Physical Layer Solutions for Beyond 5G

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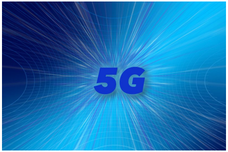
Overview

5G New Radio: Milestones

- 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).
- 5G PHY Layer: Above 6 GHz, massive MIMO, multiple OFDM numerologies.
- 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 flexible, new spectrum- and energy-efficient physical layer (PHY) techniques for beyond 5G 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

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 beyond 5G 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!*

The Concept of Index Modulation (IM)

- IM is a novel digital modulation technique, which utilizes the indices of the building blocks of 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 of the past 50 years,
  $\rightarrow$ 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 flexibility requirements of beyond 5G.

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.

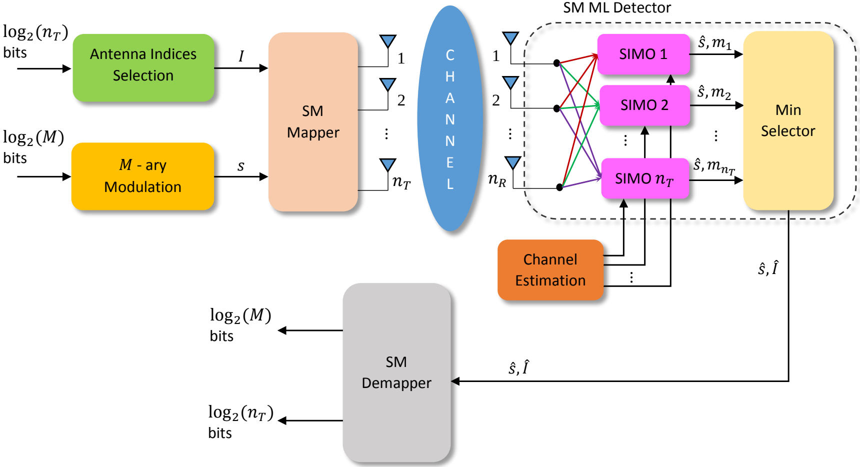
Industrial Potential of IM

- 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.

SM Transceiver



Block diagram of the SM transceiver for an $n_T \times n_R$ MIMO system. s (or $\hat{s}$) and I (or $\hat{I}$) $\in \{1, 2, \ldots, n_T\}$ denote the selected (or estimated) M-ary constellation symbol and transmit antenna index, respectively and $m_n, n = 1, 2, \ldots, n_T$ is the minimum metric provided by the nth SIMO ML detector.

Studies on SM

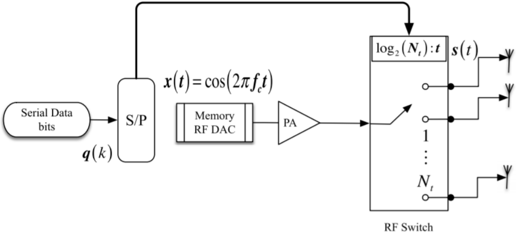
- The first studies on SM concept date back to the beginning of 2000s where different terminologies were used by researchers.
- After the inspiring works of Mesleh *et al.* and Jeganathan *et al.*, numerous papers on SM have been published.
- Some studies on SM:
  → Generalized, spectrum-, and energy-efficient 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.

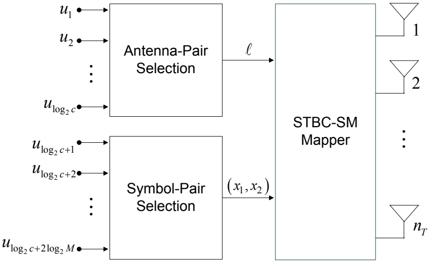
Space Shift Keying (SSK)



- 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.

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



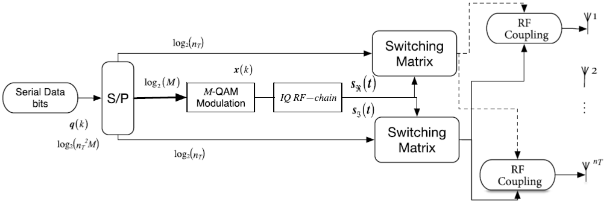
STBC-SM, Four Transmit Antennas ($n_T = 4$ and $c = 4$)

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

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

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.

