Media-Based Modulation for Beyond 5G Wireless Networks

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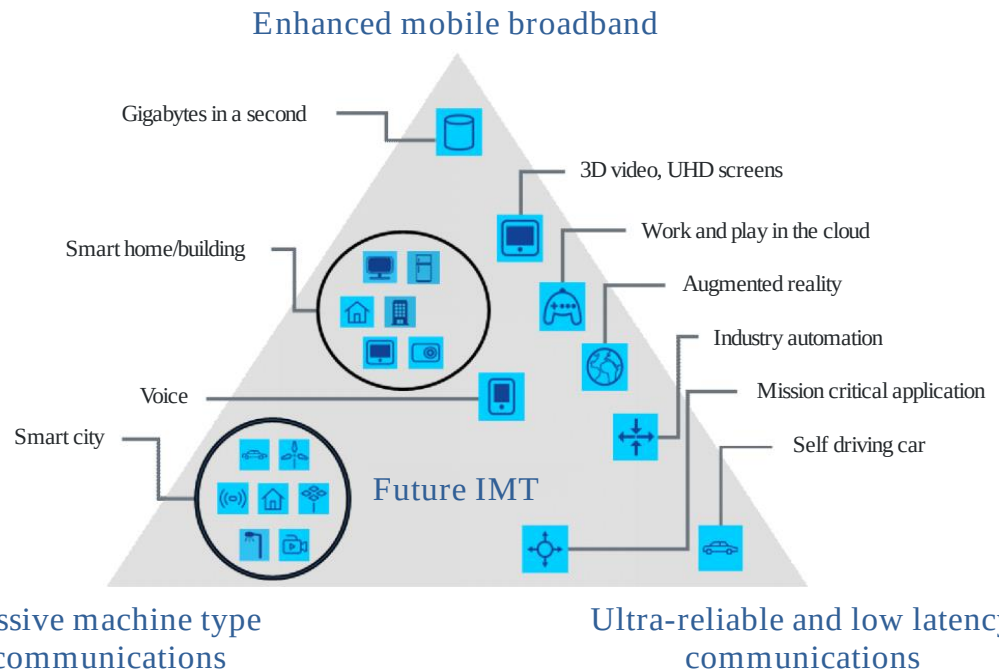
Overview

From 4G to the 5G New Radio

- Ongoing debate on 5G wireless technology!
  $\rightarrow$ a simple evolution compared to 4G systems, or a radically new communication network.
- 5G wireless networks:
  $\rightarrow$ 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:
  $\rightarrow$ a downlink peak date rate of 20 Gbps and
  $\rightarrow$ 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

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!*

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
$\rightarrow$ ...

Industrial Potential of IM

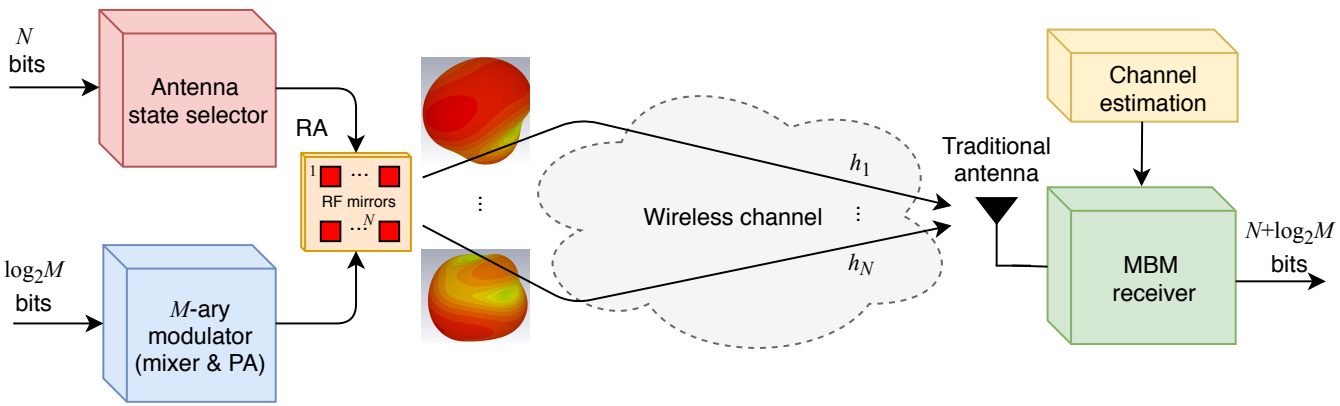
- Although IM techniques have received tremendous academic interest since the beginning of this decade, major industrial partners and leading 5G initiatives have realized their undeniable potential very recently.
- Samsung Electronics conducted a 5G prototype trial in Nov. 2016 and validated the performance 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.

