Index Modulation: A Promising Technique for Next-Generation Wireless Communication Systems

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Our studies are supported by Turkish Academy of Sciences (TÜBA)-GEBİP and Science Academy (Bilim Akademisi)-BAGEP Programmes, and TUBITAK projects with grant numbers 114E607 and 117E869.

July, 2018

Overview

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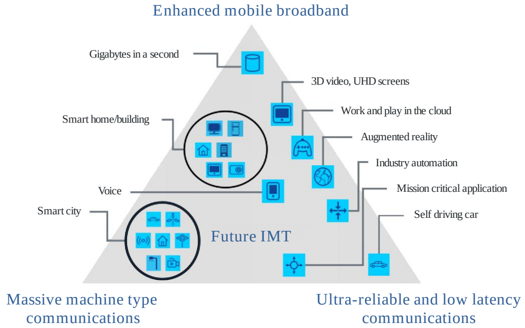
From 4G to the 5G New Radio

- Ongoing debate on 5G wireless technology!
  → a simple evolution compared to 4G systems, or a radically new communication network.
- 5G wireless networks:
  → provide higher bandwidths and much higher data rates with lower latency, enable a variety of new applications such as connected autonomous cars, smart appliances and the Internet of Things (IoT).



"IMT Vision - Framework and overall objectives of the future development of IMT for 2020 and beyond," *Rec. ITU-R M.2083-0*, Sep. 2015.

Towards the 5G New Radio

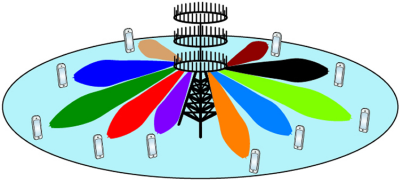
- The Feb. 2017 draft report of ITU on the key performance requirements of IMT-2020:
  → a downlink peak date rate of 20 Gbps and
  → a downlink peak spectral efficiency of 30 bits/sec/Hz.
- 3GPP successfully completed the first implementable 5G New Radio specification in Dec. 2017. 3GPP 5G Standalone Release (June 2018).
- One thing has become certain during standardization of 5G: *There is no single enabling technology that can achieve all of the applications being promised by 5G networking.*
- The necessity of more flexibility, new spectrum- and energy-efficient physical layer (PHY) techniques for 5G and beyond wireless networks.

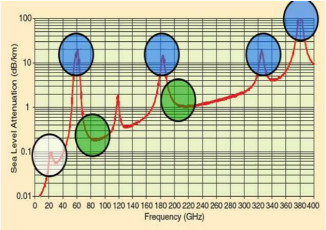
Press Release: ITU Agrees on Key 5G Performance Requirements for IMT-2020.
http://www.itu.int/en/mediacentre/Pages/2017-PR04.aspx

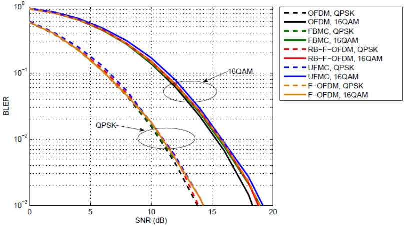
First 5G NR Specs Approved.
http://www.3gpp.org/news-events/3gpp-news/1929-nsa_nr_5g

PHY Solutions Towards 5G

- Attractive PHY solutions to meet the goals of 5G NR:
  → *Massive multi-user multiple-input multiple-output (MIMO) systems*
  → *Millimeter-wave communications (<52.6 GHz for NR-Release 1)*
  → *Non-orthogonal waveform designs (GFDM, UFMC, FBMC)*







New PHY Solutions for Beyond 5G

- To address the vast variety of user applications, 5G and beyond radio access technologies (RATs) should have a strong flexibility support and employ novel PHY techniques with higher spectral/energy efficiency and lower transceiver complexity.
- Unconventional transmission methods based on the promising concept of index modulation (IM) may have potential and impact to shape 5G and beyond RATs due to their inherently available advantages over conventional systems.
- *Initial skepticism of both academia and industry on the potential of IM technologies has now gone away.*
- *IM is not another simple digital modulation alternative, but rather can be a game-changing communication paradigm whose time has come!*

Industrial Potential of IM

- Although IM techniques have received tremendous academic interest since the beginning of this decade, major industrial partners and leading 5G initiatives have realized their undeniable potential very recently.
- Samsung Electronics conducted a 5G prototype trial in Nov. 2016 and validated the performance of spatial modulation (SM), which is by far the most popular form of IM.
- During 3GPP RAN1#87 meeting in Nov. 2016 and 3GPP TSG RAN WG1 NR Ad-Hoc Meeting in Jan. 2017, InterDigital Communications has proposed that SM can be further evaluated for 5G NR.
- At the IEEE 5G Roadmap Workshop (co-located with *IEEE Int. Conf. Commun. 2017 (ICC 2017)* in May 2017), SM has been regarded as one of emerging wireless paradigms along with mmWave mobile, full-duplex (FD) wireless, and massive MIMO systems.