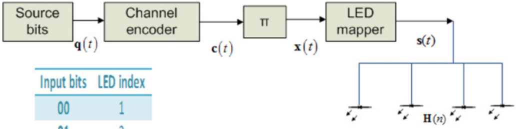
Quadrature Spatial Modulation (QSM)



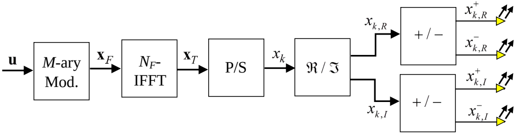
- A clever modification of the classical SM to improve the spectral efficiency while maintaining its advantages such as operation with single RF chain and ICI free transmission.
- The real and imaginary parts of the complex M-ary data symbols are separately transmitted using the SM principle.
- Spectral efficiency (bpcu): $2\log_2(n_T) + \log_2(M)$

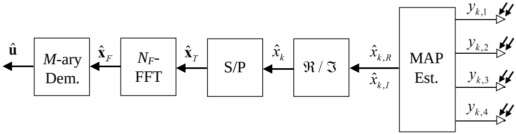
R. Mesleh, S. Ikki, and H. Aggoune, "Quadrature spatial modulation," *IEEE Trans. Vehicular Tech.*, vol. 64, no. 6, pp. 2738–2742, Jun. 2015.

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

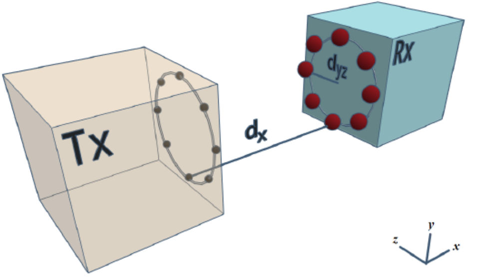
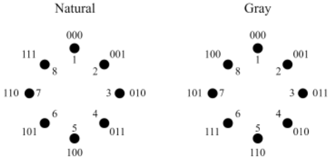


Fig. 1. The molecular MIMO system of interest for $n_{Tx} = n_{Rx} = 8$. Each spherical receiver antenna's closest point is d_{yz} away from the center of the UCA, and the receiver antennas of radius r_r are angular-wise $\frac{\pi}{4}$ radians apart from each other. Note that the radius of the transmitter 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", *IEEE Transactions on Communications (to appear)*, Feb 2019.

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 was the PHY design, whose one of the core components is the waveform → the selection of the corresponding waveform has paramount importance.
- 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 → 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.

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.

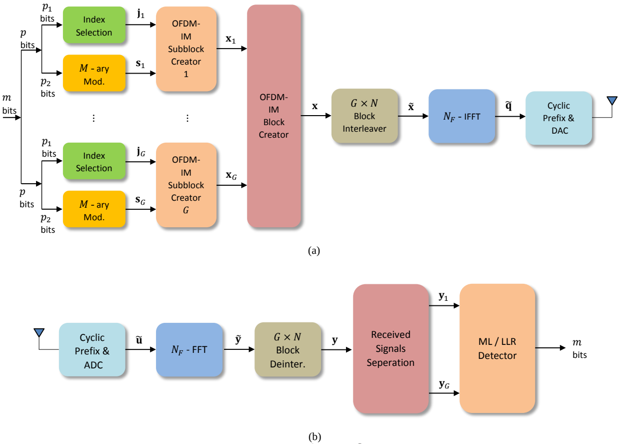
OFDM-IM Transceiver

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

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

$$p_2 = K \log_2 M$$

$$p = p_1 + p_2$$



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.
- 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.

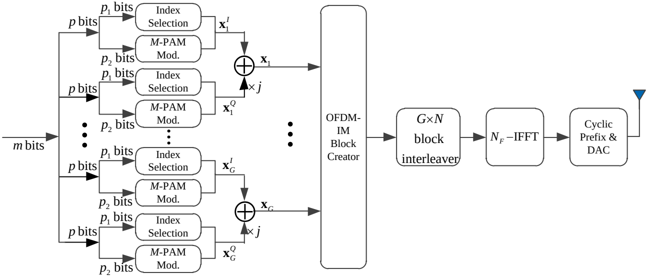
Recent Advances in OFDM-IM

- 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.

Generalized OFDM-IM Schemes

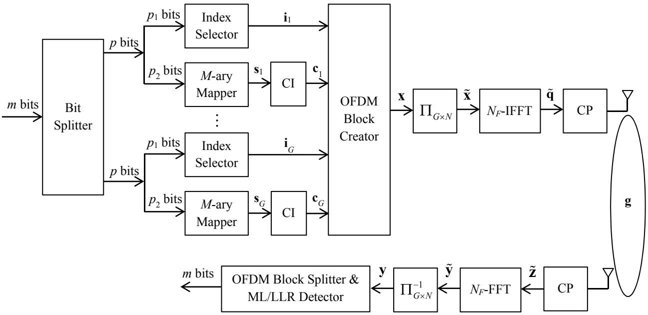
- Two generalized OFDM-IM schemes (OFDM-GIM-I and OFDM-GIM-II) have been proposed.
- In OFDM-GIM-I scheme, the number of active subcarriers are no longer fixed and it is also determined according to the information bits to transmit more bits per subblock compared to OFDM-IM.
- The OFDM-GIM-II scheme aims to further improve the spectral efficiency by applying IM independently for I/Q components of the complex data symbols similar to the QSM scheme.



