Wireless Communication Systems: Orthogonal or Non-orthogonal?

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Reference

Peng Wang, Jun Xio and Li Ping, “Comparison of Orthogonal and Non-Orthogonal Approaches to Future Wireless Cellular Systems” to appear in *IEEE Vehicular Technology Magazine*.

Will be available at

http://www.ee.cityu.edu.hk/~liping

Contents

- Overview
- Power Efficiency
- Multi-User Gain (MUG)
- Practical Systems
- Conclusions

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Historical View

1G | 2G | 3G | 4G

AMPS TACS GSM IS-95 WCDMA CDMA-2000

orthogonal

non-orthogonal

orthognal?
non-orthognal?
hybrid?

Options

- Orthogonal approaches
  - FDMA
  - TDMA
  - OFDMA
  - Orthogonal CDAM
- Non-orthogonal approaches
  - Random CDMA
  - Interleave-Division multiple access (IDMA)
- Hybrid approaches
  - OFDM-CDMA
  - OFDM-IDMA

Applications

- Delay-insensitive services: e.g., email
  - No rate constraints for each user;
  - Orthogonal schemes are advantageous;

- Delay-sensitive services: e.g., speech and video
  - Rate constraints for each user
  - Non-orthogonal schemes are advantageous;

An Overall Comparison

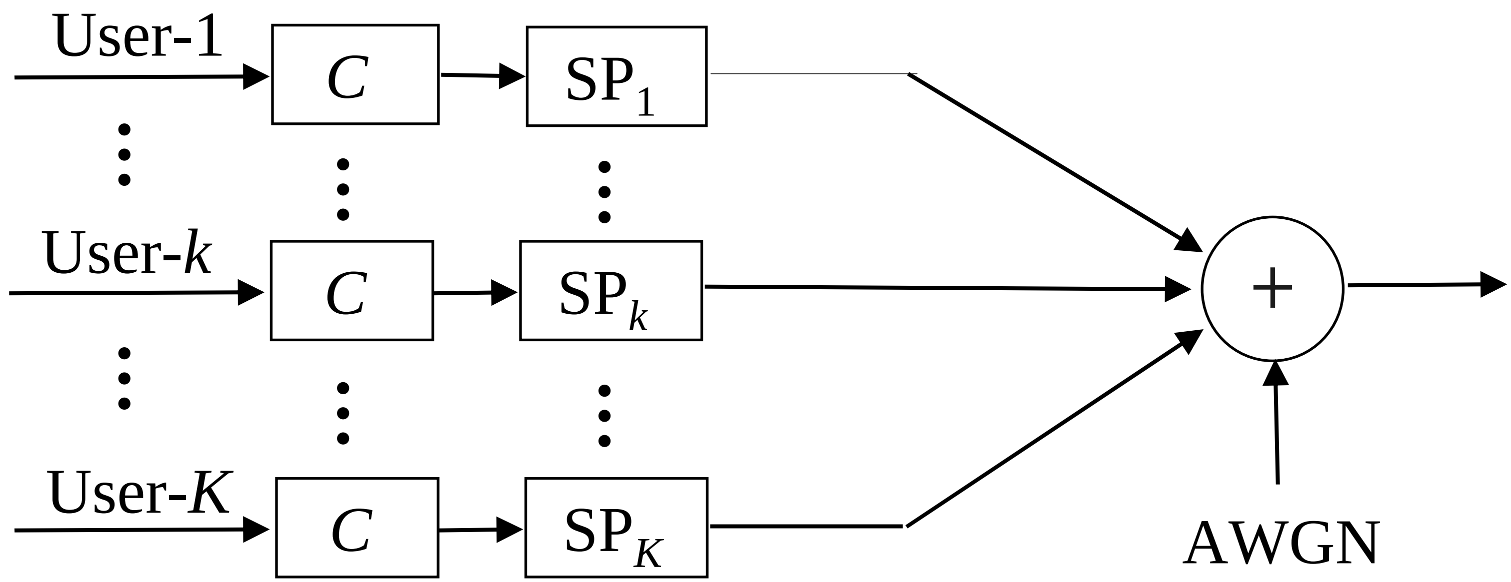
	FDMA/ OFDMA	TDMA	CDMA with SUD	IDMA	OFDM-CDMA	OFDM-IDMA
Intra-cell interference	No	No	Sensitive	Suppressed by MUD	Sensitive	Suppressed by MUD
Cross-cell interference	Sensitive	Sensitive	Mitigated	Mitigated	Mitigated	Mitigated
To achieve high single-user rate	High-order modulation	High-order modulation	Difficult	Superposition coding	Difficult	Superposition coding
Near-far effect	Insensitive	Insensitive	Sensitive	MUG	Sensitive	MUG
Treatment for ISI	Cyclic prefix	Equalization	Rake receiver	CBC detection	Cyclic prefix	Cyclic prefix
Synchronization	Yes	Yes	No	No	Yes	Yes

orthogonal non-orthogonal hybrid

Multi User Gain

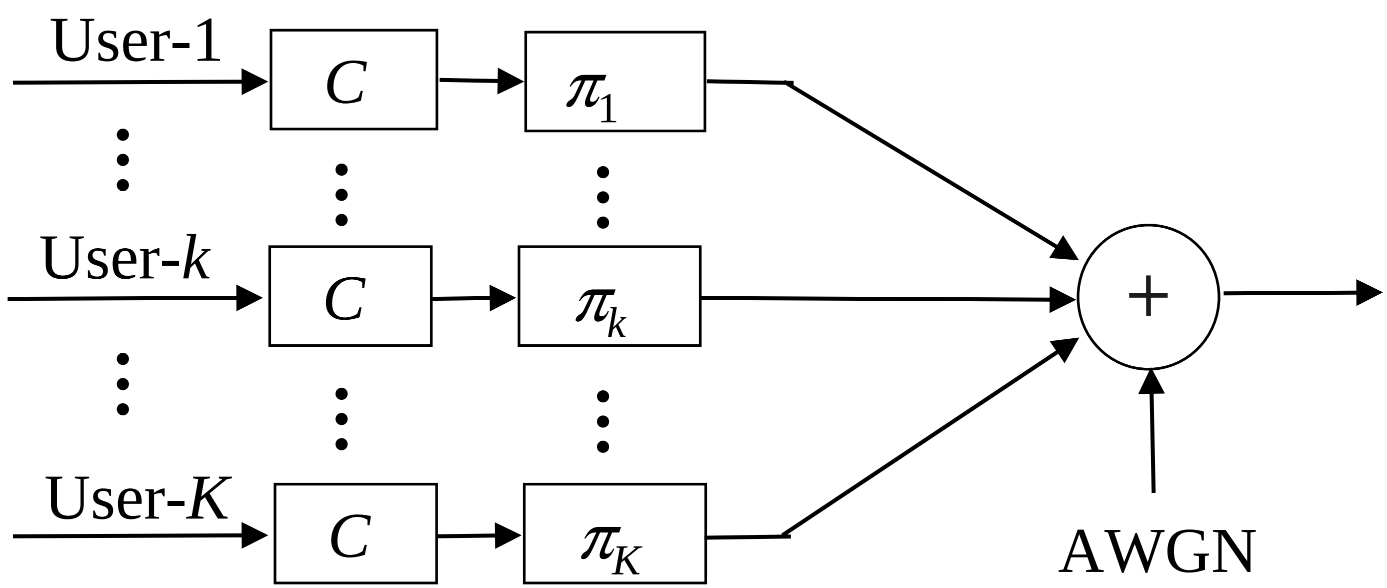
MUG

CDMA Principles



The spreaders SP_1, …, SP_K must be user-specific.

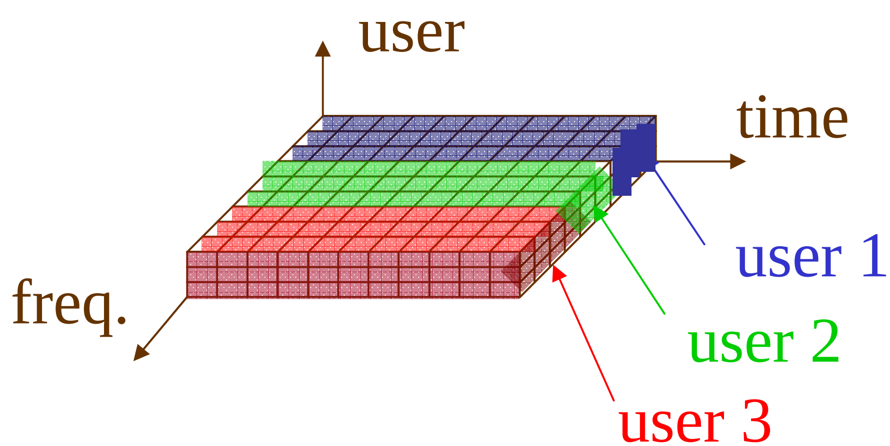
IDMA Principles



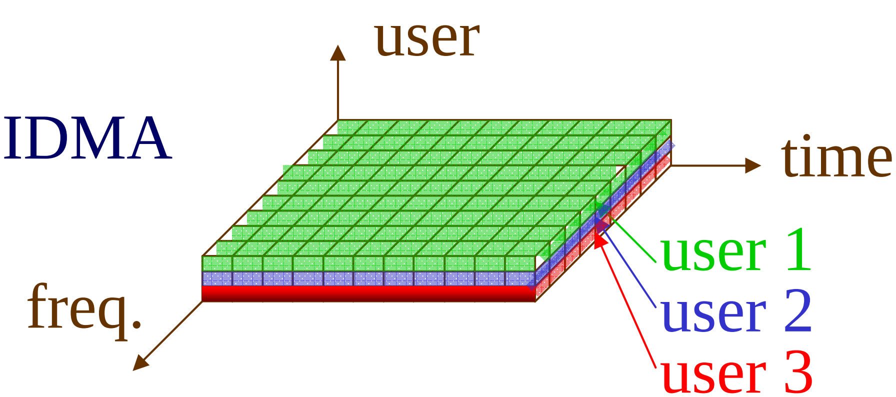
The interleavers $\pi_1, \ldots, \pi_K$ must be user-specific.

