CONTRIBUTED PAPER

Multidimensional Index Modulation for 5G and Beyond Wireless Networks

This article comprehensively examines the flexible utilization of existing index modulation techniques to satisfy the challenging and diverse requirements of 5G and beyond services.

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ABSTRACT | Index modulation (IM) provides a novel way for the transmission of additional data bits via the indices of the available transmit entities compared with classical communication schemes. This study examines the flexible utilization of existing IM techniques in a comprehensive manner to satisfy the challenging and diverse requirements of 5G and beyond services. After spatial modulation (SM), which transmits information bits through antenna indices, application of IM to orthogonal frequency-division multiplexing (OFDM) subcarriers has opened the door for the extension of IM into different dimensions, such as radio frequency (RF) mirrors, time slots, codes, and dispersion matrices. Recent studies have introduced the concept of multidimensional IM by various combinations of 1-D IM techniques to provide higher spectral efficiency (SE) and better bit error rate (BER) performance at the expense of higher transmitter (Tx) and receiver (Rx) complexity. Despite the ongoing research on the design of new IM techniques and their implementation challenges, proper use of the available IM techniques to address different requirements of 5G and beyond networks is an open research area in the literature. For this reason, we first provide the dimensional-based categorization of available IM domains and review the existing IM types regarding this categorization. Then, we develop a framework that investigates the efficient utilization of these techniques and establishes a link between the IM schemes and 5G services, namely, enhanced mobile broadband (eMBB), massive machine-type communications (mMTCs), and ultrareliable low-latency communication (URLLC). In addition, this work defines key performance indicators (KPIs) to quantify the advantages and disadvantages of IM techniques in time, frequency, space, and code dimensions. Finally, future recommendations are given regarding the design of flexible IM-based communication systems for 5G and beyond wireless networks.

KEYWORDS | 1-D; enhanced mobile broadband (eMBB); index modulation (IM); massive machine-type communication (mMTC); multidimensional; orthogonal frequency-division multiplexing with IM (OFDM-IM); spatial modulation (SM); ultrareliable low-latency communication (URLLC).

NOMENCLATURE

3GPP	Third-generation partnership project.
4G	Fourth generation.
5G	Fifth generation.
6G	Sixth generation.
BER	Bit error rate.
BLER	Block error rate.
BPSK	Binary phase shift keying.
BS	Base station.
CFO	Carrier frequency offset.
CIM-SM	Code index modulation with SM.
CIM-SS	Code index modulation spread spectrum.
CI-OFDM-IM	Coordinate interleaved OFDM-IM.
CFIM	Code-frequency index modulation.
CP	Cyclic prefix.
CR	Cognitive radio.

Manuscript received July 23, 2020; revised October 31, 2020; accepted November 20, 2020. Date of publication December 9, 2020; date of current version January 20, 2021. This work was supported in part by the Scientific and Technological Research Council of Turkey (TUBITAK) under Grant 218E035. *(Corresponding author: Seda Doğan Tusha.)*

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Digital Object Identifier 10.1109/JPROC.2020.3040589

CS	Compressed sensing.
CSI	Channel state information.
DL	Downlink.
DM	Dispersion matrix.
DMBM	Differential media-based modulation.
DM-OFDM	Dual-mode OFDM.
DM-SCIM	Dual-mode single carrier with IM.
DP-SM	Dual-polarized SM.
DS-SS	Direct sequence spread spectrum.
DSM	Differential spatial modulation.
DSTSK	Differential space–time shift keying.
EE	Energy efficiency.
eMBB	Enhanced mobile broadband.
ESIM-OFDM	Enhanced subcarrier index modulation OFDM.
ESM	Enhanced spatial modulation.
FD	Full duplex.
FFT	Fast Fourier transform.
FSK	Frequency shift keying.
FTN-IM	Faster-than-Nyquist signaling with IM.
GB	Grant-based.
GCIM-SS	Generalized CIM-SS.
GF	Grant-free.
GFDM	Generalized frequency-division multiplexing.
GFDM-IM	GFDM with IM.
GFDM-SFIM	GFDM with space–frequency IM.
GPQSM	Generalized precoding-aided QSM.
GPSM	Generalized precoding-aided SM.
GSFIM	Generalized space–frequency IM.
GSM	Generalized spatial modulation.
GSSK	Generalized space shift keying.
GSTFIM	Generalized space–time–frequency IM.
GSTSK	Generalized space–time shift keying.
IAI	Interantenna interference.
IAS	Interantenna synchronization.
ICI	Intercarrier interference.
IFFT	Inverse fast Fourier transform.
IM	Index modulation.
IMMA	IM-based multiple access.
IM-OFDM-SS	Index-modulated OFDM spread spectrum.
IoT	Internet-of-Things.
I/Q	In-phase and quadrature.
ISI	Intersymbol interference.
ISM-OFDM	SM-OFDM with subcarrier IM.
IUI	Interuser interference.
JA-MS-STSK	Joint alphabet MS-STSK.
JA-STSK	Joint alphabet STSK.
KPI	Key performance indicator.
LLR	Log-likelihood ratio.
LMG-SSTSK	Layered multigroup steered STSK.
LMS-GSTSK	Layered multiset GSTSK.
LTE	Long-term evolution.
L-OFDM-IM	Layered OFDM-IM.
MAC	Medium access control.
MA-SM	Multiple active spatial modulation.
MBM	Media-based modulation.
MIMO	Multiple-input multiple-output.
ML	Maximum likelihood.
MM-OFDM	Multiple-mode OFDM.
mMTC	Massive machine-type communications.
mmWave	Millimeter wave.
MRC	Maximum ratio combining.
MSF-STSK	Multi-space–frequency STSK.
MS-STSK	Multiset STSK.
NB-IoT	Narrowband Internet-of-Things.
NOMA	Nonorthogonal multiple access.
NR	New radio.
OFDM	Orthogonal frequency-division multiplexing
OFDMA	Orthogonal frequency-division multiple access.
OFDM-GIM	OFDM with generalized IM.
OFDM-IM	OFDM with IM.
OFDM-I/Q-IM	OFDM with I/Q IM.
OFDM-ISIM	OFDM with interleaved subcarrier IM.
OFDM-STSK	OFDM with STSK.
OFDM-STSK-IM	OFDM-STSK with frequency IM.
PAPR	Peak-to-average power ratio.
PHY	Physical layer.
PLS	Physical layer security.
PM	Polarization modulation.
PolarSK	Polarization shift keying.
PSK	Phase shift keying.
PSM	Precoded spatial modulation.
PU	Primary user.
QAM	Quadrature amplitude modulation.
QCM	Quadrature channel modulation.
QSM	Quadrature spatial modulation.
RF	Radio frequency.
Rx	Receiver.
SC	Single carrier.
SC-FDMA	Single-carrier frequency-division multiple access.
SC-IM	Single-carrier with IM.
SCS	Subcarrier spacing.
SD	Spatial diversity.
SE	Spectral efficiency.
SFSK	Space–frequency shift keying.
SIM-OFDM	Subcarrier IM OFDM.
SM	Spatial modulation.
SM-MBM	SM with MBM.
SMX	Spatial multiplexing.
SPSK	Space-polarization shift keying.
SSK	Space shift keying.
STBC	Space–time block coding.
STBC-QSM	Space–time block-coded QSM.
STBC-SM	Space–time block-coded SM.
STCM	Space–time channel modulation.
STFSK	Space–time–frequency shift keying.

STSK	Space–time shift keying.
ST-MBM	Space–time MBM.
ST-QSM	Space–time QSM.
SU	Secondary user.
SURLLC	Secure ultrareliable low-latency communication.
TCM	Trellis-coded modulation.
TCSM	Trellis-coded SM.
TC-QSM	Trellis-coded QSM.
TI-MBM	Time-indexed MBM.
TI-SM	Time-indexed SM.
TI-SM-MBM	Time-indexed SM-MBM.
TTI	Transmission time interval.
Tx	Transmitter.
UE	User equipment.
UL	Uplink.
URLLC	Ultrareliable low-latency communication.
V2X	Vehicle-to-everything.
VLC	Visible light communication.
V-BLAST	Vertical Bell Laboratories Layered Space–Time.
ZTM-OFDM-IM	Zero-padded trimode IM-aided OFDM.

I. INTRODUCTION

The rapid growth of smart devices and services, such as sensors, smartphones, ultrahigh-definition video streaming, wearable electronics, autonomous driving, drones, the Internet-based smart homes, and a broad range of augmented reality and virtual reality applications, leads to enormous data traffic that cannot be handled by 4G LTE-based communication systems [1]. Nearly tenfold increase in the global mobile data traffic is envisioned from 2020 (57 exabytes/month) to 2030 (5016 exabytes/month) [2]–[4]. In an effort to support this overwhelming data volume and variety in 5G NR systems, the International Telecommunication Union classifies numerous applications and use cases into three main services, named eMBB, mMTC, and URLLC [5], [6]. eMBB use case is a continuation of 4G LTE systems with moderate reliability and high data rate requirements. In mMTC, providing service to a massive number of UEs is the main priority, while URLLC is the most challenging service for 5G NR systems due to the strict requirements for ultrareliability with low latency [5]–[8]. In line with this trend, securing communication is essential for wireless networks, but it is disregarded during 5G standardizations. Thus, security is one of the pivotal requirements that need to be satisfied in the 6G and beyond networks, especially for scenarios with URLLC [9]. In short, a surprisingly diverse range of requirements poses two main challenges for researchers and engineers worldwide: 1) providing service in the presence of intensive data traffic over the current communication systems and 2) supporting a wide range of applications and use cases.

A. IM Can Revive Wireless Networks

Many researchers are putting tremendous effort into finding solutions to the aforementioned problems. In order to accomplish the former 1), spectrum-efficient approaches have been proposed by academia and industry, such as massive MIMO signaling, mmWave communications, and NOMA schemes [10], [11]. Besides high SE, 5G NR and beyond communication systems require a much more flexible structure for the latter 2). In this spirit, plenty of work has been done to achieve flexibility in the MAC layer and PHY for the future generation systems [12]–[14]. In order to attain a high degree of freedom in the MAC layer, various radio resource management and multiuser scheduling techniques have been studied in the literature [15]–[17]. From the perspective of the PHY design, multinumerology concept has been adopted for conventional OFDM systems [14], [18]. Variable SCSs up to 120 kHz and minislot design that can consist of two, four, or seven OFDM symbols have been introduced to meet different latency constraints.

In addition to the waveform-based approach, the use of different modulation options in the PHY has been also considered as the source of flexibility to support various UE demands. Three traditional modulation schemes, QAM, FSK, and PSK, offer different performances under a variety of radio channel conditions [19], [20]. Especially, transmission with lower order modulations provides robustness against channel impairments at the cost of a decrease in SE, while the use of higher modulation orders maximizes achievable data rate under satisfactory channel conditions. Therefore, adaptive modulation selection with respect to the channel conditions has been adopted in modern communication systems [19]. However, flexibility stemming from the adaptive selection of modulation schemes is limited by the modulation order in these traditional schemes. On the other hand, recently, reputed IM techniques have drawn substantial attention from the researchers because of their inherently flexible structure and promising advantages in terms of SE, EE, complexity, and reliability [21]–[23].

The main idea of IM is the utilization of the available transmit entities, such as antenna indices in space, subcarrier indices in frequency, and slot indices in time, to convey additional information bits along with the conventional M-ary symbols [21]–[23]. Application of IM in various domains enables an attractive tradeoff among SE, EE, transceiver complexity, interference immunity, and transmission reliability [24], [25]. Therefore, the concept of IM has introduced new research opportunities for 5G and beyond wireless systems. Inspired by the performance of 1-D IM types, such as SM and OFDM-IM, the multidimensional IM concept, which is composed of various combinations of 1-D IM options, has been introduced in recent studies. Despite the ongoing active research on IM techniques, the following important questions remain unanswered within the context of emerging IM solutions: how can the vast flexibility of IM be utilized for 5G and

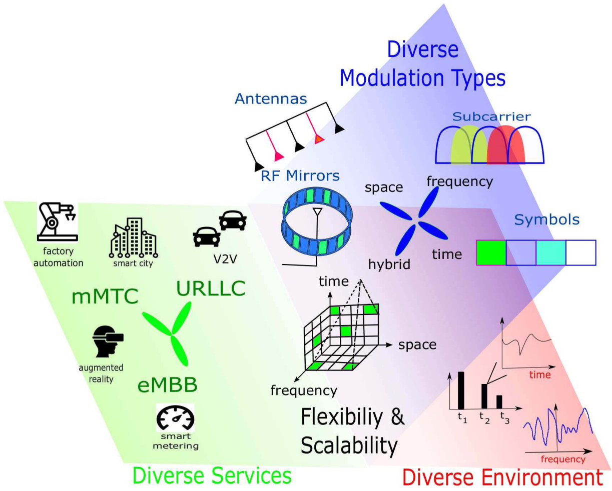

Fig. 1. *Diverse IM variants for various services and channel conditions.*

beyond systems, and how can IM solutions fulfill the broad range of user and application demands, as delineated in Fig. 1.