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.

Coordinate Interleaved OFDM-IM

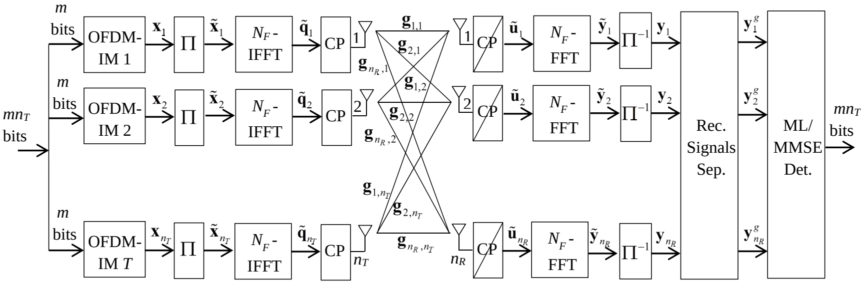
- Exploits the diversity potential of the plain OFDM-IM scheme by integrating the principle of coordinate interleaved orthogonal designs (CIODs) to OFDM-IM.
- Its main idea is to distribute the real and imaginary parts of a complex data symbol over two active subcarriers of the OFDM-IM scheme to obtain additional diversity gain.



E. Basar, "OFDM with index modulation using coordinate interleaving," *IEEE Wireless Commun. Lett.*, vol. 4, no. 4, pp. 381-384, Aug. 2015.

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.

Dual Mode OFDM-IM (DM-OFDM-IM)

- The concept of DM-OFDM-IM is a clever solution to overcome the spectral efficiency limitation of OFDM-IM by activating all subcarriers while still exploiting IM.
- All subcarriers are modulated and the index information is carried by the signal constellations assigned to the subcarrier groups.
- Two distinguishable signal constellations, a primary and a secondary constellation, are determined to transmit the data symbols from the active and inactive subcarriers of the OFDM-IM scheme, respectively.
- Multiple-mode OFDM-IM (MM-OFDM-IM) is proposed later by using the full permutation of modes to convey a higher number of IM bits.

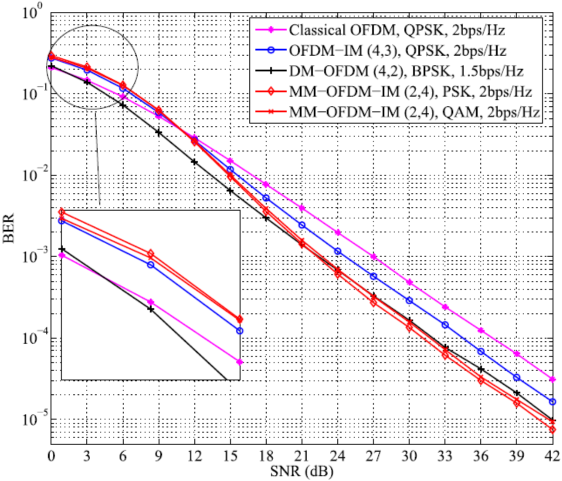
SUBBLOCK STRUCTURES OF OFDM-IM AND DM-OFDM SCHEMES FOR $N = 4$ AND $K = 2$

IM bits	OFDM-IM Subblocks	DM-OFDM Subblocks
[0 0]	$\begin{bmatrix} s_1 & 0 & s_2 & 0 \end{bmatrix}$	$\begin{bmatrix} s_1 & \tilde{s}_1 & s_2 & \tilde{s}_2 \end{bmatrix}$
[0 1]	$\begin{bmatrix} 0 & s_1 & 0 & s_2 \end{bmatrix}$	$\begin{bmatrix} \tilde{s}_1 & s_1 & \tilde{s}_2 & s_2 \end{bmatrix}$
[1 0]	$\begin{bmatrix} s_1 & 0 & 0 & s_2 \end{bmatrix}$	$\begin{bmatrix} s_1 & \tilde{s}_1 & \tilde{s}_2 & s_2 \end{bmatrix}$
[1 1]	$\begin{bmatrix} 0 & s_1 & s_2 & 0 \end{bmatrix}$	$\begin{bmatrix} \tilde{s}_1 & s_1 & s_2 & \tilde{s}_2 \end{bmatrix}$

T. Mao, Z. Wang, Q. Wang, S. Chen, and L. Hanzo, "Dual-mode index modulation aided OFDM," *IEEE Access*, vol. 5, pp. 50-60, Feb. 2017.

