Practical MIMO Architecture Enabling Very High Data Rates

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Objectives

Identify MIMO-OFDM Architecture that allows

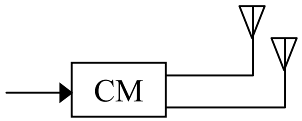
- 200+ Mbps data rates (10+ bps/Hz)
- Practical implementation options
- Backward compatibility to .11a/g

Outline

- Background & motivation
  - MIMO based on space-time coding
  - MIMO based on BICM+spatial mux
- Transmitter/receiver architecture
- PER simulation results and SNR requirements
- Preamble format
- CFO compensation
- Channel estimation

STC vs. SM: background

STC: Coded Modulation (CM)

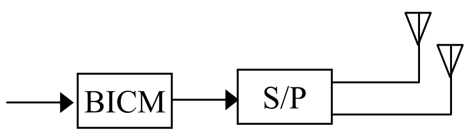


- Space-time trellis coding (STTC) ~ [Tarokh'98]
- Space-time block coding (STBC) ~ [Alamouti'98], [Tarokh'99]
- Space-frequency coding (SFC) (STC+OFDM) ~ [Paulraj'00], [Lu'00]
- Group space-time-frequency block coding (GSTFC) ~ [Liu'02]
- TCM + STBC ~ [Gong'02]

SM: Bit-Interleaved Coded Modulation (BICM)

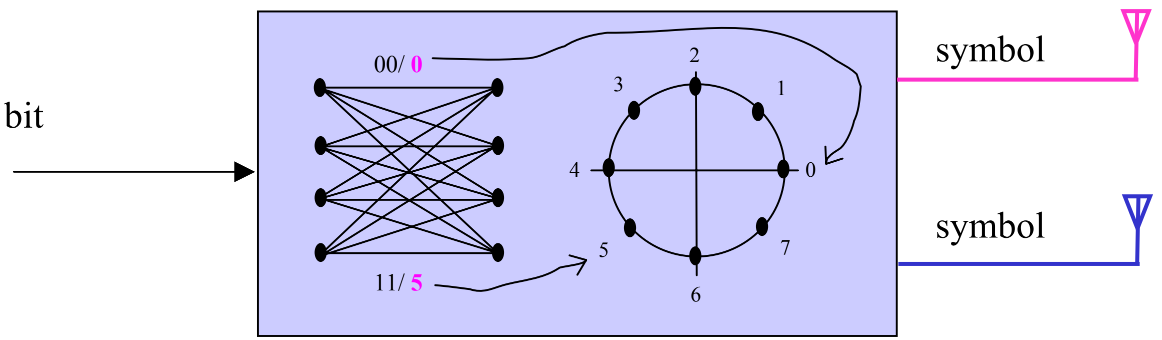
- BICM + Spatial multiplexing

  ~ [Tonello'00], [Duman'01], [Lu'02], [Park'03]

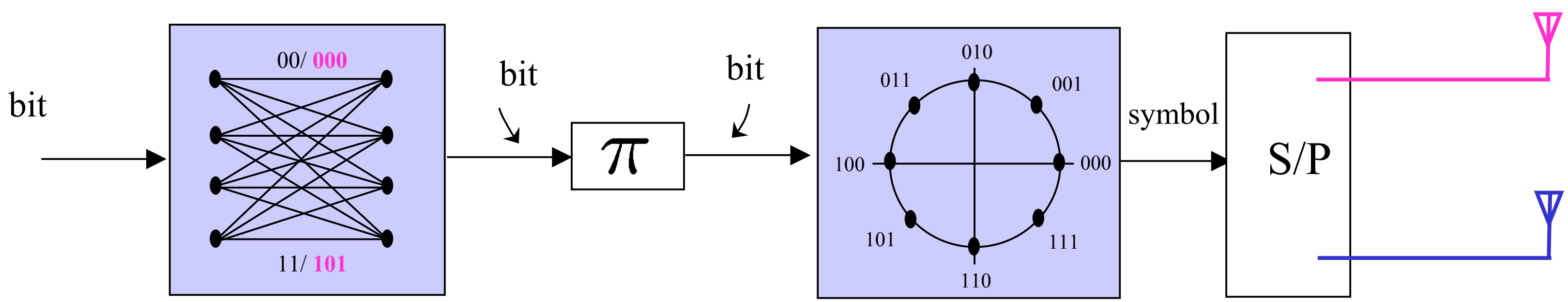


STC vs. BICM+SM: philosophy

STC



BICM+SM

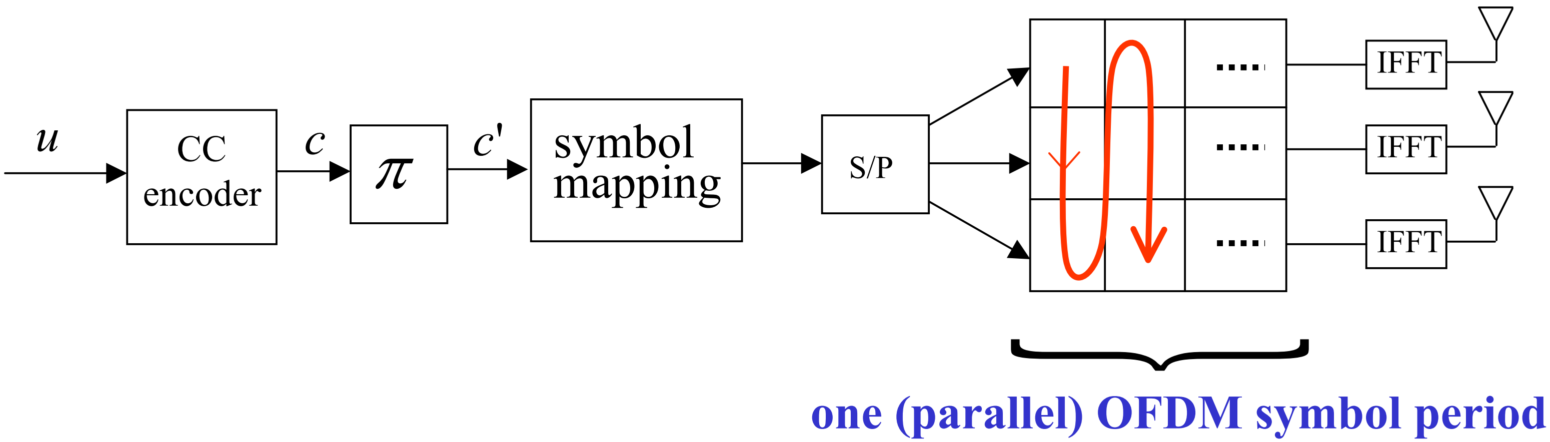


STC vs. BICM+SM: summary

- STC offers improved reliability through explicit enhancement of diversity gain
  - Suffers rate loss
  - Data rate increase possible with higher order constellation
- BICM+SM allows transmission of independent information streams, leading to high data rates
  - No explicit attempt to explore diversity
  - Yet capacity-achieving
- For high data rate applications, BICM+SM is the way to go
  - SNR advantage in achieving the same data rate
  - RF implementation difficulties associated with large constellations (phase sensitivity, PA backoff requirements, etc)

