IDMA: Overview and Applications

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References

C. Xu, Y. Hu, C. Liang, J. Ma and Li Ping, "Massive MIMO, Non-Orthogonal Multiple-Access and Interleave Division Multiple Access", Invited paper, *IEEE Access* July 2017.

Software packages are available at:
http://www.ee.cityu.edu.hk/~liping/Research/Simulationpackage/

Contents

- Background
- Basic principles of IDMA
- Power control in IDMA
- Potential applications of IDMA in 5G
- Conclusions

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Prior works

IDMA was inspired by the following prior works:

- Multi-user detection (MUD) (1998 Verdu and Poor)
- Turbo codes (1993 Berrou, Glavieux and Thitimajshima)
- LDPC codes (Gallager, Mackay, Richardson and Urbanke)
- Iterative MUD (1998, Reed, Schlegel, Alexander and Asenstorfe)
- Iterative detection for interleaved codes (1998 Moher)
- Trellis code multiple access (2001, Brannstrom, Aulin and Rasmussen)
- Unequal power control for optimal CDMA systems (1998 Muller, Lampe and Huber)

CDMA

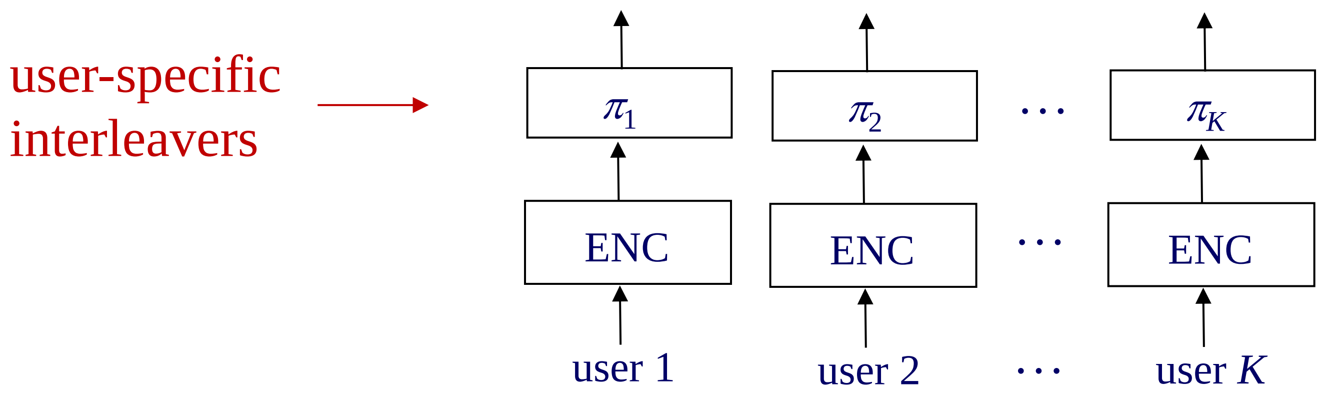
The optimal information theoretic approach to multiple access is random codebooks . This is an elegant concept, but difficult to implement.

Direct-sequence CDMA (DS-CDMA) employs spreading sequences. CDMA performance is not satisfactory. This is the reason that OFDMA has been used in 4G.

Is there a simple way to construct random codebooks with low-cost detection?

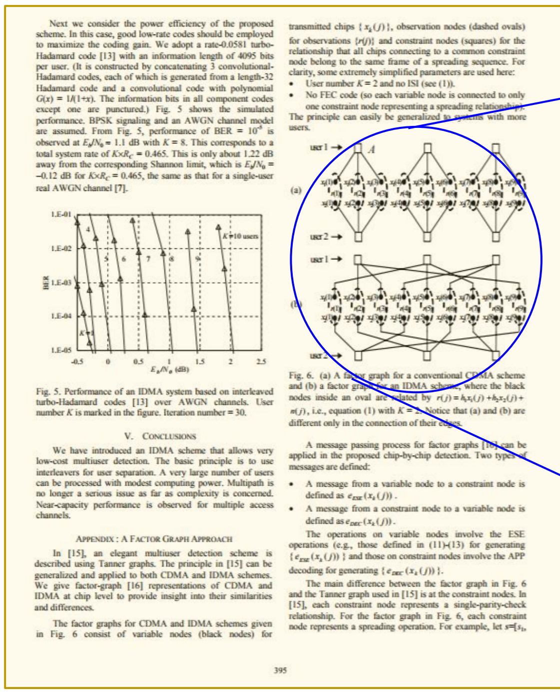
IDMA

- Random interleaving a random code results in another random code.
- Unlike spreading, interleaving does not incur any rate loss.



DS-CDMA vs IDMA on graph

The difference between CDMA and IDMA was explained in the following graph.



Next we consider the power efficiency of the proposed scheme. In this case, good low-rate codes should be employed to maximize the coding gain. We adopt a rate-0.0581 turbo-Hadamard code [13] with an information length of 4095 bits per user. (It is constructed by concatenating 3 convolutional-Hadamard codes, each of which is generated from a length-32 Hadamard code and a convolutional code with polynomial $G(x) = 1/(1+x)$. The information bits in all component codes except one are punctured.) Fig. 5 shows the simulated performance. BPSK signaling and an AWGN channel model are assumed. From Fig. 5, performance of BER = 10^{-5} is observed at $E_b/N_0 = 1.1$ dB with $K = 8$. This corresponds to a total system rate of $K \times R_C = 0.465$. This is only about 1.22 dB away from the corresponding Shannon limit, which is $E_b/N_0 = -0.12$ dB for $K \times R_C = 0.465$, the same as that for a single-user real AWGN channel [7].

Fig. 5. Performance of an IDMA system based on interleaved turbo-Hadamard codes [13] over AWGN channels. User number K is marked in the figure. Iteration number = 30.

V. CONCLUSIONS

We have introduced an IDMA scheme that allows very low-cost multiuser detection. The basic principle is to use interleavers for user separation. A very large number of users can be processed with modest computing power. Multipath is no longer a serious issue as far as complexity is concerned. Near-capacity performance is observed for multiple access channels.

APPENDIX: A FACTOR GRAPH APPROACH

In [15], an elegant multiuser detection scheme is described using Tanner graphs. The principle in [15] can be generalized and applied to both CDMA and IDMA schemes. We give factor-graph [16] representations of CDMA and IDMA at chip level to provide insight into their similarities and differences.

The factor graphs for CDMA and IDMA schemes given in Fig. 6 consist of variable nodes (black nodes) for transmitted chips $\{x_k(j)\}$, observation nodes (dashed ovals) for observations $\{r(j)\}$ and constraint nodes (squares) for the relationship that all chips connecting to a common constraint node belong to the same frame of a spreading sequence. For clarity, some extremely simplified parameters are used here:

- User number $K = 2$ and no ISI (see (1)).
- No FEC code (so each variable node is connected to only one constraint node representing a spreading relationship).

The principle can easily be generalized to systems with more users.

Fig. 6. (a) A factor graph for a conventional CDMA scheme and (b) a factor graph for an IDMA scheme, where the black nodes inside an oval are related by $r(j) = h_1x_1(j) + h_2x_2(j) + n(j)$, i.e., equation (1) with $K = 2$. Notice that (a) and (b) are different only in the connection of their edges.

A message passing process for factor graphs [16] can be applied in the proposed chip-by-chip detection. Two types of messages are defined:

- A message from a variable node to a constraint node is defined as $e_{ESE}(x_k(j))$.
- A message from a constraint node to a variable node is defined as $e_{DEC}(x_k(j))$.