Basic Differences between orthogonal and Non-orthogonal Approaches

FDMA

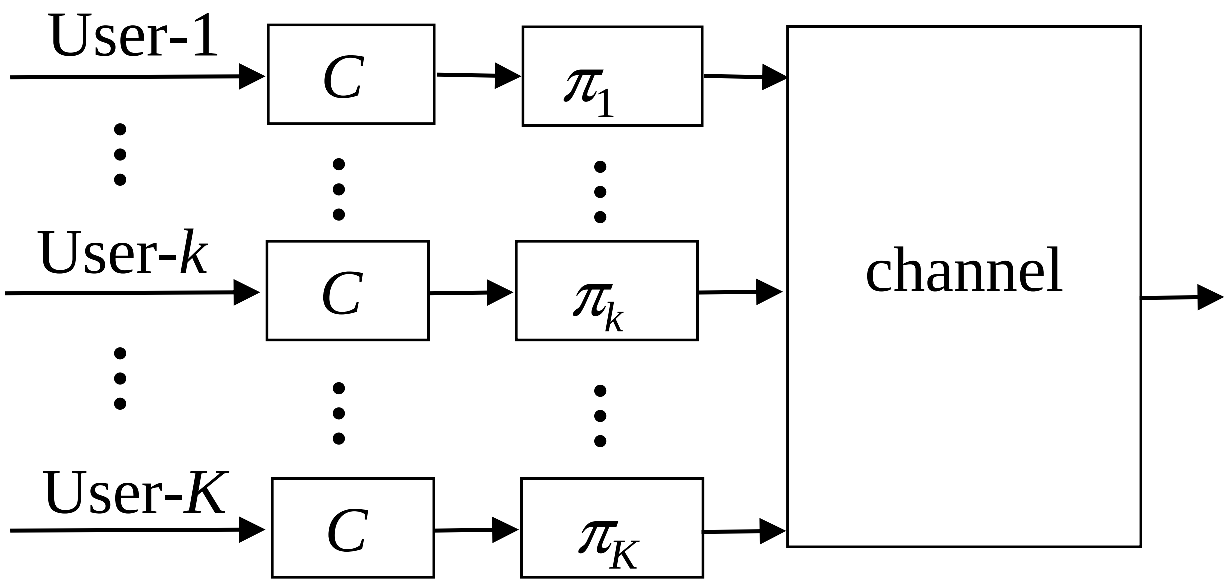


CDMA or IDMA



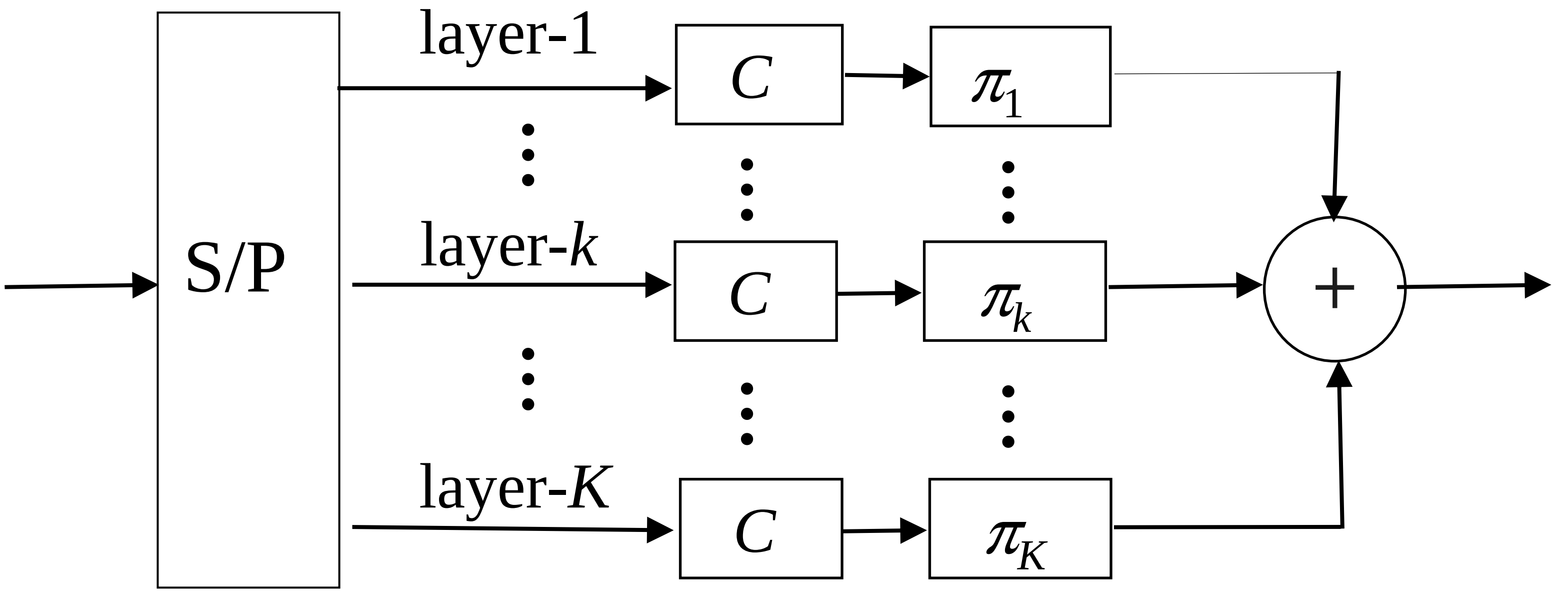
Various Applications

IDMA



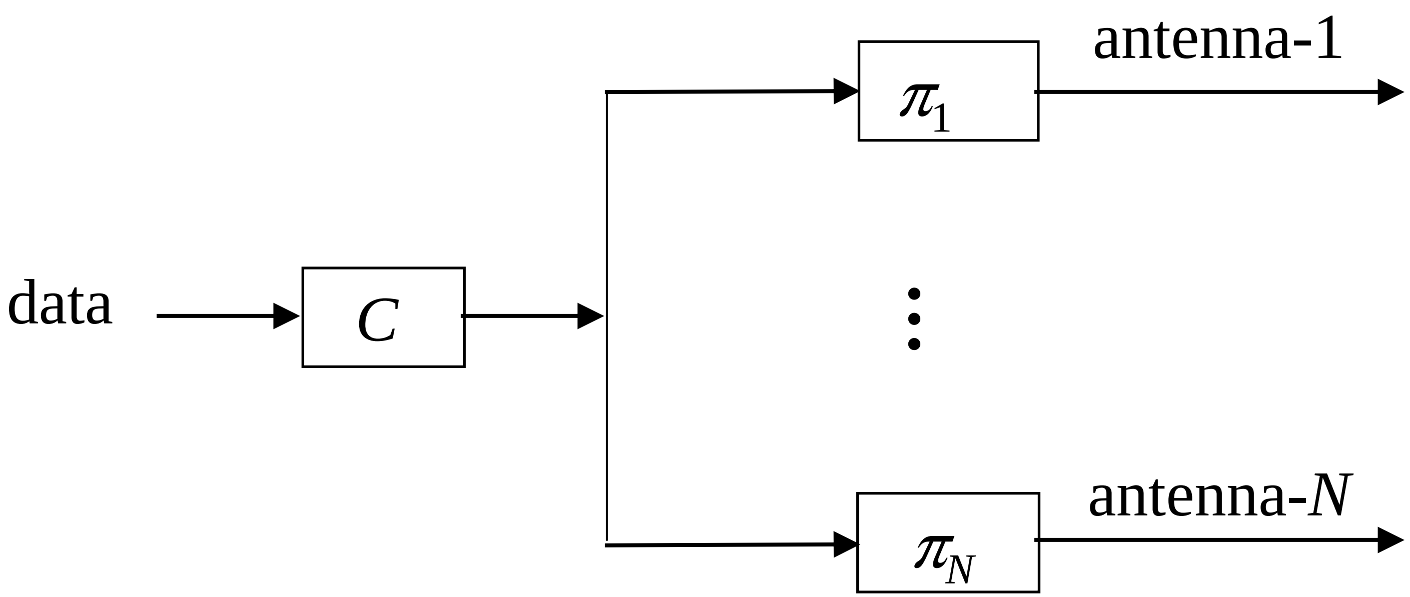
Li Ping," Interleave division multiple access and chip-by-chip multi-user detection", *IEEE Communication Magazine*, June 2005.

IDM Coded Modulation



Xiao Ma and Li Ping, "Coded modulation using superimposed binary codes," *IEEE Trans. Inform. Theory*, Dec. 2004.

IDM Space-Time Coding



Keying Wu and Li Ping, "Multilayer turbo space-time codes", *IEEE Commun. Lett.*, Jan. 2005.

OFDM-CDMA

Each user is allocated with several OFDM sub-carriers. CDMA is used for user separation in a common set of sub-carriers.