BICM+Spatial Multiplexing: Transmitter

3 Tx antenna example



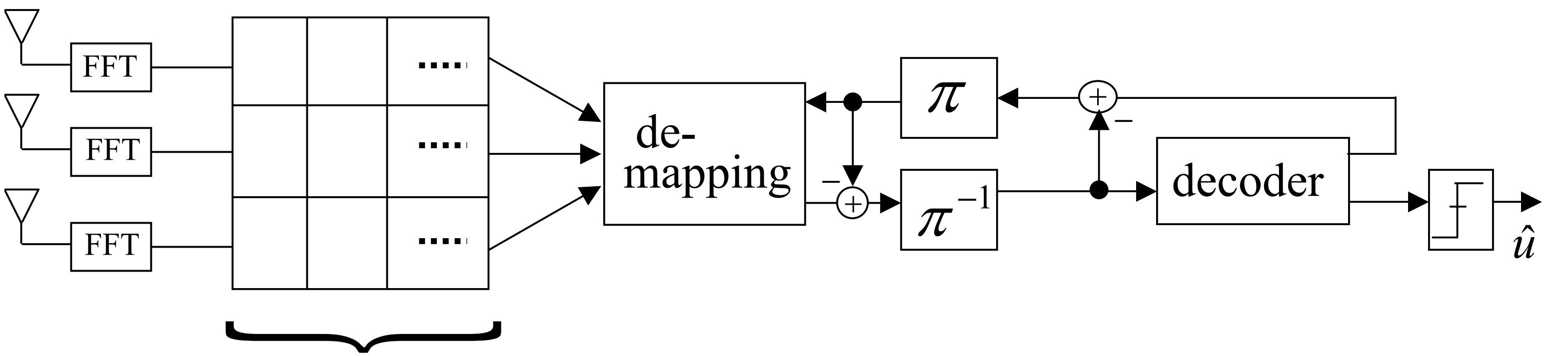
π spans this Tx array containing 64x3 modulation symbols (or 64x3x*m* coded bits, where *m* is the number of coded bits per modulation symbol).

With 1 Tx antenna, the architecture coincides with that of .11a.

Interleaver gain in iterative demapping/decoding (IDD) is smaller here than the case where the interleaver spans the whole packet, but latency and storage requirements are reduced.

BICM+Spatial Multiplexing: Receiver

3 Rx antenna example



one (parallel) OFDM symbol period

Note the baseband latency target of ~10 us (< SIFS=16 us), a serious ASIC implementation challenge.

BB latency: time that takes for the end of Rx packet that's passing ADC to reach PHY/MAC interface

SIFS: time between the end of Rx packet reaching Rx antenna and the start of ACK packet reaching Tx antenna

Suboptimal Soft-demapper with SDF

3 Tx & 3 Rx antenna example

$$\mathbf{r}' = \begin{bmatrix} H'_{11} & H'_{21} & H'_{31} \\ H'_{12} & H'_{22} & H'_{32} \\ H'_{13} & H'_{23} & H'_{33} \end{bmatrix} \mathbf{a} + \mathbf{n}' \xrightarrow{\text{QR decomposition}} \mathbf{r} = \begin{bmatrix} 1 & 0 & 0 \\ H_{12} & 1 & 0 \\ H_{13} & H_{23} & 1 \end{bmatrix} \mathbf{a} + \mathbf{n}$$

$\mathbf{a}$: modulation symbol

$\mathbf{r}'$: FFT output

$$r_1 = a_1 + n_1$$
$$r_2 = a_2 + H_{12}a_1 + n_2$$
$$r_3 = a_3 + H_{23}a_2 + H_{13}a_1 + n_3$$

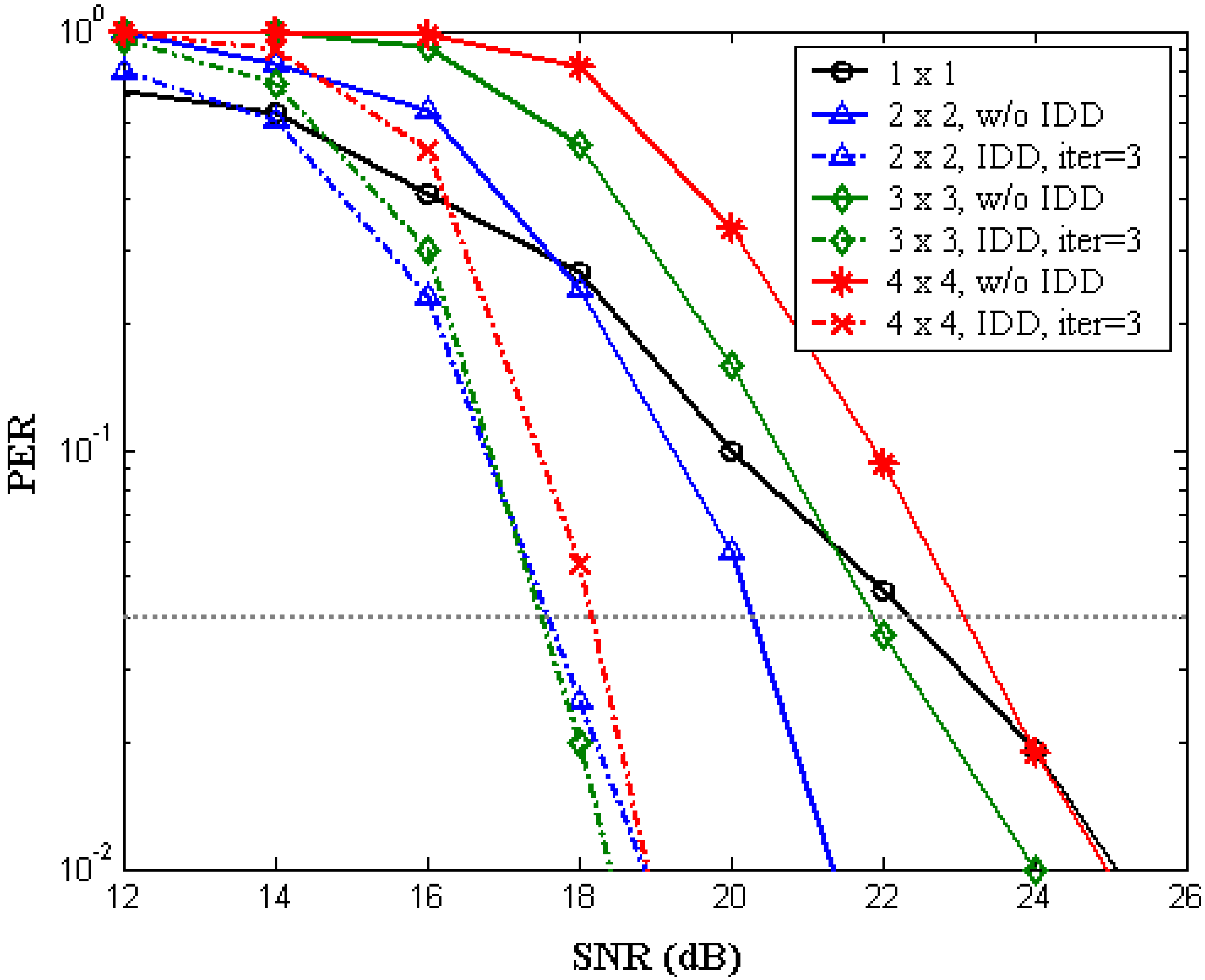
Algorithm:

Truncated-depth MAP with soft decision feedback (SDF)

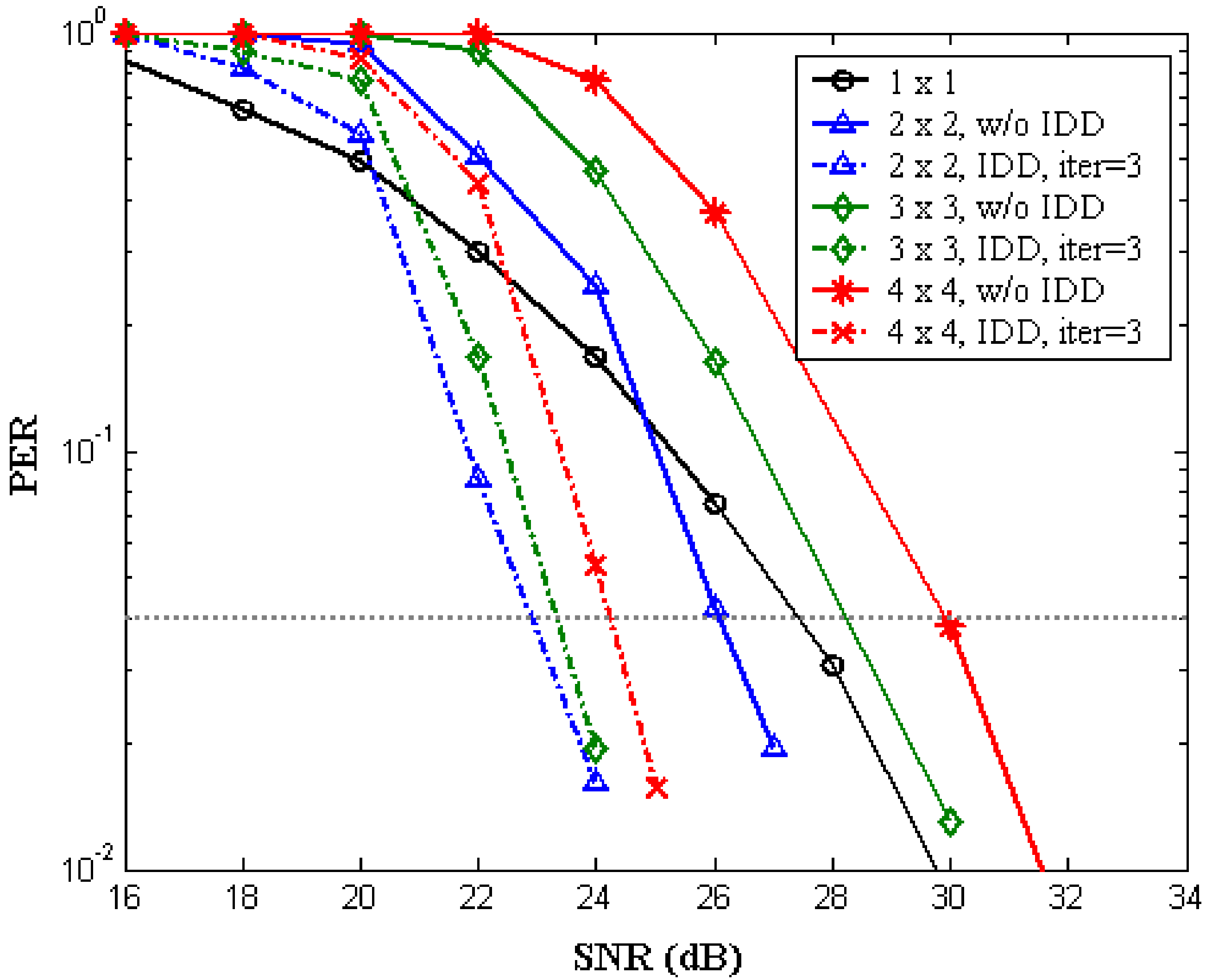
Simulation Conditions

- Convolutional code, punctured from (133, 171)
- Random or 11a-like structured interleaver, spanning one (parallel) OFDM symbol transmission period
- Gray mapping
- 64-pt FFT, 20 MHz channelization
- 512 byte packet
- Channel: quasi static fading, exponentially decaying power profile with 50 ns rms delay spread, uncorrelated channel coefficients
- Soft demapping, BCJR decoding, iteration of soft decisions between demapper and decoder (IDD)
- SNR defined as the overall Tx energy (distributed to all Tx antennas) to noise ratio