The operations on variable nodes involve the ESE operations (e.g., those defined in (11)-(13) for generating $\{e_{ESE}(x_k(j))\}$ and those on constraint nodes involve the APP decoding for generating $\{e_{DEC}(x_k(j))\}$.

The main difference between the factor graph in Fig. 6 and the Tanner graph used in [15] is at the constraint nodes. In [15], each constraint node represents a single-parity-check relationship. For the factor graph in Fig. 6, each constraint node represents a spreading operation. For example, let $s=[s_1,$

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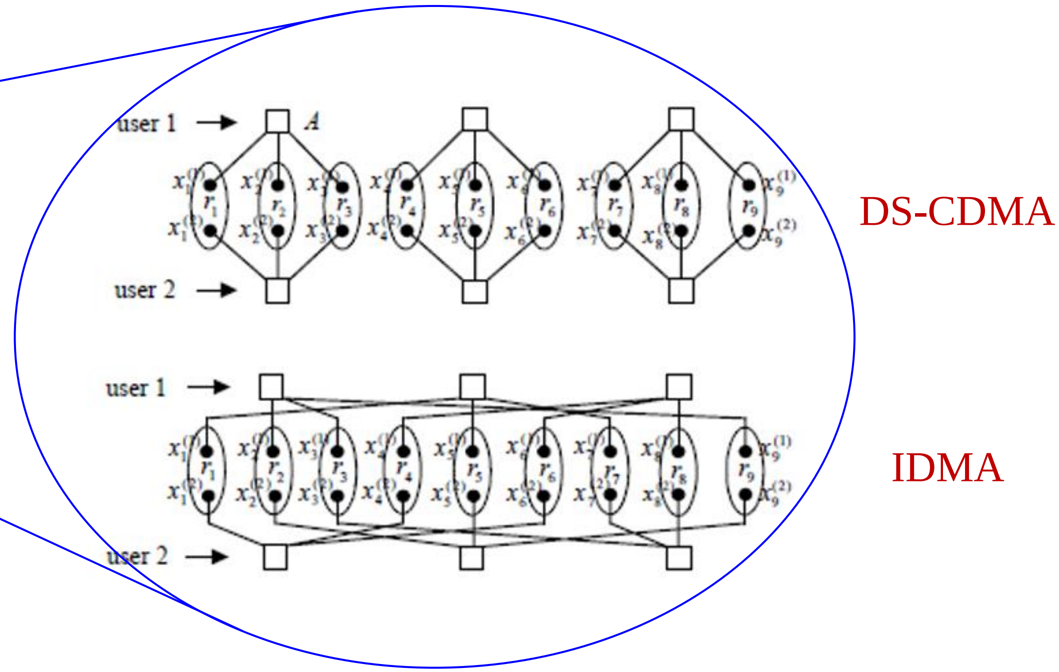

Li Ping, Lihai Liu and W. K. Leung, “A simple approach to near-optimal multiuser detection: interleave-division multiple access,” *IEEE WCNC'03*.

IDMA and NOMA

The following paper explained the following concepts:

- Non-orthogonal multiple access
- Un-equal power control and SIC
- Implementation of NOMA using IDMA

Comparison of Orthogonal and Non-Orthogonal Approaches to Future Wireless Cellular Systems

Peng Wang, City University of Hong Kong, Jun Xiao, University of Electronic Science and Technology of China, and Li Ping, City University of Hong Kong

Abstract: *This article provides a comparative study of different multiple access techniques. It is demonstrated that non-orthogonal approaches have a spectral-power efficiency advantage over orthogonal ones for delay-sensitive applications in fading environments, and that this theoretical advantage can be realized in practice by exploiting recent progress in transmission and detection techniques. The practical aspects of these multiple access techniques are also discussed and compared.*

Multiple access (MA) is a basic function in wireless cellular systems. Generally speaking, MA techniques can be classified into orthogonal and non-orthogonal approaches. In orthogonal approaches, signals from different users are orthogonal to each other, i.e., their cross correlation is zero, which can be achieved by time-division multiple-access (TDMA), frequency-division multiple-access (FDMA) and orthogonal-frequency division multiple-access (OFDMA). Non-orthogonal schemes allow non-zero cross correlation among the signals from different users, such as in random waveform code-division multiple-access (CDMA) [1], trellis-coded multiple-access (TCMA) [2] and interleave-division multiple-access (IDMA) [3].

First and second generation cellular systems are dominated by orthogonal MA approaches (with the exception of the American IS-95). The main advantage of these approaches is the avoidance of intra-cell interference. However, careful cell planning is necessary in these systems to curtail cross-cell interference. In particular, sufficient distance must exist between re-used channels, resulting in reduced cellular spectral efficiency.

Non-orthogonal CDMA techniques have been adopted in second and third generation cellular systems (e.g., IS-95, CDMA2000 and uplink WCDMA). Compared with its orthogonal counterparts, CDMA is more robust against fading and cross-cell interference, but is prone to intra-cell interference. Due to its spread-spectrum nature, CDMA is inconvenient for data services (e.g., wireless local area networks (WLANs) and 3GPP high speed uplink/downlink packet access (HSUPA/HSDPA) standard) that require high single-user rates.

This article presents a comparative study of orthogonal and non-orthogonal MA schemes. We will illustrate that non-orthogonal approaches have a spectral-power efficiency advantage over orthogonal ones for delay-sensitive applications in fading environments. This advantage is referred to as multi-user gain (MUG) below. We will also illustrate that MUG is realizable in practice by exploiting recent progress in interleave-division multiple-access (IDMA) and the related low-cost chip-by-chip (CBC) multi-user detection (MUD) algorithm. The gain is significant for high-rate applications.

It is envisaged that delay-sensitive applications (such as speech and video services) will contribute a considerable part of the traffic demand in the future, and so the discussion in this article may provide useful guidelines on the evolution path for future wireless cellular systems.

Our focus is mainly on uplink multiple access channels (MACs), but most findings in this article can be applied to downlink broadcast channels (BCs)

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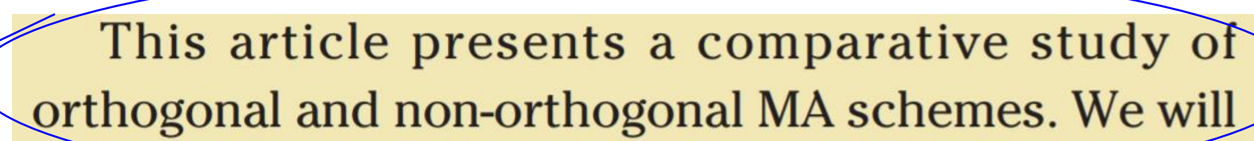

This article presents a comparative study of orthogonal and non-orthogonal MA schemes. We will

P. Wang, J. Xiao, and Li Ping, "Comparison of orthogonal and non-orthogonal approaches to future wireless cellular systems," *IEEE Vehicular Technology Magazine*, Sept. 2006.