Reconfigurable Antennas: A New Frontier for IM

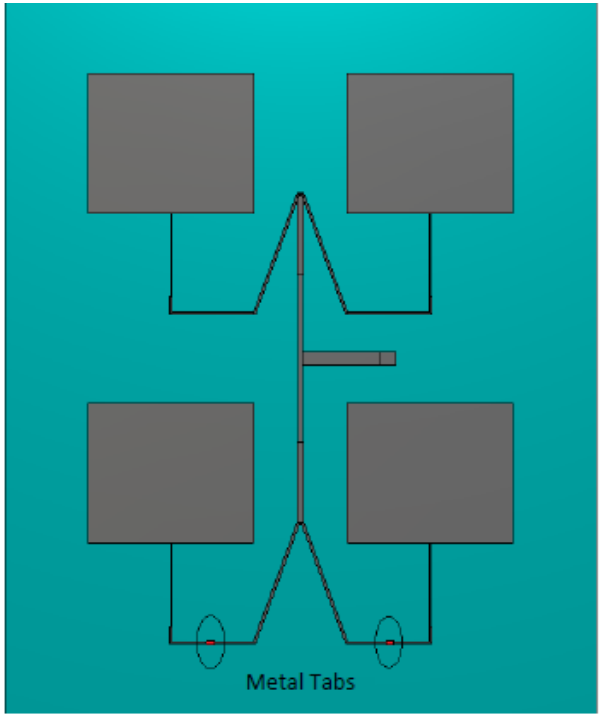
- IM can be also implemented for the radio frequency (RF) mirrors of a reconfigurable antenna (RA).
- An RF mirror is an RA element that contains a PIN diode, which can be turned on or off according to the information bits to alter the radiation pattern of an RA.
- Media-based modulation (MBM), which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