BICM+Spatial Mux: ¾ CC, 16QAM, $(\tau = 1)$ MAP+SDF demapping

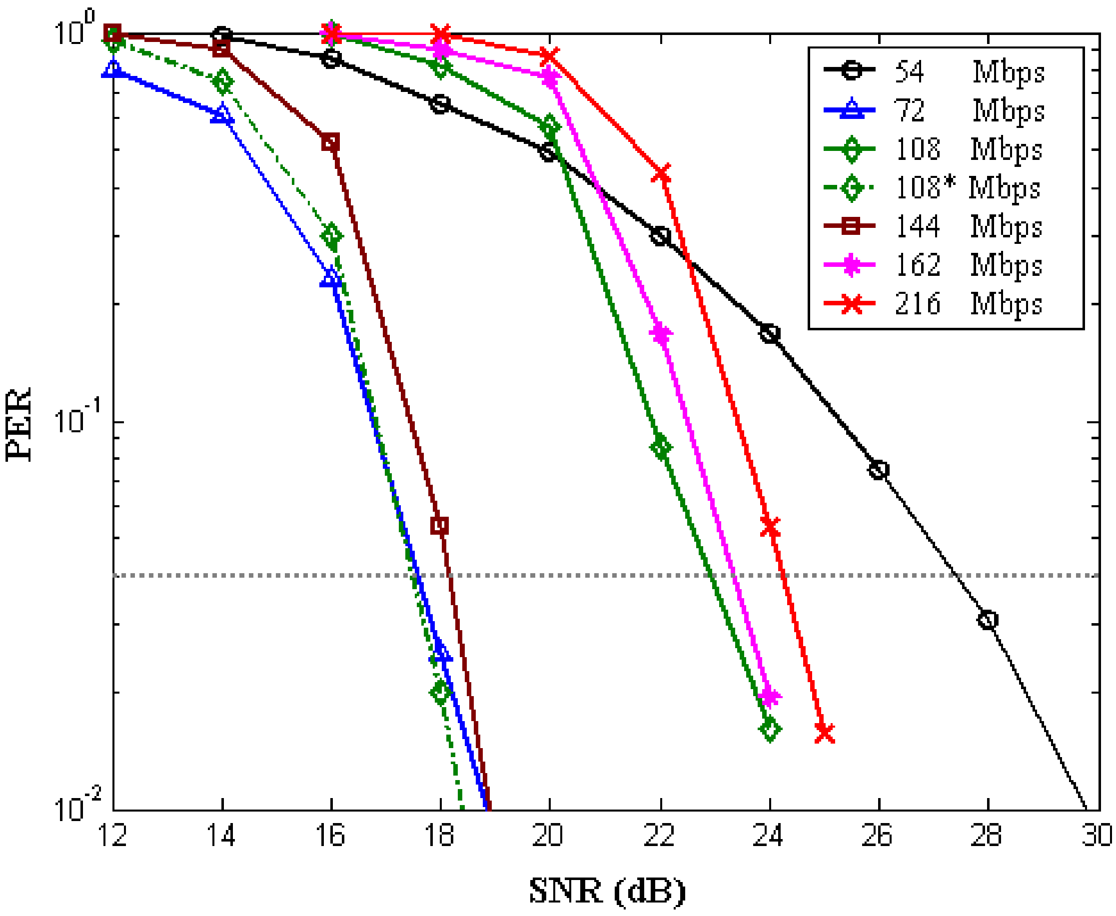


BICM+Spatial Mux: ¾ CC, 64QAM, $(\tau = 1)$ MAP+SDF demapping



BICM+Spatial Mux: ¾ CC, 16/64QAM, $(\tau = 1)$ MAP+SDF demapping

IDD with 3 iterations in all MIMO cases



Ant.	16QAM 3/4 CC	64QAM 3/4 CC
1 x 1	36	54
2 x 2	72	108
3 x 3	108*	162
4 x 4	144	216

Possible High Data Rates

Table 80—Contents of the SIGNAL field

Rate (Mbits/s)	R1–R4
6	1101
9	1111
12	0101
18	0111
24	1001
36	1011
48	0001
54	0011

802.11a data rates

Tx-Rx antenna	**16QAM, 3/4 CC**	**64QAM, 3/4 CC**
1 x 1	36	54
2 x 2	**72**	**108**
3 x 3	**108***	**162**
4 x 4	**144**	**216**

6 possible .11n data rates (Mbps)

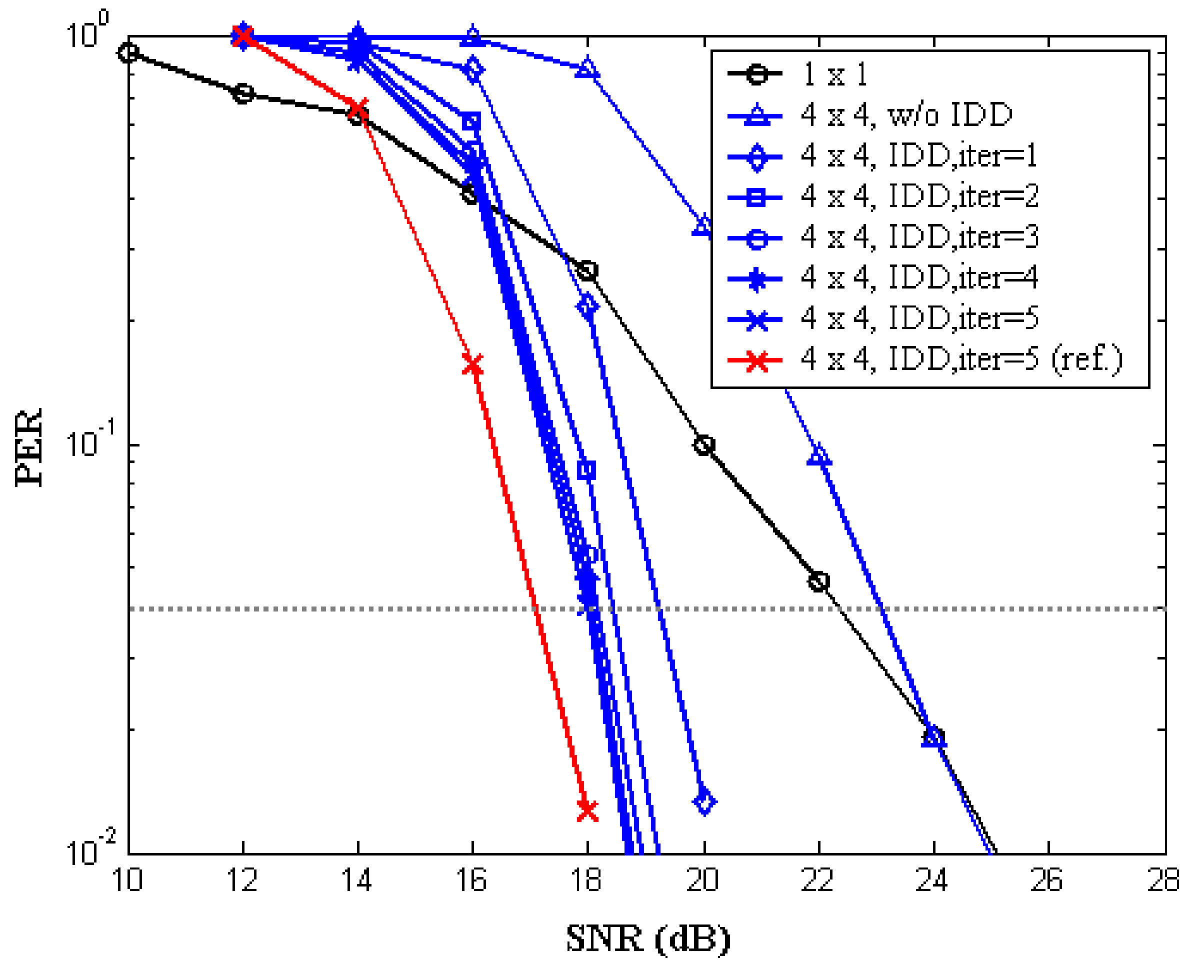
Rate information can implicitly specify the number of Tx antennas.

Other Possible High Data Rates

Tx-Rx antenna	**16QAM, 1/2 CC**	**64QAM, 2/3 CC**
1 x 1	24	48
2 x 2	48	**96**
3 x 3	**72**	**144**
4 x 4	**96**	**192**

How many iterations are needed?

