Index Modulation Techniques for 5G Wireless Networks

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From 4G to 5G

- The increasing demand for
  - ✓ higher data rates
  - ✓ better quality of service (QoS) and
  - ✓ fully mobile and connected wireless networks

- New solutions beyond 4G wireless systems are required.

- 5G wireless networks will achieve 10 times higher
  - ✓ spectral efficiency
  - ✓ energy efficiency

  than current 4G wireless networks and will support data rates up to 10 Gbps.

- Dramatic changes in the design of different layers for 5G communications systems are inevitable.

5G PHY Solutions

- Strong candidates for the physical layer design of 5G networks:
  - Massive multiple-input multiple-output (MIMO) systems
  - Filter bank multicarrier (FBMC) modulation,
  - Relaying technologies
  - Millimeter wave communications

- In this presentation, we deal with the potential and implementation of index modulation (IM) techniques for MIMO and multicarrier communications systems which are expected to be two of the key technologies for 5G systems.

- We focus on two promising applications of IM:
  - Spatial modulation (SM)
  - Orthogonal frequency division multiplexing with IM (OFDM-IM)

Index Modulation (IM) Concept

- IM is a novel digital modulation scheme with high spectral and energy efficiency.

- The indices of the building blocks of the considered communications systems are used to convey additional information bits.

- Two promising forms of the IM concept:
  - ✓ Spatial modulation (SM) → The indices of the transmit antennas of a MIMO system
  - ✓ OFDM with IM (OFDM-IM) → The indices of the subcarriers of of an OFDM system

- There has been a growing interest on IM techniques over the past few years

Spatial Modulation (SM)

- Pioneering works of Mesleh et al. and Jeganathan et al.

- Strong and well-established competitors such as vertical Bell Labs layered space-time (V-BLAST) and space-time coding (STC) systems.

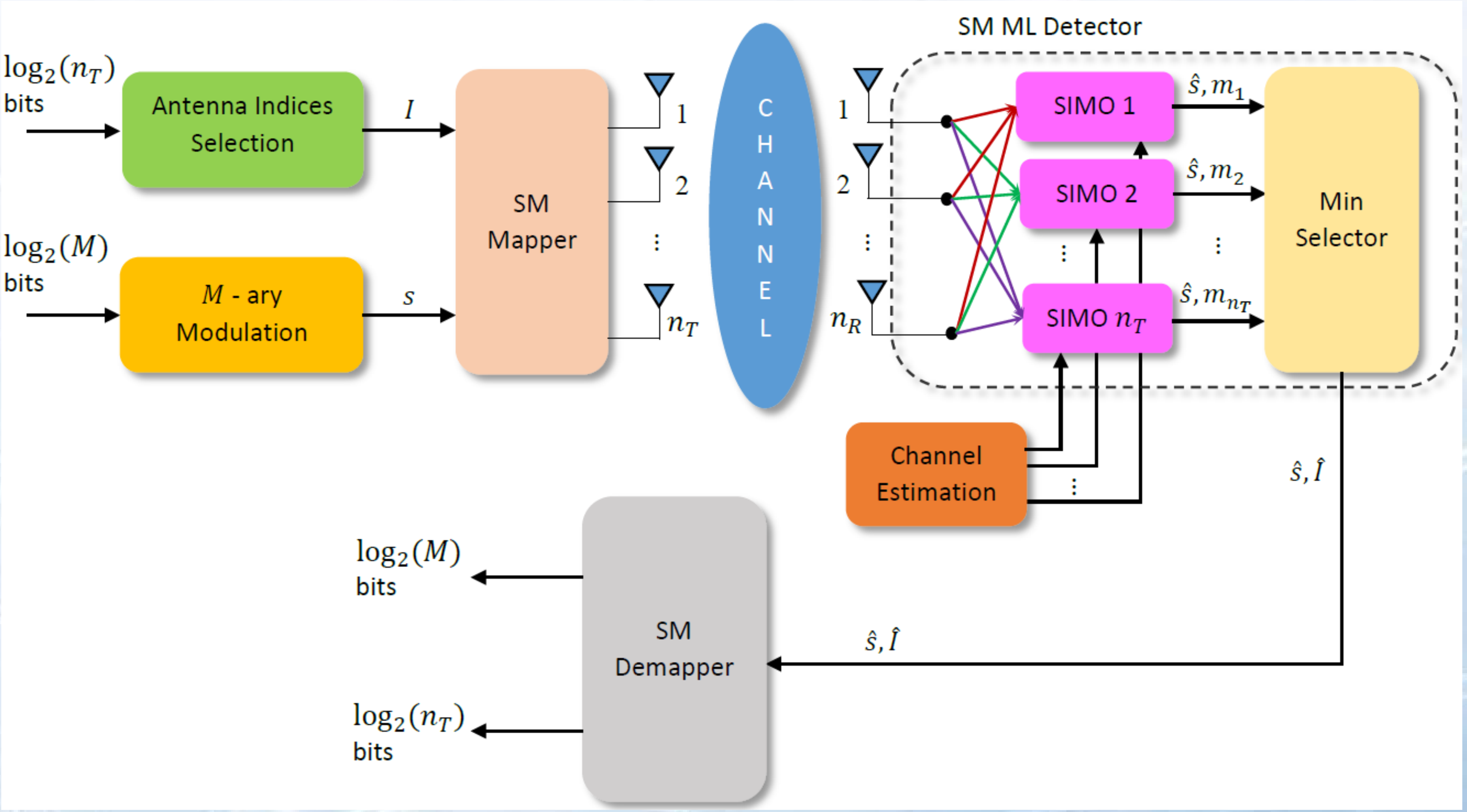
- SM schemes have been regarded as possible candidates for spectral and energy-efficient next generation MIMO systems.

- The multiple transmit antennas of a MIMO system are used for a different purpose in an SM scheme. More specifically, there are two information carrying units in SM:
  - indices of transmit antennas
  - M-ary constellation symbols.

R. Mesleh, H. Haas, S. Sinanovic, C. W. Ahn, and S. Yun, “Spatial modulation,” IEEE Trans. Veh. Technol., vol. 57, no. 4, pp. 2228–2241, Jul. 2008.

J. Jeganathan, A. Ghrayeb, L. Szczecinski, and A. Ceron, “Space shift keying modulation for MIMO channels,” IEEE Trans. Wireless Commun., vol. 8, no. 7, pp. 3692–3703, Jul. 2009.

SM Transceiver



Detection of SM

- The receiver of the SM scheme has two major tasks to accomplish:
  - detection of the active transmit antenna
  - detection of the data symbol transmitted over the activated transmit antenna.

