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MIMO-OFDM Wireless Communications

S-72.4210 Post-Graduate Course
in Radio Communications

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Outline

1. Introduction
2. MIMO and OFDM principles
3. MIMO-OFDM systems
4. Space time techniques
5. Adaptive modulation and coding
6. ICI and PAPR
7. Example of adaptive loading capacity in MIMO-OFDM
8. Summary
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Introduction

- The demand of wireless communications is constantly growing
- Future wireless systems will require a much more efficient use of the available frequency resources
- MIMO is known to boost channel capacity
- For high-data rate transmissions, the MIMO channel is frequency selective (multipath)
- OFDM can transform such channel into a set of parallel frequency-flat channels (reduce Rx complexity)
- Attractive combination of these two powerful techniques

MIMO Systems

- Equipped with multiple antennas at Tx and Rx
- Take advantage of the spatial diversity obtained by spatially separated antennas in a dense multipath scattering environment
- Allows to apply signal processing techniques in transmission and reception to:
    - Enhance the quality of the communication (diversity)
    - Increase the throughput of the system (multiplexing)
- Provide better performance without additional radio spectrum requirements (scarce and expensive resource)

Origins of MIMO

- Before 1990's, antenna arrays were used to provide diversity and/or direct the signal reception to mitigate co-channel interference
- This motivated the development of following techniques:
  - Beamforming: Focus electromagnetic energy in desired directions
  - Spatial diversity: Combination of signals in an antenna array, equipped with low correlation elements
- A single data stream is transmitted, and multiple antennas are used to decrease the variance of the received signal (i.e., improve the quality of the radio link)

Origins of MIMO

- In the mid 1990's, it has been observed that the use of multiple receive antennas allows to separate out the signals from the different transmit antennas
- In this case, multiple transceiver antennas are used for parallel multiplexing (i.e., transmit several data streams simultaneously to increase peak data rates)
- This concept is much more impressive than diversity in terms of channel capacity, because with parallel multiplexing, the capacity increases linearly with the minimum number of transmit and receive antennas
- This holds provided that the scattering environment is rich enough to allow the separation of transmission signals in Rx

OFDM Concepts

- Popular technique for transmission of signals over wireless channels
- OFDM has been adopted in several wireless standards, such as DAB, DVB-T, IEEE 802.11a (LAN) and IEEE 802.16a (LAN/MAN)
- Converts a frequency-selective channel into a parallel collection of frequency-flat subchannels
- Subcarriers have minimum frequency separation required to maintain orthogonally of their time domain waveforms