B. Related Works

Up until today, several survey and magazine articles have appeared in the literature to shed light on the prominent members of the IM family, as listed in Table 1. SM represents an early stage of the IM concept, and thus, Di Renzo *et al.* [26] have introduced the working principle of SM associated with its superiority over the mature MIMO technology in terms of hardware and cost efficiency. Moreover, beneficial insights have been provided on the exploitation of a wireless channel as a possible modulation unit. Besides SM-based MIMO investigation, in [30], the potential of STSK with MIMO has been elaborated in a comprehensive manner. Especially, a flexible framework allowing accommodation of multiple submechanisms, that is, SSK, SM, orthogonal STBC, V-BLAST, and linear dispersion codes (LDCs), has been introduced as a unified STSK scheme. Di Renzo *et al.* [31] not only have presented different aspects of SM-MIMO, including its principles, transceiver design, and hardware implementation, but also have paid attention to its integration with the emerging communication systems, such as relay-aided designs, small-cells, cooperative networks, mmWave systems, and VLCs. Design guidelines for SM-MIMO have been discussed with the emphasis on Rx design, spatial constellation optimization, and link adaptation techniques in [32]. Different from the aforementioned studies, Basar [22] has evaluated not only the future potentials and implementation feasibility of SM-MIMO architectures but also frequency-domain IM-based multicarrier systems, that is, OFDM-IM and MIMO-aided OFDM-IM. Also, the author has reviewed advanced SM technologies, such as GSM, ESM, and QSM. Basar *et al.* [23] have provided an overview of the IM variants present in the literature and elaborated on the advantages of SM, OFDM-IM, and channel modulation (CM). They have assessed the application of these modulation techniques to different networks and systems and reviewed some practical concerns for OFDM-IM, such as PAPR, ICI, and achievable rate. Sugiura *et al.* [33] have discussed the limitations of IM in space, time, and frequency. They have compared SC transmission with OFDM and examined the importance of time-limited pulses for SM. The challenges that occurred by the acquisition of CSI have been revealed for the SM technology. In [34], CM, which is MBM, has been discussed in addition to space-, time-, and frequency-domain IM variants. Yang *et al.* [28] have classified space- and frequency-domain IM techniques for vehicular and railway communications. Cheng *et al.* [27] have compared space-, frequency-, space–time-, and space–frequency-domain IM variants in terms of SE and EE. Future directions to further increase the SE of IM techniques have also been suggested. Ishikawa *et al.* [35] have shed light on the historical background of permutation modulation, SM, and IM concepts and have disclosed the road from permutation modulation to OFDM-IM. Research progresses on SM variants, performance enhancement schemes for SM, its integration with promising technologies, such as CS theory and NOMA-aided systems, and its application in emerging systems, such as mmWave and optical wireless communications, have been presented in [36]. Recently, Li *et al.* [29] have evaluated frequency-domain IM types, including OFDM-IM, DM-OFDM, and ZTM-OFDM-IM, for future wireless networks, including CR networks, relay-aided networks, and multiuser communications. The presented IM techniques in the existing magazine and survey articles are given in Table 2 and compared with the proposed survey.

C. Contributions

Against this background, the main contributions of this article are listed as follows.

1) A comprehensive review of the existing IM approaches in the literature is presented, and dimensional-based categorization is performed.
2) To the best of our knowledge, this study is the first for both providing a survey and comparison of 1-D and multidimensional IM options.
3) To further extend the understanding of these IM schemes, their differences and the tradeoff among them are identified with respect to the achievable data rate, power consumption, transmission reliability, and practical implementation.
4) The reviewed IM techniques are categorized considering the requirements of eMBB, mMTC, and URLLC services to shed light on the application of IM techniques for future use cases and applications.
5) The main benefits and shortcomings of available IM domains are quantified.
6) Finally, potential challenges and future directions on the integration of the IM concept into the prominent

Table 1 Summary of the Existing Magazine and Survey Articles on IM Techniques

Type	Ref.	Year	IM Domain(s)	Main Contributions
Magazine Articles	[26]	2011	Space	The principles of SM have been introduced and its advantages & disadvantages have been compared with the conventional MIMO.
	[22]	2016	Space, and Frequency	The potentials and implementation of IM techniques including SM and OFDM-IM for multi-user MIMO and multi carrier communication systems have been investigated.
	[27]	2018	Space, Time, and Frequency	Space, time, frequency, space-time and space-frequency IM options have been compared in terms of SE and EE.
	[28]	2018	Space, and Frequency	Space and frequency domain IM techniques have been subsumed by considering vehicular and railway communications.
	[29]	2020	Frequency	Frequency domain IM types including OFDM-IM, DM-OFDM, and ZTM-OFDM-IM have been evaluated for future wireless networks including cognitive radios, relay networks and multi-user communications.
Survey Articles	[30]	2012	Space, and Time	The potentials of MIMO signaling through STSK have been discussed, and unified STSK framework has been introduced.
	[31]	2014	Space	General aspects of SM-MIMO, its experimental evaluation and its integration with the promising communication systems have been presented.
	[32]	2015	Space	Transceiver design, spatial constellation optimization and link adaptation techniques for SM have been assessed.
	[23]	2016	Space, Time, Frequency, and Channel	Practical application of SM, OFDM-IM, and CM have been elaborated, and practical issues such as ICI, PAPR have been discussed.
	[33]	2017	Space, Time, and Frequency	Benefits and fundamental limitations have been discussed for SM, OFDM-IM and SC-IM.
	[34]	2018	Space, Time, Frequency, and Channel	Potential challenges and open issues for channel domain IM types have been provided in addition to space, time and frequency domain IM techniques.
	[35]	2018	Space, Time, Frequency, Code, and Channel	50 years history of SM and IM concepts, and the road from permutation modulation to OFDM-IM have been revealed.
	[36]	2019	Space	The integration of recent SM variants with promising technologies, such as CS theory, and their application in the future emerging systems, such as optical wireless communications, have been discussed.

wireless technologies, such as CR networks, cooperative systems, and nonorthogonal communications, are elaborated.

D. Article Organization

The organization of the survey is given in Fig. 2 via the chart flow. Section II revises the requirements of 5G and beyond services in wireless networks. Section III presents a comprehensive taxonomy of the existing IM schemes in the literature and then provides useful insights on future multidimensional IM variants. In Section IV, enabling IM techniques for 5G and beyond services is provided, and key advantages and disadvantages of the available IM domains are revealed. Section V provides potential challenges and future directions for IM-aided communication networks. Finally, Section VI concludes the work.[1]

[1]Notation: Bold, capital, and lowercase letters are used for matrices and column vectors, respectively. $(.)^T$ and $(.)^H$ denote transposition and Hermitian transposition, respectively. $\mathrm{E}[.]$ stands for expectation, and $\mathbb{C}$ is the ring of complex numbers. $\binom{\cdot}{\cdot}$ denotes the binomial coefficient, and $\lfloor . \rfloor$ is the floor function.

II. 5G AND BEYOND SERVICES AND REQUIREMENTS

In this section, three main services of 5G networks and their use scenarios are briefly explained, along with their widely accepted KPIs and benchmarks in the 3GPP standards. In addition, forecasts for beyond 5G systems are mentioned. The KPIs and their values in the standards are given in Table 3.

A. Enhanced Mobile Broadband

High data rate use cases and applications, such as virtual reality, broadband Internet access, and high definition video streaming, are grouped under the eMBB service, which can be considered as the continuation of the current 4G technology [98]. For these applications, peak data rates up to 10 Gbit/s are required for the UL and DL transmission of a UE [99]. Hence, to support the increased data rate requirements, bandwidths of at least 100 MHz and 1 GHz are proposed for sub-6-GHz and above 6 GHz bands, respectively. Furthermore, supporting a high data rate transmission for three different mobility classes must be considered: pedestrian speeds up to 10 km/h, vehicular speeds from 10 to 120 km/h, and high-speed vehicular

Table 2 Presented IM Techniques in the Existing Magazine and Survey Articles, and the Comparison With the Proposed Survey

IM Techniques	Magazine Articles					Survey Articles								
	[26]	[22]	[27]	[28]	[29]	[30]	[31]	[32]	[23]	[33]	[34]	[35]	[36]	This
SSK [37]	✓			✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
GSSK [38]	✓					✓	✓	✓	✓	✓	✓	✓	✓	✓
SM [39]	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
GSM [40]		✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
MA-SM [41]		✓						✓	✓	✓	✓	✓	✓	✓
QSM [42]		✓	✓	✓					✓	✓	✓	✓	✓	✓
PSM [43]			✓								✓			✓
GPSM [44]											✓			✓
GPQSM [45]											✓			✓
TCSM [46]						✓		✓	✓				✓	✓
TC-QSM [47]														✓
ESM [48]									✓		✓		✓	✓
STBC-SM [49]			✓				✓	✓	✓	✓		✓	✓	✓
STBC-QSM [50]														✓
DSM [51]			✓	✓					✓	✓			✓	✓
RIS-IM [52]														✓
ISM-OFDM [53]									✓					✓
SIM-OFDM [54]									✓	✓	✓	✓	✓	✓
ESIM-OFDM [55]									✓	✓	✓	✓		✓
OFDM-IM [56]		✓	✓	✓	✓				✓	✓		✓	✓	✓
OFDM-ISIM [57]			✓	✓					✓	✓		✓		✓
CI-OFDM-IM [58]									✓			✓	✓	✓
OFDM-I/Q-IM [59], [60]			✓						✓			✓	✓	✓
OFDM-GIM [59]		✓							✓	✓	✓	✓		✓
OFDM-GIM-I/Q [61]											✓			✓
DM-OFDM [62]					✓				✓	✓	✓	✓	✓	✓
MM-OFDM [63]					✓				✓		✓	✓	✓	✓
ZTM-OFDM-IM [64]					✓						✓			✓
L-OFDM-IM [65]														✓
GFDM-IM [66]									✓				✓	✓
GSFIM [67]		✓	✓					✓	✓				✓	✓
GSTFIM [68]													✓	✓
GFDM-SFIM [69]									✓					✓
MBM [70]				✓					✓			✓	✓	✓
DMBM [71]									✓		✓			✓
QCM [72]														✓
TI-MBM [73]									✓					✓
TI-SM-MBM [73]									✓					✓
SM-MBM [73]									✓					✓
TI-SM [74]									✓					✓
SC-IM [75]									✓	✓	✓	✓	✓	✓
FTN-IM [76]										✓	✓	✓		✓
DM-SCIM [77]										✓	✓	✓		✓
CIM-SS [78]									✓			✓	✓	✓
GCIM-SS [79]									✓			✓	✓	✓
CIM-SM [80]														✓
CFIM [81]														✓
IM-OFDM-SS [82]														✓
STCM [83]														✓
ST-MBM [84]														✓
STSK [85]						✓	✓	✓	✓	✓	✓	✓	✓	✓
DSTSK [85]						✓	✓	✓	✓	✓		✓	✓	✓
GSTSK [86]							✓	✓	✓	✓	✓		✓	✓
LMG-SSTSK [87]											✓			✓
LMS-GSTSK [87]														✓
SFSK [88]							✓	✓		✓	✓		✓	✓
STFSK [88]							✓	✓		✓	✓	✓	✓	✓
MS-STSK [89]									✓		✓	✓		✓
MSF-STSK [90]									✓		✓	✓		✓
OFDM-STSK [91]							✓	✓				✓		✓
OFDM-STSK-IM [92]														✓
OFDM-SFSK [93]														✓
JA-STSK [94]														✓
JA-MS-STSK [94]														✓
DP-SM [95]														✓
PolarSK [96]														✓
PM [97]														✓

speeds from 120 to 500 km/h. Therefore, increasing the SE via the development of new flexible communication schemes has become a critical demand. eMBB applications are expected to perform scheduled transmissions due to their characteristics, namely delay-tolerant and continuous. Hence, the eMBB service requires a spectrum-efficient

Table 3 KPIs for Next-Generation Services

Service Type	KPIs	Definitions
eMBB	Data rate	Supporting peak data rates of 10 Gbit/s and 20 Gbit/s for UL and DL transmission, respectively.
	Mobility	Achieving desired data rate for a given mobility class (10 km/h $\leq V \leq$ 500 km/h).
mMTC	Connection capability	Number of mMTC UEs per a cell (1.000.000 UEs per km^2).
	Power Consumption	At least 10 years of lifetime for a device by sending 20 bytes and 200 bytes for UL and DL transmission, respectively.
	Coverage	Maximum coupling loss that corresponds to total loss including antenna gain, path loss and shadowing for baseline data rate of 160 bit/s ($max_{CL} = 164$ dB).
URLLC	Latency	The elapsed time for successful transmission and reception of a packet (0.25 ms $\leq$ latency $\leq$ 1 ms).
	Reliability	Successful reception of a packet with the reliability range of ($10^{-5} \leq$ BLER $\leq 10^{-9}$).

waveform and modulation design at the cost of a moderate level of transmission latency and system complexity.