Nov. 2016: Samsung Successfully Conducts 5G Prototype Trial with China Mobile Communication Corporation. http://www.samsung.com/global/business/networks/insights/news/samsung-successfully-conducts-5g-prototype-trial-with-china-mobile-communication-corporation

"(InterDigital Communications) Evaluation of spatial modulation with spatial correlation and imperfect channel estimation," 3GPP TSG RAN WG1 Meeting #87 R1-1612658, Nov. 2016. http://www.3gpp.org/ftp/TSG_RAN/WG1_RL1/TSGR1_87/Docs/R1-1612658.zip.

The Concept of Index Modulation (IM)

- IM is a novel digital modulation technique, which utilizes the indices of the building blocks of the corresponding communication systems to convey additional information bits.
  $\rightarrow$ building blocks: transmit antennas, subcarriers, time slots, etc.
- IM techniques:
  $\rightarrow$ consider innovative ways to convey information compared to traditional communication systems,
  $\rightarrow$ offer attractive advantages in terms of spectral and energy efficiency as well as hardware simplicity,
  $\rightarrow$ appear as competitive candidates for next-generation wireless networks.
- There has been a tremendous interest in IM schemes over the past few years.

E. Basar, "Index modulation techniques for 5G wireless networks," *IEEE Commun. Mag.*, vol. 54, no. 7, pp.168-175, July 2016.

E. Basar, M. Wen, R. Mesleh, M. Di Renzo, Y. Xiao, and H. Haas, "Index modulation techniques for next-generation wireless networks," *IEEE Access*, vol. 5, pp. 16693-16746, Sep. 2017.

S. Sugiura, T. Ishihara, and M. Nakao, "State-of-the-art design of index modulation in the space, time, and frequency domains: Benefits and fundamental limitations," *IEEE Access*, vol. 5, pp. 21774-21790, Nov. 2017.

Index Modulation Types

- Traditional digital modulation schemes rely on the modulation of the amplitude/phase/frequency of a sinusoidal carrier signal for transmission, as widely considered in the field of communications over the past 50 years
  $\rightarrow$ crowded and inefficient signal constellations.
- IM systems provide alternative ways to transmit information!
- IM schemes have the ability to map information bits by altering the on/off status of their transmission entities:

$\rightarrow$ transmit antennas
$\rightarrow$ subcarriers
$\rightarrow$ radio frequency (RF) mirrors
$\rightarrow$ transmit LEDs
$\rightarrow$ relays
$\rightarrow$ modulation types

$\rightarrow$ time slots
$\rightarrow$ precoder matrices
$\rightarrow$ dispersion matrices
$\rightarrow$ spreading codes
$\rightarrow$ signal powers
$\rightarrow$ loads
$\rightarrow$ ...

Advantages of IM Techniques

- Inherent flexibility with the adjustable number of active transmit entities.
- The ability to transfer the saved transmission energy from the inactive transmit entities to the active ones to obtain an improved error performance.
- The ability to convey information in a more energy-efficient way by deactivating some of the main elements of the system, while still exploiting them for data transferring purposes.
- An increased spectral efficiency without increasing the hardware complexity due to employment of new dimensions for conveying digital information.
- Mitigation of some undesirable transmission effects, such as high inter-channel/transmit entity interference and stringent inter-transmit entity synchronization, due to the deactivation of a subset of the available transmit entities.

Remark

IM can be a remedy for the foreseen flexibility requirements of the 5G NR.

Surge of IM techniques

- Every communication system can be theoretically considered as a special case of IM!
- However, the term of IM is explicitly used to cover the family of communication systems that consider other transmit entities than amplitudes/frequency/phases to convey information.
- The introduction of *spatial modulation (SM)* and *orthogonal frequency division multiplexing with index modulation (OFDM-IM)* concepts in 2008 and 2013
  $\rightarrow$ started a new wave of alternative digital modulation schemes.
- As of today, this wave is increasingly spreading and speeding up.

R. Y. 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.

E. Basar, U. Aygolu, E. Panayirci, and H. V. Poor, "Orthogonal frequency division multiplexing with index modulation," *IEEE Trans. Signal Process.*, vol. 61, no. 22, pp. 5536-5549, Nov. 2013.