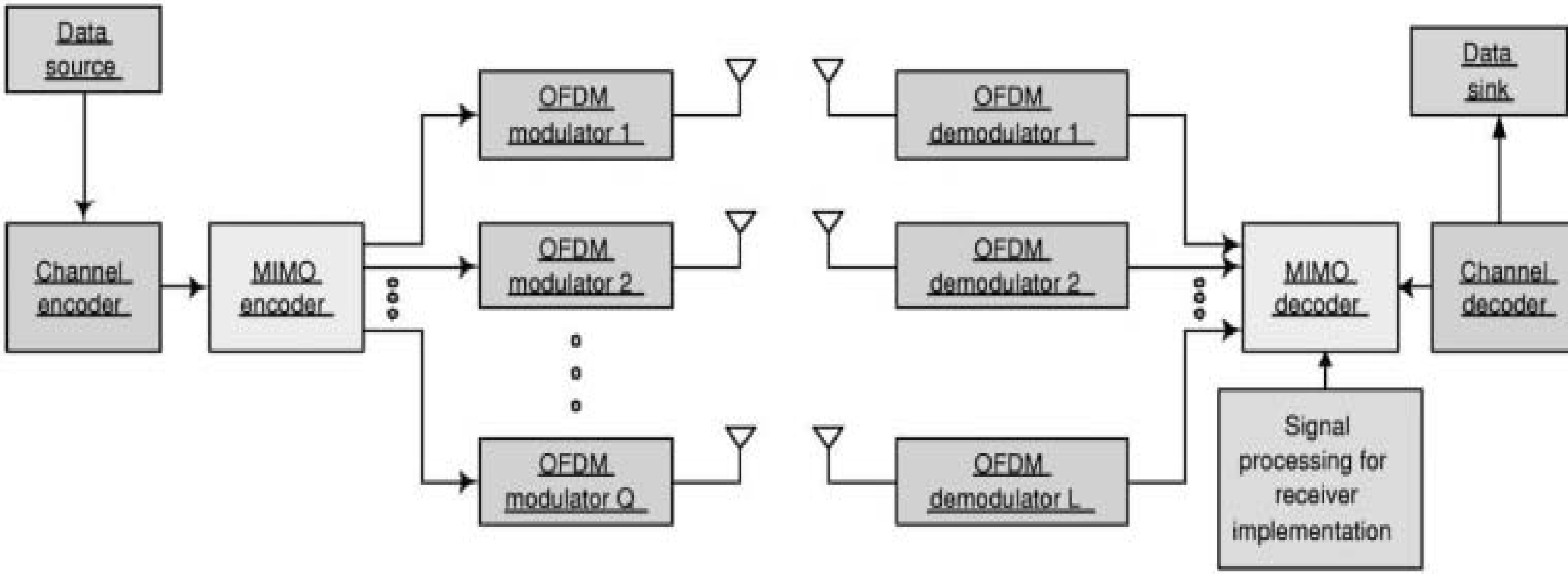
OFDM Concepts

- Signal spectra of the different subcarriers overlap in frequency (efficient use of available bandwidth)
- The Tx can adapt its signaling to match the channel if knowledge of channel condition is available at Tx
- Adaptive strategies in OFDM can approach waterpouring capacity of frequency-selective channels (large collection of narrowly spaced subchannels)
- In practice this is achieved by using adaptive bit loading techniques (different sized constellations per subcarrier)

OFDM Concepts

- A block of N information symbols is transmitted in parallel on N subcarriers
- Time duration of an OFDM symbol is N times larger than that that would correspond to a single-carrier system
- OFDM modulator can be implemented as an inverse fast Fourier transform (IFFT) followed by an DAC
- Each block of N IFFT coefficients is preceded by a cyclic prefix (CP) to mitigate ISI caused by channel time spread
- The receiver can use fast signaling processing transforms such as FFT for OFDM implementations