M. Wen, E. Basar, Q. Li, B. Zheng, and M. Zhang, "Multiple-mode orthogonal frequency division multiplexing with index modulation," *IEEE Trans. Commun.*, vol. 65, no. 9, pp. 3892-3906, Sep. 2017.

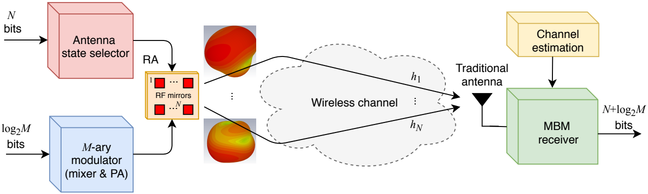
BER Performance of DM-OFDM-IM and MM-OFDM-IM



Performance comparison between classical OFDM with QPSK, "OFDM-IM (4,3), QPSK", "DM-OFDM (4,2), BPSK", and "MM-OFDM-IM (2,4), PSK/QAM".

Reconfigurable Antennas: A New Frontier for IM

- IM can be also implemented for the RF mirrors of an 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.

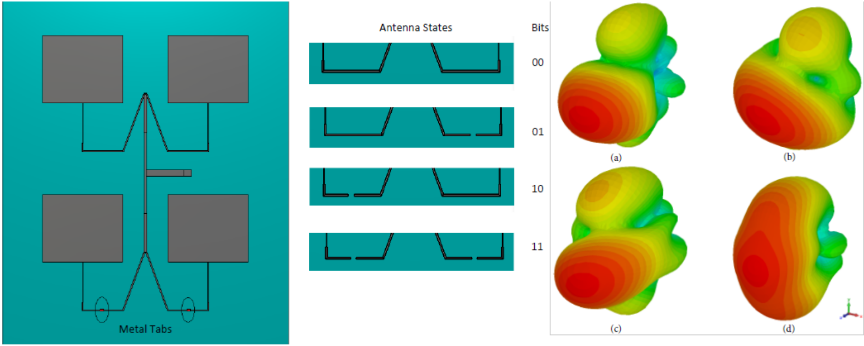


SISO-MBM transceiver equipped with a transmit RA that contains N RF mirrors.

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.

E. Basar, "Media-Based Modulation for Future Wireless Systems: A Tutorial," *IEEE Wireless Communications (to appear)*, Mar. 2019.

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.

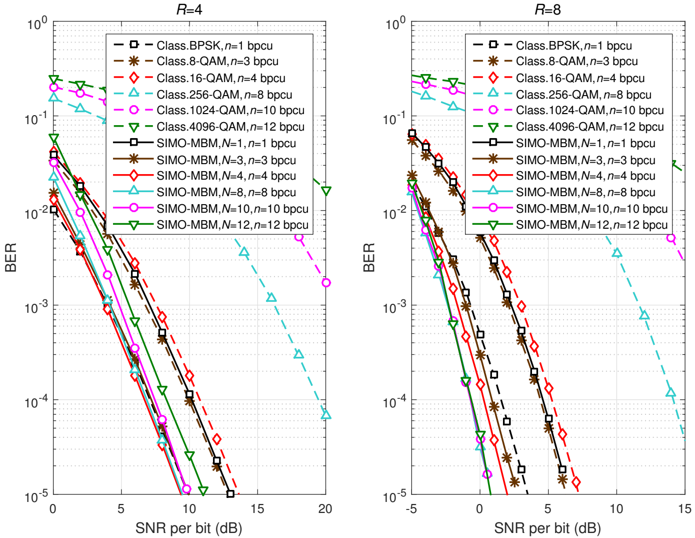
Advantages of MBM

- SIMO-MBM scheme is able to create a virtual MIMO system by using only a single RA supported by a single RF chain.
- Spectral efficiency of MBM increases linearly with the number of parasitic elements (RF mirrors) mounted in RA.
- Spectral efficiency of the MBM scheme can be significantly boosted by MIMO operation.
- MBM provides a significantly better error performance compared to traditional M-ary modulated systems since the Euclidean distance between MBM constellation points, which are random fade realizations, remains the same even with increasing spectral efficiency values.
- The inherent sparsity in the signal model of MBM schemes enables the use of compressed sensing-based detectors.