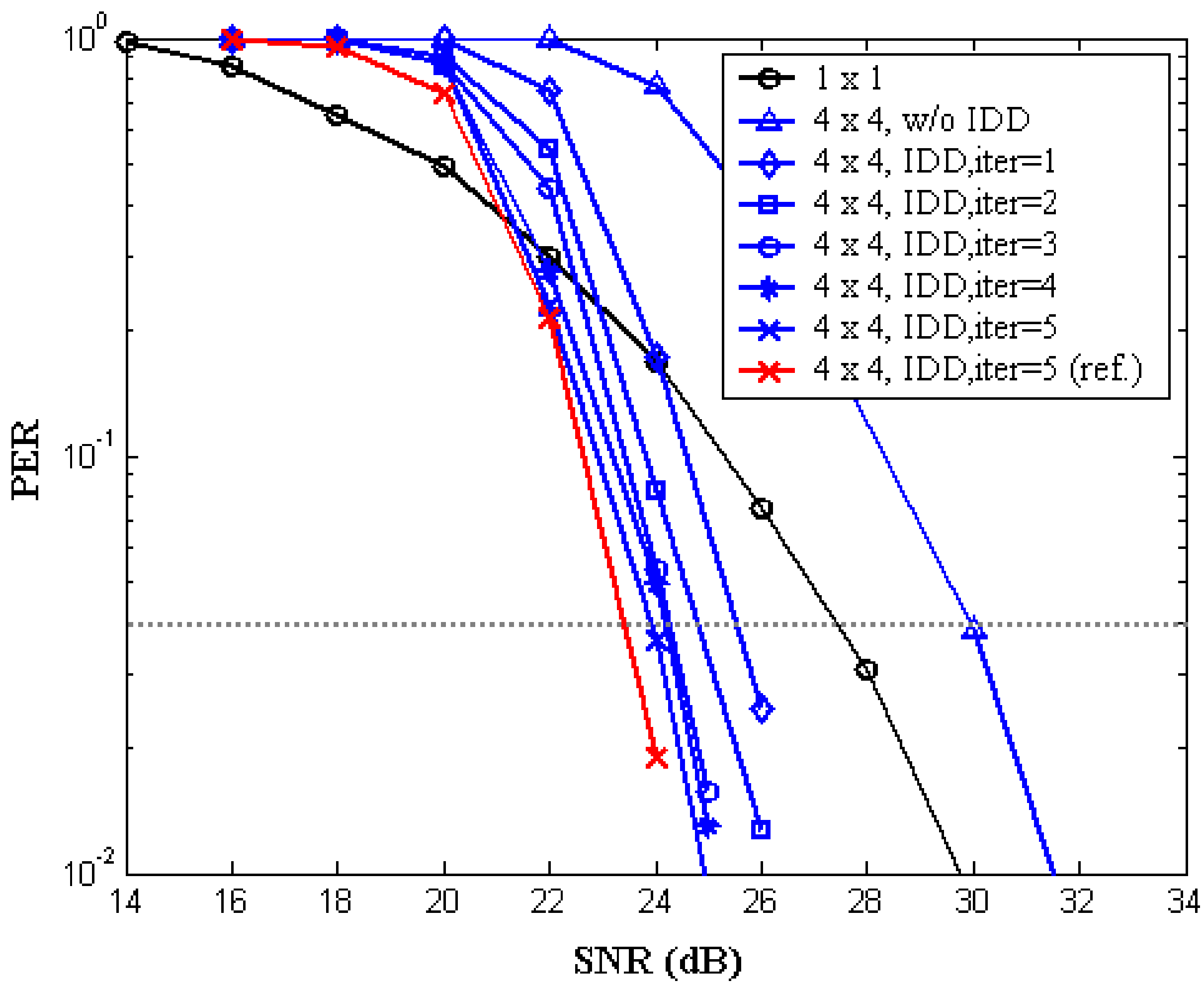
BICM+Spatial Mux: ¾ CC, 16QAM, $(\tau = 1)$ MAP+SDF demapping



Ref. curve:
coding & interleaving
over whole packet

How many iterations are needed?

BICM+Spatial Mux: ¾ CC, 64QAM, $(\tau = 1)$ MAP+SDF demapping



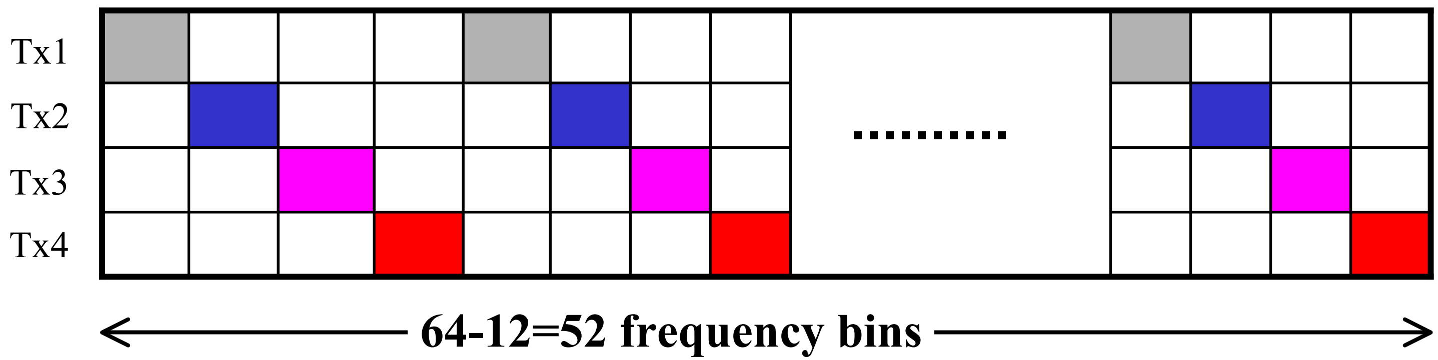
Ref. curve:
coding & interleaving
over whole packet

Observations

- 4x4 BICM+SM with suboptimal MAP+SDF enables 200+Mbps.
  - Achieves target PERs at SNRs lower than that required for 802.11a 54 Mbps data rate (1x1)
  - Suboptimal finite depth MAP with SDF
  - 3 IDD iterations used with bit-level interleaver spanning one Tx array (N_t parallel OFDM symbols) rather then whole packet
  - Even 1 iteration provides substantial gain
- Once IDD is employed, the off-the-shelf CC performs comparable to turbo/LDPC codes.
- Simulation results may be somewhat optimistic in that channel coefficients are uncorrelated, but validate BICM+SM for high data rate application.

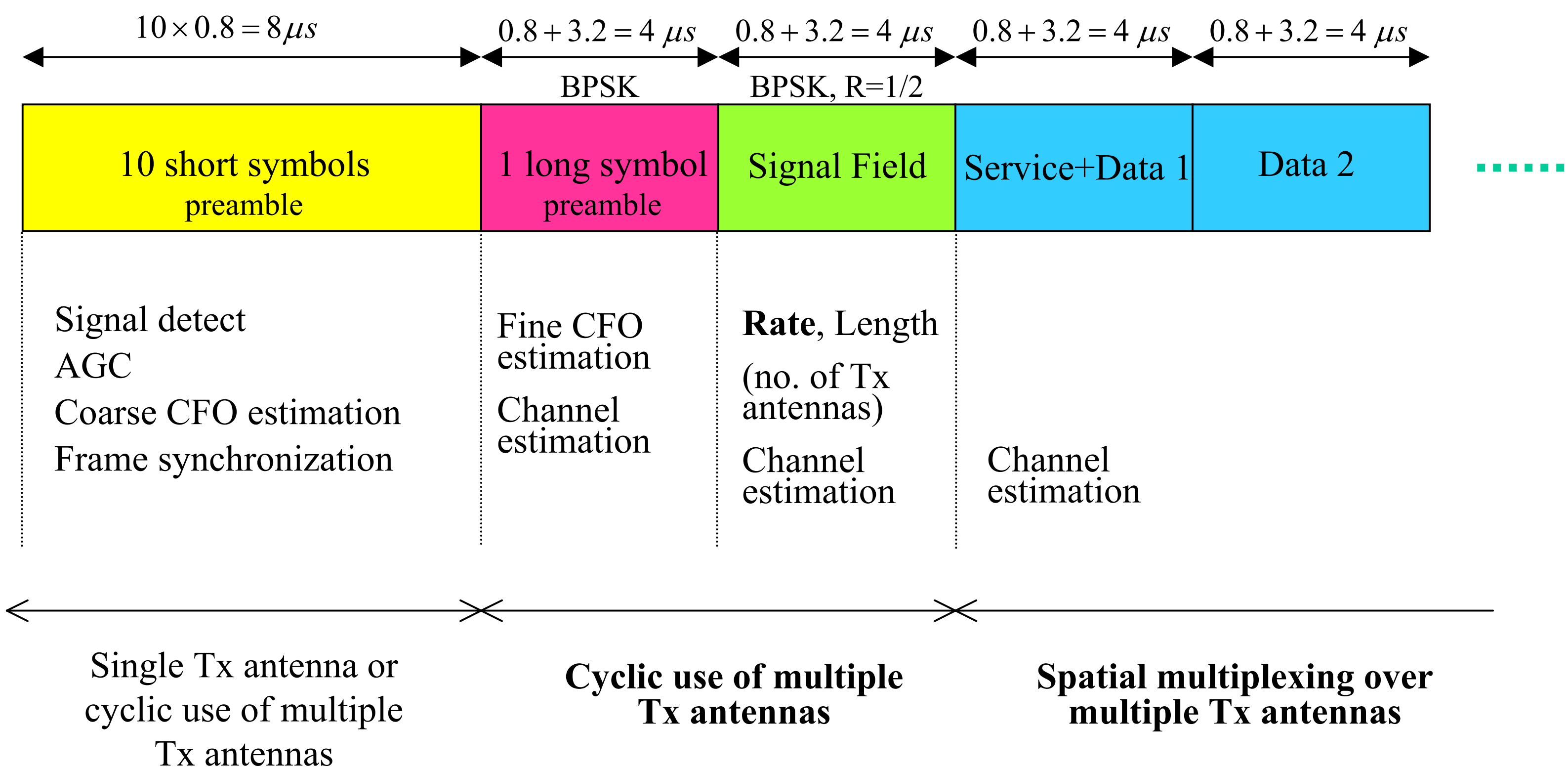
Preamble Structure, Channel Estimation and CFO Correction