MIMO-OFDM System



MIMO-OFDM Tx MIMO-OFDM Rx

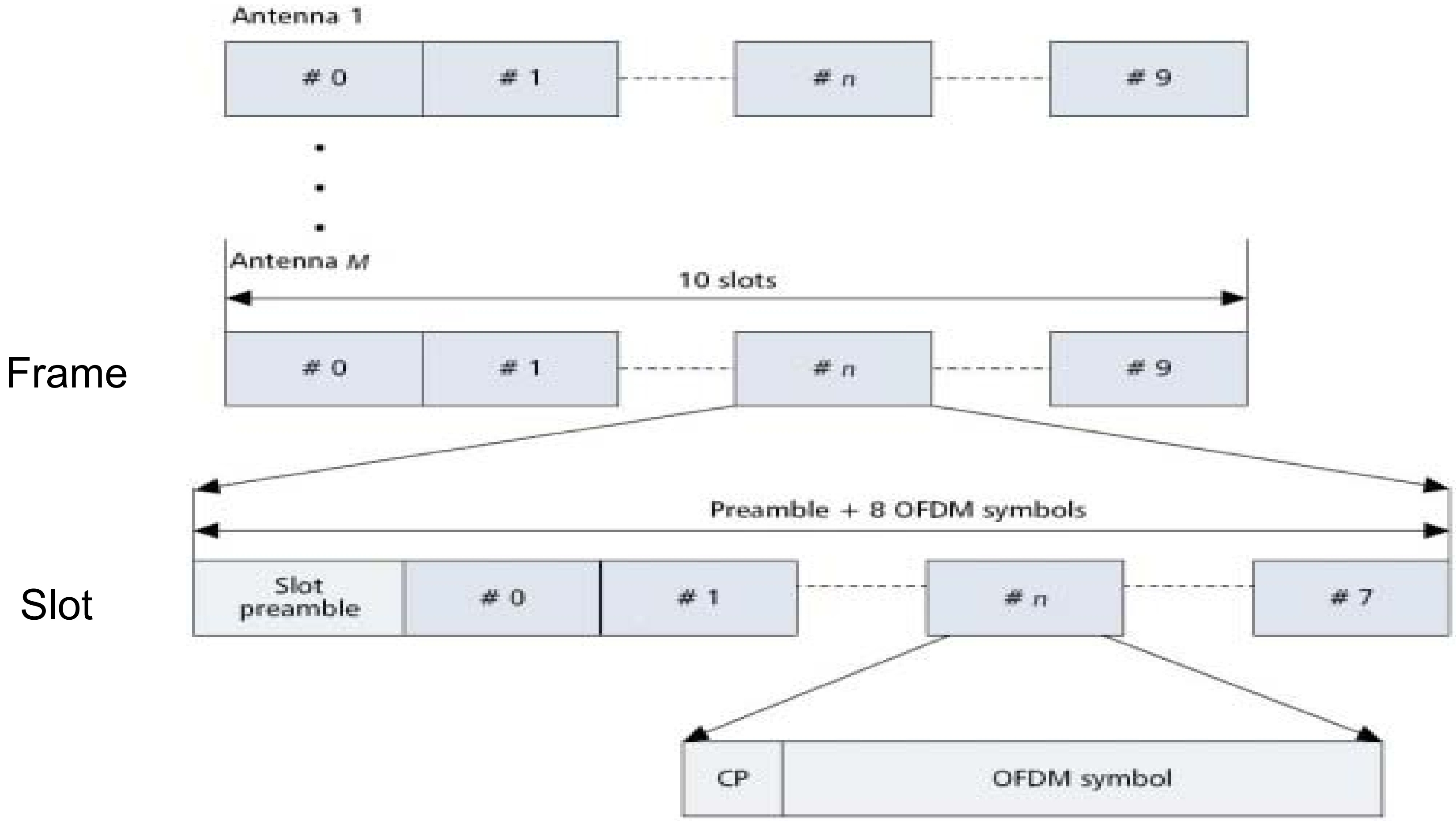
MIMO-OFDM Tx

- Source bitstream encoded by FEC encoder
- Coded bitstream mapped to a constellation by digital modulator, and encoded by MIMO encoder
- Each of parallel output symbol stream corresponding to a certain Tx antenna follows the same Tx process:
    - Insertion of pilot symbols (synchronization)
    - Modulation by inverse FFT
    - Attachment of CP and Preamble
- Finally, data frame is transferred to IF/RF stage for Tx

MIMO-OFDM Rx

- The received symbol stream from different Rx antennas are fist synchronized
- Preambles and CPs are extracted from Rx symbol stream
- Remaining OFDM symbols demodulated by FFT
- Frequency pilots are extracted from the demodulated OFDM symbols, and are used for channel estimation
- Estimated channel matrix aids the MIMO decoder
- Estimated Tx symbols are demodulated and decoded

MIMO-OFDM Frame Structure



MIMO-OFDM Frame Structure

- In the time domain, a frame is a minimum transmission unit that includes 10 slots
- Each slot consists of 1 slot preamble and 8 OFDM symbols
- The preamble is used for time synchronization
- Each OFDM symbol in a slot is attached to a CP that is used to reduce ISI and simplify channel equalizer
- The frame is structured such that data and pilot symbols are transmitted over subcarriers (timing phase, timing frequency, and frequency offset estimation)

Space-Time Techniques

- Current space-time processing techniques for MIMO typically fall into two categories:
    - Data-rate maximization (spatial multiplexing)
    - Diversity maximization (space-time coding)

Spatial Multiplexing (SM)