- The optimum maximum likelihood (ML) detector of SM has to make a joint search over all transmit antennas and constellation symbols to perform these two tasks.

- The suboptimal detector of SM deals with the aforementioned two tasks one by one, i.e., first, it determines the activated transmit antenna, second, it finds the data symbol transmitted over this antenna.

Advantages of SM

- Simple transceiver design: Since only a single transmit antenna is activated, a single radio frequency (RF) chain can handle the transmission for the SM scheme.
- Inter-antenna synchronization (IAS) and inter-channel interference (ICI) are completely eliminated.
- Operation with flexible MIMO systems: SM does not restrict the number of receive antennas as the V-BLAST scheme.
- High spectral efficiency: Due to the use of antenna indices as an additional source of information, the spectral efficiency of SM is higher than that of single-input single-output (SISO) and orthogonal STC systems.
- High energy efficiency: The power consumed by the SM transmitter is independent from number of transmit antennas while information can be still transferred via these antennas. Therefore, SM appears as a green and energy-efficient MIMO technology.

Disadvantages of SM

- The spectral efficiency of SM increases logarithmically with n_T, while the spectral efficiency of V-BLAST increases linearly with n_T.

- The channel coefficients of different transmit antennas must be sufficiently different SM.

- Since SM transfers the information using only the spatial domain, plain SM cannot provide transmit diversity as STC systems.

- We may conclude that SM provides an interesting trade-off among complexity, spectral efficiency and error performance.

- SM has been regarded as a possible candidate for spectral and energy-efficient next generation wireless communications systems (Wang et al).

C.-X. Wang, F. Haider, X. Gao, X.-H. You, Y. Yang, D. Yuan, H. Aggoune, H. Haas, S. Fletcher, and E. Hepsaydir, “Cellular architecture and key technologies for 5G wireless communication networks,” IEEE Commun. Mag., vol. 52, no. 2, pp. 122–130, Feb. 2014.

Studies on SM

- The first studies on SM concept date back to the beginning of 2000s where different names were used by researchers. After the inspiring works of Mesleh et al. and Jeganathan et al., numerous papers on SM have been published.

- Some studies on SM:
  - ✓ Generalized, spectral and energy-efficient variations of SM
  - ✓ Low-complexity detector types
  - ✓ Block/trellis coded SM systems with transmit/time diversity
  - ✓ Adaptive modulation, transmit antenna selection and precoding,
  - ✓ Performance analysis for different fading channel types and channel estimation errors
  - ✓ Differential SM systems
  - ✓ Cooperative SM systems and so on.

M. Di Renzo, H. Haas, A. Ghrayeb, S. Sugiura, and L. Hanzo, “Spatial modulation for generalized MIMO: Challenges, opportunities, and implementation,” Proc. of the IEEE, vol. 102, no. 1, pp. 56–103, 2014.

P. Yang, M. Di Renzo, Y. Xiao, S. Li, and L. Hanzo, “Design guidelines for spatial modulation,” IEEE Commun. Surveys Tutorials, vol. 17, no. 1, pp. 6–26, First quarter 2015.

Generalized SM (GSM) Schemes

- GSM scheme → First attempt to not only increase the spectral efficiency of SM but also ease the constraint on number of transmit antennas.

- In the GSM scheme, more than one active transmit antennas are selected to transmit the same data symbol.

- Number of active transmit antennas: n_A
- Number of bits transmitted in spatial domain: $\left\lfloor \log_2 \binom{n_T}{n_A} \right\rfloor$

- Spectral efficiency (bpcu) : $\left\lfloor \log_2 \binom{n_T}{n_A} \right\rfloor + \log_2 M$

- Increasing the efficiency due to: $\log_2(n_T) \le \left\lfloor \log_2 \binom{n_T}{n_A} \right\rfloor$ for $n_T = 2^n (n = 1, 2, \ldots)$

A. Younis, N. Serafimovski, R. Mesleh, and H. Haas, “Generalised spatial modulation,” in (ASILOMAR), 2010 Asilomar Conf. Signals, Systems and Computers, Nov. 2010, pp. 1498–1502.

Multiple-Active SM (MA-SM)

- Extension of GSM.
- Different data symbols are transmitted from the selected transmit antennas to further boost the spectral efficiency.
- Spectral efficiency (bpcu) : $\left\lfloor \log_2 \binom{n_T}{n_A} \right\rfloor + n_A \log_2 M$
- MA-SM provides an intermediate solution between two extreme cases: SM and V-BLAST.
- Provides significantly higher spectral efficiency than classical SM.

J. Wang, S. Jia, and J. Song, “Generalised spatial modulation system with multiple active transmit antennas and low complexity detection scheme,” IEEE Trans. Wireless Commun., vol. 11, no. 4, pp. 1605–1615, Apr. 2012.

Enhanced SM (ESM)

- The ESM scheme considers multiple signal constellations and the information is transmitted by the combination of active transmit antennas and signal constellations.

- As an example, for two transmit antennas and four bpcu transmission, the ESM scheme transmits two bits by the joint selection of active transmit antennas and signal constellations.
- In this example, one QPSK and BPSK signal constellations (one ordinary and one rotated) can be used.

- Transmission vectors (for this example):

$$\{0,0\},\{0,1\},\{1,0\} \text{ and } \{1,1\} \rightarrow [\mathcal{S}_4 \quad 0]^{\mathrm{T}},[0 \quad \mathcal{S}_4]^{\mathrm{T}},[\mathcal{S}_2 \quad \mathcal{S}_2]^{\mathrm{T}} \text{ and } \left[\mathcal{S}_2 e^{j\theta} \quad \mathcal{S}_2 e^{j\theta}\right]^{\mathrm{T}}$$

$$\mathcal{S}_2 \rightarrow \text{BPSK}$$

$$\mathcal{S}_4 \rightarrow \text{QPSK}$$

$$\theta : \text{rotation angle}$$

C.-C. Cheng, H. Sari, S. Sezginer, and Y. Su, “Enhanced spatial modulation with multiple signal constellations,” IEEE Trans. Commun., vol. 63, no. 6, pp. 2237–2248, Jun. 2015.

Quadrature (SM)

- A clever modification of the classical SM to improve the spectral efficiency while maintaining its advantages such as operation with single RF chain and ICI free transmission.

- The real and imaginary parts of the complex *M*-ary data symbols are separately transmitted using the SM principle.