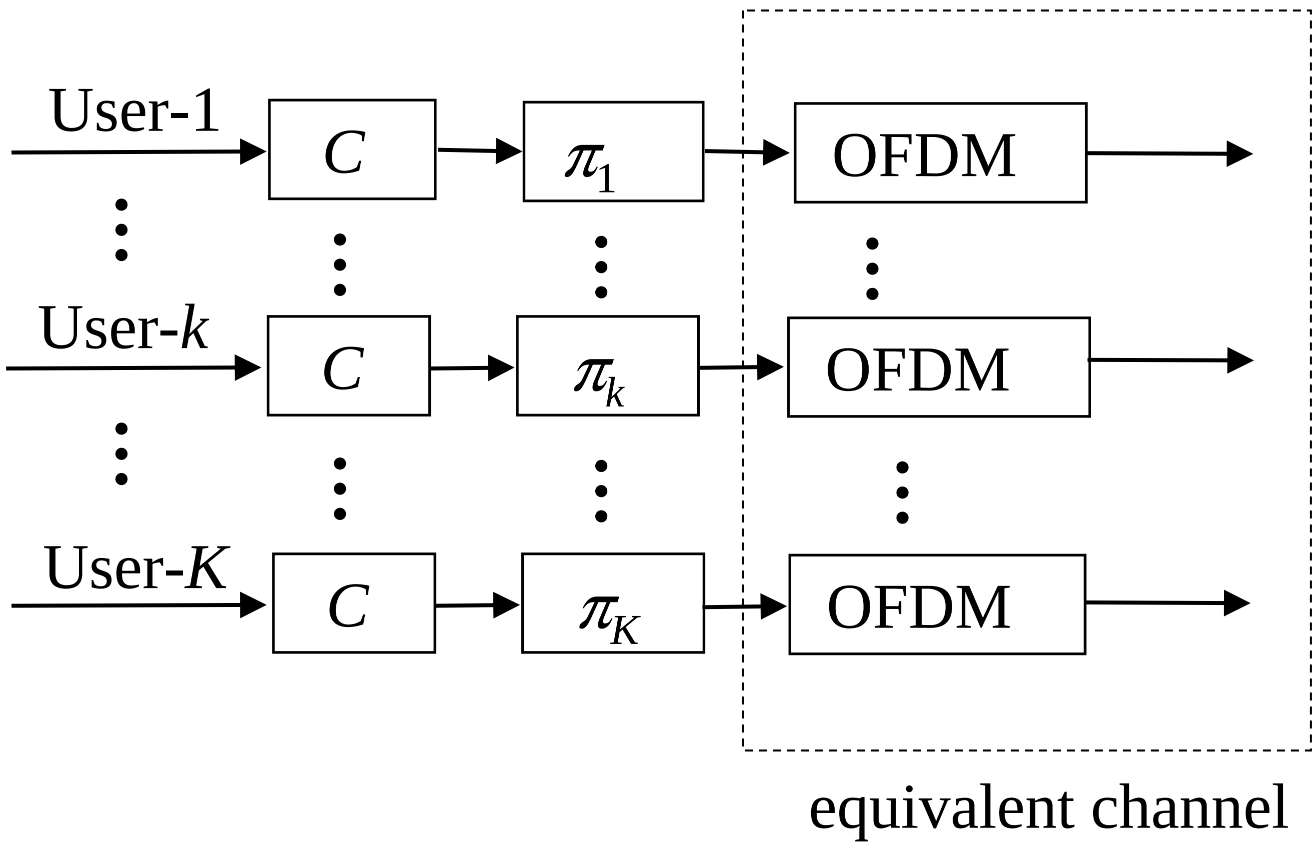
- Advantages
  - CDMA is robust against fading and cross-cell interference;
  - OFDM provides a simple treatment of ISI.

- Disadvantages
  - Intra-cell interference is induced by CDMA;
  - Frame synchronization is required for OFDM.

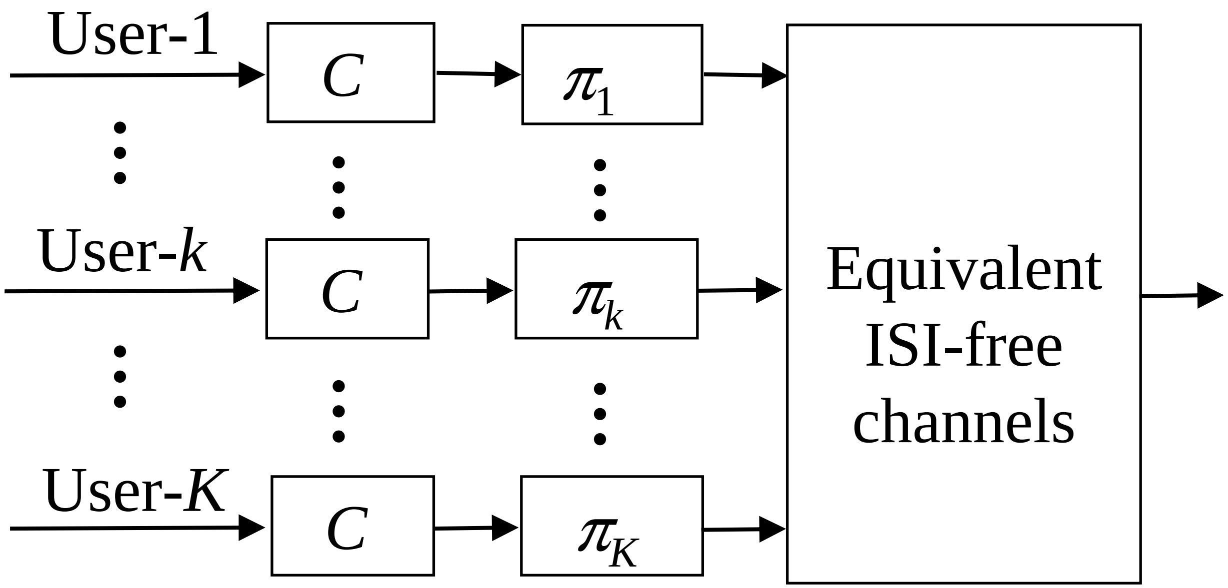
OFDM-IDMA

- OFDM-IDMA inherits most advantages of OFDM-CDMA;
- Low cost iterative MUD;
- OFDM-IDMA is easy to analyze and optimize.

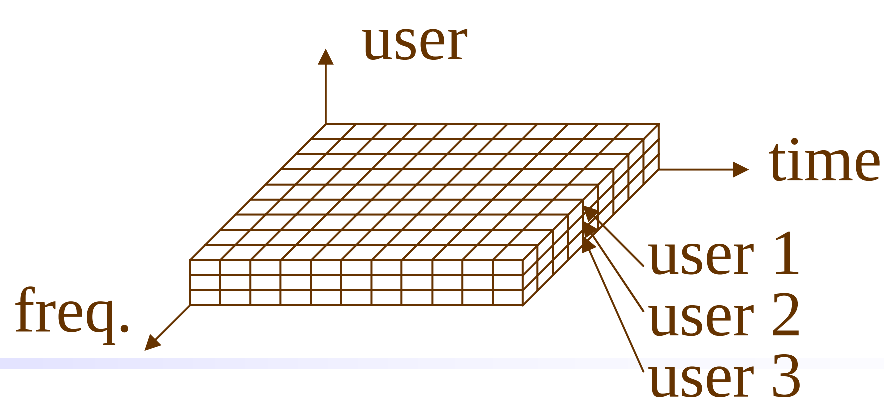
OFDM-IDMA Principles



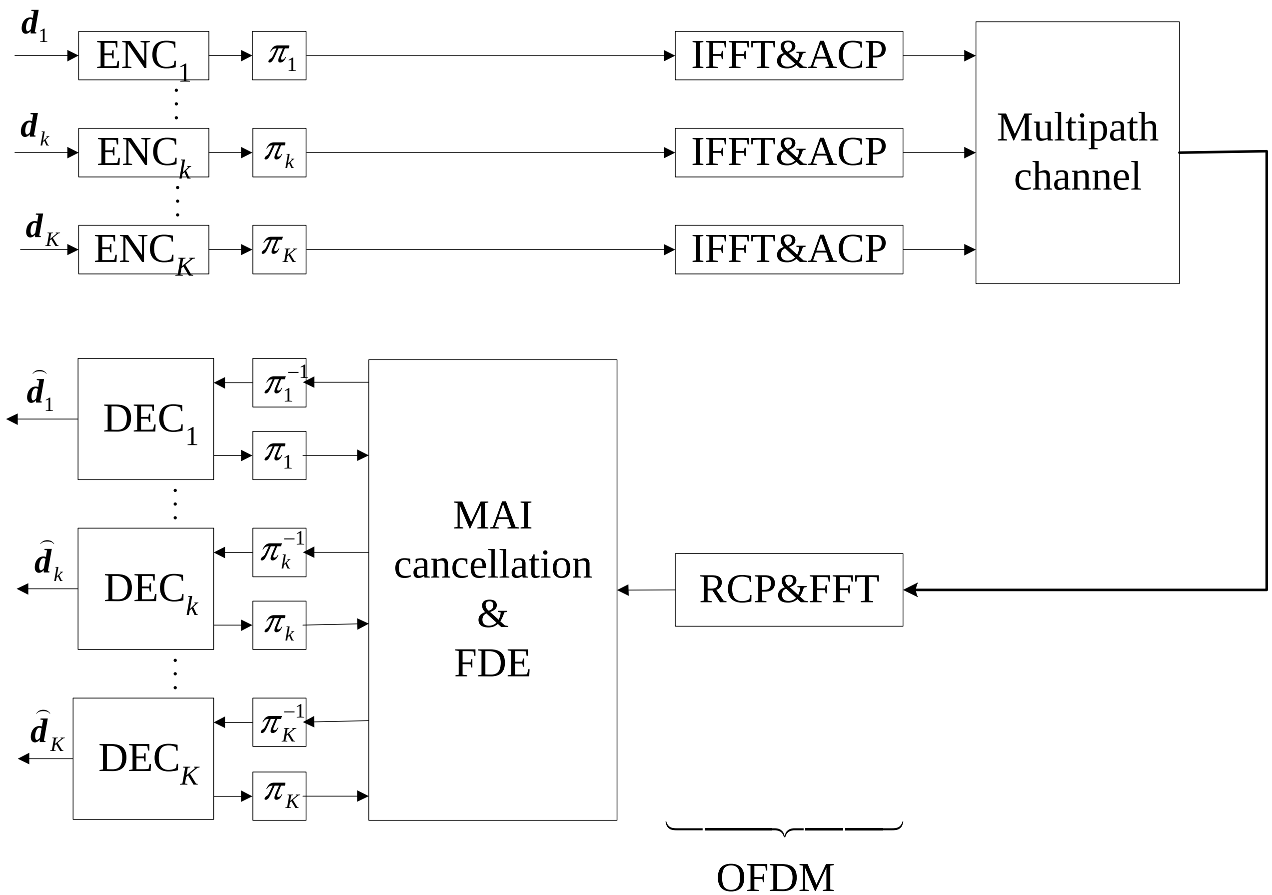
OFDM-IDMA with Equivalent Channels



Signals are superimposed on a 2D time-frequency plan.



OFDM-IDMA Transceiver



Chip-interleaving makes iterative MUD more effective.