- Multiplexes multiple spatial channels to send as many independent data as possible over different antennas
- There are four spatial multiplexing schemes: diagonal BLAST, horizontal BLAST, V-BLAST and turbo BLAST
- The method to estimate Tx signals has three steps:
  - Estimate the channel matrix (training sequence)
  - Determine optimal detecting order and nulling vectors
  - Detect the received signals based on optimal detecting order and successive interference cancellation

Space-Time Coding (STC)

- Jointly encodes the data streams over antennas, and therefore aims to maximize diversity gain
- There are two main space-time coding schemes:
  - STTC obtains coding and diversity gain due to coding in ST dimension (decoding complexity increases with modulation constellation, state number, code length)
  - STBC is based on orthogonal design and obtains full diversity gain with low decoding complexity (Alamouti code is a special case with double Tx antennas)

Comparison of STC and SM

MIMO candidates	STBC	Spatial multiplexing
Data rate	U → High S → Low	S → High U → Low
Diversity gain	S	U
Spatial correlated channel	S	S → Low U → High
Channel estimation	Insensitive	Insensitive → Low Sensitive → High
LOS	S	U
Antenna configuration	S → 2 Tx	S → Tx ≥ Rx
S: Suitable U: Unsuitable		

Iterative Decoding

- Channel coding undoubtedly plays in important role in digital communications systems
- MIMO-OFDM system decoders will work at low SNR
- Two kinds of codes are promising candidates for FEC:
  - Turbo Code: Use parallel concatenation of at least two codes with an interleaver between component encoders. Decoding is based on alternately decoding the component codes and passing extrinsic information to next decoding stage (Shannon Bound @ BER 10^{-5})
  - Low Density Parity Check (LDPC): Linear block code whose parity check matrix is composed of 0 elements dominantly. LDPC code shows good error correction capacity with soft iterative decoding by the sum-product algorithm or belief propagation (BP) algorithm

Adaptive Modulation and Coding (AMC)

- Time-varying wireless channel conditions implies a time-varying system capacity
- The principle of AMC is to change the modulation and coding format in accordance with instantaneous fluctuations of channel conditions
- Channel conditions should be estimated based on feedback from the receiver
- The implementation of AMC offers several challenges:
  - Errors in channel measurements
  - Delay in reporting the channel measurements

Intercarrier Interference Cancellation

- The frequency offset caused by oscillator inaccuracies or Doppler shift results in ICI that degrade BER performance
- Although frequency synchronization is used, the residential frequency offset causes a number of impairments:
    - Attenuation and rotation of each of the subcarriers
    - ICI between subcarriers
- ICI mitigation is needed to increase the achievable data rates over the wireless medium

Peak-to-average Power Ratio (PAPR)

- The main limitation of OFDM-based transmission systems is the high PAPR of the transmitted signal
- Large peaks will occasionally reach the amplifier saturation region and result in signal distortion
- Several PAPR reduction schemes have been proposed and investigated:
    - Partial transmit sequence (PTS) scheme: efficient and distortionless scheme by optimally combining signal subblocks
    - Selective mapping (SLM): some statistically independent sequences are generated from the same information, and the sequence with the lowest PAPR is transmitted