Disadvantages of MBM

- In order to obtain channel state information (CSI), the receiver has to be trained with pilot signals from all possible antenna states.
- The design of RAs that can support a high number of sufficiently different radiation patterns is not a straightforward task.
- Radiation-related parameters have to be carefully monitored to ensure that effective communication is possible with all generated radiation patterns.
- The possible high correlation among different radiation patterns (fade realizations) may become the Achilles' heel of MBM-based systems by limiting the achievable performance.
- Similar to all IM-based schemes, the performance of MBM is not satisfactory for a small number of receive antennas, particularly, for a single receiving antenna.

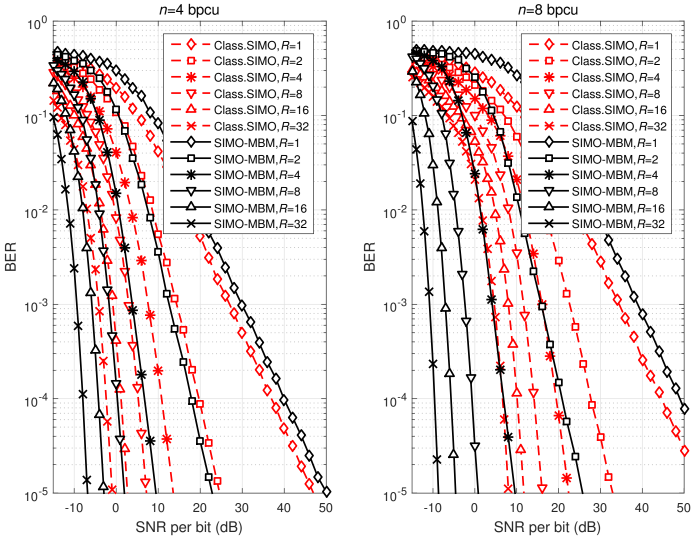
BER Performance of MBM Schemes



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: $\mathbf{y} = \mathbf{h}s + \mathbf{n}$.

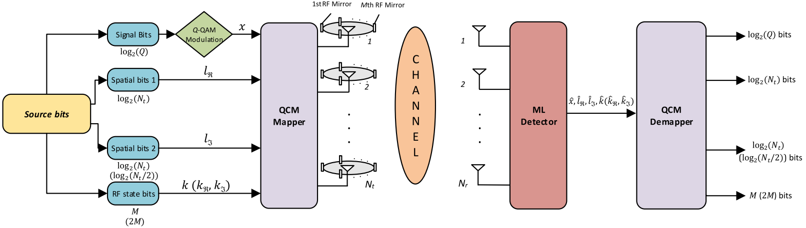
BER Performance of MBM Schemes-II



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).

MIMO-Aided MBM Schemes

- To reduce the implementation complexity associated with the transmitter hardware and training overhead, spatial multiplexing-aided MIMO-MBM is introduced.
- MBM is also combined with generalized SM (GSM), space shift keying (SSK) and quadrature SM (QSM), and promising results reported with a simple MIMO implementation using a single RF chain.



E. Seifi, M. Atamanesh, and A. K. Khandani, "Media-based MIMO: A new frontier in wireless communication," Oct. 2015.

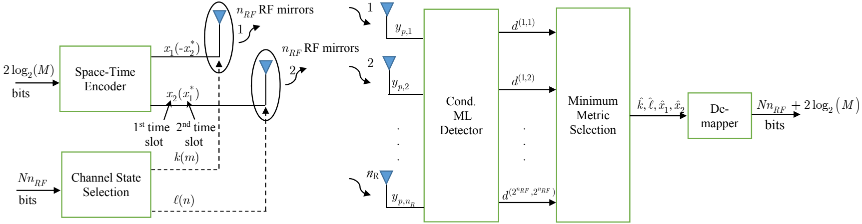
Y. Naresh and A. Chockalingam, "On media-based modulation using RF mirrors," IEEE Trans. Veh. Technol., vol. 66, no. 6, pp. 4967–4983, June 2017.

Z. Bouida, H. El-Sallabi, A. Ghrayeb, and K. A. Qaraqe, "Reconfigurable antenna-based space-shift keying (SSK) for MIMO Rician channels," IEEE Trans. Wireless Commun., vol. 15, no. 1, pp. 446–457, Jan. 2016.

I. Yildirim, E. Basar, and I. Altunbas, "Quadrature channel modulation," IEEE Wireless Commun. Lett., vol. 6, no. 6, pp. 790–793, Dec. 2017.

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.