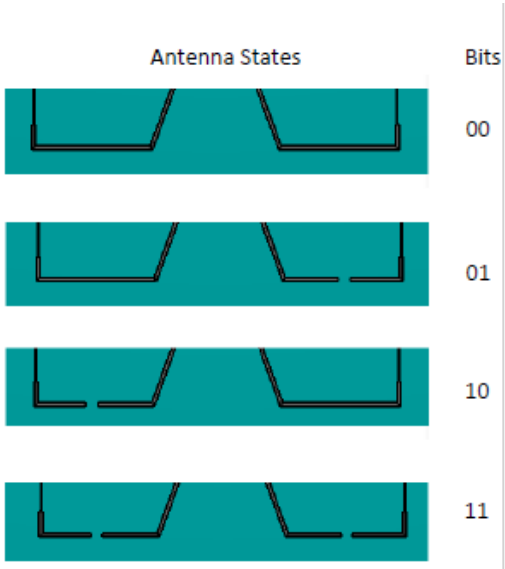


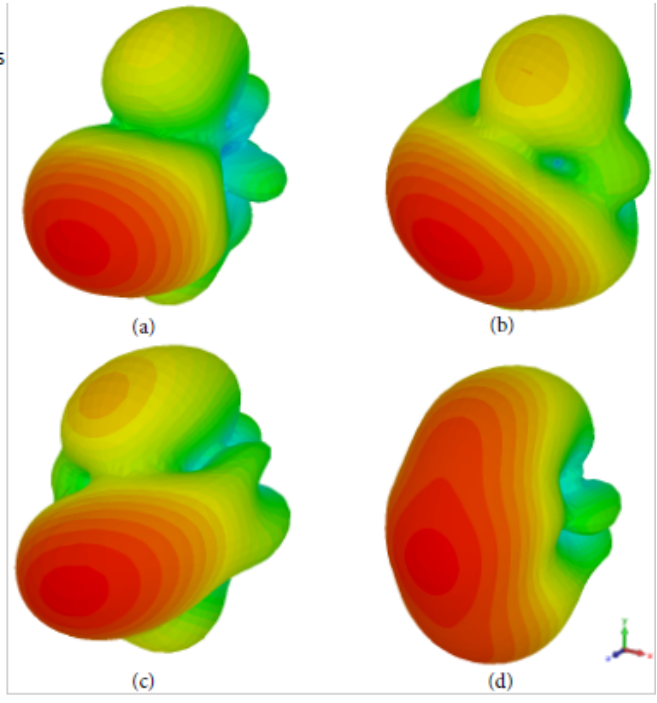
SISO-MBM transceiver equipped with a transmit RA that contains N RF mirrors.

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.