B. Massive Machine-Type Communications

In the context of IoT, a connection of a massive number of UEs to a network is expected in the next-generation systems [100], [101]. The coexistence of numerous machine-type and mobile UEs in the network puts pressure on service providers to satisfy the diverse demands [16]. Various applications of the IoT, such as smart cities, connected vehicles, smart agriculture, public safety, and asset tracking, require different levels of coverage area, battery life, and connection capability [102]. Unlike the human-oriented higher data rate communication in the LTE systems, providing service for massive machine-type UEs with lower data rate is the primary focus of mMTC. Although mMTC is latency-tolerant, long waiting time occurs due to the scheduling of a large number of UEs. Therefore, random access mechanisms are proposed as promising solutions for mMTC [103]. However, the current OFDM technology requires strict synchronization between the UEs to avoid inter-user-interference (IUI) [104]. mMTC use cases with ultralow power consumption and wide coverage area are grouped into NB-IoT by the 3GPP [105]–[107]. The standards adopt OFDMA and SC-FDMA for DL and UL transmissions and introduce SCS of 3.75 kHz for UL transmission over random access channels. Narrowband transmission, which leads to a low data rate, is performed to reduce power consumption and guarantee a lifetime exceeding ten years. In order to reduce the cost, mMTC UE is equipped with a single antenna, and half-duplex transmission is adopted. Retransmission of a packet is allowed to improve the coverage area at the expense of at most 10-ms transmission latency.

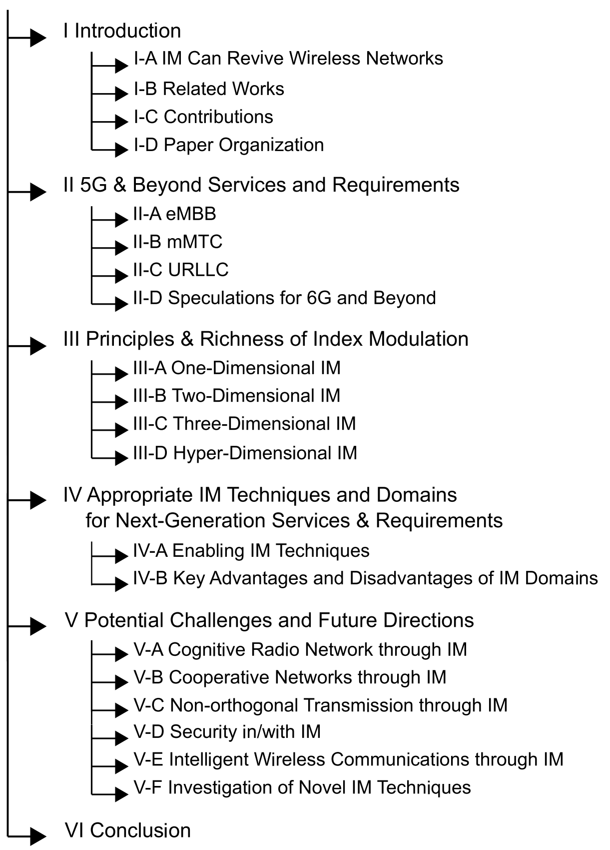

Fig. 2. ***Organization of the survey.***

C. Ultrareliable Low-Latency Communication

In 5G and beyond wireless systems, achieving ultrareliability and low latency is a crucial and very challenging task. URLLC use cases and applications need to guarantee BLER values up to 10^{-9} within the latency bounds of 0.25 ms [14], [18], [108]. The latency refers to the round trip time required for the successful transmission and reception of the transmitted data packet. In the current systems, the long handshaking processes between a UE and BS, data processing time, and TTI are the major barriers in achieving low-latency communications [109]. Moreover, the smallest resource unit is a subframe that consists of 14 OFDM symbols corresponding to a TTI of 1 ms for 15-kHz SCS. This rules out the possibility of any transmission faster than 1 ms. Thus, the minislot concept is adopted in 5G NR to meet the different latency requirements. For DL transmission, no latency occurs due to the handshaking since the BS manages the communication. However, the handshaking process between UE and BS is mandatory in UL transmission to establish reliable communication at the cost of an extra delay that corresponds to three TTIs. This is in addition to the reduction in SE and EE due to the signaling overhead and the processing complexity, respectively. Hence, the UL latency for 4G LTE systems is almost doubled compared with DL. Moreover, UL with GB transmission further leads to the waste of resources due to its sporadic nature. In GB access, BS assigns available resources to a UE continuously. However, UE with URLLC utilizes the resources intermittently. In the literature, GF access is extensively investigated to avoid the latency caused by the handshaking process [7]. However, UEs with GF transmission are exposed to collisions that reduce system reliability. Hence, interference immune multiple accessing schemes are required for achieving URLLC.

D. Speculations for 6G and Beyond

As in 5G systems, underlying applications and used cases will be the driving factors in 6G and beyond wireless networks [110]. For instance, 6G is expected to open the door for a wide range of unprecedented services, such as self-driving cars, virtual reality, flying vehicles, human body, and holographic communications [111]. Hence, the future of wireless system operators must simultaneously deliver much higher data rates, higher security, and communication reliability within a shorter latency compared with the aforementioned scenarios of 5G. For example, a five-time increase in average data consumption per UE and down to 0.1-ms latency is expected by 2024 [112]. Moreover, a service of joint eMBB and URLLC with security constraints and other combinations of eMBB, mMTC, and URLLC are envisioned to represent these new applications and use cases. In this context, artificial intelligence, machine learning, reconfigurable intelligent surfaces (RISs), unmanned aerial vehicles (UAVs), and terahertz (THz) communications are mainly speculated among potential technologies in beyond 5G [113]. Extensive research is afforded by both academia and industry for beyond 5G wireless networks in the industrialized countries. In China, several research groups are established to enhance intelligent manufacturing. Horizon 2020 ICT-09-2017 project considers mmWave and THz spectrum as a possible solution for scenarios with joint eMBB and latency limitations. Moreover, in [114], IM is considered as a complementary technology to conventional OFDM-based multiplexing in order to achieve flexibility in 6G systems.

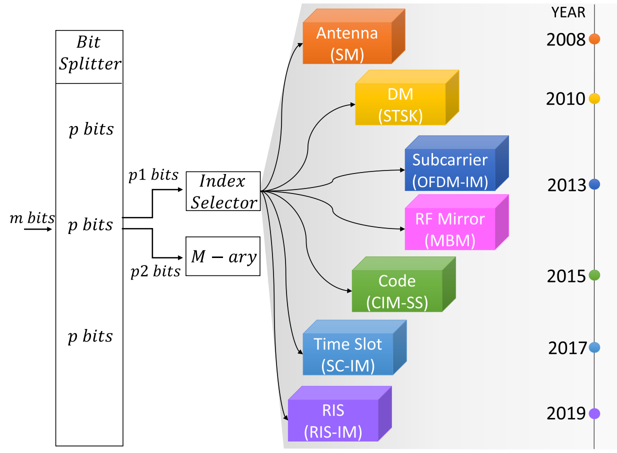

Fig. 3. ***Basic implementation of IM, and the timeline of substantial IM techniques.***

III. PRINCIPLES AND RICHNESS OF INDEX MODULATION

IM deals with the mapping of data bits to information-bearing transmit entities, such as antennas, subcarriers, RF mirrors, DMs, codes, time slots, and different combinations thereof. In order to convey additional information bits along with conventional M-ary symbols, partial activation of the entities in a given domain is performed through IM. Although the initial proposal of the IM concept dates back to almost the beginning of the century, it has drawn substantial attention from the research community over the last decade [37]. Fig. 3 illustrates the timeline of the substantial IM variants in the literature.

In spite of the fact that 1-D IM methods are well known, a comprehensive overview of the multidimensional IM methods is lacking in the literature. In view of this, first, this section reveals the applied multidimensional IM domains in the literature and provides their dimensional-based categorization in detail, as illustrated in Fig. 4. Later, the existing IM techniques are subsumed regarding the dimensional-based categorization. In Table 4, the right-angled triangle demonstrates the available IM options in the literature regarding their application domains, where the diagonal and off-diagonal cells correspond to 1-D and multidimensional IM schemes, respectively. Note that 2-D IM placed in diagonal cells is only DM-based IM types, and their combinations with the other IM schemes are minimum 3-D IM. Also, the unfilled cells denote the unexplored multidimensional IM variants.

A. 1-D Index Modulation

The 1-D IM corresponds to fundamental IM techniques that lay the foundations for multidimensional IM types. As illustrated in Fig. 4, space, frequency, time, code, channel, and polarization domains are elaborated under this category.

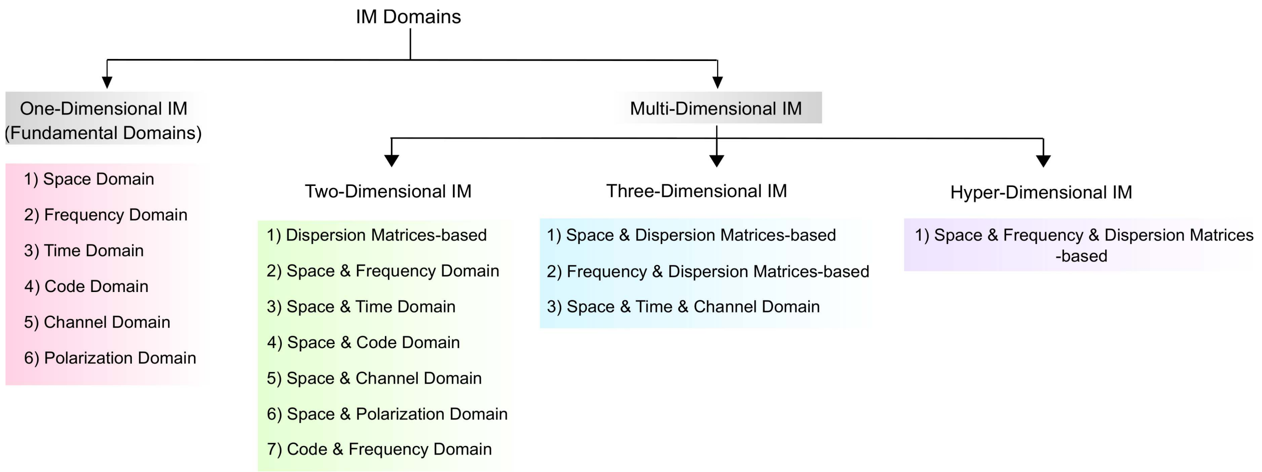

Fig. 4. ***Dimensional-based categorization of the existing IM domains in the literature.***

1) Space-Domain IM: Two different physical entities consisting of antennas and RISs are evaluated in the context of space-domain IM.

SMX and SD are well-known techniques for boosting transmission rate through sending independent information bits over independent channels and increasing reliability through emitting the same information bits over independent channels for conventional $N_t \times N_r$ MIMO systems, respectively [119], [120]. N_t and N_r represent the number of Tx and Rx antennas, respectively. However, hardware complexity, strict synchronization requirement between Tx antennas, and decoding complexity should be alleviated to reap the advantages of MIMO systems. First, activation of N_t Tx antennas at each transmission interval requires N_t RF chains, which might be impractical for mMTC devices. Second, all data symbols should be transmitted at the same time; thus, IAS is needed. Third, the Rx is subject to a heavy decoding process due to the active N_t Tx antennas.

a) IM via antennas: The space-domain IM is introduced via SSK that utilizes a single antenna out of N_t Tx antennas [37], [121]. The index of the active antenna conveys $m = \log_2(N_t)$ information bits, while the antenna itself does not carry M-ary symbol. There are N_t different combinations of the information bits to decide the active antenna. For the ith combination, the transmission vector $\mathbf{x_i}$ presents the status of N_t antennas, and it is expressed as

$$\mathbf{x_i} \triangleq [0 \quad 0 \quad 0 \quad 1 \quad 0 \quad \cdots \quad 0]^T \tag{1}$$

where the active antenna has unit transmission power, while 0 refers to the inactive antennas. SSK attains a logarithmic increase on SE with N_t, while SE of conventional SMX methods linearly increases with N_t. Thus, achieving higher data rates through SSK can be impractical due to the need for higher number of Tx antennas. GSSK allows the utilization of multiple Tx antennas to carry the information bits [38]. For N_k active antennas, $\lfloor \log_2 \binom{N_t}{N_k} \rfloor$ data bits are conveyed by the indices of multiple active antennas. Hence, $\mathbf{x_i}$ corresponds to

$$\mathbf{x_i} \triangleq \left[0 \quad \frac{1}{\sqrt{N_k}} \quad \cdots \quad 0 \quad \frac{1}{\sqrt{N_k}} \quad 0 \quad \cdots \quad 0\right]^T. \tag{2}$$

Since multiple Tx antennas are active, IAS is a necessity for GSSK. Otherwise, the system performance is affected by IAI. Moreover, the channels between the activated Tx and Rx antennas should be as independent as possible to achieve a performance gain via spatial selectivity. Thus, the distance between Tx antennas in an array should be more than half of the wavelength $(\lambda/2)$.