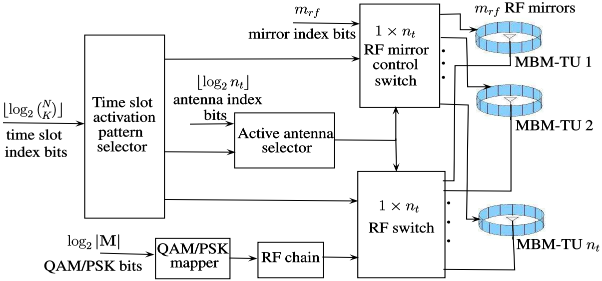
Transceiver structure of the STCM scheme for a $2 \times n_R$ MIMO system. n_{RF}: number of RF mirrors at each transmit antenna, M: constellation size, k, l, m, n: selected channel states, $N \in \{1, 2\}$.

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.

Multi-Dimensional Index Modulation

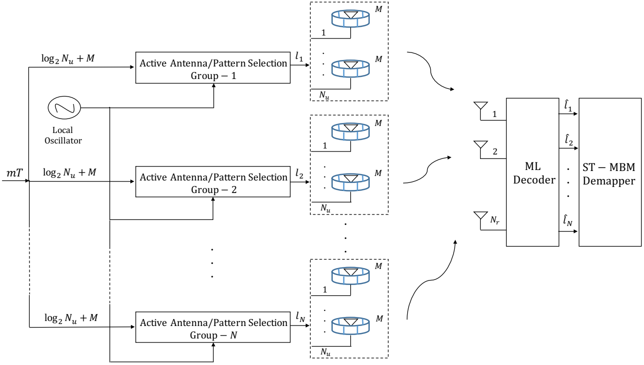
- Multi-dimensional IM concept is presented by considering the broad applicability of IM techniques.
- Time-indexed MBM, SM-MBM and time-indexed SM-MBM (TI-SM-MBM) schemes are introduced.
- Additionally, load modulation schemes are investigated by modulating the antenna impedances that control the antenna currents.



B. Shamasundar, S. Bhat, S. Jacob, and A. Chockalingam, "Multidimensional index modulation in wireless communications," IEEE Access, vol. 6, pp. 589–604, Feb. 2018.

Space-Time Media-Based Modulation

- A general framework is presented for MBM from the perspective of space-time coding.
- The proposed scheme exploits one of the prominent IM solutions, SSK, and Hurwitz-Radon family of matrices in order to achieve transmit diversity gain with a single RF chain.



Z. Yigit, E. Basar, "Space-time media based modulation," *IEEE Transactions on Signal Processing (to appear)*, Mar. 2019.

Unsolved Problems for MBM

- For implementation of MBM schemes, novel RA architectures that can generate a sufficiently high number of antenna states with relatively low correlation, have to be designed.
- The designed RAs have to radiate efficiently for all possible states at the same frequency band and need to be compact in size for possible MIMO employment or IoT applications.
- Novel SIMO- and MIMO-based MBM transceiver architectures with high spectral efficiency and/or improved error performance can be designed for diverse 5G and beyond application categories.
- More comprehensive practical implementation campaigns and measurements over practical setups need to be carried out to assess the performance of MBM technologies in real-world scenarios.

Recent Advances and Possible Future Directions for IM

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.

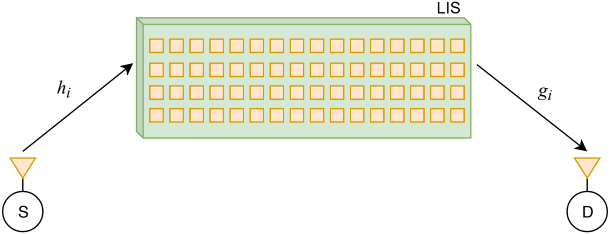
Transmission Through Large Intelligent Surfaces

- There has been a growing interest in controlling the propagation environment in order to increase the quality of service for wireless communications:
  i) Media-based modulation
  ii) Spatial scattering modulation
  iii) Beam index modulation.
- On the other hand, large intelligent surfaces/walls/reflect-arrays/ metasurfaces are smart devices that control the propagation environment with the aim of improving the coverage and signal quality.
- *It is completely different from existing MIMO, beamforming, amplify-and-forward relaying and backscatter communication paradigms.*
- Here, the large number of small, low-cost, and passive elements on a LIS only reflect the incident signal with an adjustable phase shift without requiring a dedicated energy source for RF processing, decoding, encoding, or retransmission.

E. Basar, "Transmission Through Large Intelligent Surfaces: A New Frontier in Wireless Communications," *submitted to EuCNC 2019 (Online: ArXiv:1902.08463)*, Feb. 2019.

Maximum Received SNR Through Intelligent Reflection

- Transmission through a LIS in a dual-hop communication scenario without a line-of-sight path between S and D.