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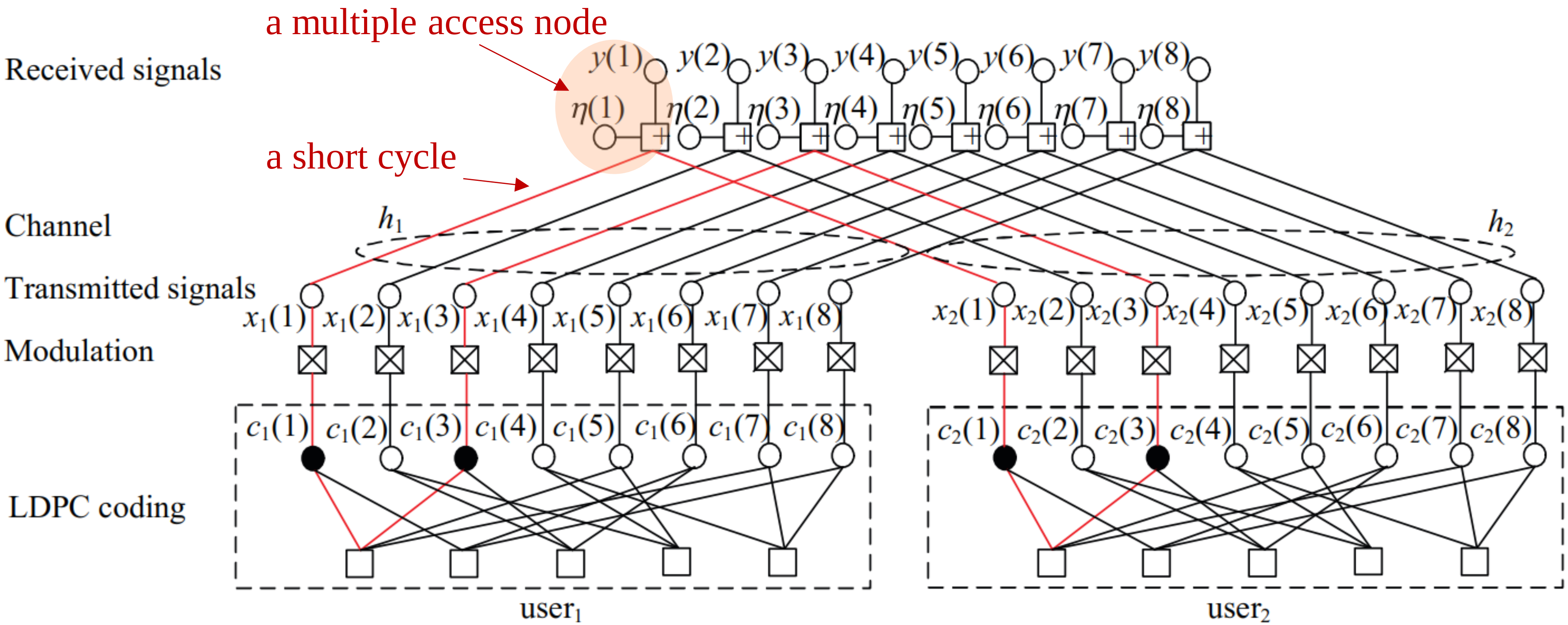
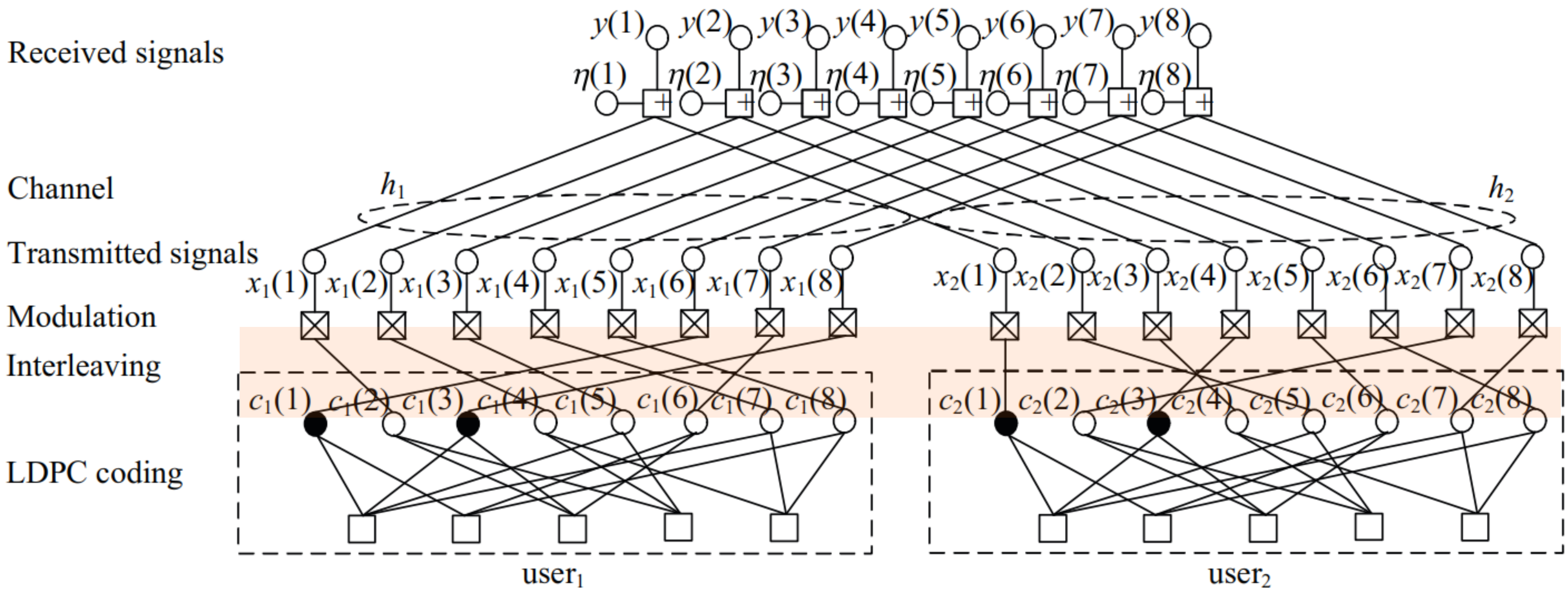
DS-CDMA on graph

- Spreading is equivalent to repetition coding. It can be part of FEC coding.
- Short cycles are detrimental to iterative decoding.

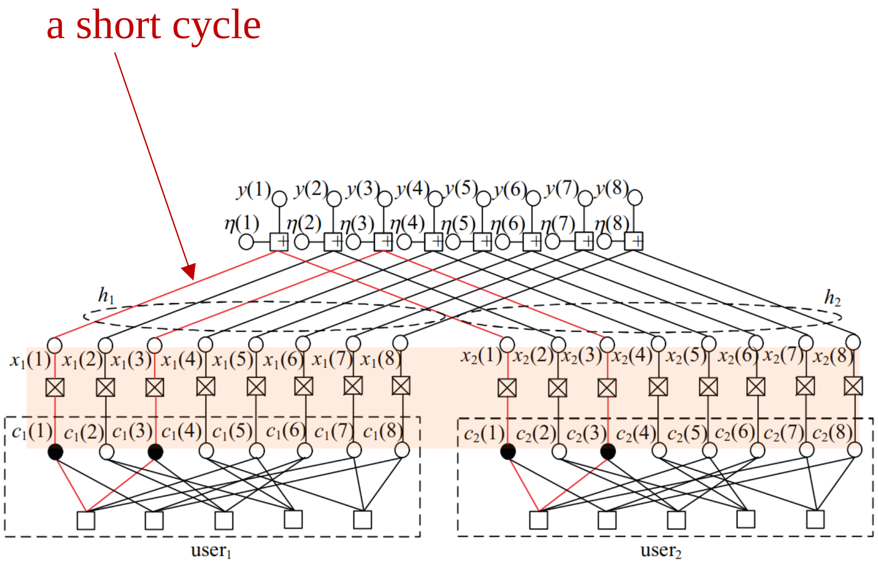


IDMA on graph

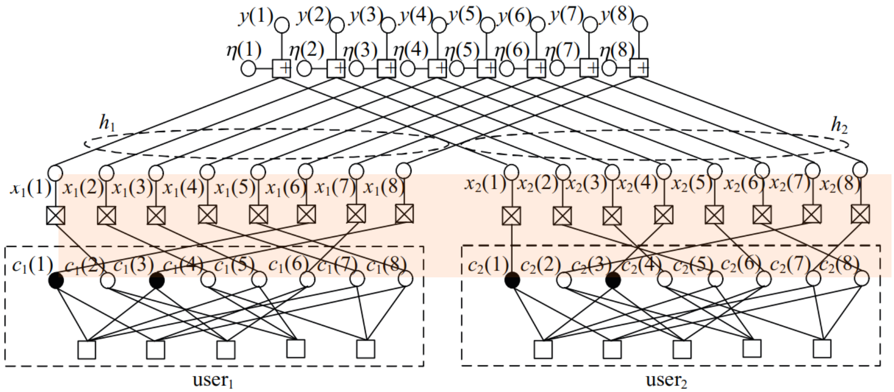
IDMA can be characterized by a sparse graph with randomized connections. Interleaving reduces short cycles in a statistical sense.