The invention of the SM is an important breakthrough that not only paves the way for the introduction of the general IM concept to the wireless communication realm but also sheds light on its development [39], [122]–[124]. Besides conveying information bits via the index of active Tx antenna, SM also performs conventional M-ary symbol transmission. In this case, the transmission vector $\mathbf{x_i}$ is expressed as

$$\mathbf{x_i} \triangleq [0 \quad 0 \quad 0 \quad s_l \quad 0 \quad \cdots \quad 0]^T \tag{3}$$

where $s_l \in \mathcal{S}$, where $\mathcal{S}$ is the set of M-ary symbols $\mathcal{S} = \{s_0 \ s_1 \ \cdots \ s_{M-1}\}$. For each transmission interval, $\log_2(N_t)$ and $\log_2(M)$ bits are carried by the active antenna index and M-ary symbol, respectively. Thus, the number of transmitted bits per channel use (bpcu) for SM is

$$\eta = \log_2(N_t) + \log_2(M) \text{ [bpcu]}. \tag{4}$$

SM provides better SE than SSK while protecting the zero IAI feature. To improve both SE and achievable performance, GSM activates N_k Tx antennas for the transmission

Table 4 Comprehensive Taxonomy of 1-D and Multidimensional IM Variants

Space	SSK* [37] GSSK* [38] SM* [39] GSM* [40] MA-SM* [41] QSM* [42] ESM* [48] TCSM [46] TC-QSM [47] STBC-SM* [49] STBC-QSM [50] PSM [43] GPSM [44] GPQSM [45] RIS-IM+ [52]						
Frequency	ISM-OFDM [53] GSFIM [67] GSTFIM [68] GFDM-SFIM [69]	SIM-OFDM [54] ESIM-OFDM [55] OFDM-IM [56] OFDM-ISIM [57] CI-OFDM-IM [58] OFDM-GIM [59] DM-OFDM [62] MM-OFDM [63] GFDM-IM [66] OFDM-I/Q-IM [59], [60] ZTM-OFDM-IM [64] L-OFDM-IM [65]					
Time	TI-SM [74] TI-SM-MBM [73]	...	SC-IM [75] FTN-IM [76] DM-SCIM [77]				
Code	CIM-SM [80]	CFIM [81]	...	CIM-SS [78] GCIM-SS [79] IM-OFDM-SS [115]			
Channel	SM-MBM [73] QCM [72]	...	TI-MBM [73] TI-SM-MBM [73]	...	MBM [70] DMBM [71] STCM [83] ST-MBM [84]		
DMs	LMS-GSTSK [87] MS-STSK [89] JA-STSK [94] JA-MS-STSK [94]	OFDM-STSK-IM [92] MSF-STSK [90]	...	...	...	DSM* [51] STSK [85] DSTSK [85] GSTSK [86] STFSK [88] OFDM-STSK [91] SFSK [93] LMG-SSTSK [116]	
Polarization	SPSK [117] DP-SM [95], [118]	...	...	...	...	...	PolarSK [96] PM [97]
Modulation Domain	**Space**	**Frequency**	**Time**	**Code**	**Channel**	**DMs**	**Polarization**

Note - $(.)^{*}$: IM via antennas, $(.)^{+}$: IM via RIS

of the same data symbol, given that $1 \leq N_k < N_t$ [40]. Thus, $\mathbf{x_i} \triangleq [0 \; s_l \; \cdots \; 0 \; s_l \; 0 \; \cdots \; 0]^T$, and the SE rises to

$$\eta = \left\lfloor \log_2 \binom{N_t}{N_k} \right\rfloor + \log_2(M) \text{ [bpcu]}. \quad (5)$$

The transmission of different data symbols through the activated antennas is performed by MA-SM [41]. As a result of the efficient implementation of IM with the conventional QAM/PSK, the achievable rate increases to

$$\eta = \left\lfloor \log_2 \binom{N_t}{N_k} \right\rfloor + N_k \log_2(M) \text{ [bpcu]}. \quad (6)$$

A new perspective to SM is introduced through QSM where the I/Q parts of complex data symbols are transmitted by two different Tx antennas [42], [125]. The selection of two Tx antennas requires $2\log_2(N_t)$ data bits. Hence, the transmission rate for QSM equals

$$\eta = 2\log_2(N_t) + \log_2(M) \text{ [bpcu]}. \quad (7)$$

Although not emphasized sufficiently in the literature, a particular strength of the QSM is that it exploits the spatial selectivity by conveying the real and imaginary parts of the data symbol separately. In order to further boost the data rate of SM, ESM proposes the transmission of information bits by the use of two different QAM/PSK sets, that is, $\mathcal{S}_1$ and $\mathcal{S}_2$, for the two active Tx antennas [48]. It should be ensured that the same number of data bits is transmitted at each transmission interval. Otherwise, error propagation occurs due to asynchronization between the data blocks. Therefore, higher order modulation $\mathcal{S}_2$ is used when one of the two antennas is activated, while lower order modulation $\mathcal{S}_1$ is utilized in the presence of two active antennas. Moreover, the selected modulation types decide the BER performance of ESM. If the Euclidean distance between the symbols modulated with $\mathcal{S}_1$ and $\mathcal{S}_2$ is higher than that of SM, better BER performance is achieved than SM, and vice versa. The aforementioned space-domain IM types suffer from a lack of diversity gain. In [46], TCSM is presented with the implementation of TCM over the antenna combinations of SM. In this way, the spatial distance between the antennas within the same subblock is maximized without increasing the power consumption. Also, in [47], TCM is incorporated with QSM (TC-QSM) to further improve the error performance of SM systems. On the other hand, in order to achieve transmit diversity gain for any number of Tx antennas, STBC-SM and ST-QSM are proposed in [49], [50], and [126], respectively. ST-QSM divides the existing N_t antennas into two subsets (N_{t1} and N_{t2}) to carry two complex symbols. The real and imaginary parts of the symbols are transmitted over the subcarriers that are independently chosen from the first and second subsets. The total number of the active subcarriers in each set corresponds to (N_{k1} and N_{k2}). Moreover, the IM concept is applied to Rx antennas via preprocessing/precoding of the transmission vector with the knowledge of CSI at Tx and named PSM or Rx SM [43], [127]. GPQSM is introduced in [44] and [45]. GPSM corresponds to SM at Rx, while GPQSM is the QSM with multiple active antennas at Rx.

b) IM via RISs: RIS concept has been extensively investigated in the past few years. Intelligent surfaces consist of small, low cost, and a high number of passive elements that control the reflection features of the incoming signals. For a comprehensive overview of the RIS concept, interested readers are referred to [128]–[131]. RIS-assisted IM concept is introduced in [52]. It is shown that IM can be applied to the passive elements, as well as Tx and Rx antennas.

2) Frequency-Domain IM: Indexing of the subcarriers in the frequency domain is proposed to improve both SE and EE of the conventional OFDM systems. SIM-OFDM divides incoming data bits into two parts [54]. The ON–OFF keying data bits decide the status of N_{sc} subcarriers in an OFDM block, and the remaining bits are conveyed through N_a subcarriers whose status is ON. However, the inconsistent number of the total bits per OFDM block results in error propagation and degrades the BER performance of SIM-OFDM. ESIM-OFDM splits the OFDM block into $N_{\mathrm{sc}}/2$ subblocks with two subcarriers, and it only activates a single subcarrier ($N_a = 1$) per subblock to avoid error propagation [55]. Inspired by the SM, SIM-OFDM and ESIM-OFDM are the early attempts for frequency-domain IM. However, their performances are not satisfactory, and their implementations are impractical. Hence, the general concept for frequency-domain IM is first introduced by OFDM-IM [56].

In OFDM-IM, available subcarriers are partitioned into N_G subblocks, and each subblock includes $N_b = N_{\mathrm{sc}}/N_G$ subcarriers. N_a subcarriers out of N_b subcarriers are activated according to $p_1 = \lfloor \log_2 \binom{N_b}{N_a} \rfloor$ bits. The remaining $p_2 = N_a \log_2(M)$ bits are utilized to modulate the active subcarriers. The number of transmitted bits per OFDM-IM subblock is

$$p = p_1 + p_2 = \left\lfloor \log_2 \binom{N_b}{N_a} \right\rfloor + N_a \log_2(M). \tag{8}$$

Then, OFDM-IM subblocks are concatenated to generate an OFDM block, and the remaining process is the same as conventional OFDM. IFFT is applied to the OFDM block, and CP is added to avoid ISI. Thus, the SE of OFDM-IM is

$$\eta = \frac{N_G}{N_{\mathrm{sc}} + N_{\mathrm{cp}} - 1} \left(\left\lfloor \log_2 \binom{N_b}{N_a} \right\rfloor + N_a \log_2(M) \right) \text{ [bits/s/Hz]} \tag{9}$$

where N_{cp} is the CP size in the frequency domain. At Rx, the ML detector is used for joint estimation of the active subcarriers and the QAM/PSK symbols after CP removal and FFT process. However, the ML detector is impractical for large N_{sc} values. Hence, in [56], the LLR detector is proposed for OFDM-IM. In order to both reduce correlation and exploit frequency diversity, interleaving for an OFDM block is employed by OFDM-ISIM [57]. Lower correlation between the active subcarriers improves the detection performance at Rx and, consequently, the BER. CI-OFDM-IM achieves an additional diversity gain through the transmission of real and imaginary parts of a complex data symbol over two active subcarriers via the CI orthogonal design. Therefore, CI-OFDM-IM provides higher reliability than both OFDM-IM and OFDM-ISIM [58]. In addition, OFDM-I/Q-IM utilizes different information bits to generate the I/Q parts of data symbols [59], [60].

In OFDM-IM, the N_a value is fixed for all OFDM subblocks. On the other hand, OFDM-GIM allows varying N_a values for the different subblocks to enhance the SE of OFDM-IM [59], [61]. Further SE improvement is achieved with DM-OFDM that uses two different QAM/PSK sets $\mathcal{S}_1$ and $\mathcal{S}_2$ for N_a and $N_b - N_a$ subcarriers, respectively [62]. In this way, all the subcarriers are modulated within a subblock. Hence, the achieved SE by DM-OFDM equals

$$\eta = \frac{N_G}{N_{\mathrm{sc}} + N_{\mathrm{cp}} - 1} \left(\left\lfloor \log_2 \binom{N_b}{N_a} \right\rfloor + N_a \log_2(M_1) + (N_b - N_a) \log_2(M_2) \right) \text{ [bits/s/Hz]} \tag{10}$$

where M_1 and M_2 are the constellation size of $\mathcal{S}_1$ and $\mathcal{S}_2$, respectively. Inspired by DM-OFDM, two promising schemes, including MM-OFDM and ZTM-OFDM-IM, are introduced in the literature [63], [64]. MM-OFDM uses multiple QAM/PSK sets within a subblock to enhance the SE, while ZTM-OFDM-IM performs fractional subcarrier activation by two different QAM/PSK sets. In order to further increase the SE of the OFDM-IM systems, in [65], L-OFDM-IM is proposed by division of p incoming bits into L layers, where N_{a_L} out of N_{b_L} subcarriers is activated, given that $N_b = N_{b_L} + N_{a_L}(L-1)$.

The aforementioned frequency-domain IM types are based on OFDM technology. In [66], IM is applied to GFDM, instead of OFDM. GFDM performs block-based transmission over T time slots, and each block consists of K subsymbols composed by N_{sc} subcarriers. Moreover, each block can include a different number of subsymbols. GFDM alleviates the strict synchronization requirement of OFDM since nonorthogonal pulse shaping is allowed. In this regard, GFDM-IM combines the benefits of GFDM-IM flexibility.

3) Time-Domain IM: Inspired by the frequency-domain IM, SC-IM is proposed in the time domain [75]. An SC block with K_s symbols is divided into K_G subblocks that consist of $K_b = K_s/K_G$ symbols. Data transmission is performed at the time intervals corresponding to active K_a symbols, and the remaining $K_b - K_a$ symbols are set to zero. SC subblocks are concatenated to generate an SC block, and then, CP is added before its transmission over a multipath channel. The SE of SC-IM is

$$\eta = \frac{K_G}{K + K_{\text{cp}} - 1}\left(\left\lfloor \log_2 \binom{K_b}{K_a} \right\rfloor + K_a \log_2(M)\right) \text{ [bits/s/Hz]} \qquad (11)$$

where K_{cp} refers to the CP size in the time domain. At Rx, an ML or LLR detector is utilized to find the nonzero symbols after CP removal and frequency-domain equalization [56]. It is worth mentioning that interleaving at Tx is needed to tear the correlation between the active symbols if the channel is nonselective in time. Thus, deinterleaving is required at Rx. FTN-IM has been proposed since the passive symbols in the SC block alleviate the effect of ISI [76], [132]. Furthermore, DM-SCIM utilizes two different QAM/PSK sets for further increasing the SE of SC-IM, as in DM-OFDM [77].