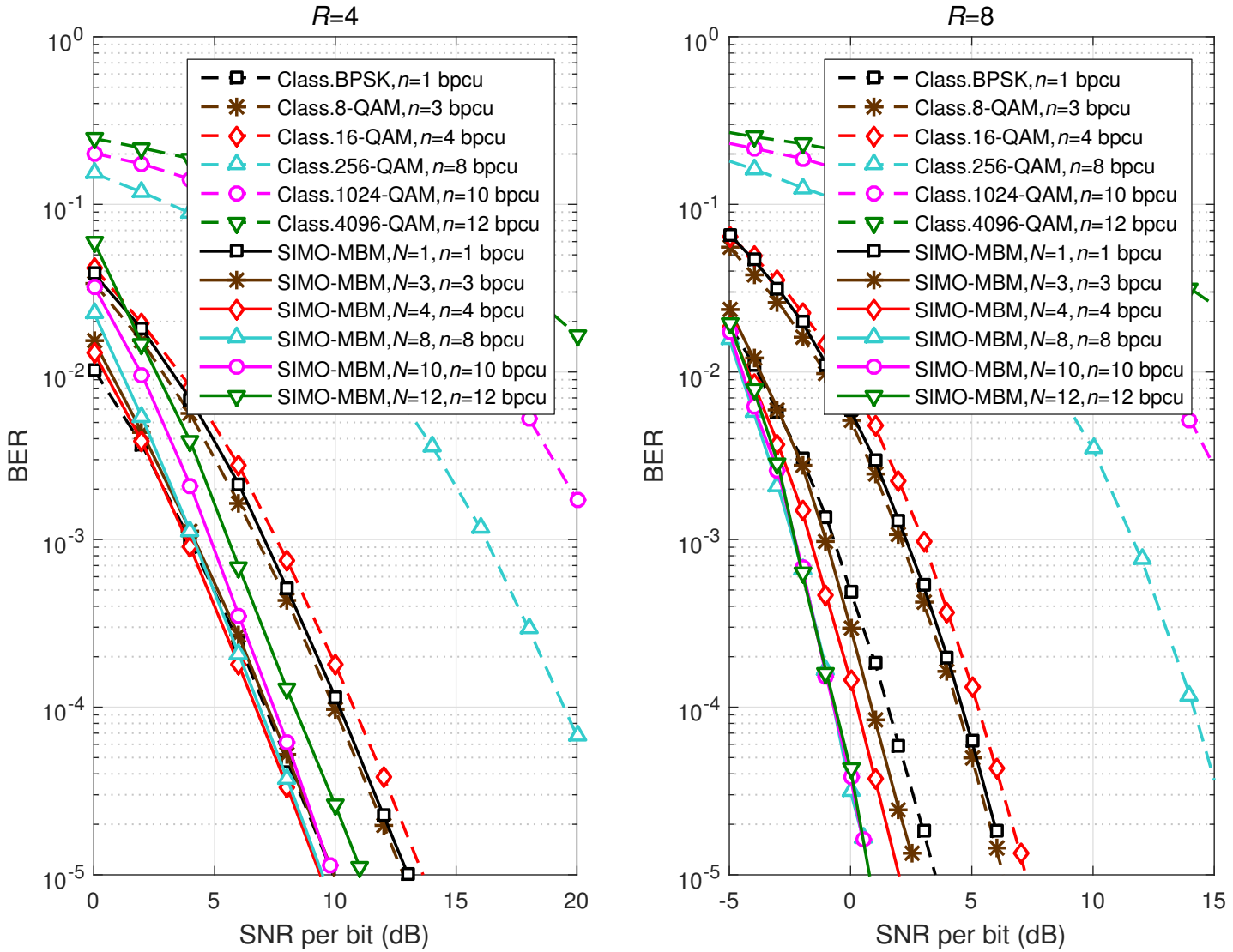
Advantages of MBM

- 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.