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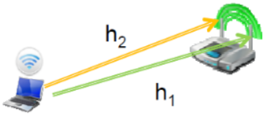
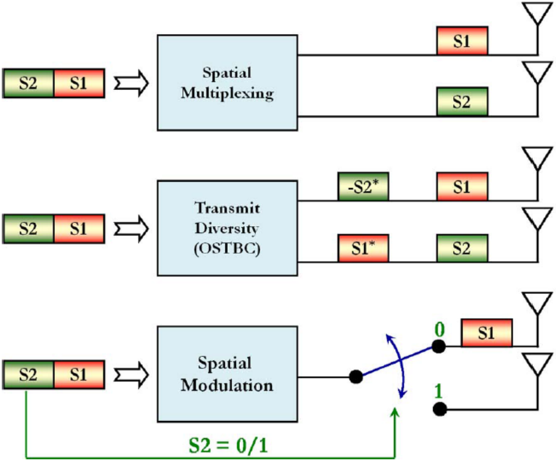
MIMO Technology

- Multiple-input and multiple-output (MIMO) systems offer:
  → Improvement in error performance
  → Higher data rates
  → Better quality-of-service (QoS)
  → Better coverage
- MIMO in Standards: IEEE 802.11n (Wi-Fi), HSPA+ (3G), IEEE 802.16 WiMAX, Long Term Evolution (LTE) (4G), LTE-Advanced, 5G, Beyond 5G.



Three MIMO Modes



M. Di Renzo, H. Haas, A. Ghrayeb, S. Sugiura, and L. Hanzo, "Spatial modulation for generalized MIMO: Challenges, opportunities, and implementation," *Proc. IEEE*, vol. 102, no. 1, pp. 56-103, Jan. 2014.

Spatial Modulation (SM)

- Pioneering works of Mesleh *et al.* and Jeganathan *et al.* in 2008-2009.
- 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 spectrum- 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:
  $\rightarrow$ indices of transmit antennas
  $\rightarrow$ 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.

Advantages of SM

- Simple and low-cost 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.
  $\rightarrow$ 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 for SM.
- Since SM transfers the information using only the spatial domain, plain SM cannot provide transmit diversity as STC systems.

Conclusion

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

Remark

SM has been regarded as a possible candidate for spectrum- and energy-efficient next generation wireless communication systems.

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.

Nov. 2016: Samsung Successfully Conducts 5G Prototype Trial with China Mobile Communication Corporation

http://www.samsung.com/global/business/networks/insights/news/samsung-successfully-conducts-5g-prototype-trial-with-china-mobile-communication-corporation

Studies on SM

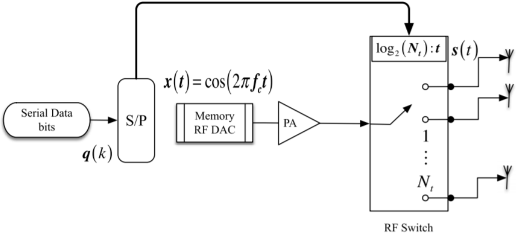
- The first studies on SM concept date back to the beginning of 2000s where different terminologies were used by researchers.
- After the inspiring works of Mesleh *et al.* and Jeganathan *et al.*, numerous papers on SM have been published.
- Some studies on SM:
  - → Generalized, spectrum-, and energy-efficient 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
  - → Performance analysis under hardware impairments
  - → 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. IEEE*, vol. 102, no. 1, pp. 56–103, Jan. 2014.

P. Yang, M. Di Renzo, Y. Xiao, S. Li, and L. Hanzo, "Design guidelines for spatial modulation," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 1, pp. 6-26, First Quart. 2015.

E. Basar, M. Wen, R. Mesleh, M. Di Renzo, Y. Xiao, and H. Haas, "Index Modulation Techniques for Next-Generation Wireless Networks," *IEEE Access*, vol. 5, pp. 16693-16746, Sep. 2017.

Space Shift Keying (SSK)



- The simplest form of the family of space modulation techniques.
- In SSK system, data are transmitted through spatial constellation symbols only.
- SSK scheme requires no RF chains at the transmitter and the transmitter can be entirely designed through RF switches.
- Since no information is modulated on the carrier signal, it can be generated once and stored for further use in all other transmissions.
- Spectral efficiency (bpcu) : $\log_2(n_T)$

R.Mesleh, O. Hiari, A. Younis, and S. Alouneh, "Transmitter design and hardware considerations for different space modulation techniques," *IEEE Trans. Wireless Commun.*, vol. 16, no. 11, pp. 7512–1722, Nov. 2017.

Generalized Spatial Modulation (GSM)

- Extension of SM to a system with multiple RF chains.
- Different data symbols are transmitted from the selected transmit antennas to further boost the spectral efficiency.
- Spectral efficiency (bpcu): $\left\lfloor \log_2 \binom{n_T}{n_A} \right\rfloor + n_A \log_2 M$
- GSM provides an intermediate solution between two extreme cases: SM and V-BLAST:
  $\rightarrow n_A = 1$: GSM=SM
  $\rightarrow n_A = n_T$: GSM=V-BLAST
- Provides significantly higher spectral efficiency than classical SM.