4) Code-Domain IM: By taking the advantage of DS-SS technology, CIM-SS has been proposed in [78]. The information-bearing unit is the spreading code available in a predefined table of spreading codes. In [78], two orthogonal Walsh codes (w_1 and w_2) are stored in the lookup table. The incoming two bits are combined to generate a subblock, and one bit in each subblock chooses a code (N_{ac}) to spread the remaining bit over a time duration. I/Q parts of a complex symbol are modulated by orthogonal Walsh codes. GCIM-SS uses the code table with N_{ct} size, where $\lfloor \log_2(N_{ct}) \rfloor$ defines the number of bits required for choosing a code [79], [133]. Hence, the SE of GCIM-SS is

$$\eta = \frac{1}{N_{ct}}(2\lfloor \log_2(N_{ct}) \rfloor + \log_2(M)) \text{ [bits/s/Hz].} \qquad (12)$$

At Rx, distinct N_{ct} correlators are used for the I/Q parts of the complex symbol. The correlator that gives the maximum absolute value corresponds to the utilized code at Tx. Later, despreading and conventional QAM/PSK demodulation are applied to obtain the transmitted information bits. CIM is also applied in the frequency domain with the aid of OFDM and named IM-OFDM-SS [82], [115]. In order to obtain diversity gain, IM-OFDM-SS spreads data symbols over several subcarriers via spreading codes. ML- and MRC-based detectors are used at Rx. Also, a generalized framework for multiuser scenarios is introduced in [82].

5) Channel-Domain IM: MBM transmits information bits via different channel realizations generated by the ON–OFF status of the available RF mirrors, which are located in the vicinity of the Tx antenna [70], [124], [134]–[136]. In other words, each channel realization corresponds to a different point in the constellation diagram at the Rx. No additional energy is required to transmit the bits by MBM. Moreover, it is shown that $1 \times N_r$ SIMO systems with MBM can harvest the same energy as $N_t \times N_r$ MIMO systems, yielding $N_t = N_r$ [70]. Unlike SSK, SE of MBM linearly increases with the number of RF mirrors (N_{rf}). Thus, the transmission rate of MBM with a single RF mirror activation ($N_{\text{am}} = 1$) is

$$\eta = N_{\text{rf}} + \log_2(M) \text{ [bpcu].} \qquad (13)$$

The main issue for MBM is the requirement of CSI at Rx. $2^{N_{\text{rf}}}$ channel realizations need to be estimated in the presence of N_{rf} mirrors. Usually, the estimation of CSI is performed through the training process. However, it leads to severe signaling overhead for the system, especially in the case of a higher number of RF mirrors. To overcome this, DMBM is proposed in the literature, where the estimation process is avoided by encoding consecutive data blocks at the cost of performance degradation [71]. In [83] and [84], STCM and ST-MBM incorporate STBCs into channel-domain IM for the purpose of achieving diversity gain. Especially, STCM adopts Alamouti's STBC as the core, and ST-MBM amalgamates the Hurwitz–Radon family of matrices [32] with the MBM principles to allow a single RF chain-based transmission.

6) Polarization-Domain IM: In order to provide both higher multiplexing gain and higher SE for the single RF MIMO systems, PolarSK is introduced in [96]. PolarSK uses the available P polarization states, that is, linear polarization, circular polarization, and elliptic polarization, to transmit the incoming bits as in SSK. In a recent study, a novel IM scheme, that is, PM, utilizes polarization characteristics to carry extra information bits along with the complex data symbols. Especially, not only vertical and horizontal polarizations but also the axial ratio and tilt angle of elliptic polarization are used for conveying the information bits through IM [97].

B. 2-D Index Modulation

The 2-D IM corresponds to the simultaneous activation of information-bearing units in two different dimensions, such as space & frequency and space & time, as given in Fig. 4.

1) Dispersion Matrix-Based IM: STSK introduces an innovative information-bearing unit, that is, DMs, for conventional MIMO systems [85], [137]. STSK exploits the time domain along with the space domain through block-based transmission as $\mathbf{Y} = \mathbf{HX} + \mathbf{N}$, where $\mathbf{Y} \in \mathbb{C}^{N_r \times T}$, $\mathbf{H} \in \mathbb{C}^{N_t \times N_r}$, and $\mathbf{X} = \mathbf{D}s \in \mathbb{C}^{N_t \times T}$ denote the received block, the multipath channel, and the transmitted block, respectively. $\mathbf{D} \in \mathbb{C}^{N_t \times T}$ refers to the DM to spread the M-ary symbol (s) over space and time dimensions, and T is a block duration. An STSK block ($\mathbf{X} = \mathbf{D}s$) is generated by the different combinations of Q DMs with the M-ary symbols in a given modulation set. Also, SSK and SM can be assessed as the special cases of STSK, given that $T = 1$. Thus, STSK provides diversity gain along with multiplexing gain by adjusting the number of DMs (Q), STSK block duration (T), and the number of Tx and Rx antennas (N_t, N_r). To exemplify, a single DM and the modulation set with $M = M_1$ complex symbols, or two DMs and the modulation set with the $M = M_1/2$ complex symbols can generate different STSK blocks to transmit $(\log_2(QM)/T)$ bits [85]. It should be noted that the correlation between Q DMs should be as low as possible to improve the detection performance at Rx. This is one of the ongoing research areas pertaining to the design of DMs [138], [139]. Generalized STSK (GSTSK) is developed to choose P DMs at each transmission interval [86]. Hence, the achievable rate by GSTSK is

$$\eta = \frac{\left\lfloor \log_2 \binom{Q}{P} \right\rfloor + P \log_2(M)}{T} \text{ [bpcu]}. \tag{14}$$

The BER performance of STSK is affected by ISI under frequency-selective channel conditions. Therefore, SFSK proposes the utilization of the conventional F-FSK to spread the data symbol in space, time, and frequency, instead of M-QAM/PSK [88]. An SFSK block corresponds to the multiplication of the F-FSK symbol with the DM. At Rx, square-law and ML detectors are used to detect the active frequencies and the DM, respectively. Moreover, STFSK amalgamates STSK and SFSK. The information bits are modulated by M-QAM/PSK, F-FSK, and the index of active DM.

To exploit the robustness of OFDM against the frequency-selective channels, STSK has been combined with OFDM and named OFDM-STSK [91]. Before the conventional OFDM transmission, $J = N_{\mathrm{sc}}/T$ STSK blocks of size $N_t \times T$ are concatenated, where it is assumed that N_{sc} is the multiple of T. Thereafter, IFFT is applied, followed by CP addition. In other words, STSK blocks are modulated by OFDM. In this way, each column of the STSK block is transmitted by a subcarrier and corresponds to the frequency-flat channel. The transmission rate of STSK and OFDM-STSK is equal, given that $N_{\mathrm{sc}} \gg N_{\mathrm{cp}}$. Different from the SFSK in [88], the OFDM-SFSK approach is proposed in [93], where the data symbol is spread over space and frequency dimensions. Indeed, OFDM-SFSK and OFDM-STSK follow the same idea of achieving robustness against time-varying OFDM channels. Differently, DMs in OFDM-SFSK are generated by the circular shifting of sparse vectors that also provides robustness against ICI for OFDM systems. In [116], the LMG-SSTSK is proposed for multiuser MIMO DL systems by combining OFDM, STSK, and Tx beamforming. Moreover, DSM avoids heavy channel estimation by differentially encoding two successive data blocks at Tx [51]. For this purpose, DSM exploits the time domain along with the space domain through block-based transmission as in STSK. In DSM, it is assumed that $T = N_t$. Each column of $\mathbf{X}$ corresponds to a transmission interval in which a single antenna is activated.

2) Space- and Frequency-Domain IMs: Two transmit entities, that is, antennas and subcarriers, are used simultaneously to carry the information. Incoming bits are divided into three parts for antenna indexing, subcarrier indexing, and conventional M-ary modulation [53], [67], [140]. ISM-OFDM is proposed to alleviate the ICI impact for V2X communication [53]. Since a single antenna is activated at each transmission interval, the transmission rate of ISM-OFDM considering (4) and (9) equals

$$\eta = \frac{N_G}{N_{\mathrm{sc}} + N_{\mathrm{cp}} - 1} \left(\lfloor \log_2 N_t \rfloor + \left\lfloor \log_2 \binom{N_b}{N_a} \right\rfloor + \log_2(M) \right) \text{ [bpcu]}. \tag{15}$$

Instead of the conventional SM, GSFIM combines OFDM-IM with MA-SM in order to activate multiple Tx antennas and subcarriers at each transmission interval [67]. Regarding (6) and (9), the achieved rate by GSFIM corresponds to the total number of transmitted bits by OFDM-IM and MA-SM. Moreover, GSFIM has been evaluated in the context of GFDM, named GFDM with SFIM (GFDM-SFIM) that provides higher SE than GSFIM for a given BER performance [69].

3) Space- and Time-Domain IMs: Simultaneous indexing of the transmission entities in both space and time is evaluated in [73] and [74]. Considering the time slots, Tx antennas, and RF mirrors as separate units, two different space- and time-domain IM schemes are presented: TI-SM and TI-MBM.

In TI-SM, Tx is equipped with N_t antennas and one RF chain, while Rx contains N_r antennas. As in (11), the active symbols for SC-IM are chosen by $\lfloor \log_2 \binom{K_b}{K_a} \rfloor$ bits. Then, $K_a \log_2(N_t)$ bits corresponding to (4) decide the active Tx antenna. TI-MBM only requires a single Tx antenna supported by N_{rf} RF mirrors. MBM is applied to transmit the additional bits, instead of SM. Hence, considering (13), the number of information bits conveyed by TI-MBM equals the total number of information bits carried by both SC-IM and MBM.

4) Space- and Channel-Domain IMs: SM-MBM and QCM are employed through the combination of MBM with SM and QSM, respectively [72], [74]. Basically, SM-MBM and QCM perform transmission through indexing both Tx antennas and RF mirrors. Therefore, N_t antennas are equipped with N_{rf} RF mirrors at Tx. The transmission rate of SM-MBM corresponds to $\eta = \log_2(N_t) + N_{\text{rf}} + \log_2(M)$ [bpcu]. Considering the QSM principles, QCM transmists $\eta = 2\log_2(N_t) + N_{\text{rf}} + \log_2(M)$ [bpcu].

5) Space- and Code-Domain IMs: A novel MIMO transmission scheme is developed based on IM in space and code domains [80]. The transmission rate of CIM-SM is given by

$$\eta = \frac{1}{N_{ct}}\left[2\left\lfloor \log_2 N_{ct} \right\rfloor + \log_2(N_t) + 2\log_2(M)\right] \text{ [bpcu]} \quad (16)$$

which corresponds to the total number of bits conveyed by CIM and SM. First, the Rx process of CIM is employed, followed by ML detector to decide the utilized antenna and the transmitted data symbols.

6) Space- and Polarization-Domain IMs: In [117], SPSK is introduced via the utilization of dual-polarized antennas. Besides the active antenna, the utilized polarization type also carries information bits. Moreover, SM and PM are combined in DP-SM to avoid the spatial correlation in SM-MIMO systems [95], [118]. As a result, the achievable SE is also increased since the space limitation in SM-MIMO systems due to the required distance between the adjacent antennas is alleviated.

7) Code- and Frequency-Domain IMs: Joint CFIM is presented in [81] by simultaneous indexing in frequency and code domains in order to support multiuser communication with low-power consumption.

C. 3-D Index Modulation

The 3-D IM types are the enhanced IM types that would serve diverse requirements of 5G and beyond networks. The existing 3-D IM types are the combinations of space & DMs, frequency & DMs, and time & space & frequency domains, as given in Fig. 4.

1) Space- and Dispersion Matrix-Based IMs: The conventional STSK uses all of the available N_t Tx antennas for transmission. In order to enhance the system reliability, partial antenna activation for the transmission of the STSK block is presented in MS-STSK [89]. Moreover, the columns of the STSK block corresponding to different time intervals are multiplied by different phase shifts for reducing the correlation among the transmissions. In [94], JA-STSK and JA-MS-STSK are performed by using a joint alphabet that corresponds to the utilization of different DMs and antenna combinations over multiple time slots for increasing the throughput gain of the STSK systems. In [87], a generalized framework that can accommodate all DM-based IM techniques is introduced and named LMS-GSTSK. Especially, LDC, BLAST, SM, GSM, QSM, SSK, GSTSK, and MS-STSK can be implemented by the proper adjustment of LMS-GSTSK's parameters. Indeed, LMS-GSTSK provides adaptive dimensional IM due to its scalable structure.

2) Frequency- and Dispersion Matrix-Based IMs: CS-aided OFDM-STSK-IM is presented for further improving the SE and BER performance of OFDM-STSK [92], [141]. First, incoming m bits are divided into N_G groups, and each group contains $\lfloor \log_2 \binom{N_b}{N_a} \rfloor$ and $\log_2(QM)$ bits to activate N_a subcarriers and select a DM, respectively. Then, coordinate interleaved STSK blocks are mapped to active N_a subcarriers. A virtual domain with N_v subcarriers is introduced by CS for transmitting additional energy-free $\lfloor \log_2 \binom{N_v}{N_a} \rfloor$ bits per subblock, given that $N_v \gg N_b$. At Rx, the signal is first compressed from the virtual domain to the frequency domain, and then the ML detector is utilized to obtain the transmitted bits. In [68], the generalized GSTFIM combines GSTSK with OFDM-IM to achieve higher SE for STSK systems.