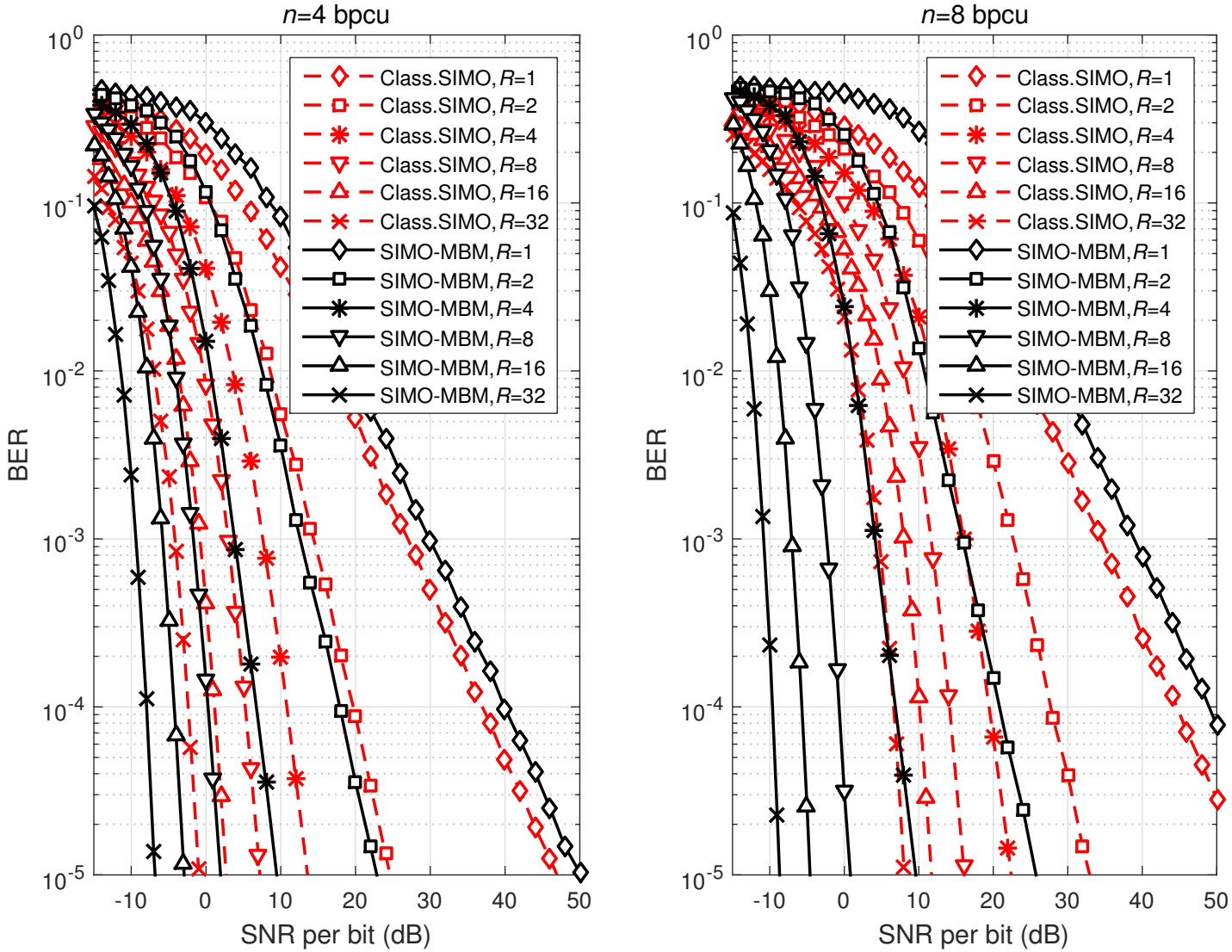
BER Performance of MBM Schemes



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

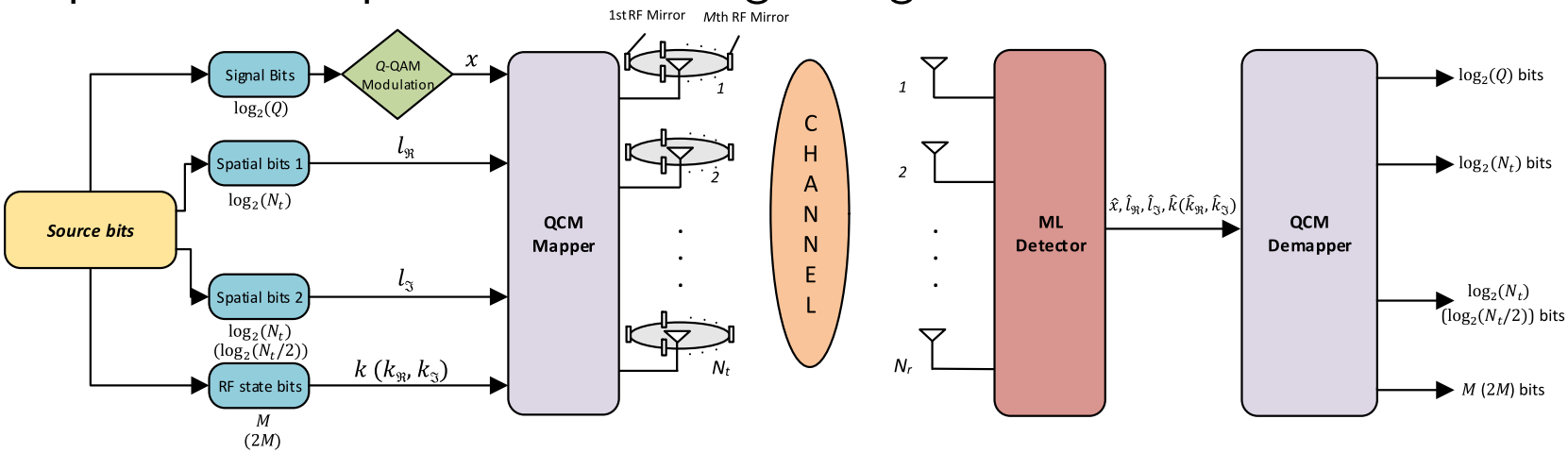
BER Performance of MBM Schemes-II



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.

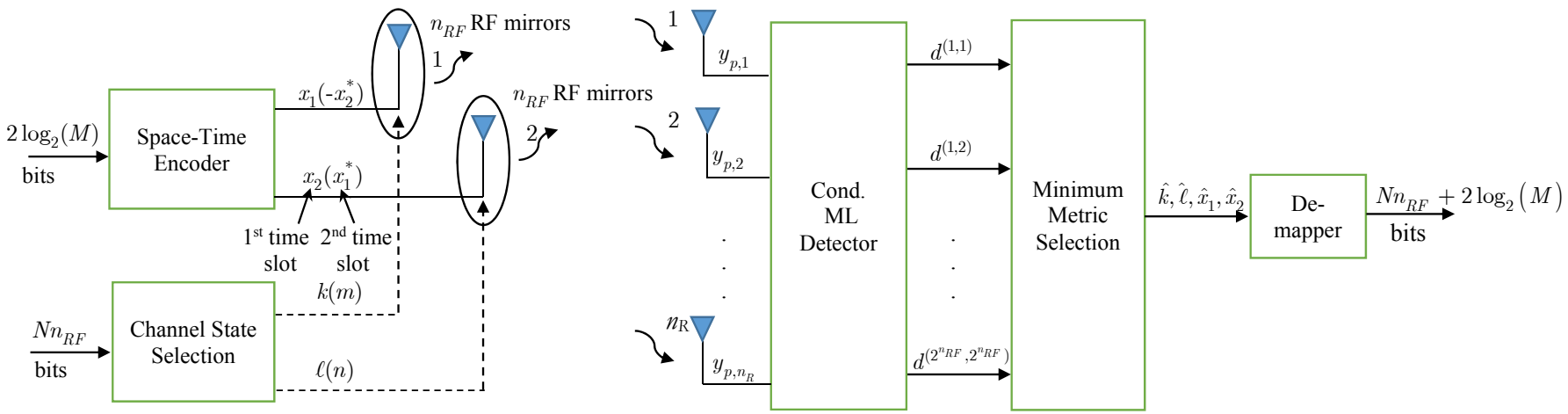
Y. Naresh and A. Chockalingam, "On media-based modulation using RF mirrors," IEEE Trans. Veh. Technol., vol. 66, no. 6, pp. 4967–4983, June 2017.