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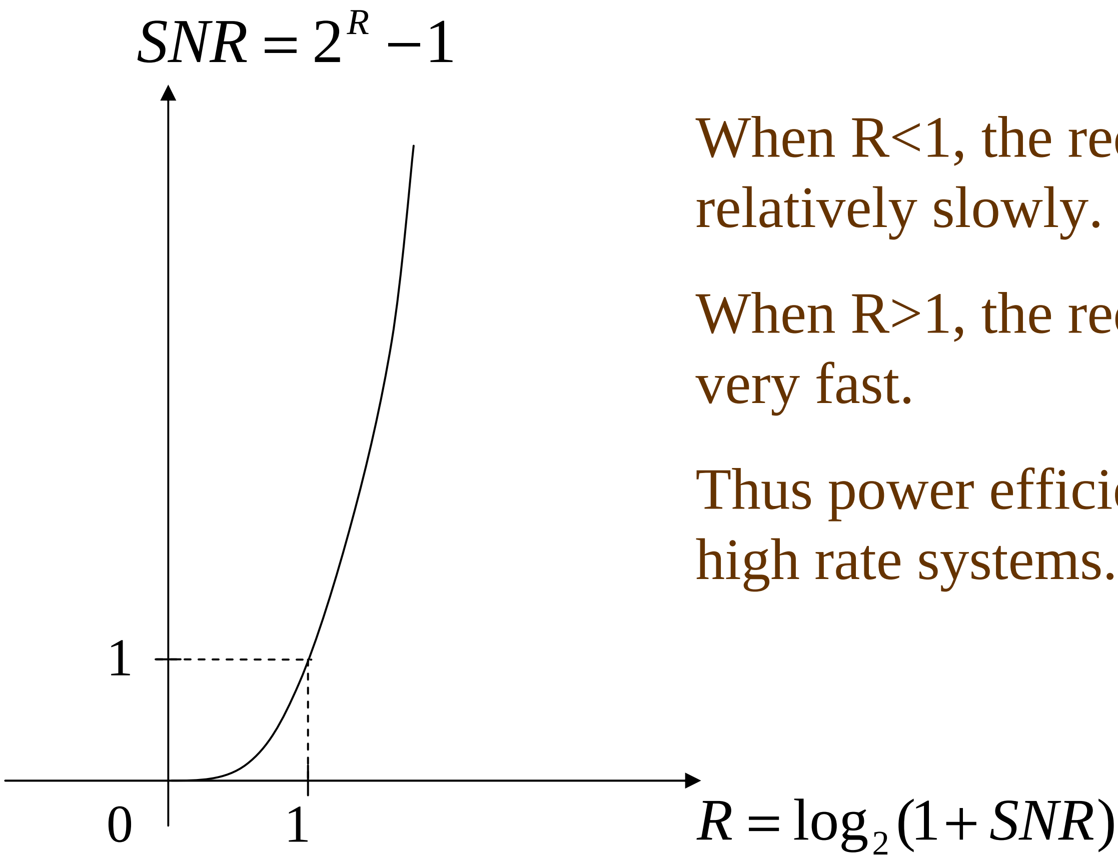
Fundamental Limits on Power Efficiency

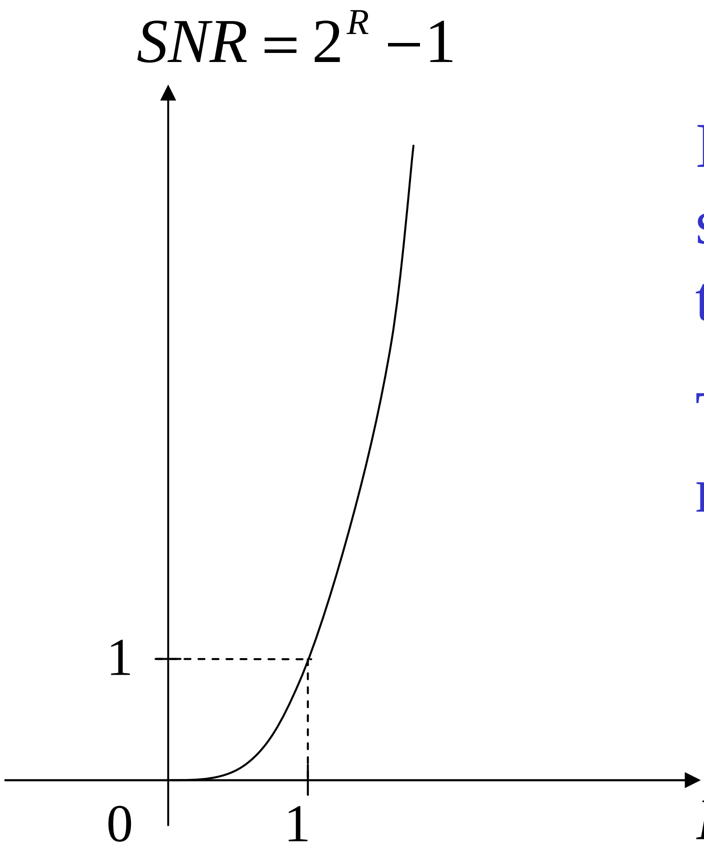


When R<1, the required power increases relatively slowly.

When R>1, the required power increases very fast.

Thus power efficiency is a crucial issue for high rate systems.

Power Efficiency and Cellular Capacity



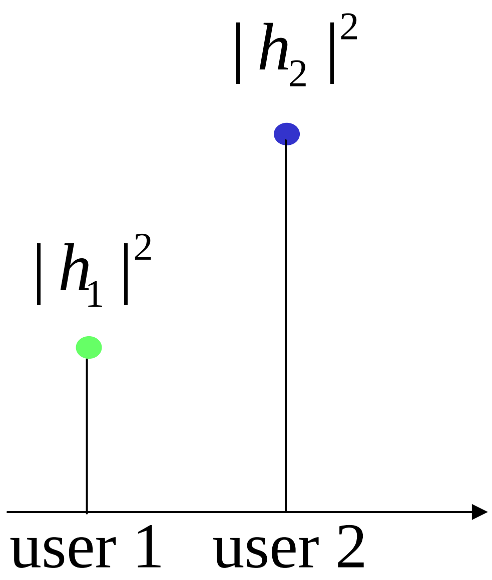
In cellular systems, the transmitted signal from one user is the interference to others.

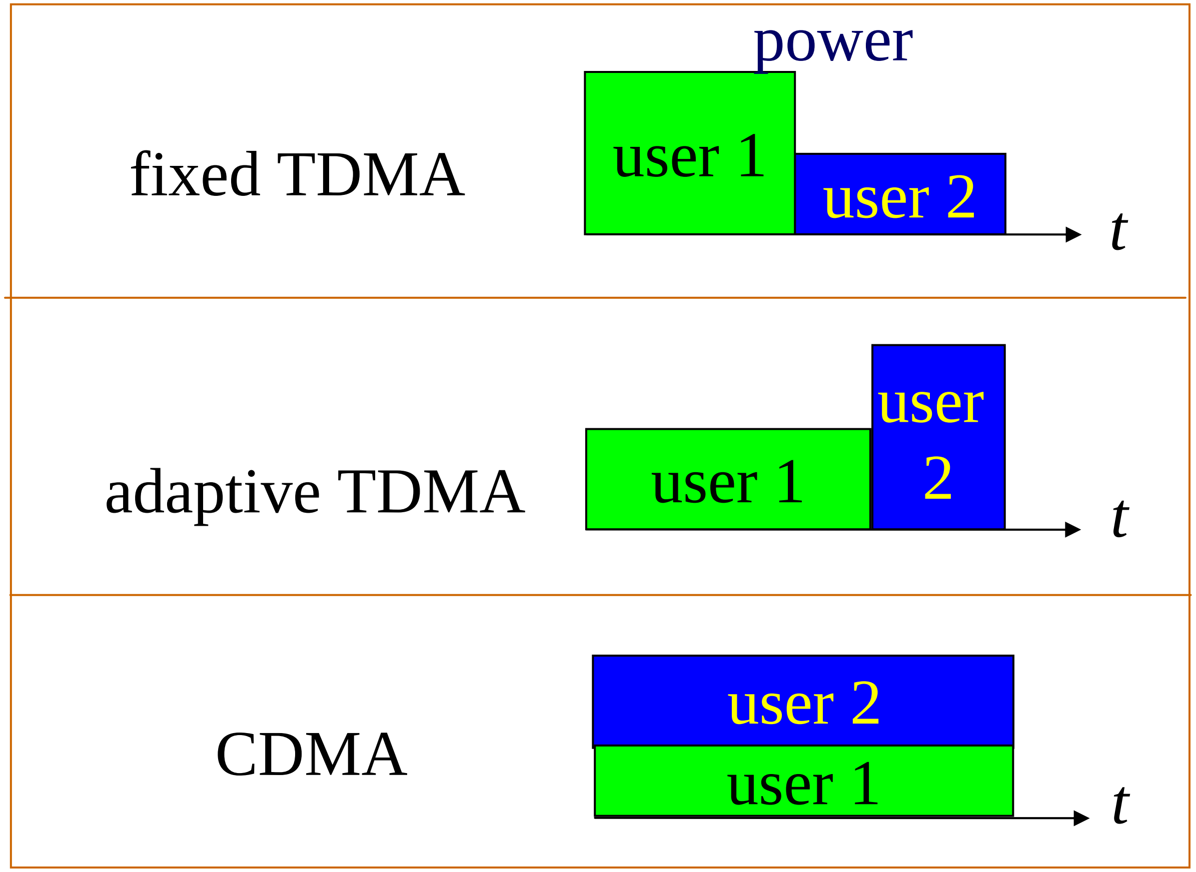
Thus power efficiency is closely related to spectral efficiency.