Number of IM Bits ($n_T = 8$ and $n_A = 4$)

SM: $\log_2(n_T) = \log_2(8) = 3$ bits

GSM: $\left\lfloor \log_2 \binom{n_T}{n_A} \right\rfloor = \left\lfloor \log_2 \binom{8}{4} \right\rfloor = \lfloor \log_2 (70) \rfloor = \lfloor 6.13 \rfloor = 6$ bits

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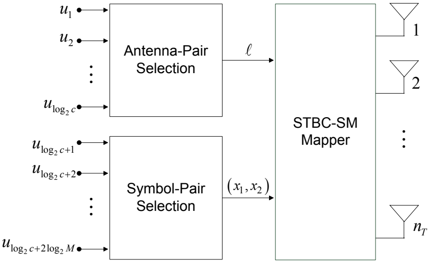
J. Wang, S. Jia, and J. Song, "Generalised spatial modulation system with multiple active transmit antennas and low complexity detection scheme," *IEEE Trans. Wireless Commun.*, vol. 11, no. 4, pp. 1605-1615, Apr. 2012.

Space-Time Block Coded Spatial Modulation (STBC-SM)



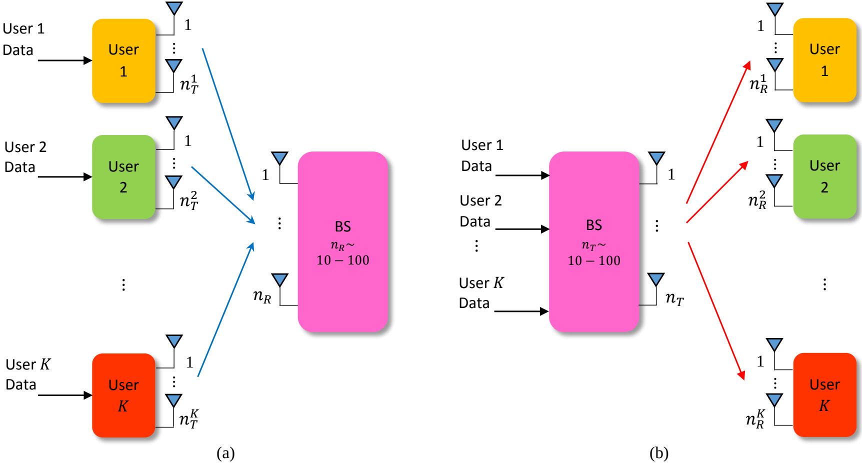
STBC-SM, Four Transmit Antennas ($n_T = 4$ and $c = 4$)

$$\chi_1 = \{\mathbf{X}_{11}, \mathbf{X}_{12}\} = \left\{ \begin{pmatrix} x_1 & x_2 & 0 & 0 \\ -x_2^* & x_1^* & 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 & x_1 & x_2 \\ 0 & 0 & -x_2^* & x_1^* \end{pmatrix} \right\}$$

$$\chi_2 = \{\mathbf{X}_{21}, \mathbf{X}_{22}\} = \left\{ \begin{pmatrix} 0 & x_1 & x_2 & 0 \\ 0 & -x_2^* & x_1^* & 0 \end{pmatrix}, \begin{pmatrix} x_2 & 0 & 0 & x_1 \\ x_1^* & 0 & 0 & -x_2^* \end{pmatrix} \right\} e^{j\theta}$$

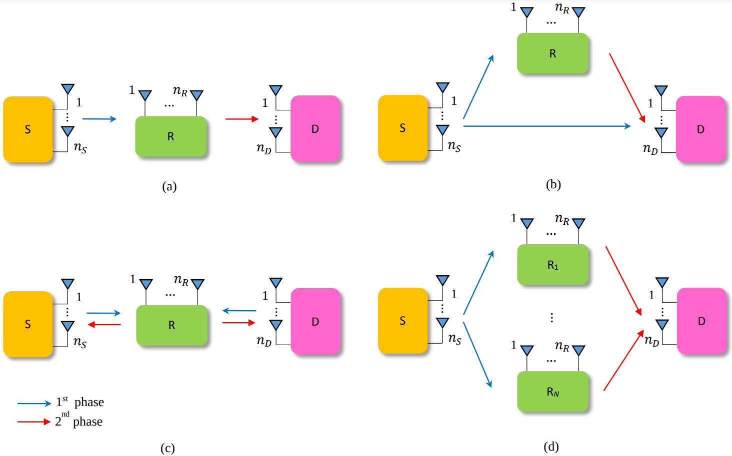
E. Basar, U. Aygolu, E. Panayirci, and H. V. Poor, "Space-time block coded spatial modulation," *IEEE Trans. Commun.*, vol. 59, no. 3, pp. 823-832, Mar. 2011.

Massive Multi-user MIMO Systems with SM



Massive MU-MIMO systems with SM (a) An uplink transmission scenario, where multiple users use SM techniques for their transmissions to the BS equipped with massive antennas (b) A downlink transmission scenario, where a BS equipped with massive antennas supports multiple users.