Training Symbol Structure (for channel/CFO estimation)



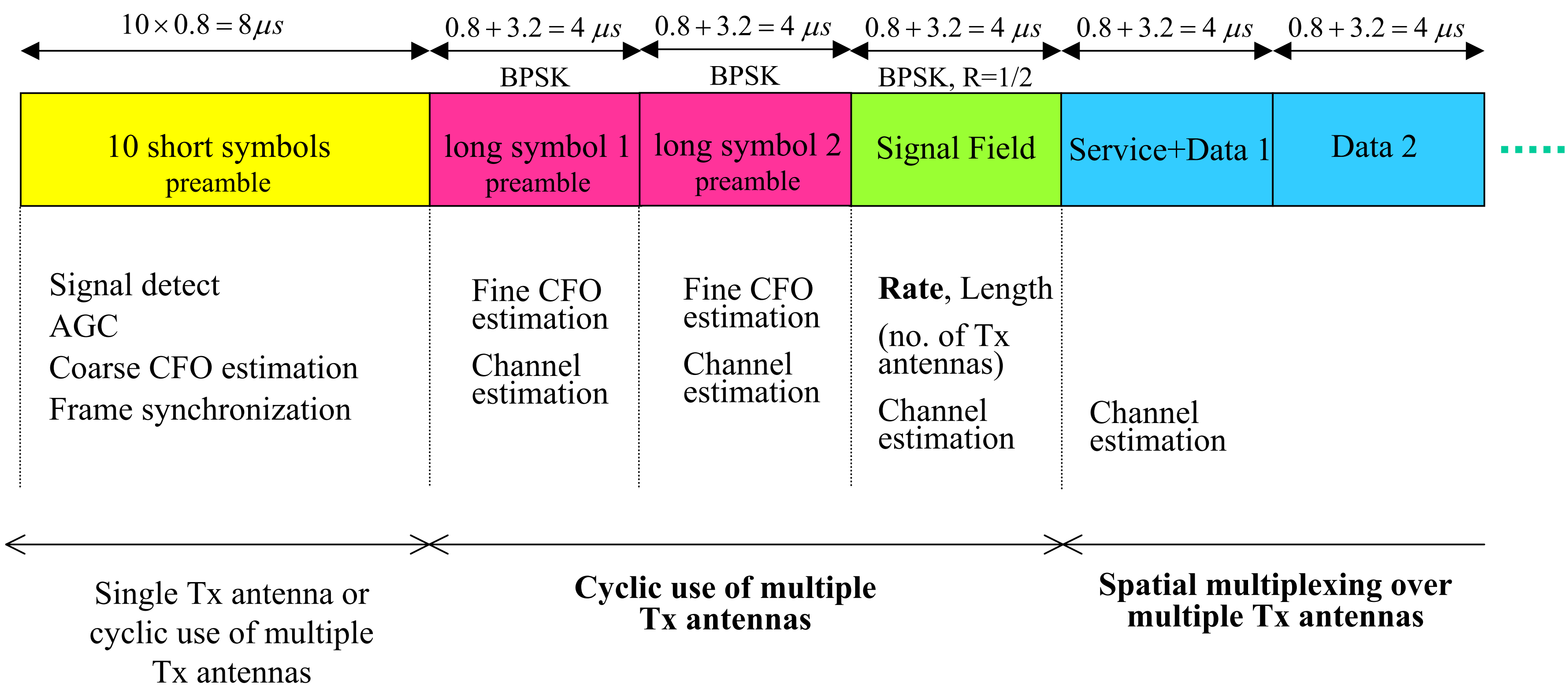
- Both the training sequence (one or two OFDM symbols) and signal field (one OFDM symbol) are transmitted in cyclic fashion. The signal field symbol is also BPSK based and enjoys high SNR, and thus can be used for channel estimation purposes.
- Fine CFO estimation can be done within one training symbol w/o CSI.
- For each transmitted modulation symbol, the receiver can estimate Nr channel coefficients. After transmission of one OFDM symbol or 52 modulation symbols, the receiver estimates 52 x Nr = 208 channel coefficients, enough for channel characterization of Nt x Nr x 13 =16 x 13 = 208 coefficients or 13 temporal taps/channel.
- Note *the receiver does not need to know the number of Tx antennas* for initial CFO/channel coefficient characterization based on training sequence and signal field.

Preamble Structure: Option 1



- Cuts down the preamble length by 4 us
- Backward compatibility with .11a relies on protection mechanism

Preamble Structure: Option 2



• Backward compatibility with .11a maintained automatically

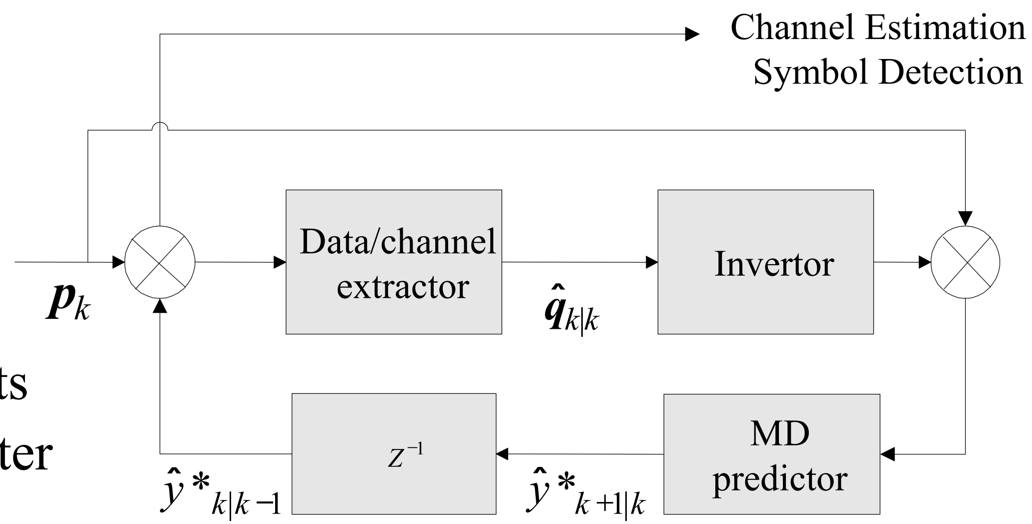
Recursive LMMSE CFO Correction

Principle

- Operates on the time-domain received samples before FFT.
- Sequentially and alternately estimates data/channel info and the phase/frequency distortion term.