DS-CDMA vs IDMA on graph



DS-CDMA



IDMA

Iterative detection on graph

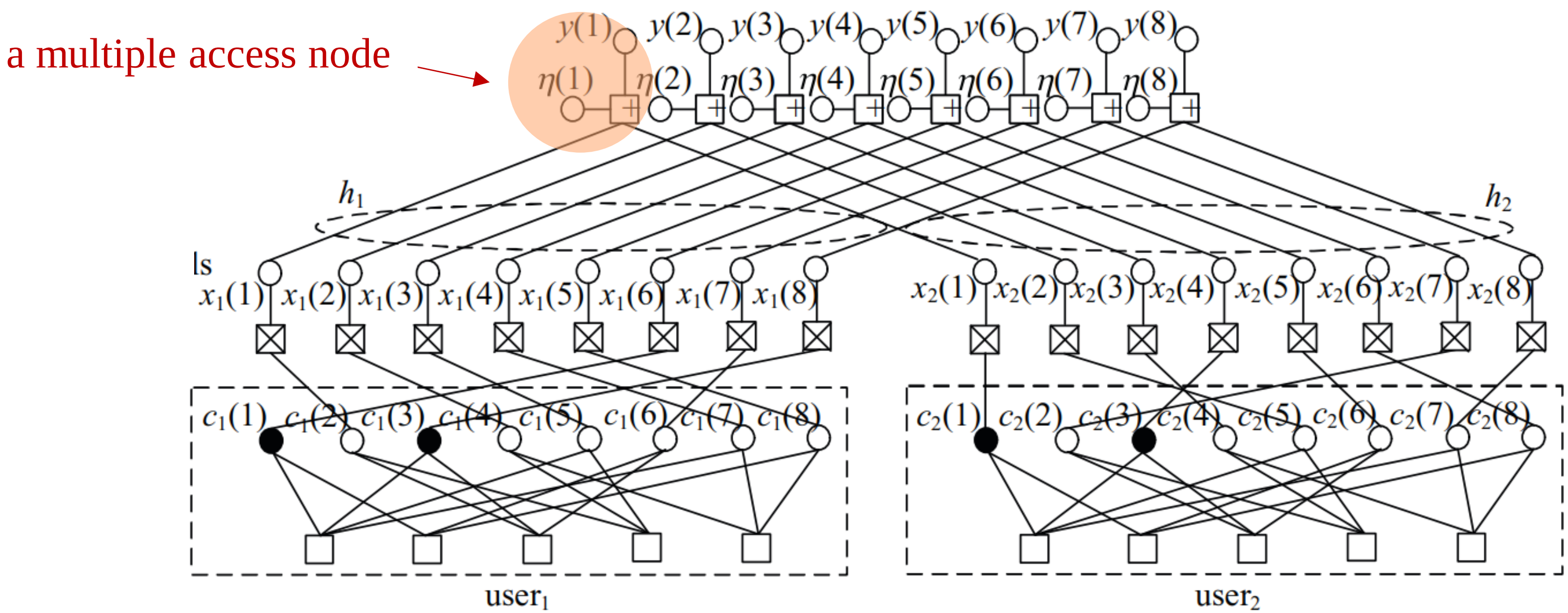
Message passing rules on a multiple access node can be based on

(1) optimal maximum likelihood (ML) estimation, or

(2) sub-optimal Gaussian approximation (GA) estimation.

The GA estimator has much lower cost.

The operations for other types of nodes are similar to those for LDPC codes.

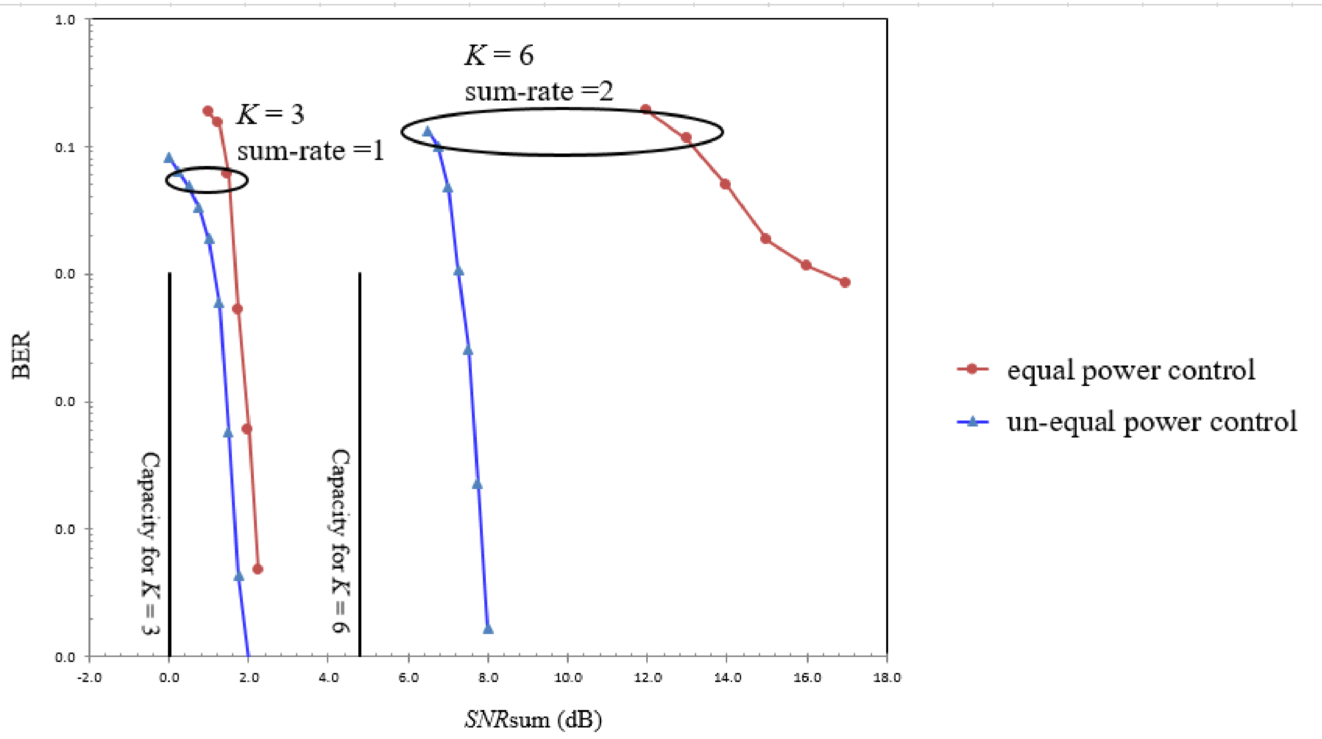


Li Ping, Lihai Liu and W. K. Leung, "A simple approach to near-optimal multiuser detection: interleave-division multiple access," *IEEE WCNC'03*.