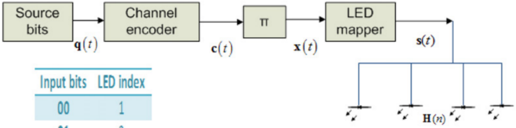
Cooperative SM Systems



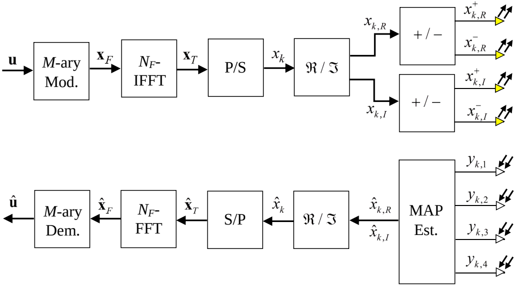
An overview of cooperative SM systems (a) Dual-hop SM with a single relay (b) Cooperative SM with a direct link between S and D (c) Network-coded SM that supports two-way communications between S and D (d) Multi-relay and distributed SM. n_S, n_R and n_D denote the number of antennas for source (S), relay (R) and destination (D) nodes.

Our studies on cooperative spatial modulation systems are supported by TUBITAK under Grant no. 114E607.

Index Modulation for Optical Communications



Input bits	LED index
00	1
01	2
11	3
10	4



R. Mesleh, H. Elgala, and H. Haas, "Optical spatial modulation," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 3, no. 3, pp. 234-244,Mar. 2011.

E. Basar, E. Panayirci, M. Uysal, and H. Haas, "Generalized LED index modulation optical OFDM for MIMO visible light communications systems," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Kuala Lumpur, Malaysia, May 2016, pp. 1-5.

Index Modulation for Molecular Communications

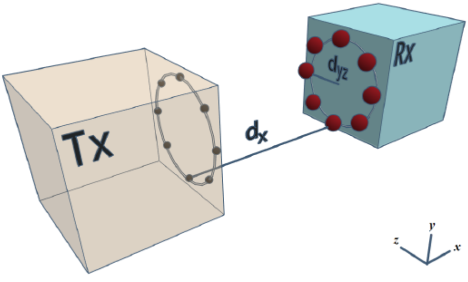
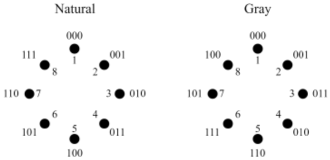


Fig. 1. The molecular MIMO system of interest for $n_{Tx} = n_{Rx} = 8$. Each spherical receiver antenna's closest point is d_{yz} away from the center of the UCA, and the receiver antennas of radius r_r are angular-wise $\frac{\pi}{4}$ radians apart from each other. Note that the radius of the transmitter UCA is equal to $d_{yz} + r_r$ for this topology. d_x denotes the closest point of a receiver antenna to its corresponding transmit antenna, and is also equivalent to $d_{Rx-Tx} - 2r_r$ given d_{Rx-Tx} is the distance between the Tx and Rx blocks' surfaces.



M. C. Gursoy, E. Basar, A. E. Pusane, T. Tugcu, "Index Modulation for Molecular Communication via Diffusion Systems", *submitted to IEEE Transactions on Communications*, June 2018.

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Orthogonal Frequency Division Multiplexing (OFDM)

- OFDM has become the most popular multi-carrier waveform in the past decade and has been included in LTE (4G), IEEE 802.11x WLAN, DVB, and IEEE 802.16e-WiMAX.
- The first step towards 5G NR is the PHY design, whose one of the core components is the waveform $\rightarrow$ the selection of the corresponding waveform has paramount importance.
- Waveform: Signal shape in the physical medium formed by a specific method.
- After a long debate on alternative waveforms for the 5G NR, cyclically prefixed-OFDM (CP-OFDM) has been chosen by 3GPP for both UL and DL of 5G NR Phase 1 $\rightarrow$ due to its attractive advantages experienced in the previous generations.
- Intensive research activities are still ongoing for the design and test of modified OFDM schemes, flexible and mixed numerologies, and candidate waveforms, such as GFDM, FBMC, and UFDM, for later phases of 5G wireless.

A. A. Zaidi and R. Baldemair. (2017, May). In the race to 5G, CP-OFDM triumphs! Available: https://www.ericsson.com/research-blog/in-race-to-5g-cp-ofdm-triumphs/

OFDM with Index Modulation (OFDM-IM)

- IM concept for OFDM subcarriers.
- OFDM-IM is a novel multicarrier transmission scheme that has been proposed by inspiring from the IM concept of SM.
- Similar to SM, the incoming bit stream is split into subcarrier index selection and M-ary constellation bits.
- 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. Panayirci, 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 GSM system.
- Actually, OFDM-IM can be thought as a massive GSM scheme where we deal with OFDM subcarriers instead of transmit antennas.
- 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 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 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.

