**.
- These have a strong impact on simpler, cheaper hardware implementations and better battery life.

DFT-Spread OFDM scheme



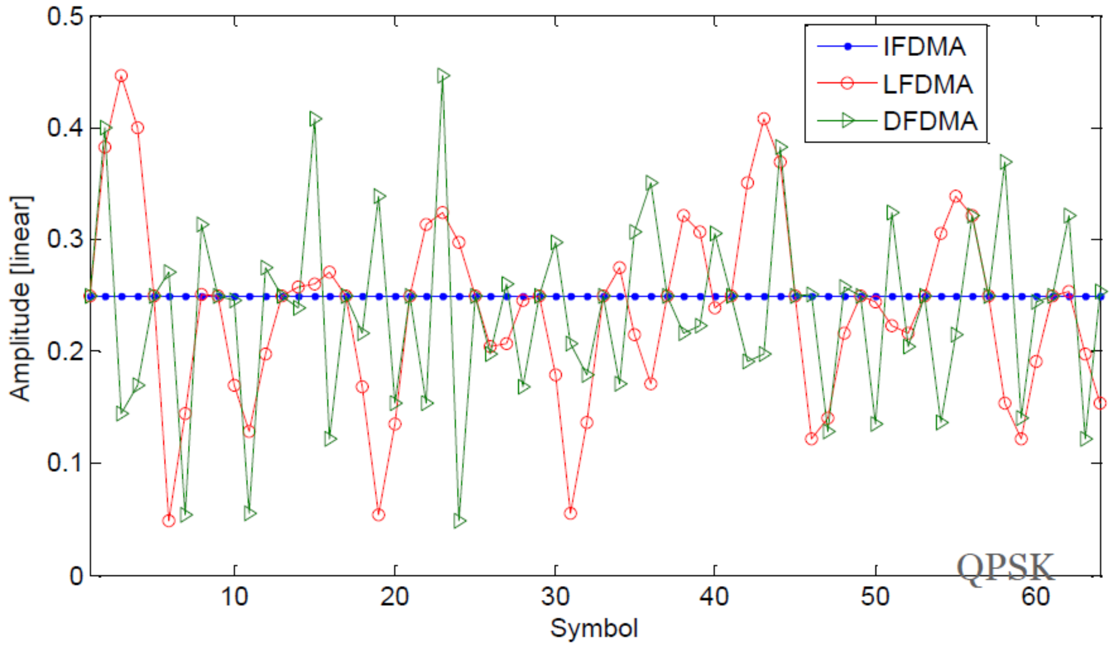
Why low PAPR

"Single Carrier": Sequential transmission of the symbols over a single frequency carrier.

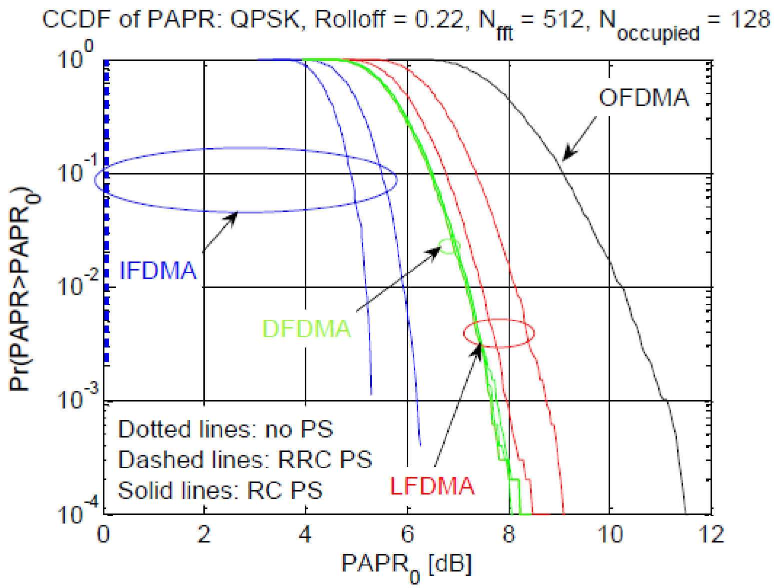


"FDMA" : User multiplexing in the frequency domain.

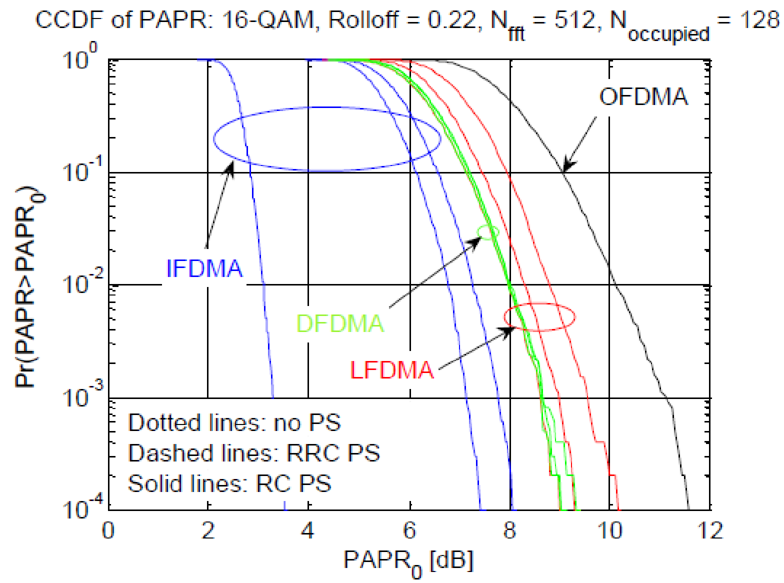
Why low PAPR


0.5
0.4
0.3
0.2
0.1
0
Amplitude [linear]
10
20
30
40
50
60
Symbol
IFDMA
LFDMA
DFDMA
QPSK