- For $h_i = \alpha_i e^{-j\theta_i}$ and $g_i = \beta_i e^{-j\psi_i}$, the instantaneous SNR at D:

$$\gamma = \frac{\left| \sum_{i=1}^{N} \alpha_i \beta_i e^{j(\phi_i - \theta_i - \psi_i)} \right|^2 E_s}{N_0}. \tag{1}$$

γ is maximized by eliminating the channel phases with the help of the LIS-induced phases as $\phi_i = \theta_i + \psi_i$ for $i = 1, \ldots, N$.

Performance of LIS-Assisted Communication Systems

- With the help of the LIS, the maximized instantaneous received SNR

$$\gamma = \frac{\left(\sum_{i=1}^{N} \alpha_i \beta_i\right)^2 E_s}{N_0} = \frac{A^2 E_s}{N_0}. \quad (2)$$

- Under the central limit theorem, we have

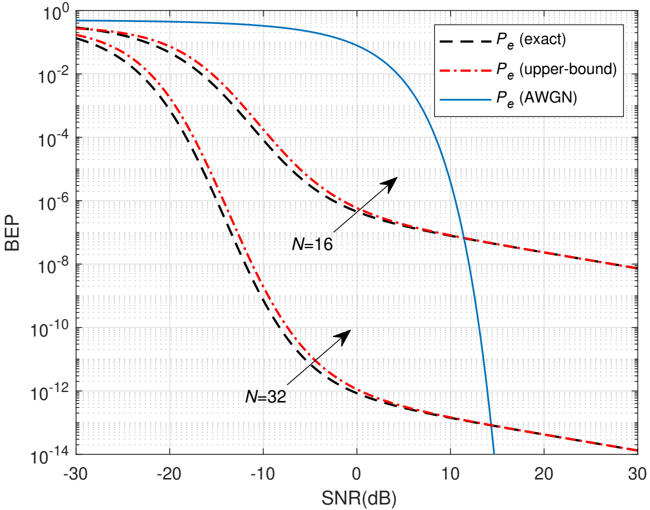
$$E\left[\gamma\right] = \frac{\left(N^2\pi^2 + N(16-\pi^2)\right) E_s}{16 N_0} \propto N^2 \frac{E_s}{N_0}. \quad (3)$$

- Bit error probability (BPSK)

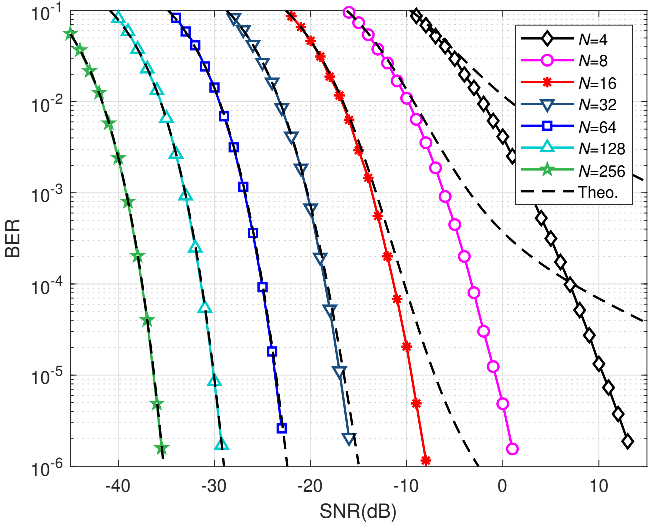
$$P_e \leq \frac{1}{2}\left(\frac{1}{1+\frac{N(16-\pi^2)E_s}{8N_0}}\right)^{\frac{1}{2}} \exp\left(\frac{-\frac{N^2\pi^2 E_s}{16 N_0}}{1+\frac{N(16-\pi^2)E_s}{8N_0}}\right). \quad (4)$$

E. Basar, "Transmission Through Large Intelligent Surfaces: A New Frontier in Wireless Communications," *submitted to EuCNC 2019 (Online: ArXiv:1902.08463)*, Feb. 2019.