	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

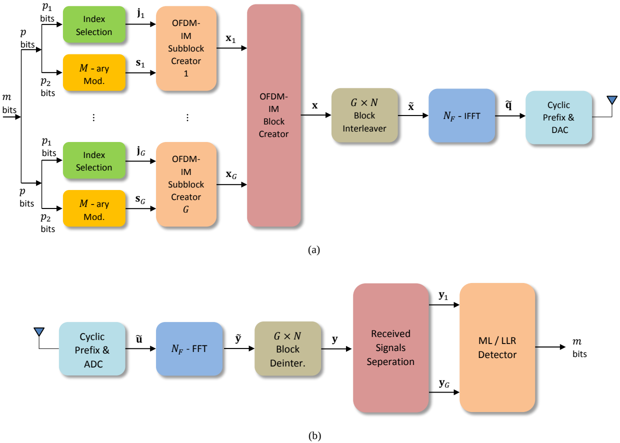
OFDM-IM Transceiver

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

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

$$p_2 = K\log_2 M$$

$$p = p_1 + p_2$$



Transceiver structure of the OFDM-IM scheme

(a) transmitter structure (b) receiver structure

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 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.
- Due to inactivation of some of the available subcarriers, OFDM-IM reduces the peak-to-average power ratio (PAPR) and is more robust to inter-carrier interference (ICI).
- OFDM-IM is also well-suited to MIMO, MU and high mobility setups as well as to optical wireless, vehicular, machine-to-machine (M2M), device-to-device (D2D) and underwater acoustic (UWA) communication systems.

Disadvantages of OFDM-IM

- The spectral efficiency of the plain OFDM-IM cannot compete with that of classical OFDM for increasing modulation orders due to inactive subcarriers of the former.
  $\rightarrow$ A limited beneficial operating interval in terms of spectral efficiency.
- Uncoded/coded error performance of OFDM-IM is generally worse than classical OFDM for low SNR values.
- The detection complexity of the optimal detector of OFDM-IM is considerably high compared to classical OFDM.
  $\rightarrow$ LLR-based detector causes a performance loss.

Remark

OFDM-IM can be a possible candidate not only for high-speed wireless communication systems but also for M2M/D2D communication systems of 5G wireless networks that require low power consumption.

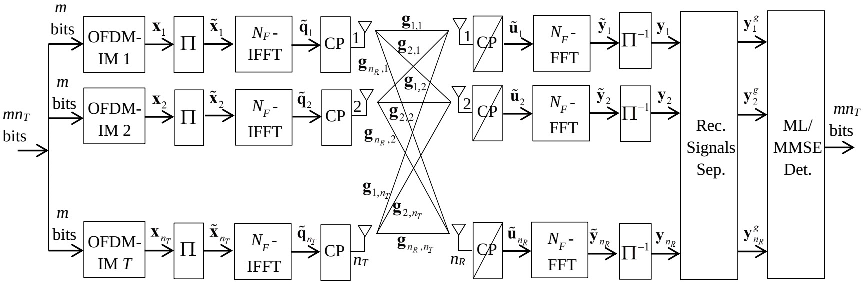
Recent Advances in OFDM-IM

- 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
  - ✓ Generalization, enhancement and optimization of OFDM-IM
  - ✓ Error performance and capacity analysis
  - ✓ Diversity methods and integration to MIMO systems
  - ✓ Its adaptation to different wireless environments (V2X, D2D, OWC, IoT)
  - ✓ PAPR/ICI/CFO issues
  - ✓ Low-complexity detection
  - ✓ Coded realizations
  - ✓ Extensions (code IM, precoder IM, DCT-OFDM/GFDM/FBMC/SC-FDE/FTN/CSK with IM)
  - ✓ Other applications (channel division multiple access, active device identification in compressive random access, storing information in flash memories, and parallel Gaussian channels)

E. Basar, M. Wen, R. Mesleh, M. Di Renzo, Y. Xiao, and H. Haas, "Index Modulation Techniques for Next-Generation Wireless Networks," *IEEE Access*, vol. 5, no. 1, pp. 16693-16746, Sep. 2017.

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.



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

E. Basar, "On multiple-input multiple-output OFDM with index modulation for next generation wireless networks," *IEEE Trans. Signal Process.*, vol. 64, no. 15, pp. 3868-3878, Aug. 2016.

E. Basar, "Multiple-Input Multiple-Output Orthogonal Frequency Division Multiplexing with Index Modulation", US Patent, US 9,960,831 B2, May 2018.

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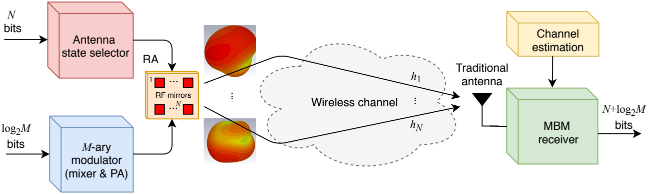
Reconfigurable Antennas: A New Frontier for IM