3) Space-, Time-, and Channel-Domain IMs: In [73], TI-SM-MBM allows joint utilization of SC-IM, SM, and MBM for the purpose of increasing SE. Accordingly, the achieved SE by TI-SM-MBM equals the summation of each individual data rate.

D. Hyperdimensional IM

Hyperdimensional IM types are relatively less investigated in the literature compared with the lower dimensional IM types due to their complex structure, as shown in Fig. 4.

1) Space-, Frequency-, and Dispersion Matrix-Based IMs: MSF-STSK combines OFDM-IM, GSM, and STSK to attain interference immunity and diversity gain [90]. Besides conventional M-ary symbols, incoming bits are carried by the indices of active DMs in space and time domains, active subcarriers in the frequency domain, and active antennas in the space domain.

Fig. 5 illustrates the multidimensional IM techniques and their constituent single-domain ones. Since GSM, MA-SM, and QSM are the advanced versions of SM,

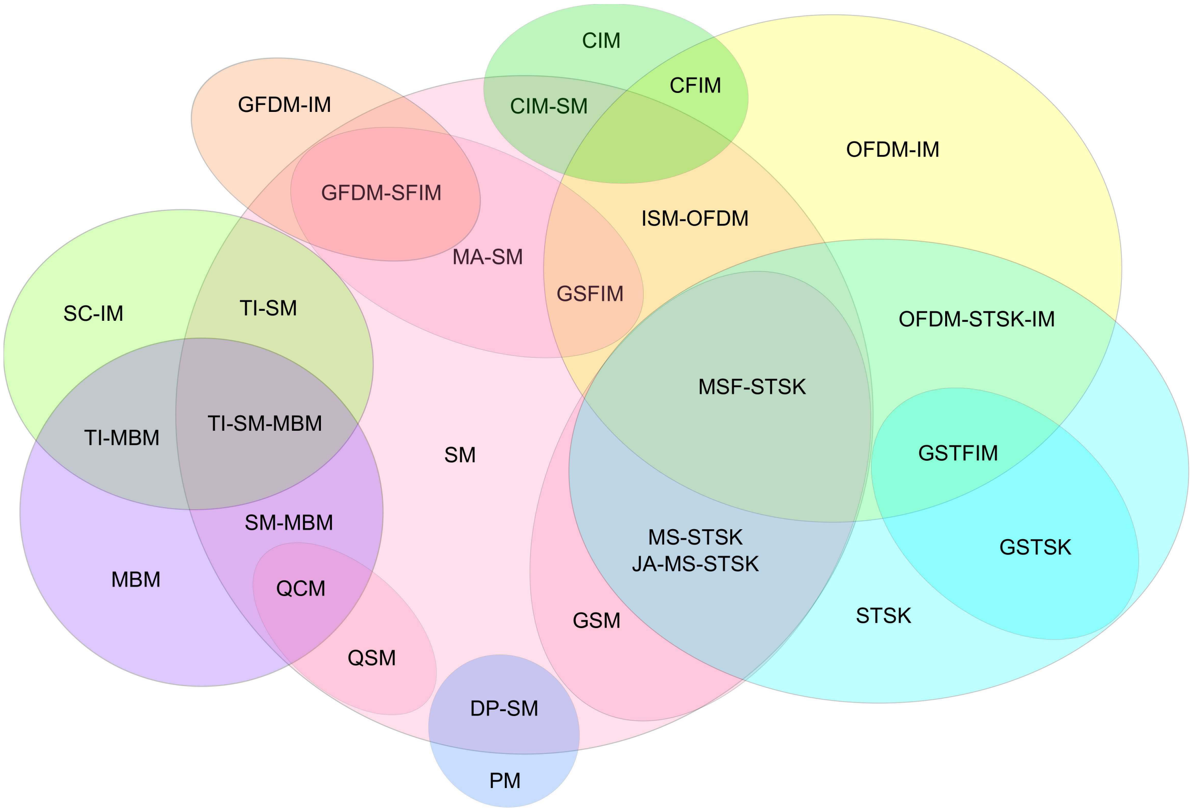

Fig. 5. ***Corresponding fundamental IM variants for the existing multidimensional IM schemes.***

they are shown in the same color. According to Fig. 5, 1-D IM schemes without intersection regions provide insights about possible novel multidimensional IM schemes.

Remark 1: IM schemes, such as QSM, STBC-SM, IM-OFDM-SS, SFSK, OFDM-STSK, and OFDM-I/Q-IM, exploit different domain(s) alongside the IM domain(s) in order to serve diverse user demands. To exemplify, STBC-SM exploits space and time dimensions for the purpose of achieving transmit diversity gain for SM systems. In the same vein, OFDM-STSK utilizes the frequency domain aiming to overcome the ISI encountered in STSK transmission, while IM is applied in space and time domains. On the other hand, QSM and OFDM-I/Q-IM utilize I and Q dimensions for enhancing the SE of OFDM-IM systems. Therefore, these IM techniques are categorized considering the number of domains in which IM is employed. Table 5 illustrates the IM techniques that

Table 5 IM Techniques With the Aid of Dimension(s) Exploitation

IM Techniques	Exploited Domain(s)				IM Domain(s)					IM Type
	Space	Time	Frequency	I/Q	Space	Time	Frequency	Code	Channel	
QSM[1] [49]				✓	✓					One-dimensional
STBC-SM [49]	✓	✓			✓					One-dimensional
ST-QSM [50]	✓	✓		✓	✓					One-dimensional
OFDM-I/Q-IM [59]				✓			✓			One-dimensional
IM-OFDM-SS [82]			✓					✓		One-dimensional
STCM [83]	✓	✓							✓	One-dimensional
ST-MBM [84]	✓	✓							✓	One-dimensional
SFSK [88]			✓		✓	✓				Two-dimensional
STFSK [88]			✓		✓	✓				Two-dimensional
OFDM-STSK [91]			✓		✓	✓				Two-dimensional
OFDM-SFSK [93]			✓		✓	✓				Two-dimensional

[1]It is also valid for QSM-based IM techniques, such as QCM and GPQSM.

Table 6 Data Rate and Computational Complexity Assessment of Space-Domain IM Techniques

IM Techniques	# RF Chain (N_{rc})	Data Rate [bpcu]	Computational Complexity at Rx
SM [39]	1	$\log_2(N_t) + \log_2(M)$	MRC $\rightarrow 2N_rN_t - N_t$ Opt. $\rightarrow N_tM(3N_r + 1)$
GSM [40]	$1 \leq N_{rc} = N_k < N_t$	$\lfloor \log_2 \binom{N_t}{N_k} \rfloor + \log_2(M)$	ML $\rightarrow N_r 2^{\lfloor \log_2 \binom{N_t}{N_k} \rfloor} M(N_k + 2)$
MA-SM [41]	$1 \leq N_{rc} = N_k < N_t$	$\lfloor \log_2 \binom{N_t}{N_k} \rfloor + N_k \log_2(M)$	ML $\rightarrow N_r 2^{\lfloor \log_2 \binom{N_t}{N_k} \rfloor} M^{N_k}(N_k + 2)$ LC $\rightarrow (2N_k^3 + 3N_k^2 - 5N_k)/6 + N_rN_k(2N_k + 1)$
QSM[1] [40], [125]	1	$\log_2(N_t^2) + \log_2(M)$	ML $\rightarrow 4N_rN_t^2M$ LC $\rightarrow 4N_t^3 + 4N_{MPA}^2MN_r$
ESM[2] [48]	1, 2	$\lfloor \log_2 (\binom{N_t}{N_{k_1}} + \binom{N_t}{N_{k_2}} + \binom{N_t}{N_{k_3}}) \rfloor +$ $\log_2(M_1)$	ML $\rightarrow \binom{N_t}{N_{k_1}} M_1^{N_{k_1}} + \binom{N_t}{N_{k_2}} M_2^{N_{k_2}} + \binom{N_t}{N_{k_3}} M_3^{N_{k_3}}$
TCSM [46]	1	$\frac{1}{R}\left(\log_2(N_t) + \log_2(M)\right)$, ($R$ = Code Rate)	Opt. $\rightarrow N_tM(3N_r + 1)$
TC-QSM [47]	1	$\frac{1}{R}\left(\log_2(N_t^2) + \log_2(M)\right)$	LC $\rightarrow 4N_t^3 + 4N_{MPA}^2MN_r$
STBC-SM [49]	2	$\frac{1}{2}\lfloor \log_2 \binom{N_t}{N_k} \rfloor + \log_2(M), (N_k = 2)$	ML $\rightarrow 2^{\lfloor \log_2 \binom{N_t}{2} \rfloor} M^2$ LC $\rightarrow 2^{\lfloor \log_2 \binom{N_t}{2} \rfloor} M$
ST-QSM [50], [126]	$2 \leq N_{rc} < N_t$	$\log_2(N_{t1}) + \log_2(N_{t2}) + \log_2(M)$	ML $\rightarrow M^2 2^{\lfloor \log_2(N_{t1}) \rfloor} + M^2 2^{\lfloor \log_2(N_{t2}) \rfloor}$
PSM [43]	1	$\log_2(N_r) + \log_2(M)$	ML $\rightarrow N_rM$
GPSM [44]	$1 \leq N_{rc} = N_k < N_t$	$\lfloor \log_2 \binom{N_r}{N_k} \rfloor + N_k \log_2(M)$	ML $\rightarrow 2^{\lfloor \log_2 \binom{N_r}{N_k} \rfloor} M^{N_k}$ LC $\rightarrow N_r + 3N_kM + M$
GPQSM [45]	$1 \leq N_{rc} = N_k < N_t$	$2\lfloor \log_2 \binom{N_r}{N_k} \rfloor + N_k \log_2(M)$	ML $\rightarrow 2^{2\lfloor \log_2 \binom{N_r}{N_k} \rfloor} M^{N_k}$ LC $\rightarrow 10N_r + 3N_rM + M$

[1] N_{MPA} corresponds to the number of the most probable active antenna indices ($2 \leq N_{MPA} < N_t$).
[2] The generalization of the computational complexity for ESM is not possible due to the variable number of antenna combinations. Here, the complexity calculation is given in order to achieve the same data rate (8 [bpcu]) with SM ($M = 64QAM, N_t = 4, N_r = N_r$). Thus, $\mathcal{S}_1, \mathcal{S}_2$, and $\mathcal{S}_3$ are used with the size of $M_1 = 16$, and $M_2 = M_3 = 4$, respectively, while $N_{k_1} = 1$, and $N_{k_2} = N_{k_3} = 2N_{k_1} = 2$.

provide dimension(s) exploitation to alleviate the shortcomings of a particular IM type.

IV. APPROPRIATE IM TECHNIQUES AND DOMAINS FOR NEXT-GENERATION SERVICES AND REQUIREMENTS

Although the variety of IM types promises appealing tradeoffs among SE, EE, BER, and flexibility, the integration of diverse IM techniques into the current communication systems bring different challenges for the Tx and Rx sides of modern communication systems due to the requirement of numerous hardware design and signal processing techniques. In this section, promising IM types are subsumed considering the requirements of eMBB, mMTC, and URLLC. Thereafter, the advantages and disadvantages of a given IM domain are quantified for establishing a clear distinction between them, and its fidelity is evaluated in terms of practical implementation.

A. Enabling IM Techniques for Next-Generation Services

The presented IM techniques in Section III are categorized considering the requirements of three main services.

1) Enhanced Mobile Broadband: The crucial requirement for eMBB is the efficient spectrum utilization, as explained in Section II-A. Therefore, the IM schemes are assessed according to their SE performance. Tables 6–8 present the data rate and the computational complexity assessment of space, frequency, time, code, and channel domains. The computational complexity at Rx is provided for both available low-complex (LC) and ML detectors and is calculated in terms of complex multiplications. It is readily seen that 1-D main IM types in space, frequency, time, code, and polarization domains lead to a decrease in SE due to both the partial transmission and the logarithmic increase on SE with the number of active information-bearing entities. In addition, in comparison to conventional schemes, the reduction in SE becomes suddenly high in the case of high-order modulation usage. To exemplify, OFDM-IM with ($N_b = 8$ and $N_a = 4$) corresponds to $2^{\lfloor \log_2 \binom{8}{4} \rfloor} = 64$ legitimate subcarrier combinations that enable the transmission of maximum number of bits through the subcarriers' indices, that is, IM bits, for $N_b = 8$. However, it results in %12 and %32 SE loss for $M = 4$ and $M = 16$, respectively, with respect to OFDM. Hence, these types of IM require an additional mechanism that allows the transmission with a higher number of M-ary symbols in support of eMBB application and use cases.