Adaptive Loading Example

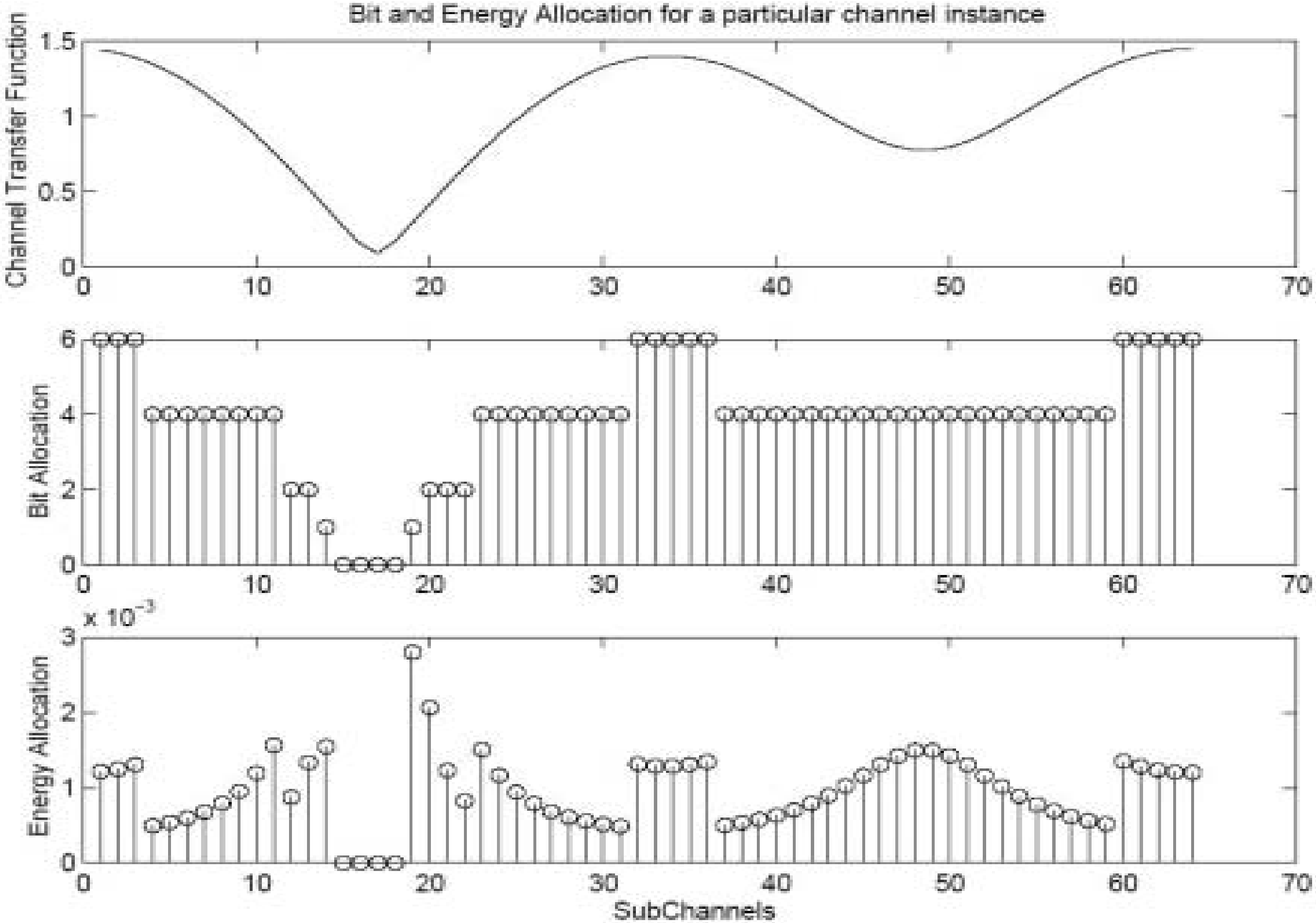
- MIMO system with M Tx antennas and N Rx antennas
- For each tone, the MIMO channel response can be represented by a matrix of size M×N with elements $h_{m,n}$
- Assuming perfect CSI at Tx & Rx, we can discompose the MIMO channel into non-interfering SISO channels (SVD).