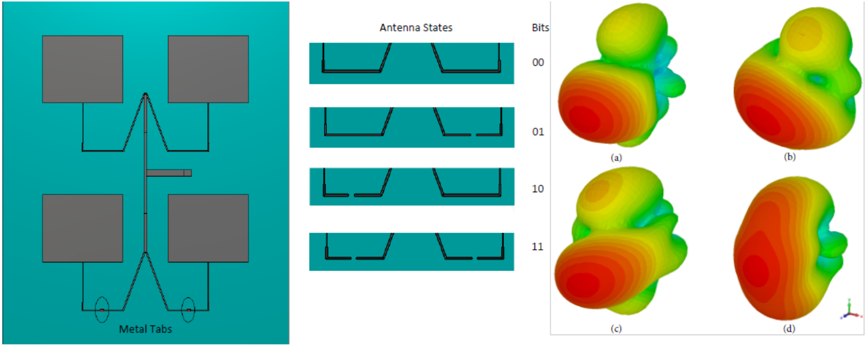
- IM can be also implemented for the radio frequency (RF) mirrors of a reconfigurable antenna (RA).
- An RF mirror is an RA element that contains a PIN diode, which can be turned on or off according to the information bits to alter the radiation pattern of an RA.
- Media-based modulation (MBM), which can be implemented by RAs, offers a completely new dimension for the transmission of digital information: the realizations of wireless channels themselves, that is, it performs the modulation of the wireless channel itself in a sense.



SISO-MBM transceiver equipped with a transmit RA that contains N RF mirrors.

A. K. Khandani, "Media-based modulation: A new approach to wireless transmission," in *Proc. IEEE Int. Symp. Inf. Theory*, Istanbul, Turkey, Jul. 2013, pp. 3050-3054.

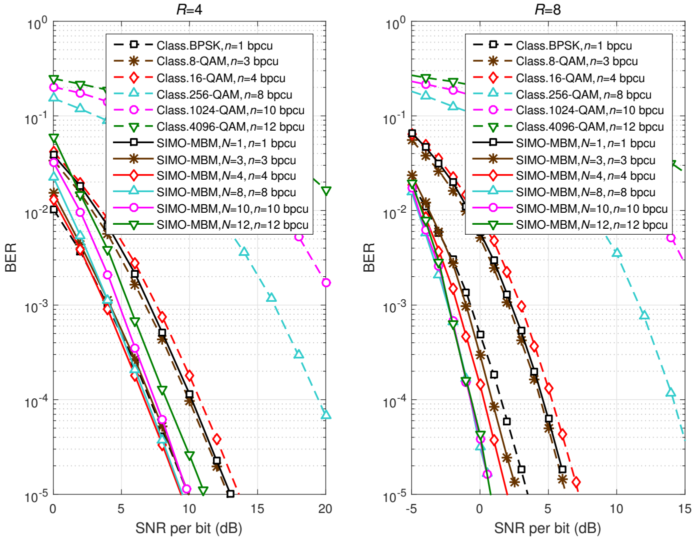
The Concept of Media-Based Modulation



A simple RA simulation model for MBM, its front view with two ideal metal tabs at lower horizontal connections, and the corresponding four antenna states obtained by altering the status of these two metal tabs.

Generated four different radiation patterns that can be used in transmission of two bits: (a) State 1, (b) State 2, (c) State 3, (d) State 4.

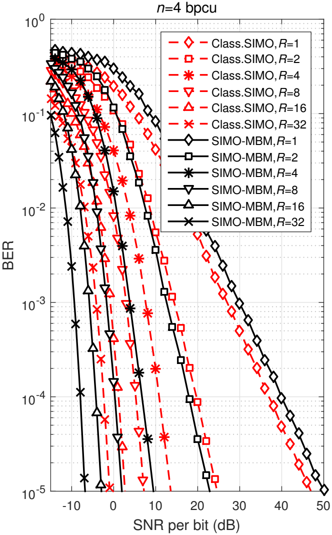
BER Performance of MBM Schemes

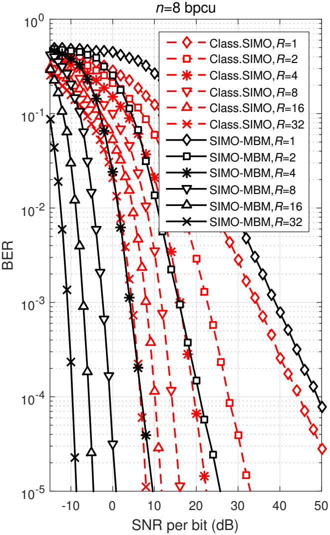


BER performance comparison of classical SIMO and MBM-SIMO schemes for different data rates.

1×4 and 1×8 SIMO systems, MBM: $\mathbf{y} = \mathbf{h}_i + \mathbf{n}$ vs Classical SIMO: $\mathbf{y} = \mathbf{h}s + \mathbf{n}$.