Contents

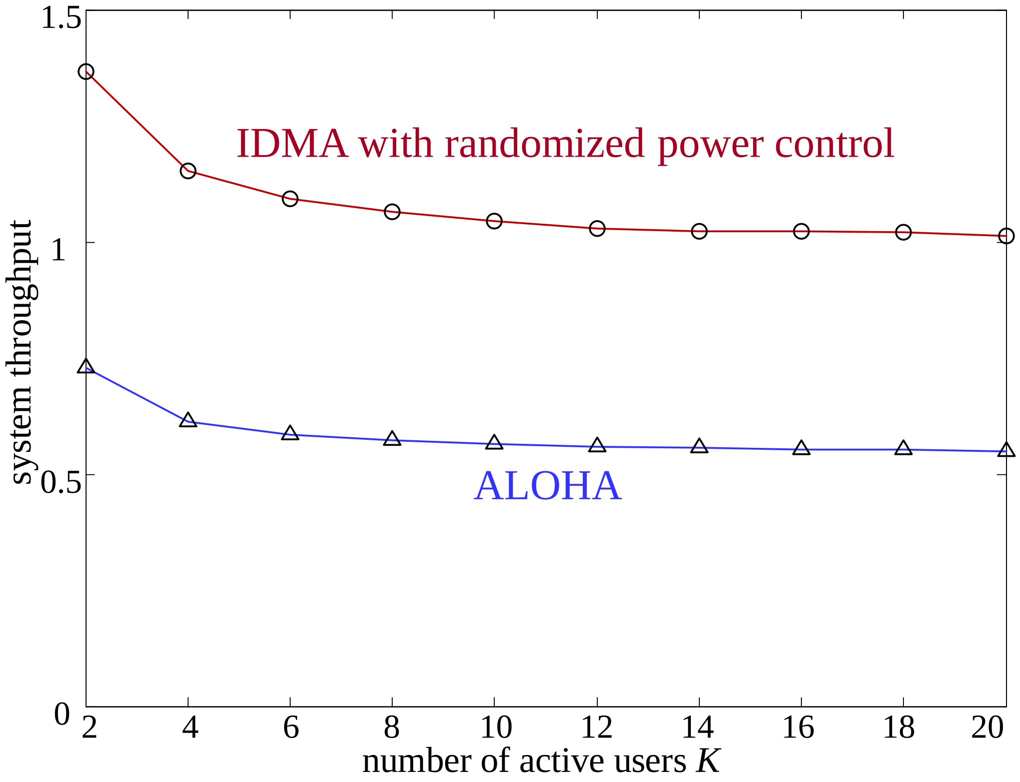
Centralized power control for IDMA

- For a small K, equal power is fine.
- For a large K, unequal power control is necessary. The principle is similar to SIC.



L. Liu, J. Tong and Li Ping, "Analysis and optimization of CDMA systems with chip- level interleavers" *IEEE Journal on Selected Areas in Communications*, 2007.

De-centralized power control for IDMA in random access channel

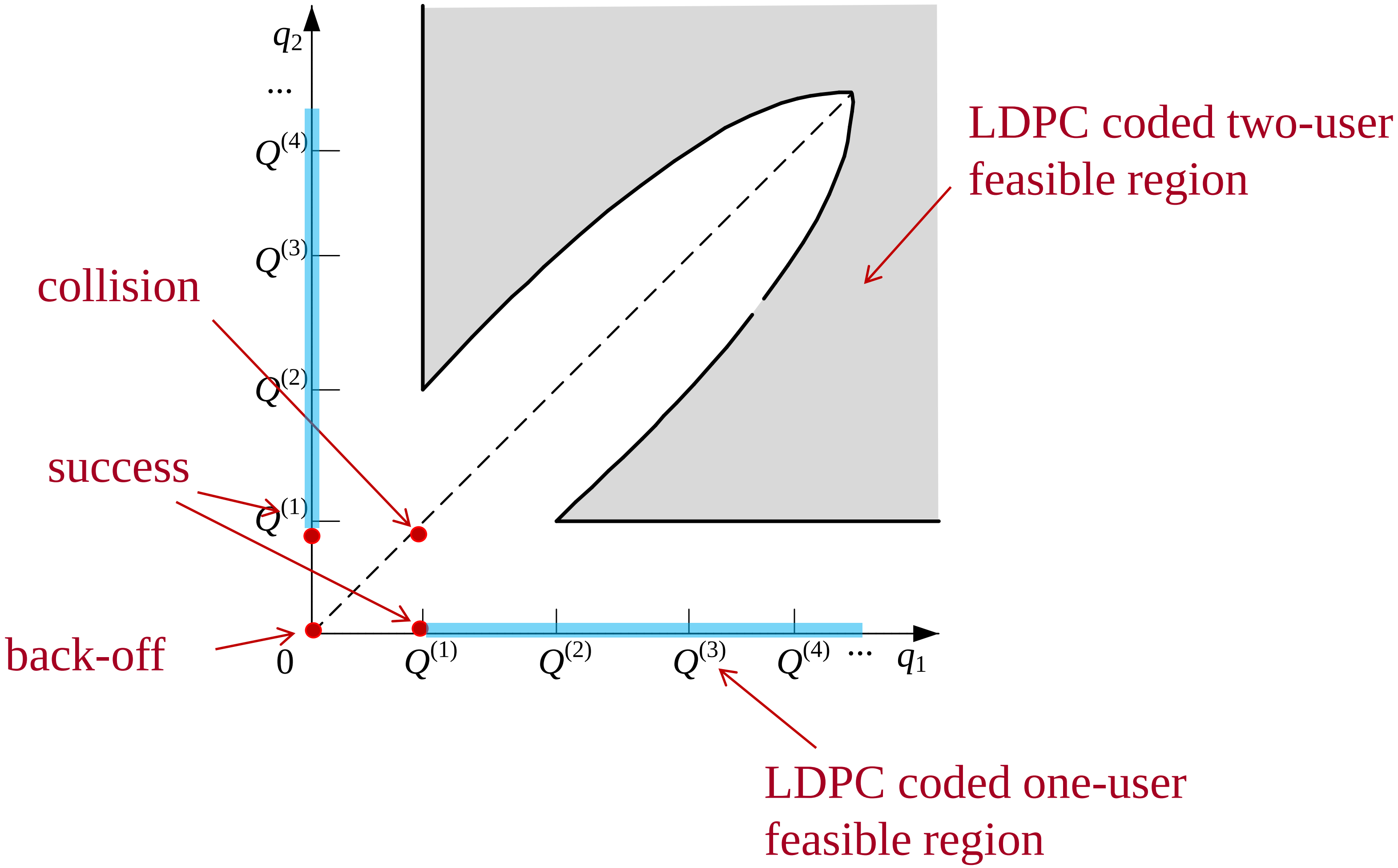


C. Xu, Li Ping, P. Wang, S. Chan, and X. Lin, "Decentralized Power Control for Random Access with Successive Interference Cancellation" *IEEE JSAC*, Nov. 2013.

C Xu, X. Wang and Li Ping, "Random access with massive-antenna arrays" *IEEE VTC* 2016.