$$\mathbf{H}i = \mathbf{U}i\ \mathbf{S}i\ \mathbf{V}i$$

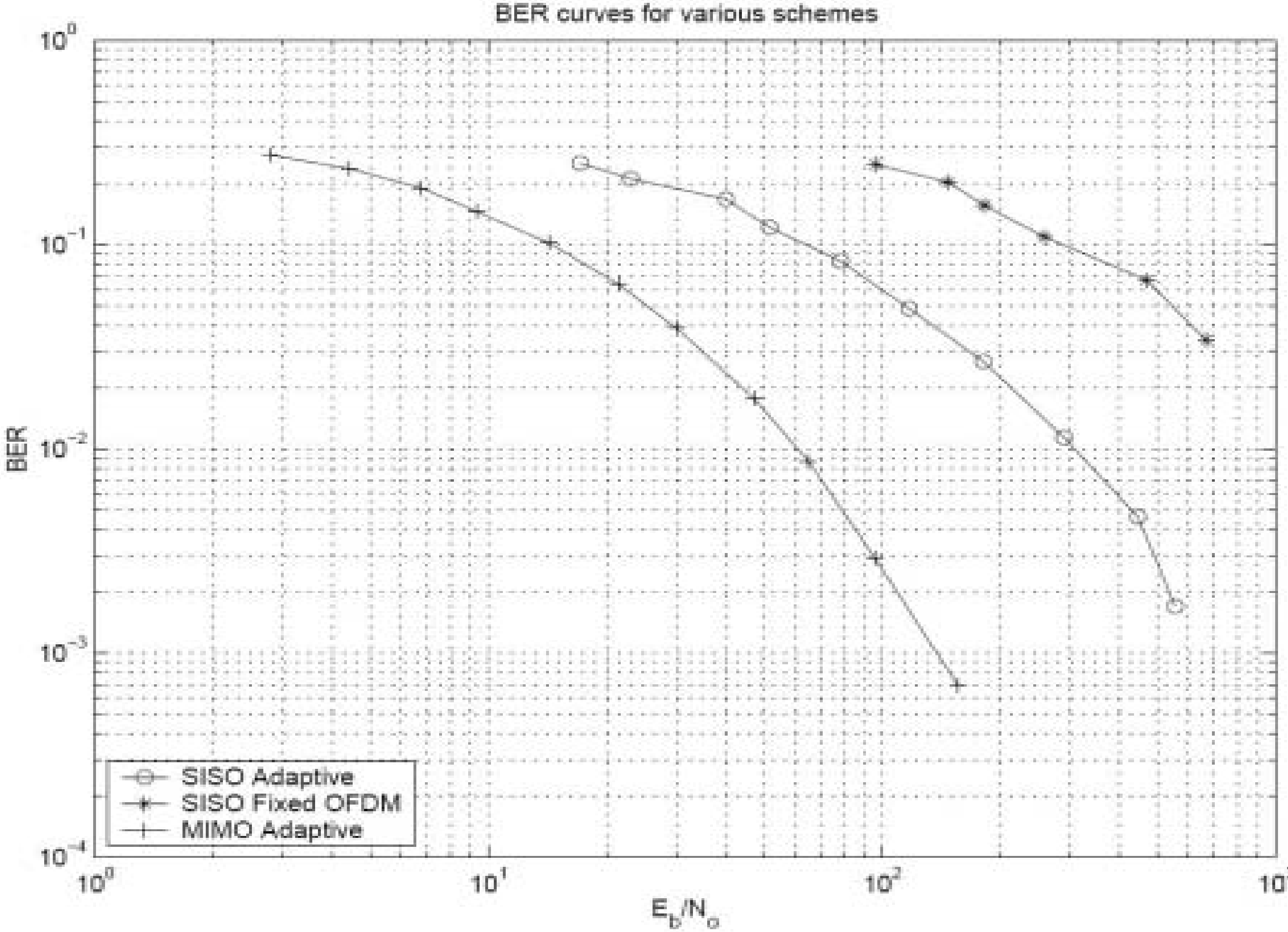
Ui and **V**i are unitary matrices, and **S**i is a diagonal matrix of singular values of **H**i

- Simulation parameters:
  - Number of subcarriers: 64
  - QAM constellations: 0, 1, 2, 4, 6, 8 bits per subcarrier

Energy and Bit Allocation



BER Performance



Summary

- MIMO-OFDM key techniques have been introduced:
  - Frame structure.
  - Comparison of STC and SM
  - Iterative decoding
  - Adaptive modulation and coding
  - Intercarrier interference cancellation
  - Peak-to-average power ratio
- The high bandwidth efficiency obtained shows that MIMO-OFDM is a potential candidate for future broadband wireless access

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Homework

1. What is a MIMO system? Why are they so important in the development of future wireless standards?
2. Why is the combination of MIMO and OFDM techniques so attractive?