GSM increases the number of IM bits, from $\log_2(N_t)$ to $\lfloor \log_2 \binom{N_t}{N_a} \rfloor$, but the number of M-ary symbols remains the same and equals one [12]. Therefore, it offers a moderate improvement in SE with the assistance of multiple antenna activation. As given in Table 6, MA-SM achieves higher SE than GSM via transmitting different data symbols through these activated antennas at the expense of lower BER, which is not a primary concern for eMBB communication.

Table 7 Data Rate and Computational Complexity Assessment of Frequency-Domain IM Techniques

IM Techniques	# Active Subcarriers (N_a)	Data Rate [bpcu]	Computational Complexity at Rx
OFDM-IM [56]	$1 \le N_a < N_b$	$N_G\left(\lfloor \log_2 \binom{N_b}{N_a} \rfloor + N_a \log_2(M)\right)$	ML → $N_G 2^{\lfloor \log_2 \binom{N_b}{N_a} \rfloor} M^{N_a}$ LLR → $N_G N_b M$
OFDM-ISIM [57]	$1 \le N_a < N_b$	$N_G\left(\lfloor \log_2 \binom{N_b}{N_a} \rfloor + N_a \log_2(M)\right)$	ML → $N_G 2^{\lfloor \log_2 \binom{N_b}{N_a} \rfloor} M^{N_a}$ LLR → $N_G N_b M$
CI-OFDM-IM [58]	$1 \le N_a < N_b$	$N_G\left(\lfloor \log_2 \binom{N_b}{N_a} \rfloor + N_a \log_2(M)\right)$	ML → $N_G 2^{\lfloor \log_2 \binom{N_b}{N_a} \rfloor} M^{N_a}$ LLR → $N_G N_b M$
OFDM-GIM[1] [59]	$1 \le N_{a_\psi} < N_b$	$\sum_{\psi=1}^{\Psi} N_{G_\psi}\left(\lfloor \log_2 \binom{N_b}{N_{a_\psi}} \rfloor +\right.$ $\left. N_{a_\psi} \log_2(M)\right)$	ML → $\sum_{\psi=1}^{\Psi} N_{G_\psi} 2^{\lfloor \log_2 \binom{N_b}{N_{a_\psi}} \rfloor} M^{N_{a_\psi}}$ LLR → $\sum_{\psi=1}^{\Psi} N_G N_b M$
OFDM-I/Q-IM [59], [60]	$1 \le N_a < N_b$	$2N_G\left(\lfloor \log_2 \binom{N_b}{N_a} \rfloor + N_a \log_2(M)\right)$	ML → $4N_G 2^{\lfloor \log_2 \binom{N_b}{N_a} \rfloor} M^{N_a}$ LLR → $4N_G N_b M$
DM-OFDM [62]	$N_{a_1} = N_{a_1}$, $N_{a_2} = N_b - N_{a_1}$	$N_G\left(\lfloor \log_2 \binom{N_b}{N_{a_1}} \rfloor + N_{a_1} \log_2(M_1) +\right.$ $\left.(N_b - N_{a_1}) \log_2(M_2)\right)$	ML → $N_G 2^{\lfloor \log_2 \binom{N_b}{N_{a_1}} \rfloor} {M_1}^{N_{a_1}} {M_2}^{(N_b - N_{a_1})}$ LLR → $N_G N_b (M_1 + M_2)$
MM-OFDM [63]	$N_a = N_b$	$N_G\left(\lfloor \log_2 (N_b!) \rfloor + N_b \log_2(M)\right)$	ML → $N_G 2^{\lfloor \log_2 (N_b!) \rfloor}$ LLR → $\frac{N_G N_b M}{2}(N_b + 1)$
GFDM-IM [66]	$1 \le N_a < N_b$	$TN_G\left(\lfloor \log_2 \binom{N_b}{N_a} \rfloor + N_a \log_2(M)\right)$	ML → $TN_G 2^{\lfloor \log_2 \binom{N_b}{N_a} \rfloor} M^{N_a}$
ZTM-OFDM-IM [66]	$N_{a_1} = N_{a_1}, N_{a_2} = N_{a_2}$, $N_{a_1} + N_{a_2} = N_a \le N_b$	$N_G\Big(N_{a_1} \log_2(M_1) + N_{a_2} \log_2(M_2)$ $\lfloor \log_2 \left(\binom{N_b}{N_a}\binom{N_a}{N_{a_1}}\right) \rfloor\Big)$	ML → $N_G 2^{\lfloor \log_2 \left(\binom{N_b}{N_a}\binom{N_a}{N_{a_1}}\right) \rfloor} {M_1}^{N_{a_1}} {M_2}^{N_{a_2}}$
L-OFDM-IM [65]	$1 \le N_{a_L} < N_{b_L} < N_b$, $N_b = N_{b_L} + N_{a_L}(L-1)$	$N_G L\left(\lfloor \log_2 \binom{N_{b_L}}{N_{a_L}} \rfloor + N_{a_L} \log_2(M)\right)$	ML → $N_G\left(2^{\lfloor \log_2 \binom{N_{b_L}}{N_{a_L}} \rfloor} M^{N_{a_L}}\right)^L$ LC → $N_G \sum_{\psi=1}^{L} M(N_{b_L} + N_{a_L}(\psi - 1))$

[1] Ψ is the size of the allowed number of different subcarriers within an OFDM-IM block.

It can be seen from Table 6 that QSM and its advanced versions provide increment only for IM bits. ESM enables the transmission of the data bits by both the active antennas' indices and the constellation type. On the other hand, achieving higher data rates with SM-based IM types is challenging in microwave frequency bands since incorporating a higher number of Tx antennas becomes infeasible for both BS and UEs because of the required distance ($\lambda/2$) between the consecutive antennas. In light of these considerations, the fundamental types of the space-domain IM are far from satisfying the requirements of eMBB use cases.

DM-SCIM provides a higher data rate than the classical SC-IM by modulating the inactive data symbols with different modulation types. Although DM-SCIM improves the SE of SC-IM types, as given in Table 8, its counterpart

Table 8 Data Rate and Computational Complexity Assessment of Time-, Code-, and Channel-Domain IM Techniques

IM Techniques	# Active Symbols (K_a)	Data Rate [bpcu]	Computational Complexity at Rx
SC-IM [75]	$1 \le K_a < K_b$	$K_G\left(\lfloor \log_2 \binom{K_b}{K_a} \rfloor + K_a \log_2(M)\right)$	ML → $K_G 2^{\lfloor \log_2 \binom{K_b}{K_a} \rfloor} M^{K_a}$ LLR → $K_G K_b M$
FTN-IM [76]	$1 \le K_a < K_b$	$K_G\left(\lfloor \log_2 \binom{K_b}{K_a} \rfloor + K_a \log_2(M)\right)$	ML → $K_G 2^{\lfloor \log_2 \binom{K_b}{K_a} \rfloor} M^{K_a}$ LLR → $K_G K_b M$
DM-SCIM [77]	$K_{a_1} = K_{a_1}$, $K_{a_2} = K_b - K_{a_1}$	$K_G\left(\lfloor \log_2 \binom{K_b}{K_{a_1}} \rfloor + K_{a_1} \log_2(M_1) +\right.$ $\left.(K_b - K_{a_1}) \log_2(M_2)\right)$	ML → $K_G 2^{\lfloor \log_2 \binom{K_b}{K_{a_1}} \rfloor} {M_1}^{K_{a_1}} {M_2}^{(K_b - K_{a_1})}$ LLR → $K_G K_b (M_1 + M_2)$
IM Techniques	**# Active Codes (N_{ac})**	**Data Rate [bpcu]**	**Computational Complexity at Rx**
CIM-SS [78]	$N_{ac} = 1, N_{ct} = 2$	$2\lfloor \log_2(N_{ct}) \rfloor + \log_2(M) =$ $2 + \log_2(M)$	ML → $2N_{ct}M$ LC → $2N_{ct} + M$
GCIM-SS [79]	$N_{ac} = 1, 2 \le N_{ct}$	$2\lfloor \log_2(N_{ct}) \rfloor + \log_2(M)$	ML → $2N_{ct}M$ LC → $2N_{ct} + M$
IM-OFDM-SS [115]	$N_{ac} = 1, 2 \le N_{ct}$	$2\lfloor \log_2(N_{ct}) \rfloor + \log_2(M)$	ML → $2N_{ct}M$ LC → $2N_{ct} + M$
IM Techniques	**# Active RF Mirrors (N_{am})**	**Data Rate [bpcu]**	**Computational Complexity at Rx**
MBM [70]	$N_{am} = 1$	$N_{rf} + \log_2(M)$	ML → $N_r 2^{N_{rf}} M, N_t = 1$
STCM [83]	$N_{am} = 1$	$2N_{rf} + 2\log_2(M)$	ML → $4N_r 2^{2N_{rf}} M^2, N_t = 2$ LC → $4N_r 2^{2N_{rf}} M$

in the frequency domain, that is, DM-OFDM, is superior to DM-SCIM due to flexible resource allocation. ZTM-OFDM-IM combines OFDM-IM and DM-OFDM in order to boost the SE of OFDM-IM systems. As seen in Table 7, it provides a significant improvement in the number of information bits carried by the indices, but it poses a limit for competing with conventional schemes under high-order modulation conditions. MM-OFDM enables not only the modulation of all subcarriers by using multiple QAM/PSK sets but also the utilization of permutations of subcarriers' combinations. In other words, DM-OFDM and MM-OFDM activate all the subcarriers as in conventional OFDM and transmit IM bits as well. The number of legitimate subcarrier combinations is increased from $\lfloor \log_2(N_b) \rfloor$ to $\lfloor \log_2(N_b!) \rfloor$ by MM-OFDM-IM. OFDM-GIM provides a degree of freedom to control the number of IM bits and M-ary symbols adaptively. Thus, it supports both OFDM-IM and OFDM transmissions. In other words, L-OFDM-IM facilitates the improvement in both IM bits and M-ary symbols at the cost of the exponential increase in the processing complexity with L, as given in Table 7.

The SE of MBM linearly increases with the number of RF mirrors. Due to the linear increase in SE with N_{rf}, SM-MBM and TI-MBM provide higher data rates compared with TI-SM. TI-SM and TI-MBM need to utilize higher modulation orders than SM-MBM for the sake of achieving the same SE. However, the use of higher modulation orders leads to degradation of the BER performance of TI-SM and TI-MBM. However, a high number of RF mirrors leads to high training overhead to estimate $2^{N_{\mathrm{rf}}}$ channel realizations. Therefore, DMBM can be a candidate solution to satisfy the demand of high SE since it removes the channel estimation at Rx, which is the UE in DL transmission. On the other hand, Rx SM provides opportunities in DL transmission for both reducing cost and increasing the EE at the UE side. GPSM can support the same throughput as conventional MIMO systems with the same processing complexity at the Rx side [44], [142], [143].

Multidimensional IM types are more appealing for the purpose of fulfilling the requirements of eMBB service. GSFIM performs transmission through antenna indices, subcarrier indices, and M-ary symbols. Also, conventional MIMO-OFDM corresponds to the special case of GSFIM. It is shown that %20 rate gain can be achieved by GSFIM under the conditions of ($N_t = 32$, $N_r = 32$, and $M = 4$). In this regard, its advanced version GSTFIM can also be considered for eMBB use cases. In addition, current OFDM technology is one of the promising solutions for eMBB applications and use cases. However, OFDM suffers from ICI in the case of high-mobility scenarios. To provide eMBB communications for the high-mobility classes defined in Table 3, instead of the conventional OFDM, ISM-OFDM can alleviate the effect of ICI without compromising the SE.

Remark 2: Among the 1-D IM types, the frequency-domain IM types can compete with the conventional OFDM in terms of SE due to its flexible structure. The advanced versions of OFDM-IM, such as DM-OFDM, MM-OFDM, and L-OFDM, are conducive to support eMBB service, even if high-order modulation types are considered. The space-domain IM types are easily defeated by conventional SMX schemes due to not only the logarithmic increase with N_T but also the transmission of a limited number of M-ary symbols. In order to overcome this limitation, MBM is deemed to be promising, but it leads to the monumental complexity at the Rx side, which cannot be handled by UE in DL transmission.

2) Massive Machine-Type Communications: Researchers in both academia and industry have been seeking technologies to provide large coverage area, low power consumption, and low cost for mMTC services where latency, data rate, and reliability are not primary concerns, as explained in Section II-B. In essence, IM provides high EE due to the energy-free carried information bits by the indices of the transmit entities. For example, OFDM-IM with ($N_b = 4$ and $N_a = 2$) transmits $p_1 = 2$ bits by the subcarriers' indices and $p_2 = 2$ bits by the modulated subcarriers with BPSK. However, the classical OFDM requires four active subcarriers to transmit $p_1 + p_2 = 4$ bits. Hence, OFDM-IM with ($N_b = 4$ and $N_a = 2$) harvests 50% of the Tx power to transmit the same number of data bits. Utilization of the same Tx power for the OFDM-IM and conventional OFDM significantly extends the coverage area for OFDM-IM. Besides the high EE, hardware and computational complexity originated by IM should be considered for mMTC applications and use cases. Please note that the SE and complexity of a given IM scheme are dependent on each other. Thus, Tables 6–8 provide the computational complexity of IM types considering the given SE. For instance, L-OFDM-IM and OFDM-IM offer the same complexity and SE, while $L = 1$.