- Spectral efficiency (bpcu): $2\log_2(n_T) + \log_2(M)$

- Transmission vectors (for two transmit antennas):

$$\{0,0\},\{0,1\},\{1,0\} \text{ and } \{1,1\} \rightarrow [s_R + js_I \quad 0]^{\mathrm{T}}, [s_R \quad js_I]^{\mathrm{T}}, [js_I \quad s_R]^{\mathrm{T}} \text{ and } [0 \quad s_R + js_I]^{\mathrm{T}}$$

$$s_R \rightarrow \text{real part of } s$$

$$s_I \rightarrow \text{imaginary part of } s$$

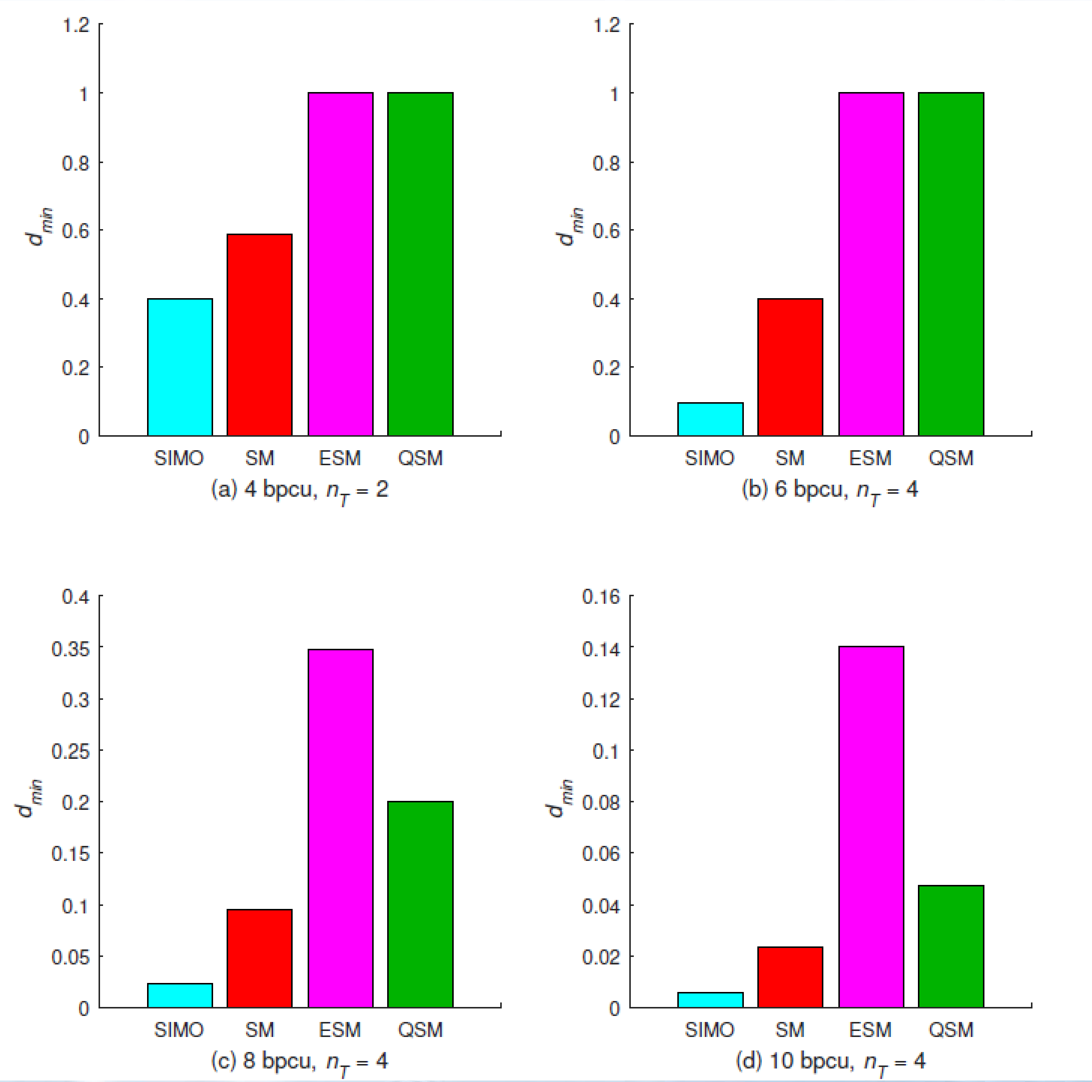
R. Mesleh, S. Ikki, and H. Aggoune, “Quadrature spatial modulation,” IEEE Trans. Vehicular Tech., vol. 64, no. 6, pp. 2738–2742, Jun. 2015.

Transmission Vectors for SM, ESM and QSM

TRANSMISSION VECTORS ($\mathbf{x}^T$) OF SM, ESM AND QSM SCHEMES FOR 4 BPCU AND TWO TRANSMIT ANTENNAS ($n_T = 2$), RED BITS INDICATE THE SINGLE BIT TRANSMITTED BY THE SPATIAL DOMAIN FOR SM, BLUE BITS INDICATE THE ADDITIONAL ONE BIT TRANSMITTED BY THE SPATIAL DOMAIN FOR ESM AND QSM