Options to Improve Power Efficiency

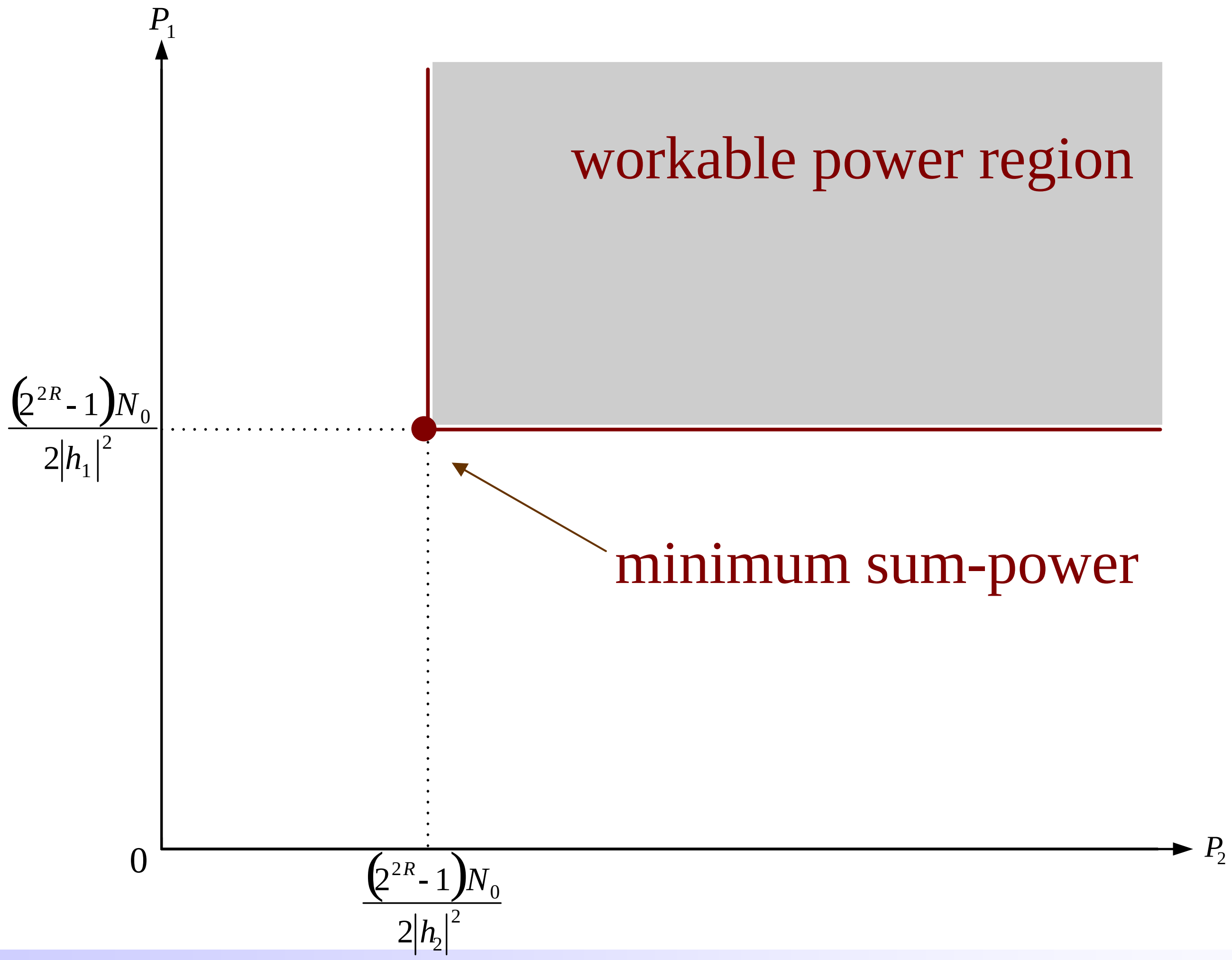
- Efficient FEC codes.
- Space-time diversity using multiple antennas (MIMO).
- Frequency diversity (OFDM & water-filling).
- Multi-user diversity:
  - Allow multiple users to transmit simultaneously;
  - Significant power gain is achievable;
  - Non-orthogonal schemes are optimal.