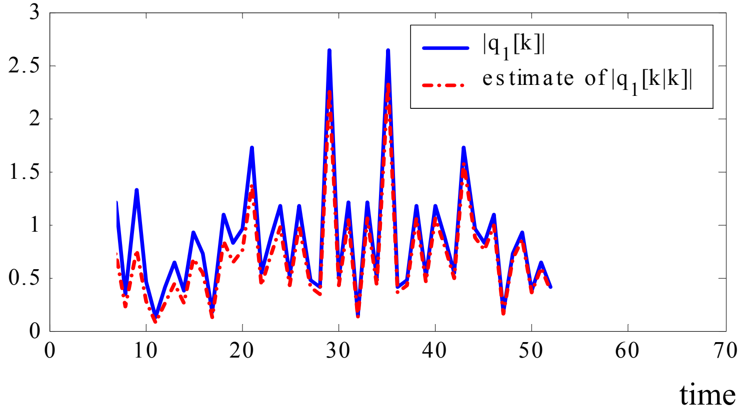
features

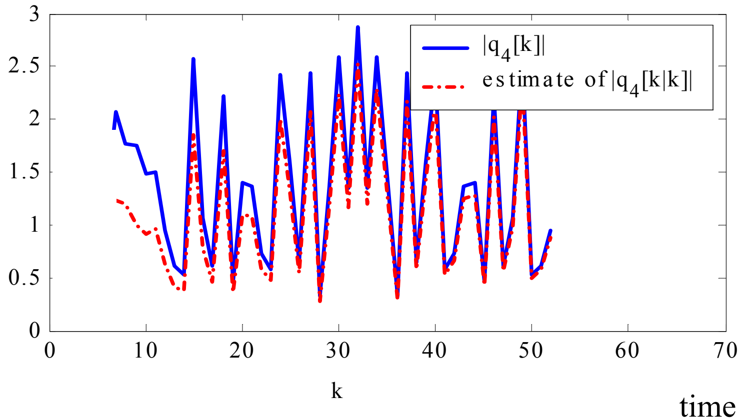
- Low complexity
- Virtually no extra latency
- Track phase/frequency drifts
- Reduce phase/frequency jitter



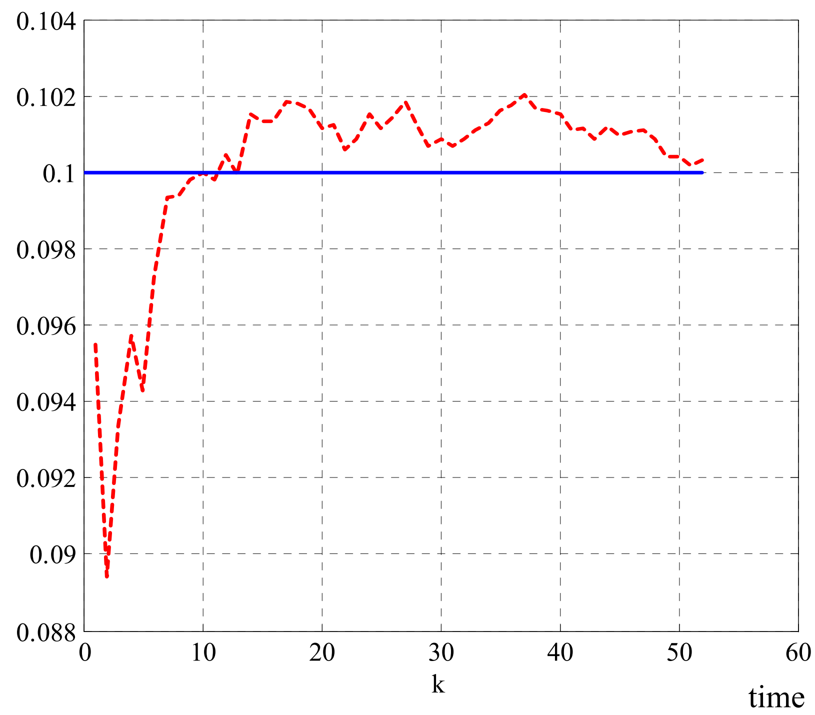
Estimated versus Actual CFO

Tracking symbol/channel information during acquisition





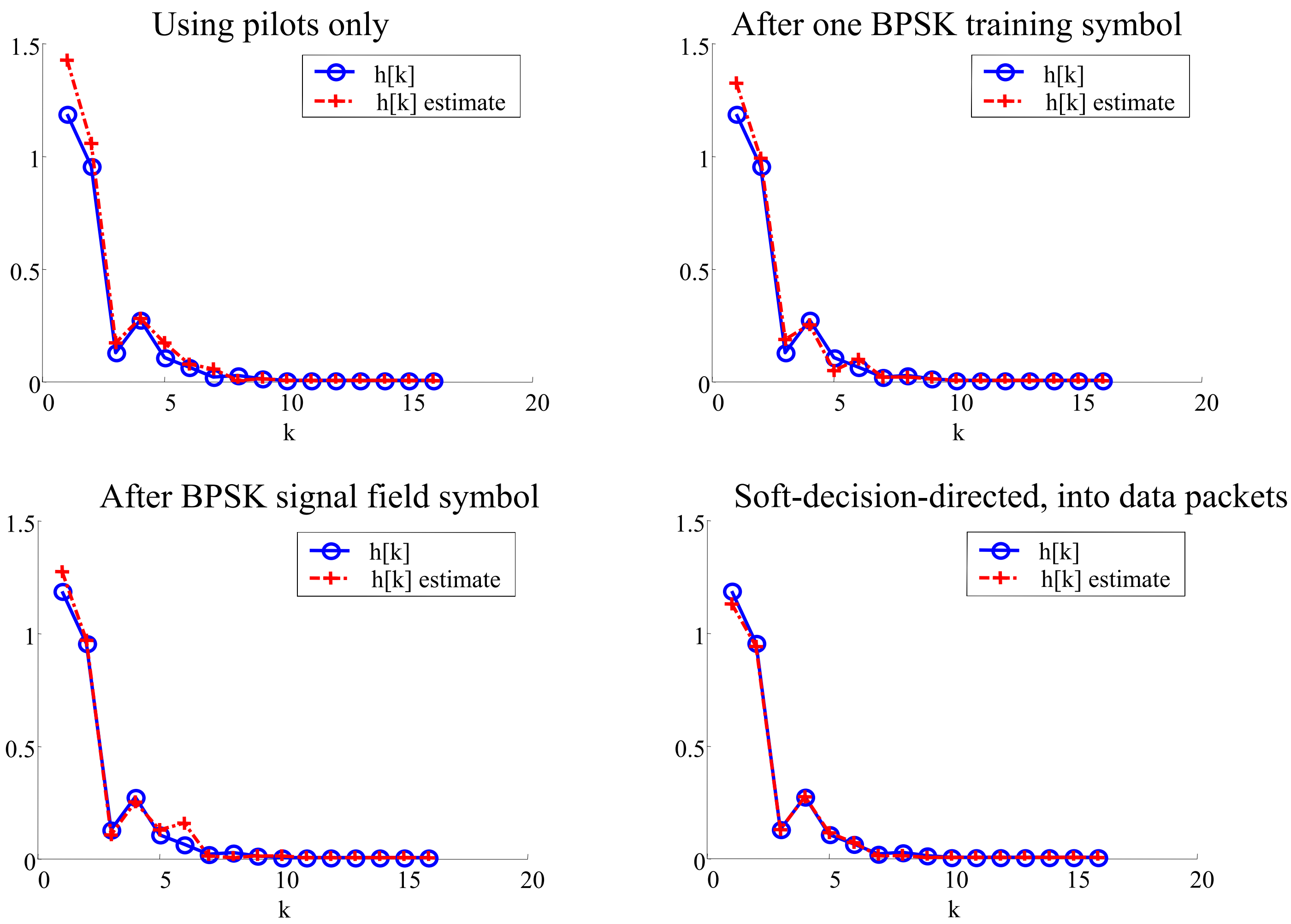
CFO estimate during acquisition with actual CFO=0.1