Bits	SM	ESM	QSM	Bits	SM	ESM	QSM
0000	$[1 \;\; 0]$	$[\frac{1+j}{\sqrt{2}} \;\; 0]$	$[\frac{1+j}{\sqrt{2}} \;\; 0]$	1000	$[0 \;\; 1]$	$[\frac{1}{\sqrt{2}} \;\; \frac{1}{\sqrt{2}}]$	$[\frac{j}{\sqrt{2}} \;\; \frac{1}{\sqrt{2}}]$
0001	$[\frac{1+j}{\sqrt{2}} \;\; 0]$	$[\frac{-1+j}{\sqrt{2}} \;\; 0]$	$[\frac{-1+j}{\sqrt{2}} \;\; 0]$	1001	$[0 \;\; \frac{1+j}{\sqrt{2}}]$	$[\frac{1}{\sqrt{2}} \;\; \frac{-1}{\sqrt{2}}]$	$[\frac{j}{\sqrt{2}} \;\; \frac{-1}{\sqrt{2}}]$
0010	$[j \;\; 0]$	$[\frac{-1-j}{\sqrt{2}} \;\; 0]$	$[\frac{-1-j}{\sqrt{2}} \;\; 0]$	1010	$[0 \;\; j]$	$[\frac{-1}{\sqrt{2}} \;\; \frac{1}{\sqrt{2}}]$	$[\frac{-j}{\sqrt{2}} \;\; \frac{-1}{\sqrt{2}}]$
0011	$[\frac{-1+j}{\sqrt{2}} \;\; 0]$	$[\frac{1-j}{\sqrt{2}} \;\; 0]$	$[\frac{1-j}{\sqrt{2}} \;\; 0]$	1011	$[0 \;\; \frac{-1+j}{\sqrt{2}}]$	$[\frac{-1}{\sqrt{2}} \;\; \frac{-1}{\sqrt{2}}]$	$[\frac{-j}{\sqrt{2}} \;\; \frac{1}{\sqrt{2}}]$
0100	$[-1 \;\; 0]$	$[0 \;\; \frac{1+j}{\sqrt{2}}]$	$[\frac{1}{\sqrt{2}} \;\; \frac{j}{\sqrt{2}}]$	1100	$[0 \;\; -1]$	$[\frac{j}{\sqrt{2}} \;\; \frac{j}{\sqrt{2}}]$	$[0 \;\; \frac{1+j}{\sqrt{2}}]$
0101	$[\frac{-1-j}{\sqrt{2}} \;\; 0]$	$[0 \;\; \frac{-1+j}{\sqrt{2}}]$	$[\frac{-1}{\sqrt{2}} \;\; \frac{j}{\sqrt{2}}]$	1101	$[0 \;\; \frac{-1-j}{\sqrt{2}}]$	$[\frac{j}{\sqrt{2}} \;\; \frac{-j}{\sqrt{2}}]$	$[0 \;\; \frac{-1+j}{\sqrt{2}}]$
0110	$[-j \;\; 0]$	$[0 \;\; \frac{-1-j}{\sqrt{2}}]$	$[\frac{-1}{\sqrt{2}} \;\; \frac{-j}{\sqrt{2}}]$	1110	$[0 \;\; -j]$	$[\frac{-j}{\sqrt{2}} \;\; \frac{j}{\sqrt{2}}]$	$[0 \;\; \frac{-1-j}{\sqrt{2}}]$
0111	$[\frac{1-j}{\sqrt{2}} \;\; 0]$	$[0 \;\; \frac{1-j}{\sqrt{2}}]$	$[\frac{1}{\sqrt{2}} \;\; \frac{-j}{\sqrt{2}}]$	1111	$[0 \;\; \frac{1-j}{\sqrt{2}}]$	$[\frac{-j}{\sqrt{2}} \;\; \frac{-j}{\sqrt{2}}]$	$[0 \;\; \frac{1-j}{\sqrt{2}}]$

Min. Squared Euclidean Distance Comparison



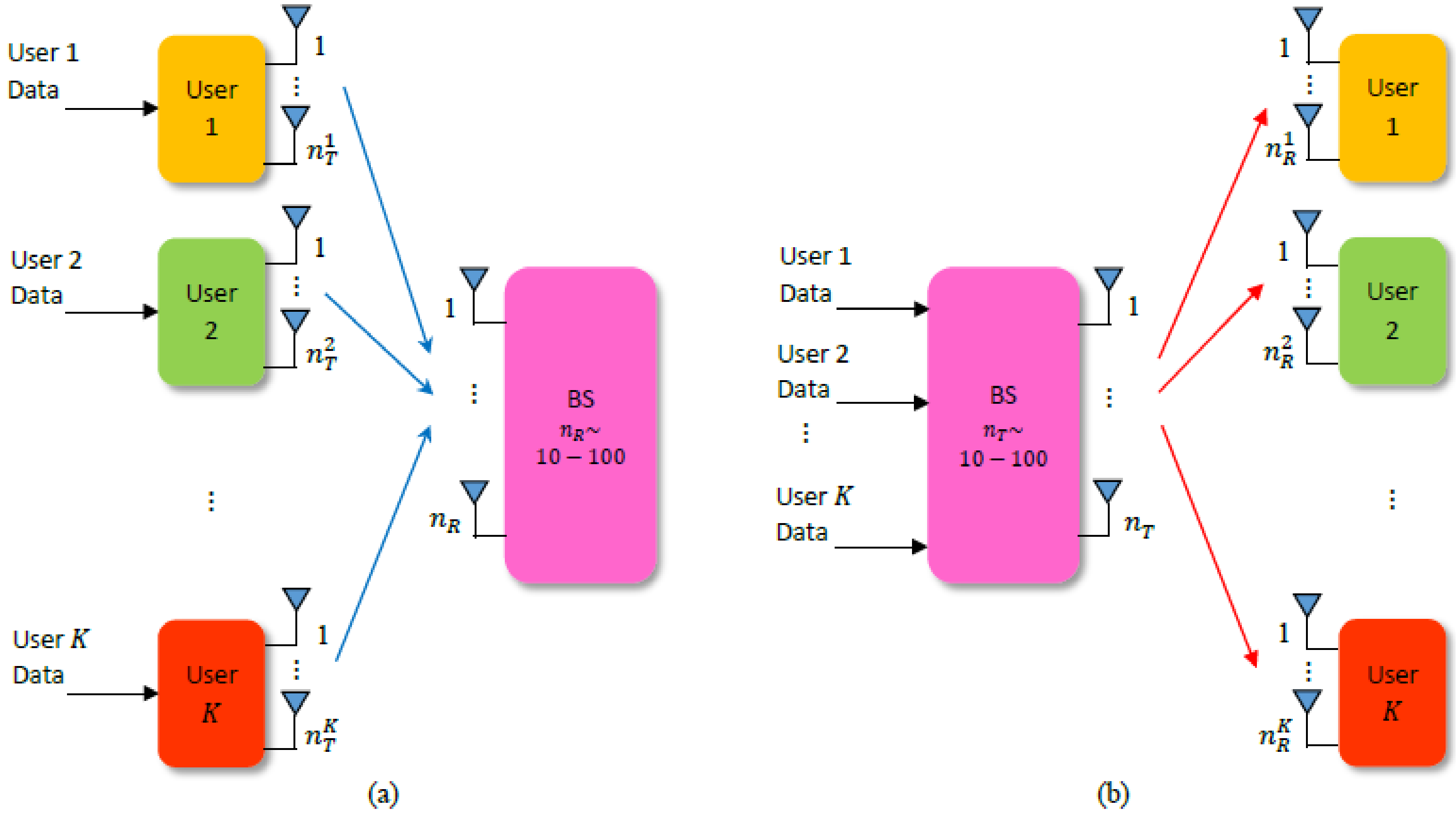
Massive Multi-user MIMO Systems with SM

- Massive MIMO concept, in which the base stations (BS) have tens to hundreds of antennas, is considered one of the potential key technologies for 5G wireless networks since it provides very high spectral and energy efficiency.
- The extension of MIMO systems into massive scale provides unique opportunities for SM systems.
- It becomes possible to transmit higher number of information bits by the spatial domain with massive MIMO systems.
- Spectral efficiency of SM cannot compete with that of V-BLAST for massive MIMO systems.
- A cheap, easy and efficient implementation solution for massive MIMO → SM

D. Basnayaka, M. Di Renzo, and H. Haas, “Massive but few active MIMO,” IEEE Trans. Vehicular Tech., vol. PP, no. 99, pp. 1–17, Oct. 2015.