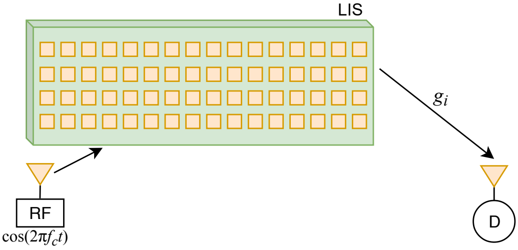
LIS-Based Scheme vs AWGN Performance



Increasing the Number of Reflectors



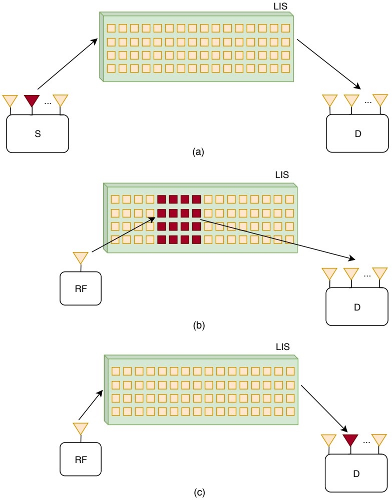
LIS As an Access Point



- The LIS plays the role of an AP (source) in our communication scenario, however, it is again consists of only low-cost and passive reflector elements.
- The LIS is supported by a near-by RF signal generator or contains an attachment that transmits an unmodulated carrier signal towards the LIS.

E. Basar, "Transmission Through Large Intelligent Surfaces: A New Frontier in Wireless Communications," *submitted to EuCNC 2019 (Online: ArXiv:1902.08463)*, Feb. 2019.

LIS-Assisted Index Modulation



E. Basar, "Large Intelligent Surface-Based Index Modulation: A New Beyond MIMO Paradigm," *IEEE Transactions on Signal Processing* (under review), Apr. 2019.

Open Problems and Future Directions

- Exploration of multiple-antenna nodes, correlated channels, different fading types, and discrete phase shifts appear as interesting future research directions.
- The extremely low SNR regions of operation may also be a remedy to the increasing need for advanced channel coding schemes to achieve ultra-reliable communication.
- Potential application of IM for transmit antennas and/or LIS regions along with other advanced/generalized designs, the design of low-complexity receiver architectures, and analyses in case of potential system imperfections, remain as interesting open research problems.

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

Guest Editors:

- Dr. Ertugrul Basar, Koç University, Turkey
- Dr. Miaowen Wen, South China University of Technology, China
- Dr. Marco Di Renzo, Universite Paris-Saclay, France
- Dr. Raed Mesleh, German Jordanian University, Jordan
- Dr. Luiqing Yang, Colorado State University, USA
- Dr. Octavia Dobre, Memorial University of Newfoundland, Canada
- Dr. Ananthanarayanan Chockalingam, Indian Institute of Science, India

To be published in 3rd Quarter of 2019!

Our Special Issue at IEEE Access

Special Issue: Advances in Signal Processing for Non-Orthogonal Multiple Access
This Special Issue in IEEE Access invites manuscript submissions in the area of Advances in Signal Processing for Non-Orthogonal Multiple Access.
Potential topics include, but are not limited to:

- Novel signal detection and transceiver design for NOMA
- Emerging applications of NOMA in 5G, IoT, V2X, and UAV
- Cooperative signal processing for NOMA
- Resource allocation and schedule in NOMA networks
- Adaptive signal processing algorithms for NOMA
- Energy efficiency optimization for NOMA systems
- Advanced channel coding and modulation schemes for NOMA
- Multiple antenna signal processing techniques for NOMA
- Machine learning for NOMA
- NOMA in wireless powered communications

Guest Editors:

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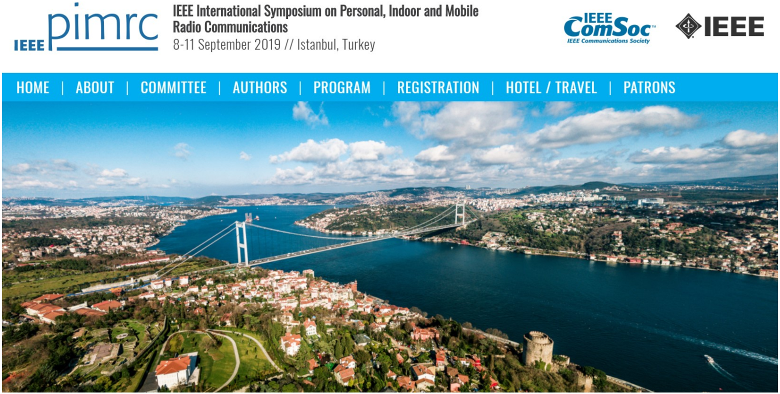
- Dr. Vincent Poor, Princeton University, USA

Submission Deadline: 31 May 2019

PIMRC 2019 @ Istanbul



- Track 1: Fundamentals and PHY
- Track Chairs: Ertugrul Basar, Sennur Ulukus, Bartolomeu F. Uchoa-Filho, Zouheir Rezki.
- 12 April 2019 (Final Extension)

Any Questions?