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.



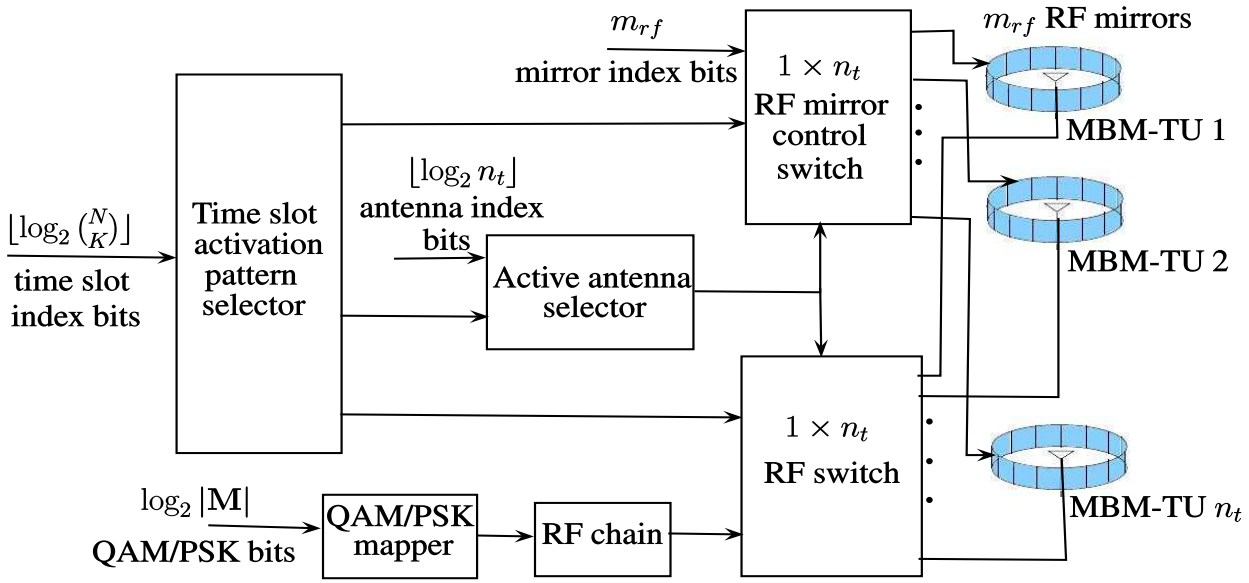
Transceiver structure of the STCM scheme for a $2 \times n_R$ MIMO system. n_{RF}: number of RF mirrors at each transmit antenna, M: constellation size, k, l, m, n: selected channel states, $N \in \{1, 2\}$.