PAPR

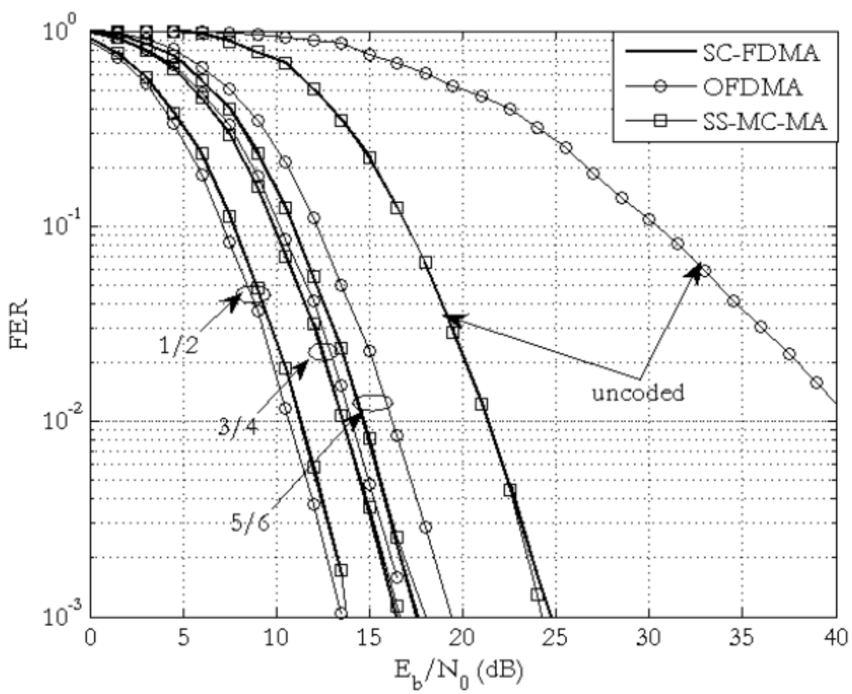


(a) QPSK

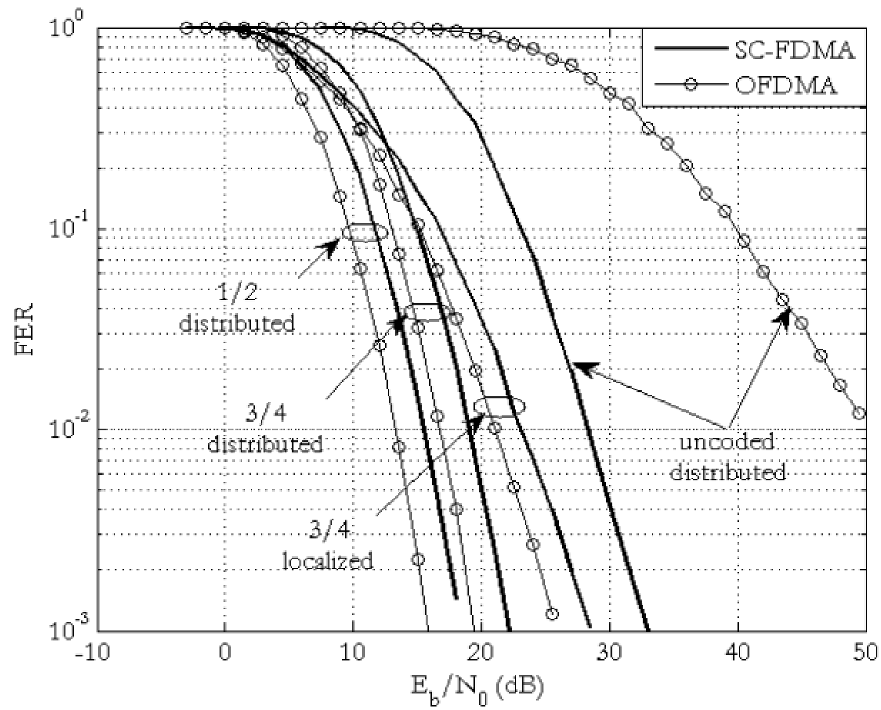


(b) 16-QAM

PER performance



QPSK



16-QAM

Conclusions

- A SC/FDE systems and in particular DFT-Spread OFDM gives similar results compared to OFDM, while avoiding its PAPR and synchronization problems.
- DFT-Spread OFDM implies implementations with low cost power amplifier and synchronization, and lower power consumption (longer battery life) compared to OFDM.
- These are desired properties for PAC mobile terminals.