S. Narayanan, M. Chaudhry, A. Stavridis, M. Di Renzo, F. Graziosi, and H. Haas, “Multi-user spatial modulation MIMO,” in IEEE Wireless Commun. Netw.Conf., 2014, pp. 671–676.

Implementation Scenarios



Massive MU-MIMO systems with SM (a) An uplink transmission scenario where User k has n_T^k transmit antennas available for SM and the BS has $n_R \sim 10-100$ receive antennas, (b) A downlink transmission scenario where User k has n_R^k receive antennas $(k = 1, 2, \ldots, K)$ and the BS has $n_T \sim 10-100$ transmit antennas available for SM.

Cooperative SM Systems

- Cooperative communications → allows the transmission of a user's data not only by its own antenna, but also by the active or passive nodes available in the network.

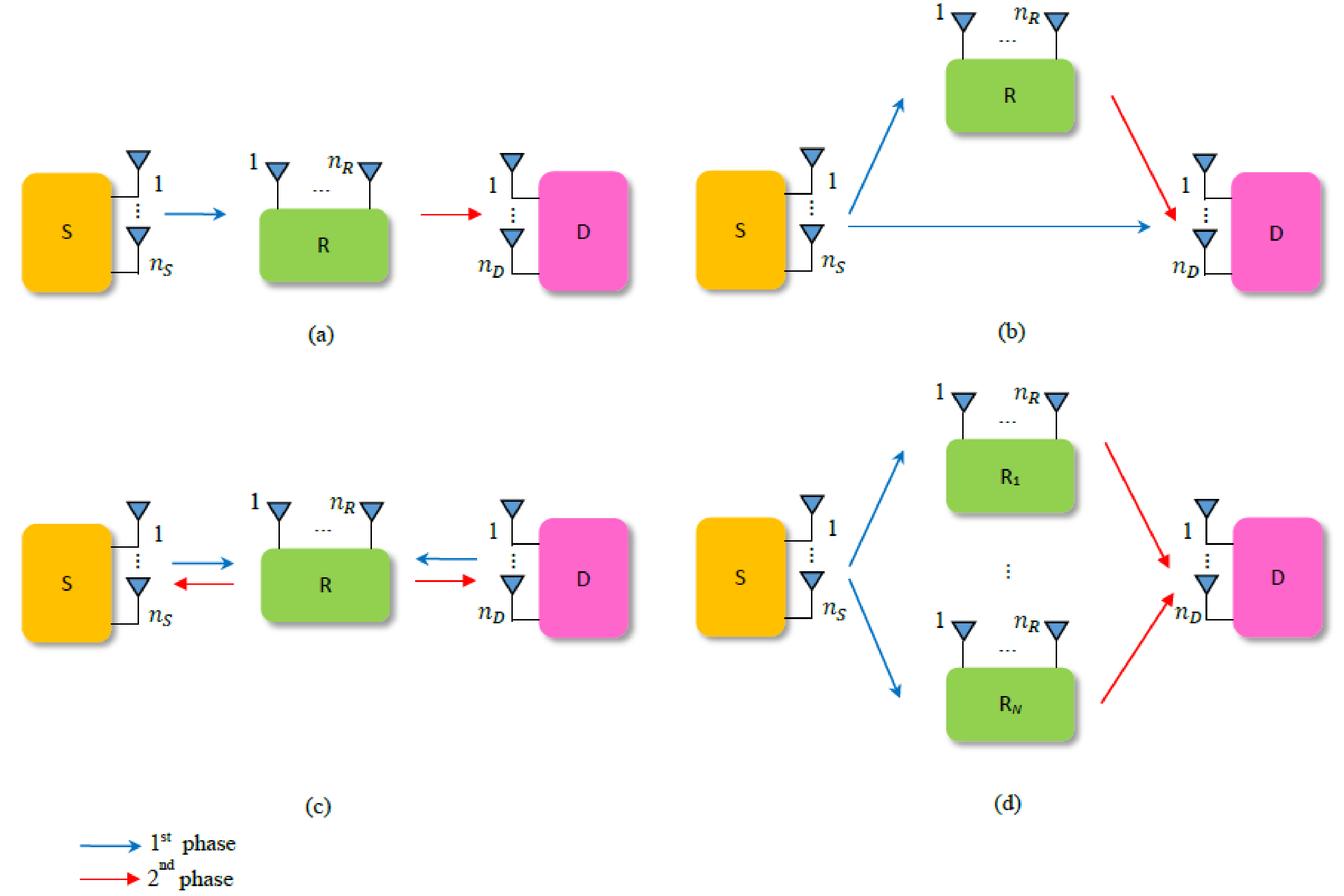
- Initially, cooperative communication systems have been proposed to create virtual MIMO systems for the mobile terminals due to the problems such as cost and hardware.

- However, more than one antennas can be employed at mobile terminals today, and cooperative communications systems can efficiently provide additional diversity gains and high data rates by improving coverage (as in LTE-A).

- Considering the effective solutions provided by SM techniques and cooperative communications systems, the combination of these two technologies naturally arises as a potential candidate for future wireless networks.

M. Di Renzo, S. Narayanan, F. Graziosi, and H. Haas, "Distributed spatial modulation: A cooperative diversity protocol for half–duplex relay–aided wireless networks," IEEE Trans. Vehicular Tech., vol. PP, no. 99, pp. 1–18, Jun. 2015.

Implementation Scenarios



An overview of cooperative SM systems (a) Dual-hop SM (b) Cooperative SM (c) Network-coded SM (d) Multi-relay and distributed SM. n_S, n_R and n_D denote the number of transmit and/or antennas for source (S), relay (R) and destination (D) nodes, respectively.

OFDM with Index Modulation (OFDM-IM)

- IM concept for OFDM subcarriers.

- (OFDM-IM) is a novel multicarrier transmission scheme which has been proposed by inspiring from the IM concept of SM.

- Only a subset of available subcarriers are selected as active, while the remaining inactive subcarriers are not used and set to zero.