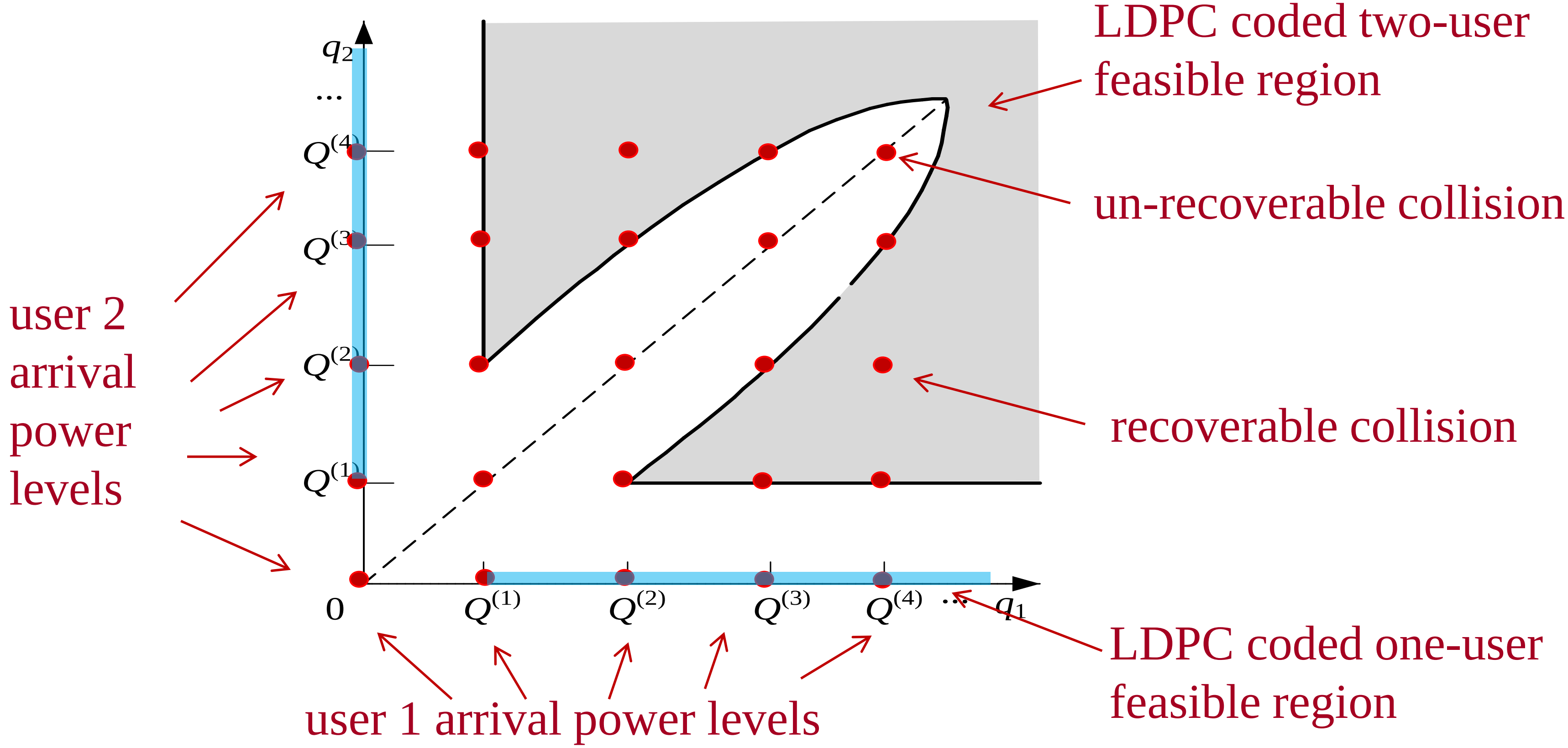
ALOHA

ALOHA only targets at one-user feasible region. Its throughput is very low.



IDMA with randomized power control (RPC)

We can enhance throughput using randomized power control to maximize the probability that arrival powers fall in the feasible region



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Potential schemes for 5G

Various approaches have been proposed for 5G, including

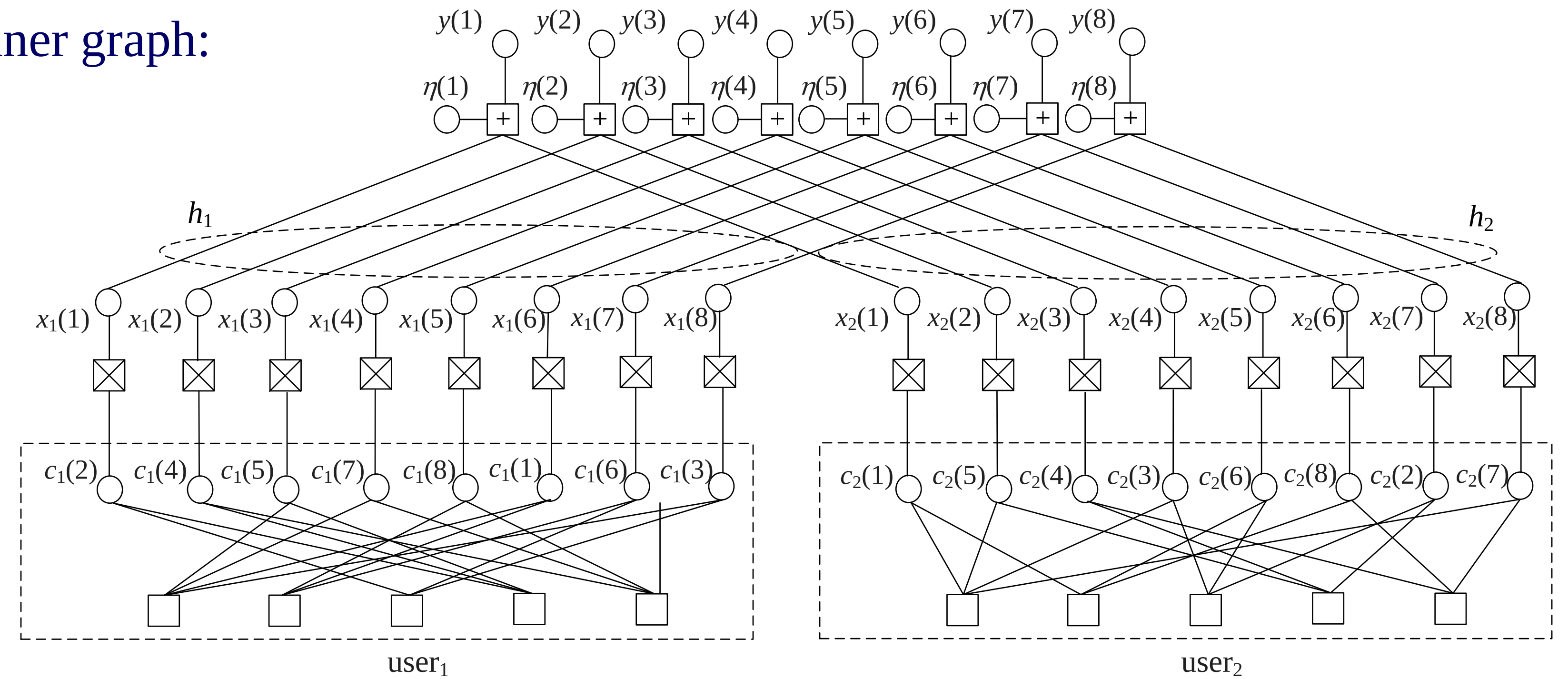
- IDMA by Nokia,
- IGMA by Samsung,
- PDMA by Datang
- RSMA by Qualcomm
- SCMA by Huawei.

All these proposals involve interleaved edge connections, similar to IDMA.