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

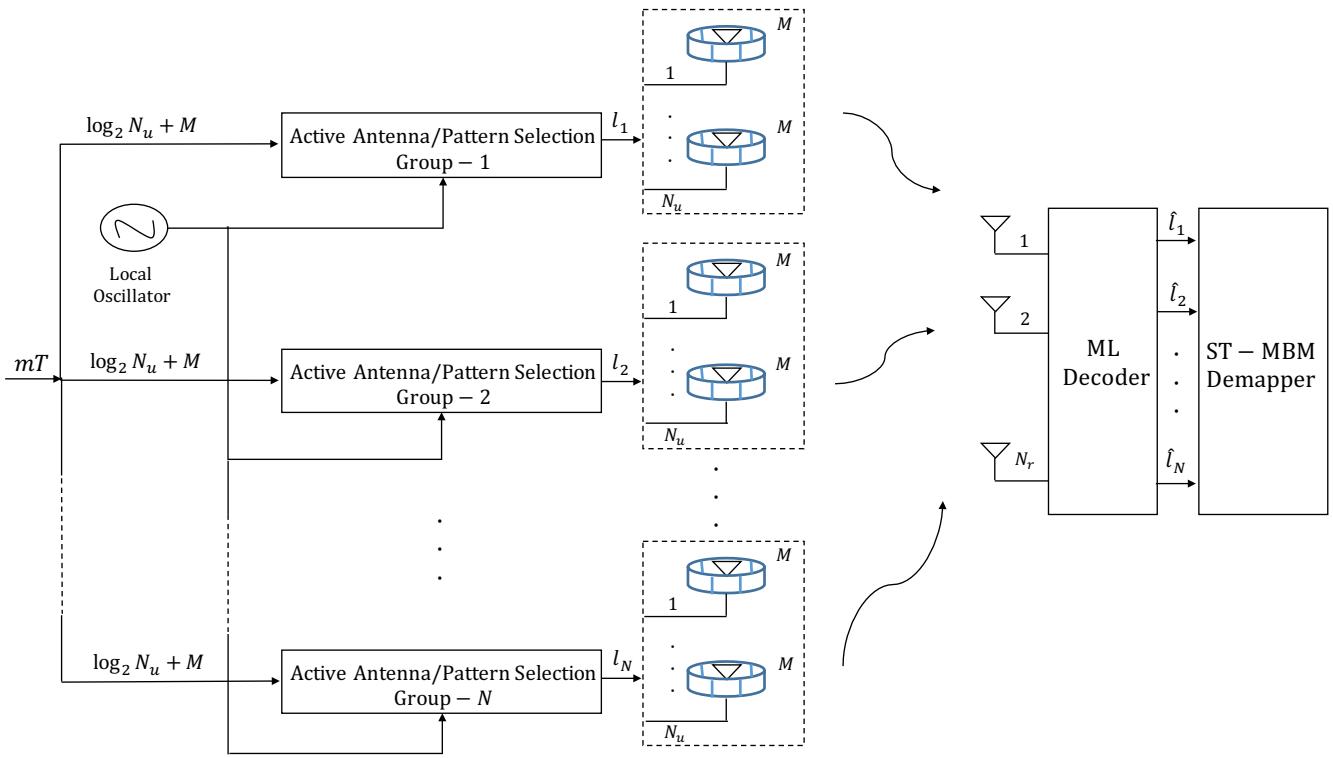
- Multi-dimensional IM concept is presented by considering the broad applicability of IM techniques.
- Time-indexed MBM, SM-MBM and time-indexed SM-MBM (TI-SM-MBM) schemes are introduced.
- Additionally, load modulation schemes are investigated by modulating the antenna impedances that control the antenna 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 (under revision), 2019.

Unsolved Problems

- 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.
- Accurate and more realistic mathematical correlation models are needed to quantify the amount of correlation among different fade realizations.
- 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.
- Low-complexity ML/near-ML/sub-optimal MBM detectors are required to unlock the potential of MBM schemes at high spectral efficiency values.
- 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.

Conclusions

- The focus is on increasing the bandwidth by going to mm-Wave bands, using massive MIMO setups to enhance the connectivity as well as considering sophisticated signal processing and channel coding techniques to improve the reliability.
- MBM emerges as an upcoming technology that can be an alternative and/or supplementary to these modern communication paradigms for beyond 5G networking.
- We hope that much more will come shortly in this new and promising communication frontier, stay tuned!

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
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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

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Submission Deadline: 31 May 2019

Any Questions?