- The information is conveyed not only by the data symbols as in classical OFDM, but also by the indices of the active subcarriers which are used for the transmission of the corresponding data symbols.

E. Basar, U . Aygolu, E. Panayırcı, and H. V. Poor, “Orthogonal frequency division multiplexing with index modulation,” IEEE Trans. Signal Process., vol. 61, no. 22, pp. 5536–5549, Nov. 2013.

How to Select the Active Indices of Subcarriers ?

- One can directly select the indices of active subcarriers similar to IM technique used for the transmit antennas of an MA-SM system.

- Actually, OFDM-IM can be thought as a massive MA-SM scheme where we deal with OFDM subcarriers instead of transmit antennas.

- However, keeping in mind that FFT size can take very large values, such as 512, 1024 or 2048 as in LTE-A standard, there could be trillions of (actually more than a googol (10^{100}) in mathematical terms) possible combinations for active subcarriers if index selection is applied directly.

- Example:
  - FFT size = 512, Number of active subcarriers = 256
  - Number of possible different combinations of active subcarriers = 472.55×10^{150}
  - An impossible task !!!

Active Indices Selection for OFDM Subcarriers

- Divide and conquer approach

- For the implementation of OFDM-IM, the single and massive OFDM-IM block should be divided into G smaller and manageable OFDM-IM subblocks each containing N subcarriers to perform IM. FFT size = $G \times N$

- For each subblock, K out of N available subcarriers can be selected as active according to

  $p_1 = \left\lfloor \log_2 \binom{N}{K} \right\rfloor$ data bits.

- Typical N values could be 2, 4, 8, 16 and 32.

- Please note that classical OFDM becomes a special case of OFDM-IM with $K = N$, i.e., when all subcarriers are activated.

Two Different Index Selection Procedures

	bits	*indices*	
$N = 4, K = 2,$ $\binom{4}{2} = 6$ $\Rightarrow p_1 = 2$ bits	$\{00\},\{01\},\{10\},\{11\}$	$[1\ \ 3]^{\mathrm{T}}, [2\ \ 4]^{\mathrm{T}}, [1\ \ 4]^{\mathrm{T}}, [2\ \ 3]^{\mathrm{T}}$	Reference Look-up Table
$N = 32, K = 16,$ $\binom{32}{16} = 601,080,390$ $\Rightarrow p_1 = 29$ bits	$\{0\,1\,0\,0\,0\,0\,1\,1\,0\,1\,0\,0\,0\,1$ $1\,0\,0\,0\,1\,1\,1\,0\,1\,1\,0\,0\,0\,1\,0\}$	$[29\ \ 28\ \ 27\ \ 26\ \ 25\ \ 19$ $17\ \ 16\ \ 15\ \ 14\ \ 13\ \ 12$ $11\ \ 8\ \ 4\ \ 2]^{\mathrm{T}}$	Combinatorial Number Theory

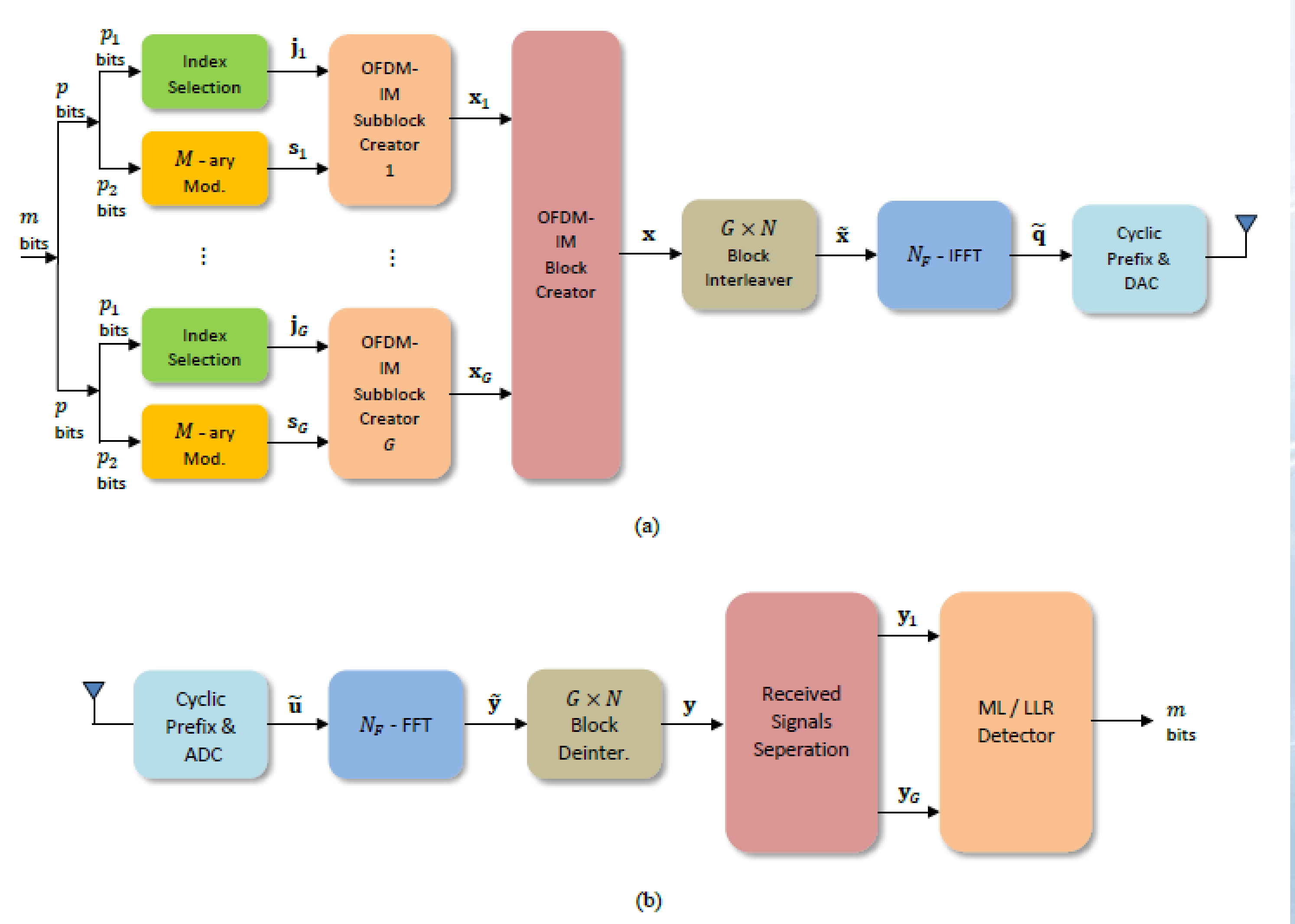
OFDM-IM Transceiver

$$m = pG = \left(\left\lfloor \log_2 \binom{N}{K} \right\rfloor + K \log_2 M \right) G$$