Fixed TDMA, Adaptive TDMA and CDMA

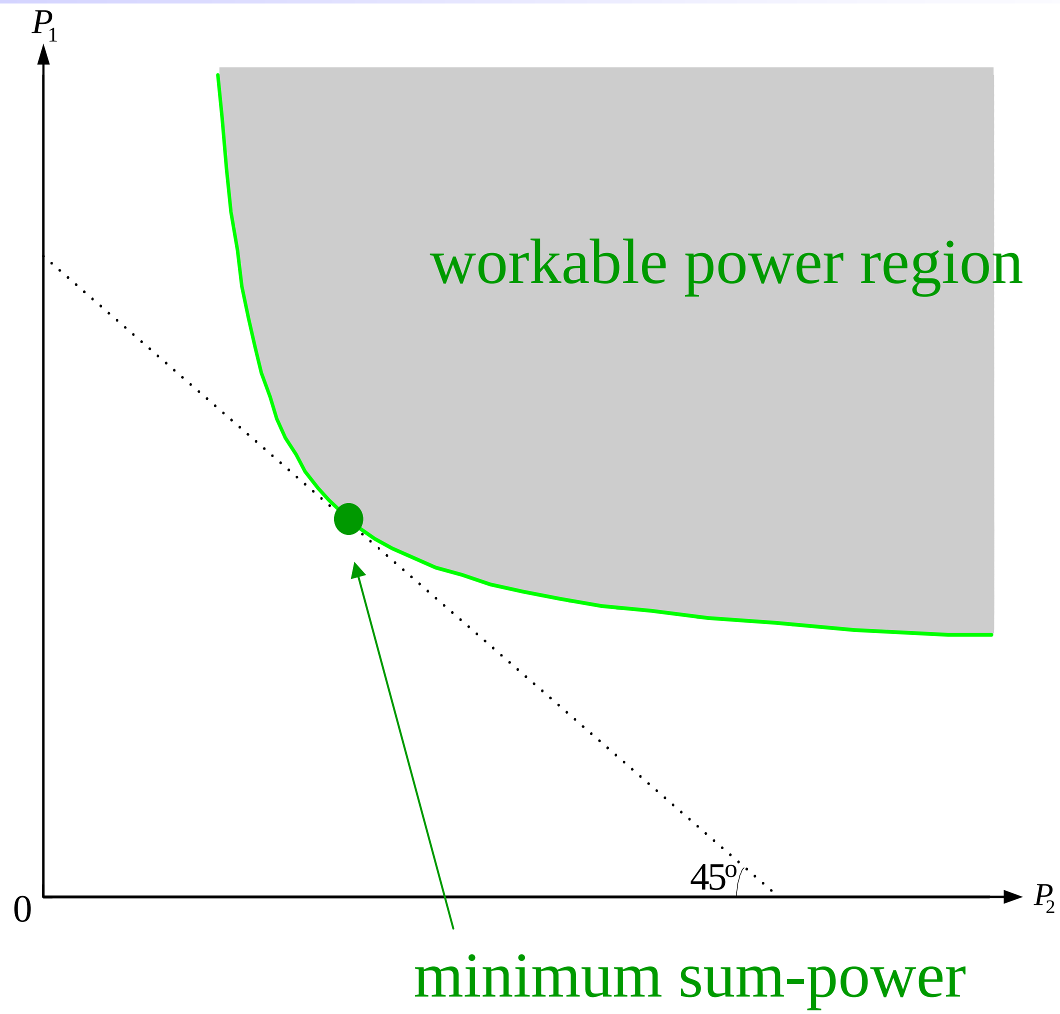




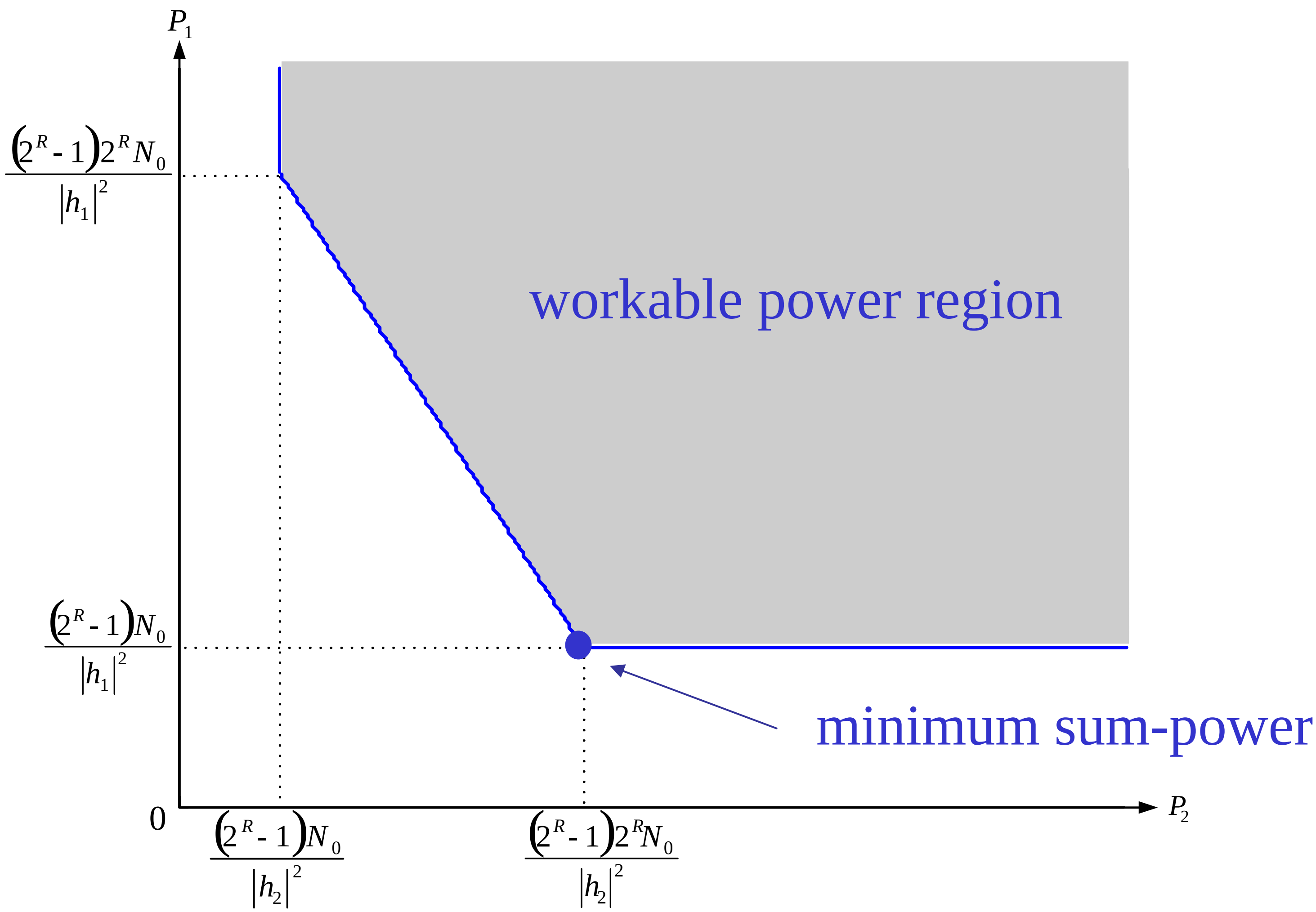
Power Region of Fixed TDMA



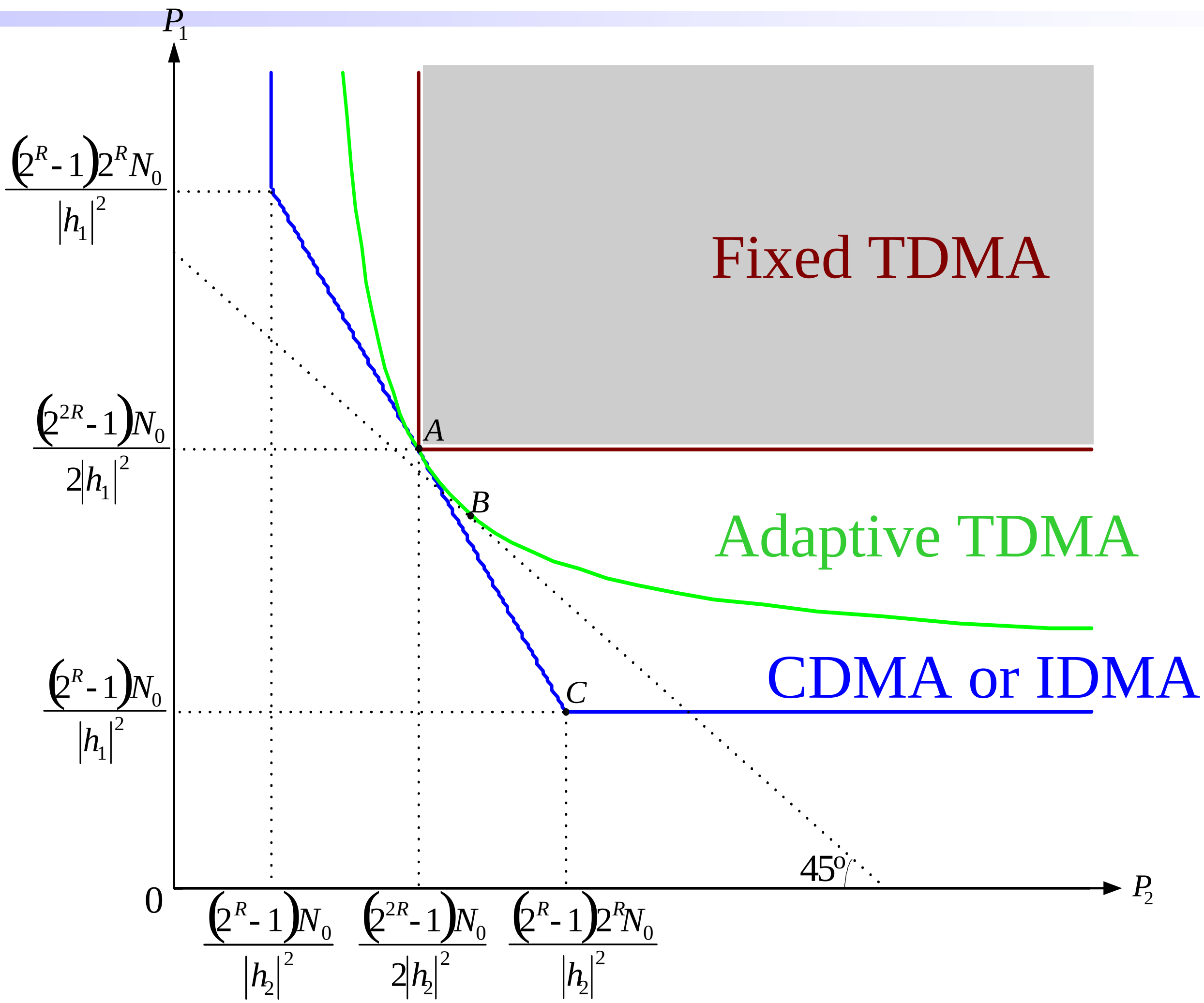
Power Region of Adaptive TDMA



Power Region of CDMA or IDMA



Power Regions Comparison



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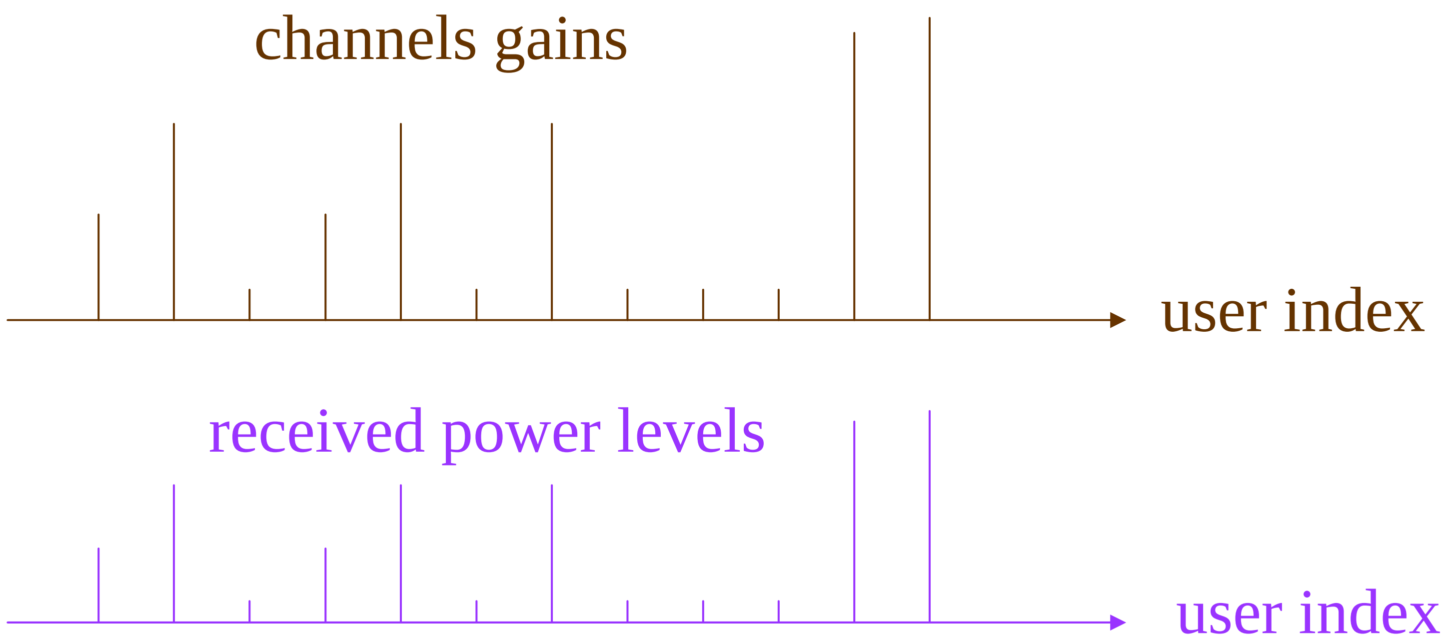
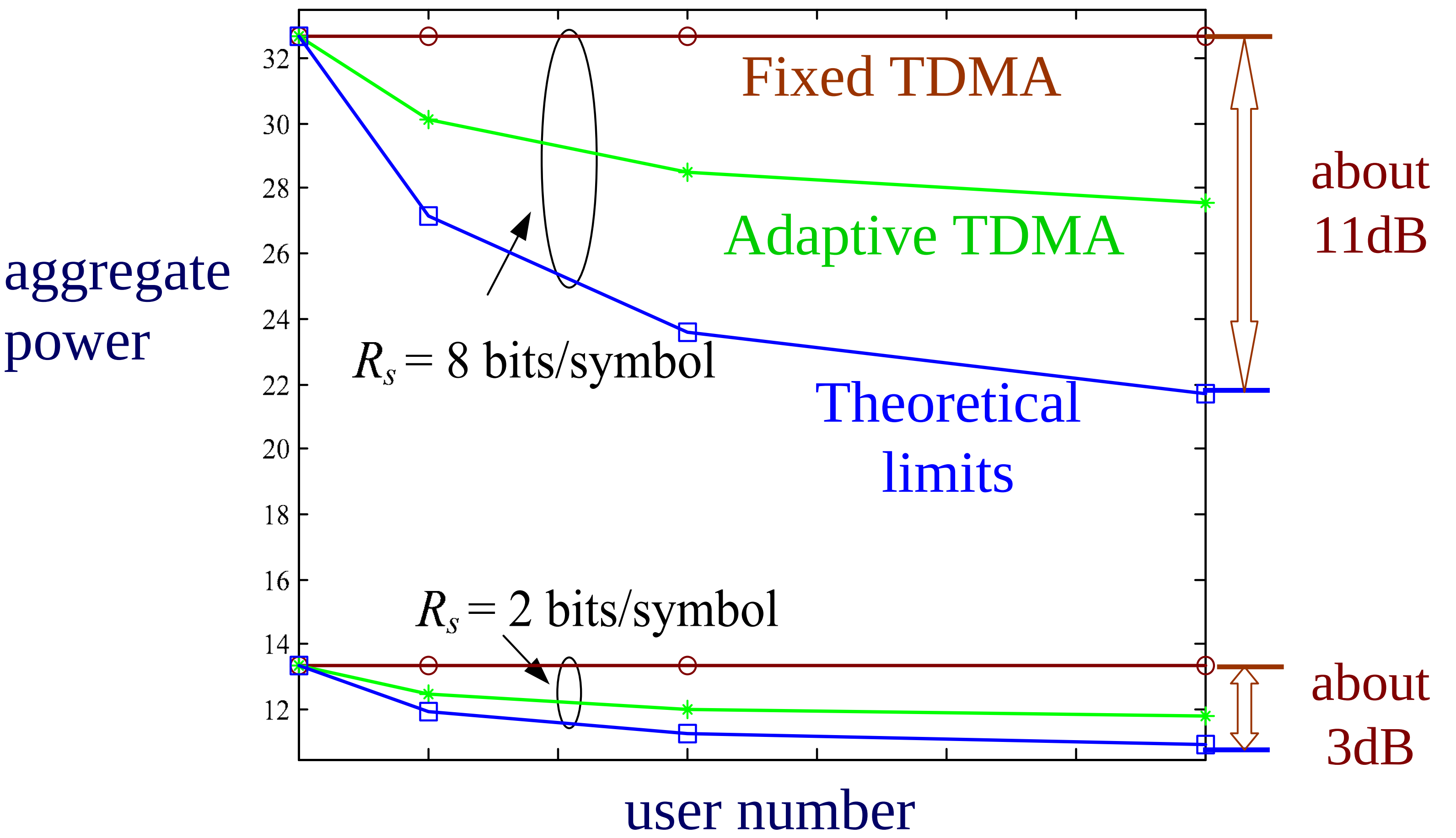
Multi-User Detection and Unequal Power Control



With multi-user detection, a combined un-equal power control and channel matching strategy can achieve optimal performance.