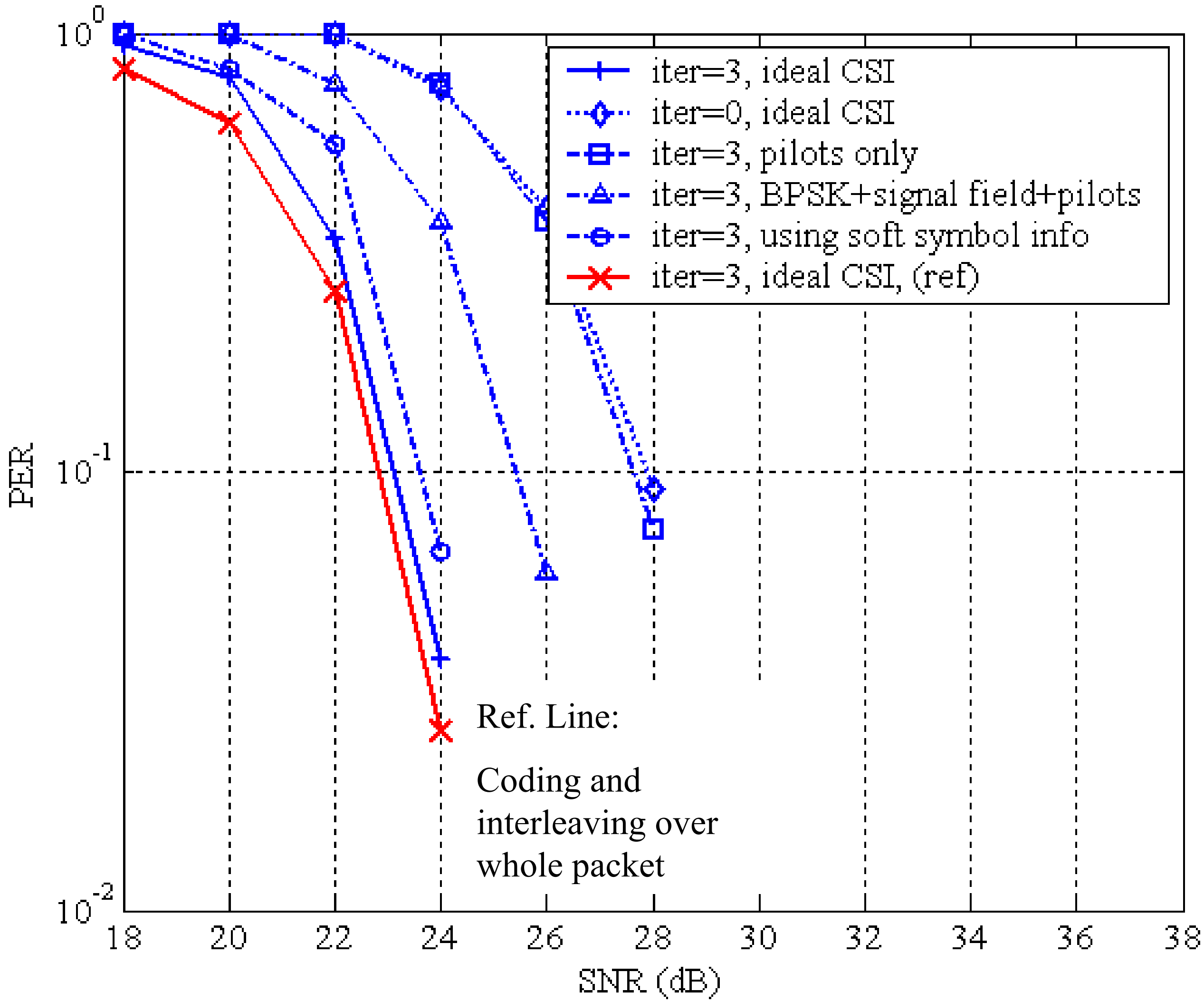
Channel Estimation

- Estimate channel's frequency response using all available resources as needed to achieve performance/complexity/latency tradeoff:
  - Pilot tones within each OFDM symbol
  - One or two BPSK training symbols (for initial estimates) – cyclic transmission
  - One BPSK signal field – cyclic transmission
  - Soft symbol info from the previous iteration (channel estimation revised to utilize soft information)

Estimated versus Real Channel Response



4x4 64QAM, SDF with τ=1 MAP, with channel estimation



Observations 2

- CFO can be estimated within one OFDM training symbol.
- Channel estimation can be done with the combination of initial training symbol(s), the use of the signal field symbol, and soft-decision-directed updates during the data portion of the packet.
  - The long training symbol(s) and the signal field symbol are transmitted in cyclic fashion to provide initial channel estimates for multiple parallel channels.
- Channel response drifts can also be handled with the proposed method.
- The long symbol preamble of 11a (8 us) can be reduced to 4 us.
- The .11a preamble format can be retained, allowing automatic guarantee of backward compatibility

Conclusions

- Practical MIMO architecture that is a natural extension of .11a has been proposed.
  - Conceptually simple and straightforward generalization of .11a to incorporate spatial dimension
  - Capable of 10+ bps/Hz (200+ Mbps/20 MHz) while offering range improvement*
  - Can retain the same preamble format as .11a, thus automatically guaranteeing backward compatibility
  - Allows straightforward ASIC implementation (no serious latency/complexity challenges)

* With 4x4 antenna configuration and uncorrelated channel coefficients; relative to 54 Mbps .11a mode