$$p_1 = \left\lfloor \log_2 \binom{N}{K} \right\rfloor$$

$$p_2 = K \log_2 M$$

$$p = p_1 + p_2$$



Detection of OFDM-IM

- Similar to SM, the receiver of OFDM-IM has to determine the active subcarriers and the corresponding data symbols in accordance with the index selection procedure used at the transmitter.
- After applying inverse operations, first, the received signals are separated since the detection of different subblocks can be carried out independently.
- The optimum but high-complexity ML detector makes a joint search over possible subcarrier activation combinations and data symbols.
- The low-complexity log-likelihood ratio (LLR) calculation based near-optimal detector determines the indices of the active subcarriers first, then, it detects the corresponding data symbols.

Advantages of OFDM-IM

- OFDM-IM provides an interesting trade-off between error performance and spectral efficiency.
- Unlike classical OFDM, the number of active subcarriers of an OFDM-IM scheme can be adjusted accordingly to reach the desired spectral efficiency and/or error performance.
- OFDM-IM can provide better bit error rate (BER) performance than classical OFDM for low-to-mid spectral efficiency values.
- OFDM-IM exhibits comparable decoding complexity using the near-optimal LLR detector.
- OFDM-IM also outperforms the classical OFDM in terms of ergodic achievable rate.
- We conclude that OFDM-IM can be a possible candidate not only for high-speed wireless communications systems but also for machine-to-machine (M2M) communications systems of 5G wireless networks which require low power consumption.

Recent Advances in OFDM-IM

- Subcarrier IM concept for OFDM has attracted significant attention from the researchers in recent times.

- It has been investigated in some up-to-date studies which deal with
  - ✓ the error performance and capacity analysis
  - ✓ generalization, enhancement and optimization of OFDM-IM,
  - ✓ Diversity methods and integration to MIMO systems.
  - ✓ Its adaptation to different wireless environments.

Y. Ko, “A tight upper bound on bit error rate of joint OFDM and multicarrier index keying,” IEEE Commun. Lett., vol. 18, no. 10, pp. 1763– 1766, Oct. 2014.

Y. Xiao, S. Wang, L. Dan, X. Lei, P. Yang, and W. Xiang, “OFDM with interleaved subcarrier-index modulation,” IEEE Commun. Lett., vol. 18, no. 8, pp. 1447–1450, Aug. 2014.

M. Wen, X. Cheng, M. Ma, B. Jiao, and H. Poor, “On the achievable rate of OFDM with index modulation,” IEEE Trans. Signal Process., vol. PP, no. 99, pp. 1–33, Nov. 2015.

E. Basar, “OFDM with index modulation using coordinate interleaving,” IEEE Wireless Commun. Lett., vol. 4, no. 4, pp. 381–384, Aug. 2015.

E. Basar, “Multiple-input multiple-output OFDM with index modulation,” IEEE Signal Process. Lett., vol. 22, no. 12, pp. 2259–2263, Dec. 2015.

R. Fan, Y. Yu, and Y. Guan, “Generalization of orthogonal frequency division multiplexing with index modulation,” IEEE Trans Wireless Commun., vol. 14, no. 10 pp 5350-5359, Oct. 2015.

Generalized OFDM-IM Schemes

- Two generalized OFDM-IM structures (OFDM-GIM-I and OFDM-GIM-II) have been recently proposed.

- In OFDM-GIM-I scheme, the number of active subcarriers are no longer fixed and it is also determined according to the information bits.

- The OFDM-GIM-I scheme can provide more flexibility for the selection of active subcarriers and can transmit more bits per subblock compared to OFDM-IM.

- Example: N=4, K=2, BPSK modulation (M=2)
  - Bits per subblock of OFDM-IM: $\left\lfloor \log_2 \binom{4}{2} \right\rfloor + 2\log_2(M) = 4$
  - Bits per subblock of OFDM-GIM-I: $\sum_{k=0}^{N} \binom{N}{k} M^k = 81, \quad \lfloor \log_2(81) \rfloor = 6$

Generalized OFDM-IM Schemes (con't)

- The OFDM-GIM-II scheme aims to further improve the spectral efficiency by applying IM independently for in-phase and quadrature components of the complex data symbols similar to the QSM scheme.

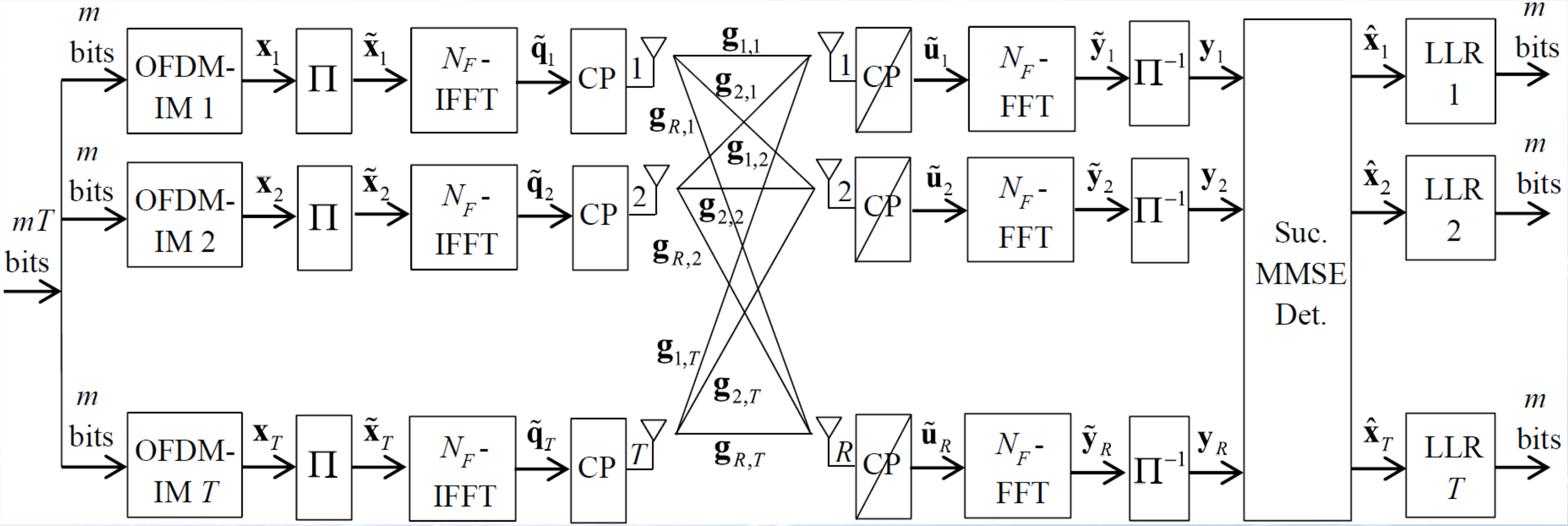
- Example: N=16, K=10, QPSK modulation (M=4)
  - Bits per subblock of OFDM-IM: $\left\lfloor \log_2 \binom{16}{10} \right\rfloor + 10\log_2(M) = 32$
  - Bits per subblock of OFDM-GIM-II: $\left\lfloor \log_2 \left(\binom{16}{10} (\sqrt{M})^K \times \binom{16}{10} (\sqrt{M})^K \right) \right\rfloor = 44$