Multi User Gain (MUG) Relative to Fixed TDMA



single cell path loss + lognormal fading

Observations

- MUG is available in near-far or fading channels.
- The optimal MUG can only be achieved by CDMA or IDMA.
- MUG increases with K or R.
- A significant portion of MUG is achievable at K =2 or 4.
- IDMA or OFDM-IDMA are low cost approaches to MUG.

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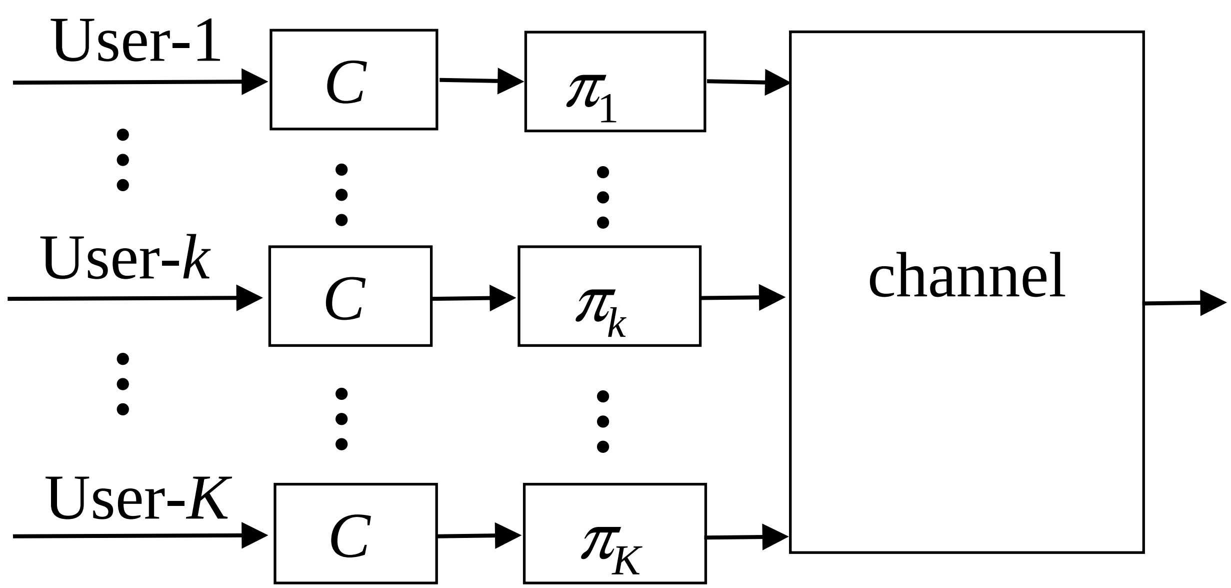
IDMA Transmission Principles

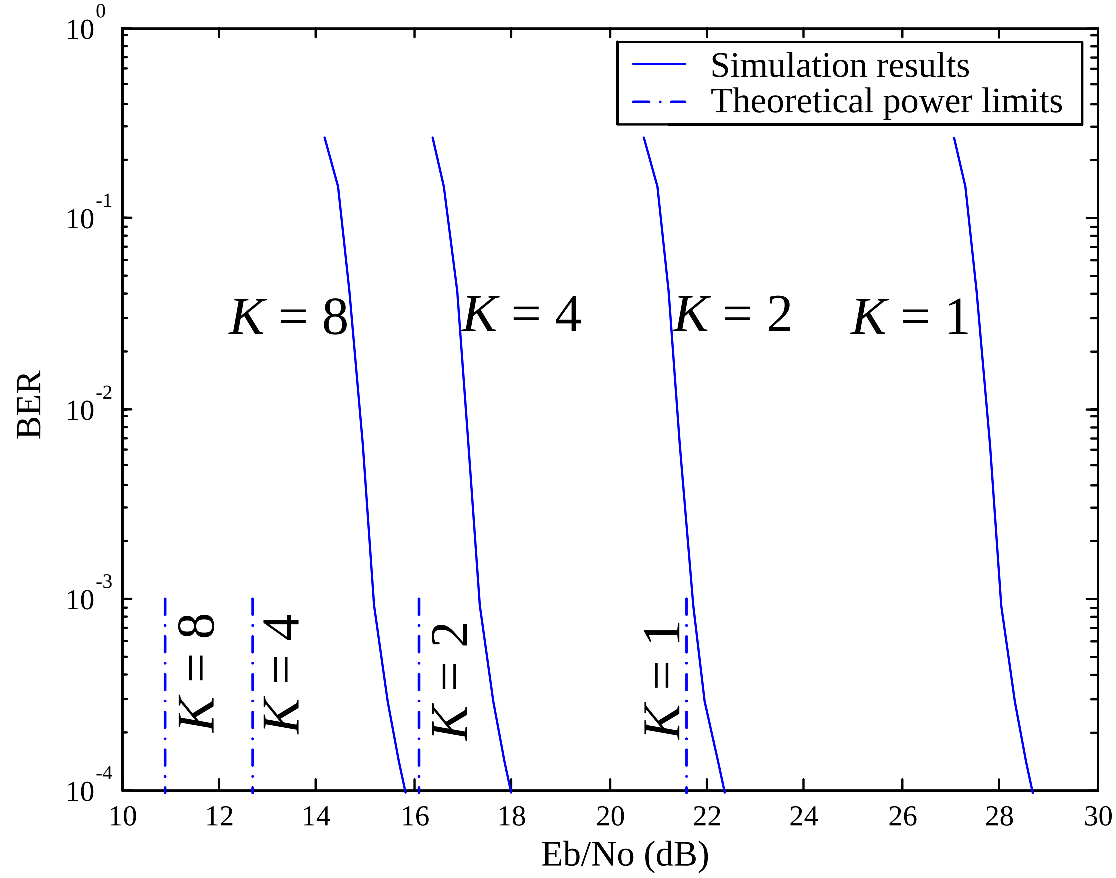


The interleavers π_1, …, π_K must be user-specific.

IDMA Detection Principles

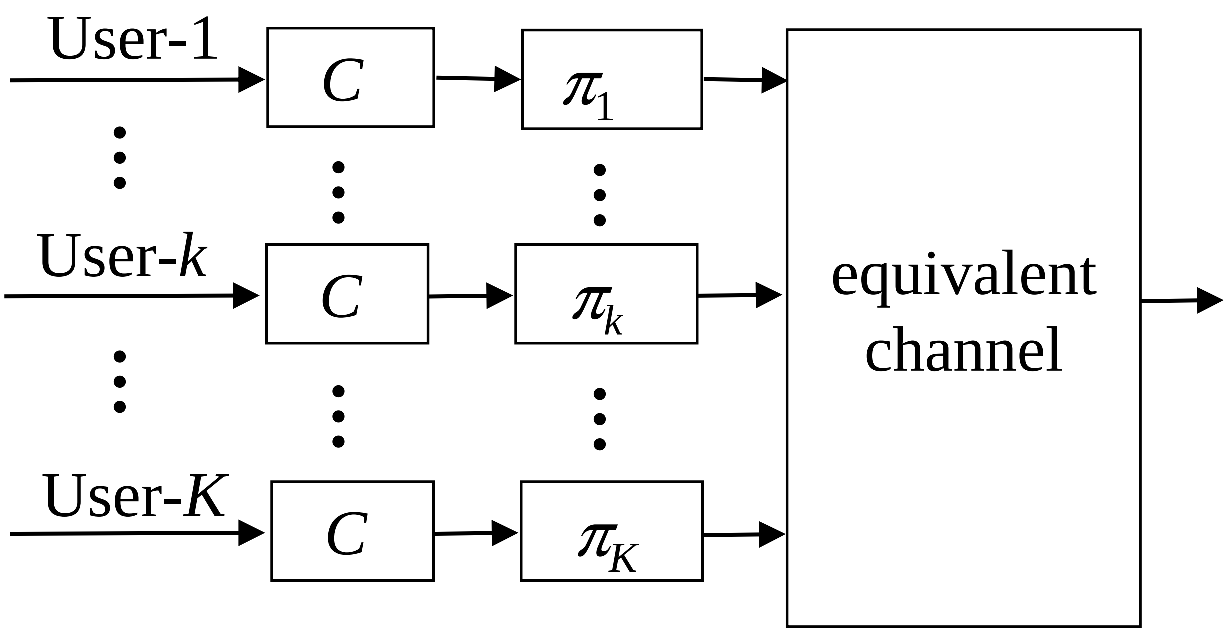
- Estimated IDMA complexity:
  6 ADD and 6 MULTI per chip per iteration per user
- The IDMA complexity (per user) is independent of user number K.
- The IDMA multi-user complexity is comparable to conventional single-user complexity.
- As a comparison, the cost for MMSE CDMA multi-user detection is $O(K^2)$ per user using matrix operations.