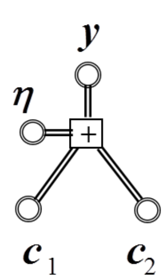
We will explain the rationales and connections of these schemes.

Protograph for IDMA

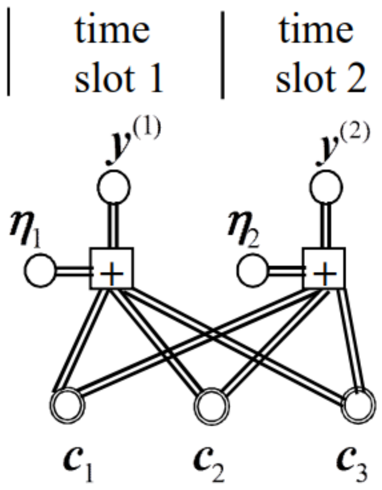
Tanner graph:



Protograph:

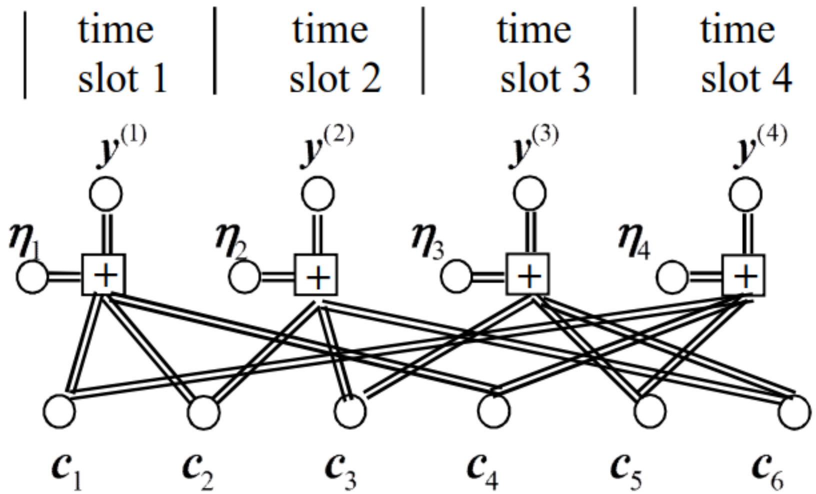


IDMA and LDS-CDMA



(a)

IDMA



(b)

SCMA, PDMA and IGMA

All these schemes rely on interleaved edge connections to avoid short cycles, which helps iterative detection.

Comparison of different schemes

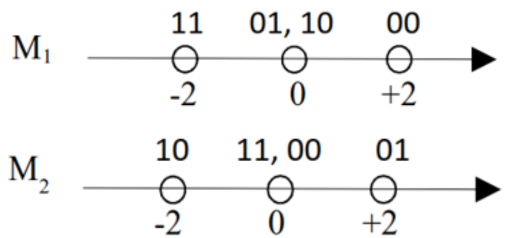
We observed similar performance among IDMA, PDMA and IGMA, which is expected since they all based on graphs with interleaved edge connections.

We will only briefly discuss SCMA and RSMA.

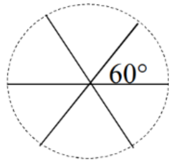
Sparse code multiple access (SCMA)

- SCMA is unique in its one-dimensional modulation.
- Such modulation requires phase control to separate the arrival phases of different users. Otherwise performance will deteriorate.
- Phase control requires a feedback link, which increases cost. Accuracy can also be a problem as phase changes faster than power.
- Phase control is also difficult in MIMO.

SCMA modulation constellation:



SCMA phase control:



The above modulation technique is based on the following paper (Fig. 3).

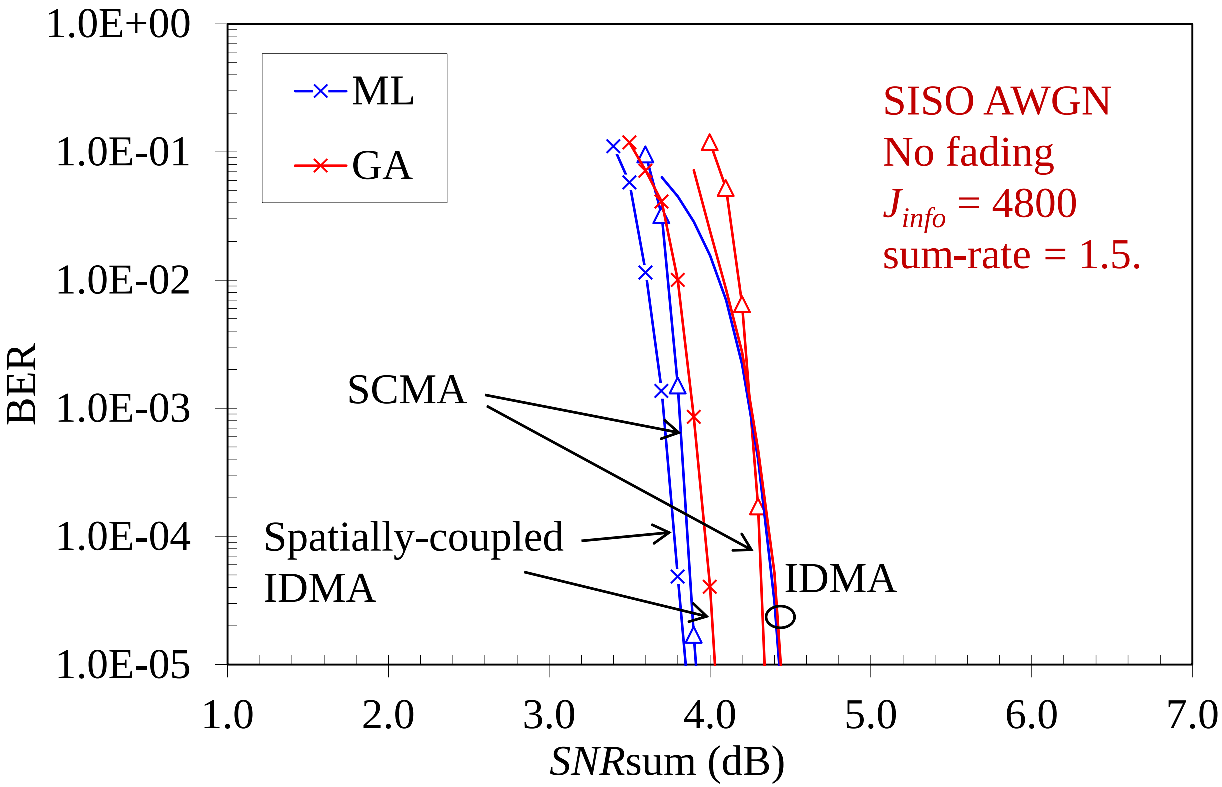
Y. Wu, S. Zhang, and Y. Chen. "Iterative multiuser receiver in sparse code multiple access systems." in *Proc. IEEE ICC*, 2015.

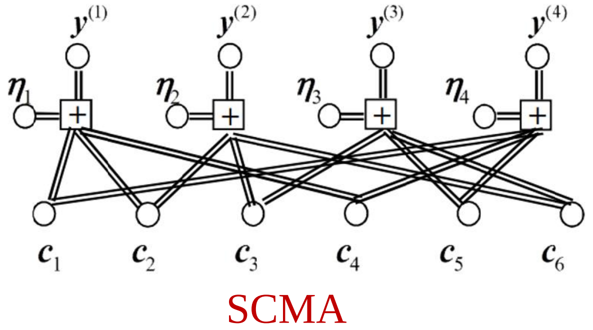
Phase control is mentioned in the following paper (the last sentence of Section III).