- Please note that the in-phase and quadrature components of a complex M-QAM symbol are the elements of a $\sqrt{M}$- ary pulse amplitude modulation (PAM) constellation, where a total of $\binom{N}{K} \times (\sqrt{M})^K$ realizations are possible per each component.

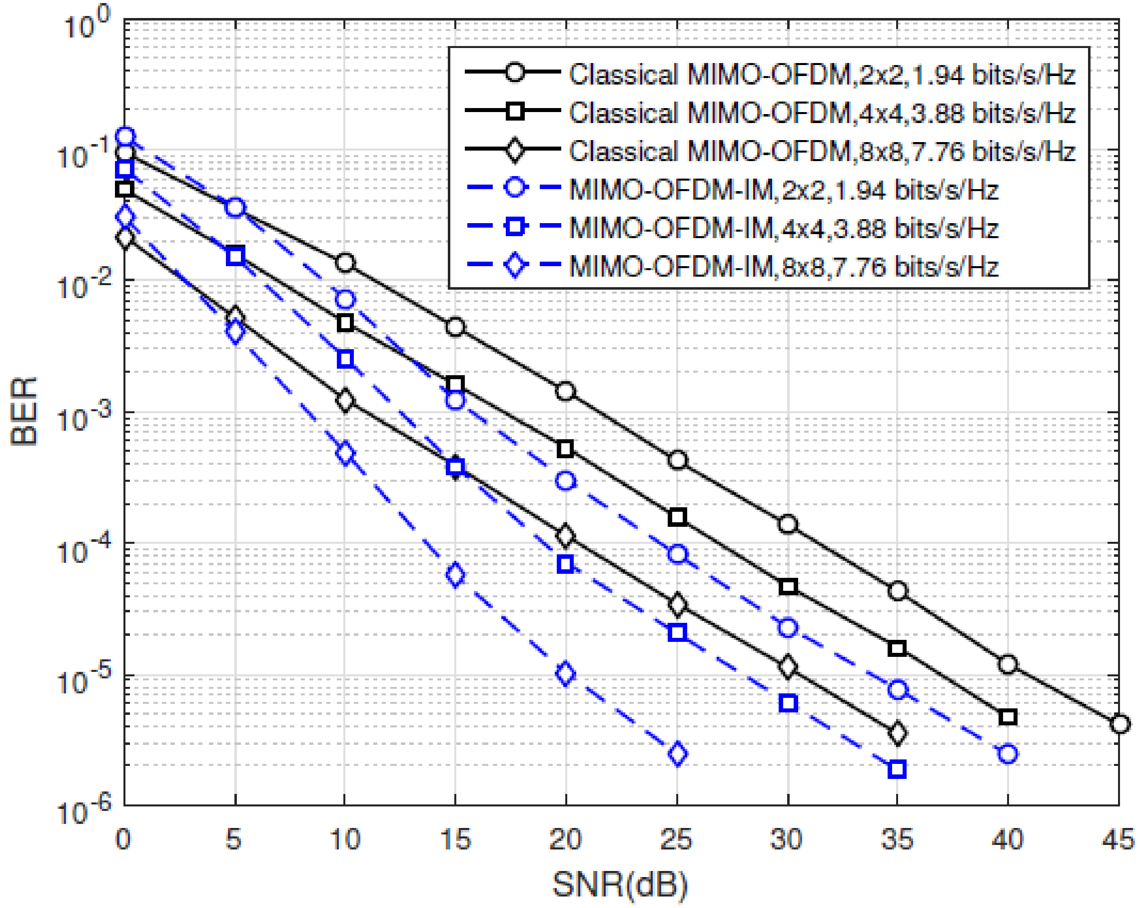
From SISO-OFDM-IM to MIMO-OFDM-IM

- The first studies on OFDM-IM generally focused on point-to-point single-input single-output (SISO) systems, which can be unsuitable for some applications due to their limited spectral efficiency.
- MIMO transmission and OFDM-IM principles are combined to further boost the spectral and energy efficiency of the OFDM-IM scheme.
- It has been shown via extensive computer simulations that due to its energy efficiency and flexible system design, MIMO-OFDM-IM can be strong alternative to classical MIMO-OFDM, which has been included in many current wireless standards.

MIMO-OFDM-IM Transceiver



BER Performance of MIMO-OFDM-IM



Uncoded BER performance of MIMO-OFDM-IM and classical MIMO-OFDM schemes for three $n_T \times n_R$ MIMO configurations: 2×2, 4×4 and 8×8. OFDM system parameters: $M = 2$ (BPSK), $N = 4$, $K = 2$, $N_F = 512$, CP length = 16, frequency-selective Rayleigh fading channel with 10 taps, uniform power delay profile, sequential MMSE detection. The 3% reduce in spectral efficiency compared to single-carrier case $(n_T \log_2 M)$ is due to CP (Reproduced from [16] with permission).

Conclusions

- IM is an up and coming concept for spectral and energy-efficient next generation wireless communications systems to be employed in 5G wireless networks.
- SM and OFDM-IM systems are two popular applications of the IM concept.
- IM techniques can provide interesting trade-offs among error performance, complexity and spectral efficiency.
- We conclude that IM schemes can be considered as possible candidates for spectral and energy-efficient 5G wireless networks.
- However, three are still interesting as well as challenging research problems need to be solved in order to further improve the efficiency of IM schemes.

THANKS FOR YOUR ATTENTION ！