Simulation Results for IDMA

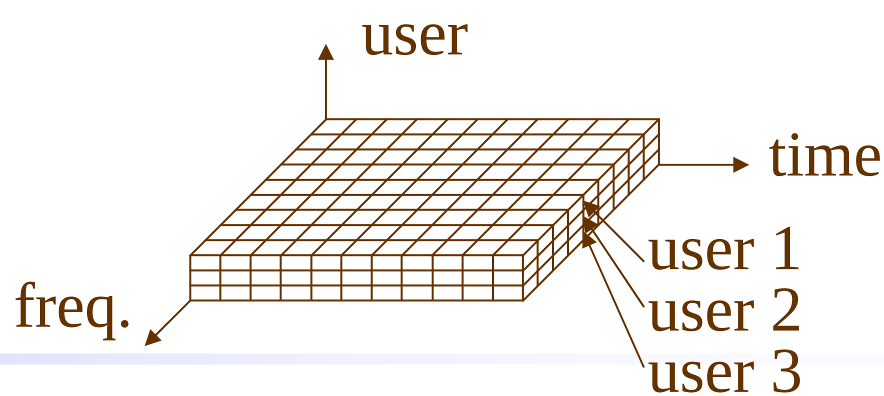


throughput=8 bits/chip, path loss + lognormal fading

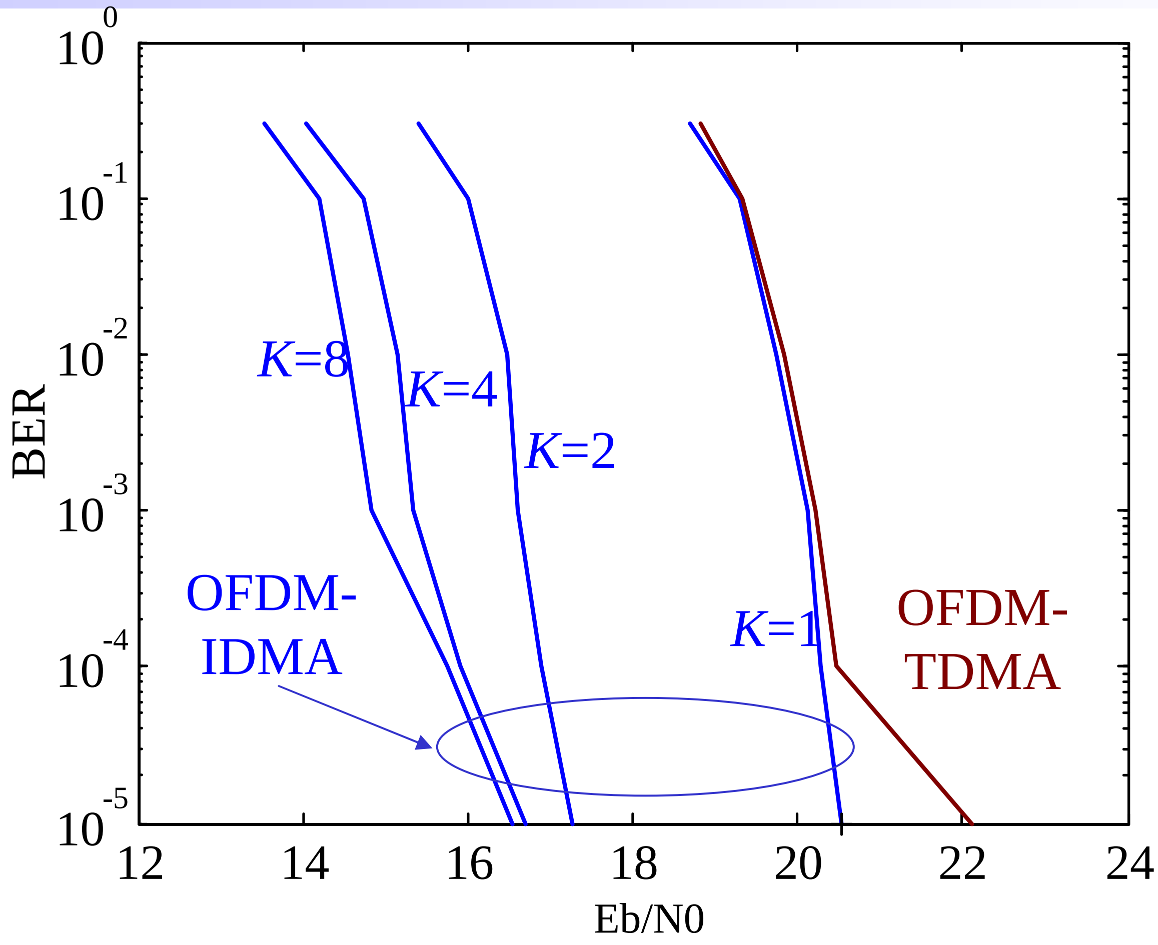
OFDM-IDMA Principles



Signals are superimposed on a 2D time-frequency plan.

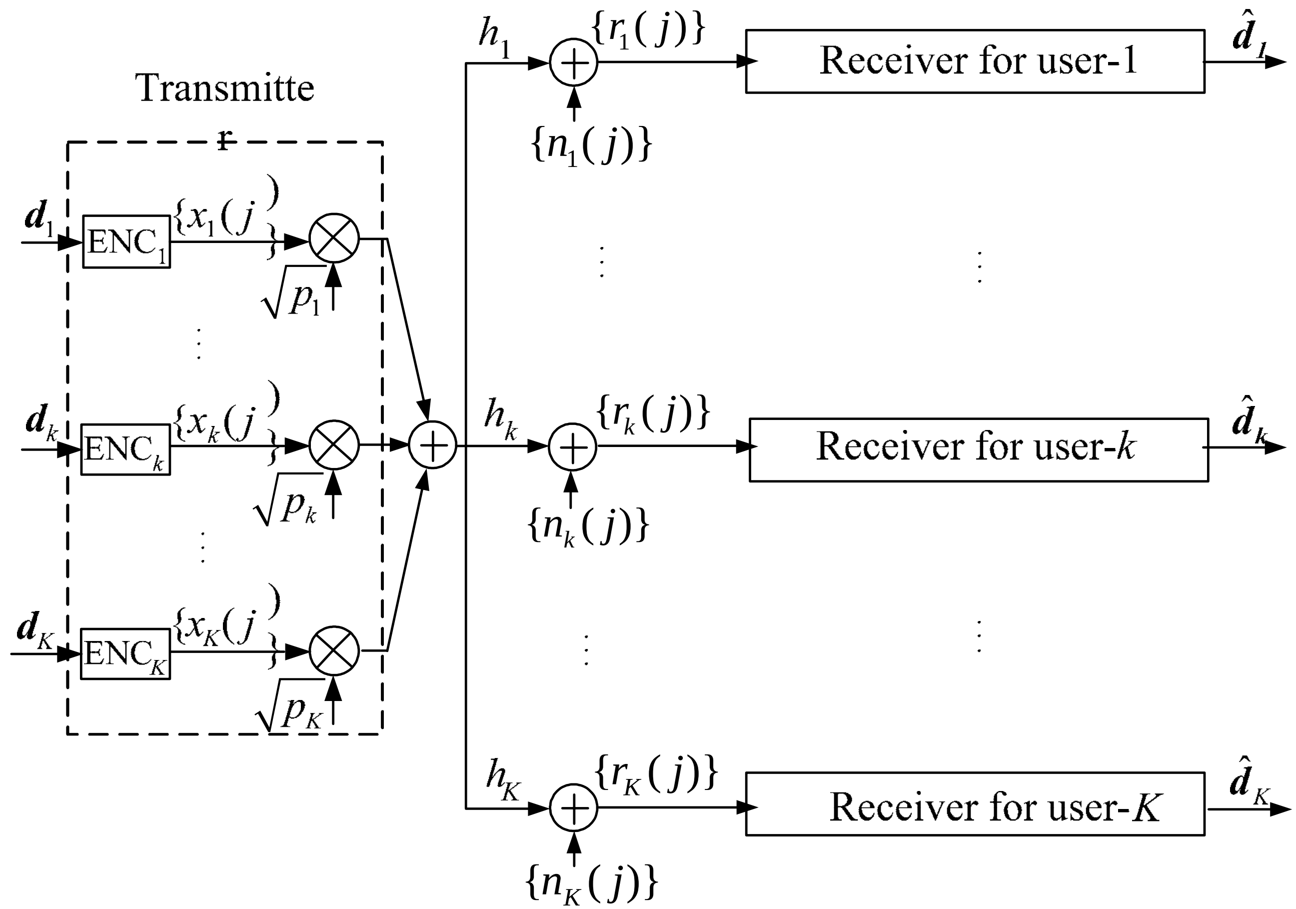


Simulation Results for OFDM-IDMA



throughput=3 bits/symbol, path loss + lognormal fading

Downlink Concerns



Cost Concern

- MUD cost is a serious concern in the downlink.
- With IDMA, for small K (e.g., 2 or 4), the MUD cost is only modestly higher than the SUD cost, while the achievable MUG can be significant.
- Thus, the MUG achieved with small K can justify the complexity increase for MUD.

Is the Gain Worth the Cost?

- A turbo code achieved about 3dB extra gain than a convolutional code.

- A turbo decoder is at least twice as complex as a convolutional decoder.

- Thus, if we can achieve more than 3 dB gain with double complexity, why not to do it?

Overall Comparison: Advantages

	FDMA/ OFDMA	TDMA	CDMA with SUD	IDMA	OFDM-CDMA	OFDM-IDMA
Intra-cell interference	No	No	Sensitive	Suppressed by MUD	Sensitive	Suppressed by MUD
Cross-cell interference	Sensitive	Sensitive	Mitigated	Mitigated	Mitigated	Mitigated
To achieve high single-user rate	High-order modulation	High-order modulation	Difficult	Superposition coding	Difficult	Superposition coding
Near-far effect	Insensitive	Insensitive	Sensitive	MUG	Sensitive	MUG
Treatment for ISI	Cyclic prefix	Equalization	Rake receiver	CBC detection	Cyclic prefix	Cyclic prefix
Synchronization	Yes	Yes	No	No	Yes	Yes

Overall Comparison: Disadvantages

	FDMA/ OFDMA	TDMA	CDMA with SUD	IDMA	OFDM-CDMA	OFDM-IDMA
Intra-cell interference	No	No	Sensitive	Suppressed by MUD	Sensitive	Suppressed by MUD
Cross-cell interference	Sensitive	Sensitive	Mitigated	Mitigated	Mitigated	Mitigated
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Conclusions

- Non-orthogonal approaches can fully exploit the advantage of MUG for delay-sensitive services in fading environments.
- MUG is significant when the throughput is high.
- IDMA provides a low-cost approach towards MUG.
- The potential MUG can also justify the cost increase for MUD in the downlink.
- Hybrid schemes can combine the advantages of both orthogonal and non-orthogonal approaches.