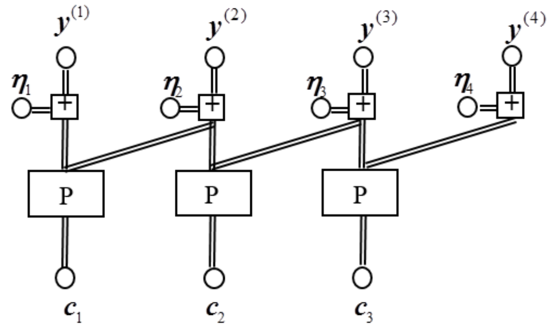
M. Taherzadeh, et al. "SCMA codebook design." in *Proc. IEEE VTC-Fall*, 2014.

Comparison of IDMA, SCMA and SC-IDMA

Complexity comparison: spatially coupled -IDMA ~ $O(16)$ vs SCMA ~ $O(64)$.







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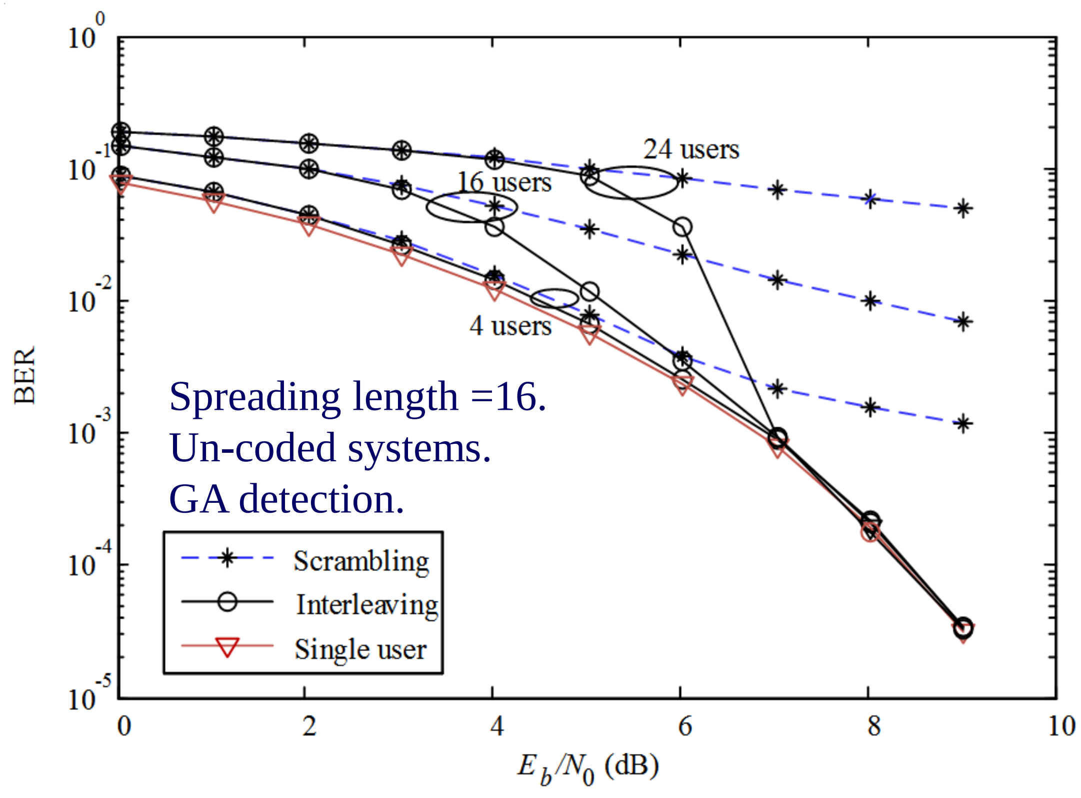
Interleaving vs scrambling



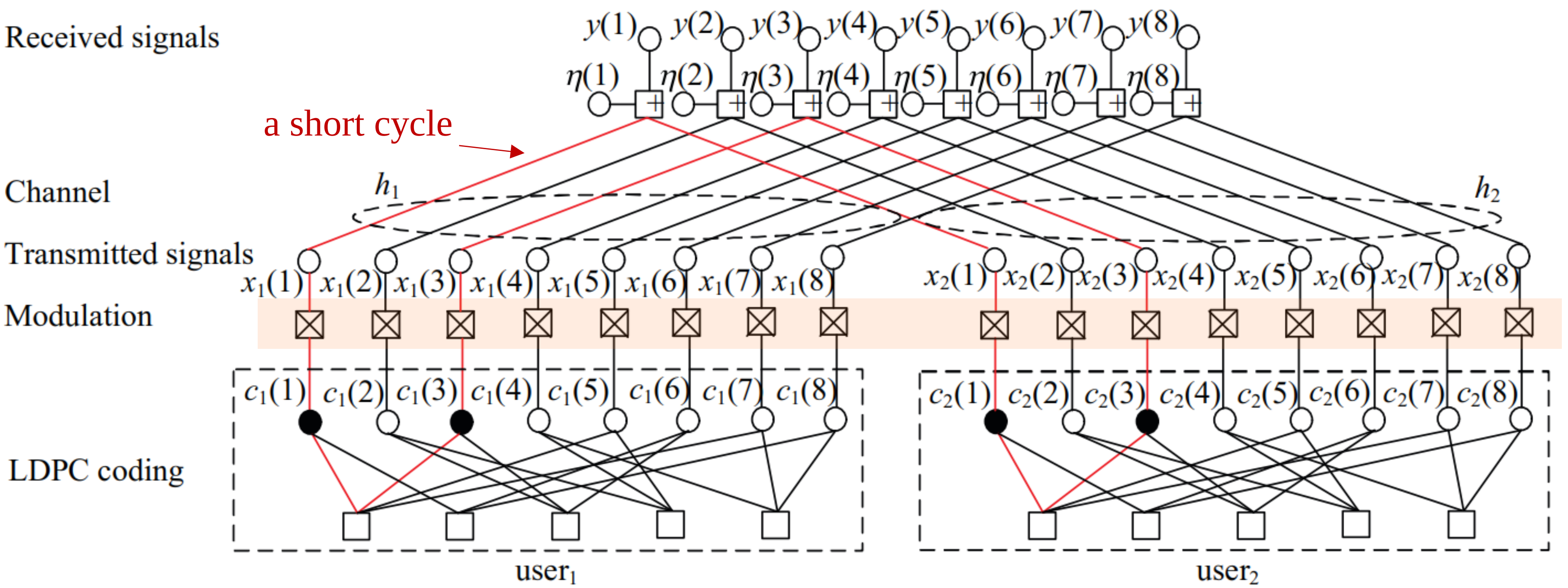
RSMA is based on scrambling, but with user-specific interleaving as an option.

Scrambling can be part of modulation. It cannot not help the short cycle problem.

Why scrambling does not work well?

Scrambling can be realized at the modulation nodes. However, scrambling cannot not help the short cycle problem.

User-specific interleaving is an option in RSMA.



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Conclusions

- IDMA is defined on a sparse graph. Interleaving facilitates iterative detection.
- IDMA can enhance performance in random access.
- Several 5G proposals are based on the same principle as IDMA: they all reply on interleaved edge connections to facilitate iterative multi-user detection.
- IDMA is also useful in MIMO (see C. Xu, et al, "Massive MIMO, Non-Orthogonal Multiple-Access and Interleave Division Multiple Access", *IEEE Access* July 2017.)

Software packages are available at:
http://www.ee.cityu.edu.hk/~liping/Research/Simulationpackage/