BER Performance of MBM Schemes-II

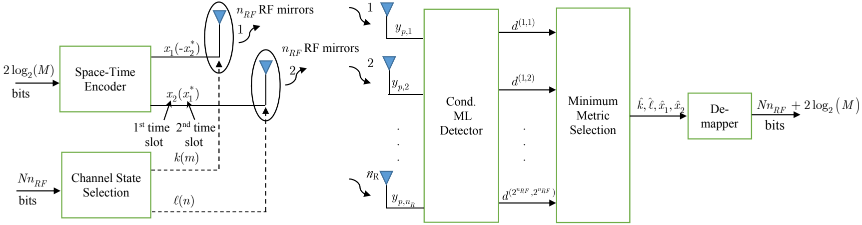




BER performance comparison of classical SIMO and MBM-SIMO schemes for different number of receive antennas, $\eta = 4/8$ bpcu (class. SIMO with $16/256$-QAM, MBM-SIMO with $M = 4/8$ RF mirrors).

Space-Time Channel Modulation (STCM)

- Although MBM exhibits appealing advantages, such as improved error performance and significant energy savings with using fewer transmit antennas compared to classical modulation schemes, plain MBM scheme cannot provide transmit diversity.
- In order to overcome this main limitation of MBM/RA systems, the scheme of STCM is proposed by exploiting both space, time and channel states domains.



Transceiver structure of the STCM scheme for a $2 \times n_R$ MIMO system. n_{RF}: number of RF mirrors at each transmit antenna, M: constellation size, k, l, m, n: selected channel states, $N \in \{1, 2\}$.

E. Basar and I. Altunbas, "Space-time channel modulation," *IEEE Trans. Veh. Technol.*, vol. 66, no. 8, pp. 7609-7614, Aug. 2017.

E. Basar and I. Altunbas, "Space-Time Channel Modulation" (pending), PCT Patent Appl. Number: PCT/TR2016/050353, Sep. 2016.

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Conclusions

- IM is an up and coming concept for spectrum- and energy-efficient next generation wireless communications systems to be employed in 5G and beyond wireless networks.
- SM and OFDM-IM systems are two popular applications of the IM concept. MBM appears as the third notable application of the IM concept.
- IM techniques can provide interesting trade-offs among error performance, complexity, and spectral efficiency.

Conclusion

We conclude that IM schemes can be considered as possible candidates for spectrum- and energy-efficient 5G and beyond wireless networks.

Remark

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.

Recent Advances and Possible Future Directions

Recent advances in IM applications:

- Massive MIMO systems
- Multi-user systems
- Cooperative networks
- Full-duplex systems
- NOMA
- Energy harvesting
- PHY security
- Vehicular communications (V2V, V2I)
- mm-Wave communications
- Waveforms designs: FBMC, GFDM, UFMC, DFT-s-OFDM, DCT-OFDM
- Optical wireless communications (VLC, FSO)
- Molecular communications

Challenging problems still exist and novel IM-based solutions can be explored for future wireless systems and standards.

Open Problems

- The design of novel generalized/enhanced/differential IM schemes with higher spectral and/or energy efficiency, lower transceiver complexity and better error performance.
- The optimization and integration of IM techniques to cooperative, massive MU-MIMO, FD, spectrum sharing, visible light, M2M, V2X, D2D communication systems to be employed in 5G and beyond wireless networks and the design of novel UL/DL/point-to-point transmission protocols.
- Exploration of totally new digital communication schemes for the application of IM techniques.
- The investigation of the potential of IM techniques via practical implementation testbeds and under real-world conditions.

Our Special Issue at IEEE Journal of Selected Topics in Signal Processing

Special Issue: Index Modulation for Future Wireless Networks: A Signal Processing Perspective
This Special Issue in IEEE J-STSP aims to capture the state-of-the-art advances in IM concepts and to collect the latest advances on the signal processing aspects of IM techniques.
Potential topics include, but are not limited to:

- Novel signal processing techniques and algorithms for IM-based systems
- Signal processing theories for new spectrum opportunities with IM techniques: massive MIMO, millimeter wave, full-duplex transmission and license assisted access
- Design of generalized/enhanced/quadrature/coded/differential IM systems
- Novel single/multi-carrier IM systems
- Practical implementation and performance analysis of IM systems
- Application of IM systems for multi-user and cooperative communication systems
- IM techniques for optical wireless communications
- Reconfigurable antenna based IM (media-based modulation) schemes
- IM-based non-orthogonal multiple access, energy harvesting, and cognitive radio schemes

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- Dr. Marco Di Renzo, Universite Paris-Saclay, France
- Dr. Raed Mesleh, German Jordanian University, Jordan
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- Prof. Octavia Dobre, Memorial University of Newfoundland, Canada
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- Alternative waveforms
- Low latency and low complexity waveforms
- Energy- and spectrum-efficient waveforms
- Novel hybrid and flexible waveforms
- Waveform design for MIMO systems
- Adaptive, flexible, differential and cognitive OFDM
- Non-orthogonal waveform design
- Physical layer security in OFDM
- Index modulation-based waveforms
- Millimeter-wave waveform design
- Effect of hardware impairments on the waveform design
- Waveform design for vehicular, D2D and M2M communications
- Implementations of beyond 5G waveforms

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Any Questions?