The 1-D space-domain IM types, including SSK and SM, significantly reduce the hardware complexity due to the use of a single RF chain at Tx, as given in Table 6. In recent studies, it has also been demonstrated that SSK can be implemented even with a simple RF signal generator [136]. In this way, further reduction is achieved at both Tx and Rx sides. Therefore, SSK and SM provide a high EE, low hardware complexity at Tx, and low computational complexity at Rx for MIMO systems. Due to the increased antenna combinations, GSM and MA-SM require multiple RF chain activation and IAS at Tx and leads to the more complex Rx than that of SM.

The EE and computational complexity of frequency-domain IM variants are dependent on the block size, the subblock size, and the number of active subcarriers. Mainly, the ML detector is used for the detection of information bits carried by the indices of active subcarriers and M-ary symbols. SIM-OFDM suffers from a complex Rx due to the block-based ML detection [54]. For example, in order to activate a quarter of the subcarriers in SIM-OFDM systems, an ML detector should search over $2^{\lfloor \log_2 \binom{128}{32} \rfloor} = 2^{100}$ subcarrier combinations to find the correct active subcarriers for ($N_{\mathrm{sc}} = 128$ and $N_a = 32$). Thus, OFDM-IM divides the OFDM block into subblocks to reduce the number of possible combinations for the ML detector. However, a larger subblock size still causes a higher complexity at Rx. Hence, OFDM-IM with the LLR detector is proposed in the literature. For OFDM-IM with $N_{\mathrm{sc}} = 128$, $N_b = 8$, $N_a = 2$, and $M = 2$, the LLR detector reduces the computational complexity four times than that of ML detector, as given in Table 7. Among 1-D IM types, spectral-efficient schemes, such as DM-OFDM, MM-OFDM, L-OFDM-IM, and ZTM-OFDM-IM, lead to the increased processing complexity at Rx. Due to the adaptive number of subcarrier activation, OFDM-GIM loses the inherent advantages of IM including EE and reliability. In fact, the achieved EE is limited due to the activation of the majority of existing subcarriers, that is, $N_b/N_a \simeq 1$. In OFDM-IM, the obtained N_b/N_a power can be utilized for achieving a higher BER performance by increasing the power per subcarrier or can be harvested for achieving a higher EE by keeping the power per subcarrier as in OFDM. In [104], the power level is utilized to provide robustness against IUI in asynchronous mMTC networks, where the sporadic nature of mMTC originates time offset between the UEs and destroys the orthogonality among them. To satisfy the requirements of NB-IoT given in Table 3, the use of direct conversion Rx is proposed for the NB-IoT devices due to its simple structure [144]. However, the direct conversion causes I/Q imbalance (IQI) and severely degrades the performance of the conventional OFDM. In [107], it is shown that the presence of inactive subcarriers in OFDM-IM allows easy estimation and compensation of the IQI.

For UL transmission, SC-IM provides higher EE than conventional SC due to the transmission of additional information bits through IM [145]. However, the inherent sparsity in the time domain leads to higher PAPR than that of classical SC. Multidimensional IM types have a complex transceiver structure for the detection of active entities in multiple domains. Thus, among the multidimensional IM techniques, TI-SM, which has a moderate number of active entities in time and space, can be considered for mMTC.

The complexity of Rx in MBM is dependent on the number of RF mirrors, which determines both the SE and the system reliability via CSI estimation accuracy. Hence, it provides a tradeoff between SE and complexity while ensuring high EE. The SE of MBM with a low number of RF mirrors is limited, but it significantly reduces the Rx complexity since the number of estimated channel realizations exponentially decreases with N_{rf}. In recent studies, a CS-based detection mechanism with low complexity is proposed at Rx to exploit the inherent sparsity of RF mirrors [146]. Besides, in [147], sparse user activity in mMTC, that is, the intermittent and sporadic characteristics of mMTC, is exploited to improve the detection performance at Rx.

Remark 3: The 1-D space-domain IM types can be considered as potential candidates for mMTC service due to low hardware complexity at TX and consequently low power consumption. MBM with a reasonable number of RF mirrors is also appropriate to obtain high EE at the UE side since no CSI is required at Tx. Partial activation in OFDM-IM and SC-IM provides robustness against IUI caused by asynchronous mMTC networks along with the high EE. In addition, the channel- and polarization-domain IM types are more appealing when the UE is insufficient to accommodate multiple Tx antennas without spatial correlation between them.

3) Ultrareliable Low-Latency Communication: As explained in Section II-C, URLLC is the most challenging service due to the simultaneous yet conflicting demands of ultrareliability and low-latency. In order to achieve the BLER values given in Table 3, IM schemes that provide diversity gain, interference immunity, and robustness against hardware impairments, such as CFO and IQI, are the promising solutions for URLLC. Achieving high reliability via IM requires sufficient selectivity between the active entities in a given IM domain. Thus, the space-domain IM techniques require $(\lambda/2)$ separation distance between Tx antennas to improve the detection performance at Rx. Proper detection of the active antennas provides a high probability for the correct estimation of both the index bits and the M-ary symbols. Otherwise, the system performance severely reduces due to the high correlation between the utilized antennas. GSM enhances the BER performance of the SM by the transmission of the same data over multiple active antennas. MA-SM requires an advanced Rx design to avoid IAI, which reduces reliability. However, its complex transceiver structure causes a long processing time. QSM exploits the spatial selectivity via the transmission of I/Q parts of the complex data symbol separately. Hence, QSM ensures the achievement of a better BER performance than the conventional SMX and SM [42]. Also, STBC-SM, ST-QSM, TCSM, and TCQSM improve the performance of SM by additional diversity and coding gains. In MBM, the correct estimation of the transmitted bits relies on the exact CSI at Rx. Hence, the estimation error in CSI can lead to catastrophic BER performance. Even though DMBM removes the necessity of CSI at Rx, it reduces the system reliability and leads to latency due to the feedback mechanism for the encoding of two consecutive data blocks.

For the sake of supporting the desired reliability, frequency-domain IM schemes require the exploitation of frequency diversity via proper mapping of the information bits to the subcarriers. In the conventional OFDM-IM, incoming data bits are directly mapped to the subcarriers within a subblock. Thus, the high correlation between the active subcarriers degrades the detection performance at Rx. Mapping of the data bits to the subcarriers located in different subblocks reduces the correlation between the activated subcarriers and enhances the BER performance.

Table 9 Comparison of Space- and Channel-Domain IM Techniques

IM Techniques	Pros	Cons	Performance Metrics						
			1	2	3	4	5	6	7
SM [39]	Single antenna activation, use of one RF chain at Tx, IAI free transmission	Logarithmic increase on SE with N_t, limited data rate	↓	↑	↓	↓	↓	↓	↑
GSM [40]	Multiple antenna activation to transmit the same data symbol, IAI free transmission	Logarithmic increase on SE with N_t, limited data rate, requirement of multiple RF chains and IAS at Tx	↓	↑	↑	↓	↓	↓	↑
MA-SM [41]	Multiple antenna activation to transmit the different data symbols, higher SE than SM/GSM	Logarithmic increase on SE with N_t, requirement of multiple RF chains and IAS at Tx, complex Rx process	↑	↑	↑	↑	↓	↑	↓
QSM [42]	Activation of two Tx antennas to transmit in-phase and quadrature parts of a complex symbol, exploiting spatial selectivity	Logarithmic increase on SE with N_t	↑	↑	↓	↓	↓	↓	↑
ESM [48]	Activation of a single and two Tx antennas for high order and low order modulations, increased Euclidean distance	Requirement of multiple RF chains and IAS at Tx, complex Rx process	↑	↑	↑	↑	↓	↑	↓
STBC-SM [48]	Use of two RF chains at Tx, achieving diversity and coding gains	Limited data rate	↓	↑	↓	↓	↑	↑	↑
MBM [70]	Linear increase on SE with N_{rf}, robustness against channel fading	Estimation of $2^{N_{rf}}$ channel realizations, high training overhead, complex Rx process	↑	↑	↓	↑	↓	↓	↑
DMBM [70]	Avoiding channel estimation at Rx	Increased processing time due to feedback mechanism, an error performance loss	↑	↑	↓	↑	↓	↓	↑

Performance Metrics - 1: SE, 2: EE, 3: Hardware Complexity at Tx, 4: Computational Complexity at Rx, 5: Tx Diversity Gain, 6: Multiplexing Gain, and 7: Interference Immunity
Sign - ↑: High ↓: Low

Therefore, OFDM-ISIM and CI-OFDM-IM attain higher reliability than the classical OFDM-IM by means of interleaving. Furthermore, CI-OFDM-IM provides an additional diversity gain with the aid of coordinate interleaving. For a given SE, DM-OFDM can provide better BER performance than OFDM-IM by proper selection of the used modulation sets [62]. However, DM-OFDM, MM-OFDM, and OFDM-GIM are sensitive to the hardware and channel impairments since there is no idle subcarrier [148]. Due to the nonorthogonal transmission in GFDM-IM, attaining the ultrareliability becomes a challenge. Moreover, resolving the ICI and ISI at Rx requires a complex Rx design that leads to extra latency. Recently, an interference immune OFDM-IM-based NOMA scheme is proposed in [149] to alleviate the effect of the collisions due to GF access of the URLLC UE.

If the wireless channel is time-invariant, the interleaving of data symbols is a necessity for SC-IM to provide ultrareliability. However, interleaving in the time domain requires storage and, thus, causes a long latency. Although the space-domain IM techniques provide multiplexing gain, they suffer from a lack of diversity gain, which is of great importance for achieving ultrareliability. Likewise, conventional SMX and STBC techniques maximize the multiplexing gain and diversity gain, respectively. STSK, which encompasses SMX, STBC, and SM, provides an attractive tradeoff among complexity, multiplexing gain, and diversity gain through the spreading of a given symbol in space and time dimensions. In this way, it is shown that STSK provides a significant improvement in BER performance [85]. To have robustness against frequency-selective channels, STSK is combined with conventional OFDM through OFDM-STSK. It should be noted that OFDM-STSK performs IM on DMs and exploits the frequency domain to improve system performance. MS-STSK increases the reliability of STSK by combining it with GSM. However, it suffers from ISI under dispersive channels. OFDM-IM and MS-STSK are coupled in MSF-STSK to provide robustness against ISI and ICI. Thus, the DM-based IM types can provide the ultrareliability by diversity gain, but the duration of the STSK block should be adjusted considering the latency constraint. In [74], it is shown that multidimensional IM schemes provide better BER performance than 1-D schemes for the same SE. This is due to a lower number of active entities in a single domain, which corresponds to a reduced correlation between them and consequently better detection performance at Rx. Finally, in [52], it is shown that RIS-aided IM at Rx can provide up to 15-dB gain in the BER performance compared with the conventional MIMO schemes. Therefore, the RIS-aided IM concept is a promising approach for URLLC, but its usage for URLLC is still an open research area in the literature.

Remark 4: The direct comparison of IM techniques in terms of BER performance is a difficult task since they should be assessed under the same SE. However, different QAM/PSK sets should be utilized for the achievement of the same SE, and thus, the performance of a given IM type is directly affected. Therefore, IM techniques that can provide diversity gain are more prominent for URLLC. In addition, the frequency-domain IM techniques provide the exploitation of frequency selectivity with the aid of interleaving, while conventional OFDM systems require a coding scheme at Tx, which leads to significant complexity at Rx, to further improve the BER performance.

In view of the above considerations, space, frequency, time, channel, code, and multidimensional IM variants are compared in Tables 9–11 in terms of SE, EE, Tx complexity,

Table 10 Comparison of Frequency-, Time-, and Code-Domain IM Techniques

IM Techniques	Pros	Cons	Performance Metrics 1	2	3	4	5
OFDM-IM [56]	Robustness against ICI, hardware impairments including CFO and IQI	Lower SE than conventional OFDM for high-order modulations	↓	↑	↓	↓	↑
OFDM-ISIM [57]	Exploiting frequency diversity with the aid of interleaving, reliable transmission	Lower SE than conventional OFDM for high-order modulations	↓	↑	↓	↓	↑
CI-OFDM-IM [58]	Transmission of in-phase and quadrature parts of a symbol by different subcarriers, exploiting the real frequency diversity, reliable transmission	Lower SE than conventional OFDM for high-order modulations	↓	↑	↓	↓	↑
OFDM-GIM [59]	Allowing different number of active subcarriers for different subblocks, higher SE than OFDM-IM	Two-stage Rx process, error propagation, sensitivity to hardware impairments	↑	↓	↑	↑	↓
DM-OFDM [62]	Use of two different modulation schemes within a subblock, higher SE than OFDM-IM	Sensitivity to hardware impairments	↑	↓	↓	↓	↓
GFDM-IM [66]	Relaxed time and frequency synchronization	Complex Rx process	↑	↑	↓	↑	↑
SC-IM [75]	Robustness against ISI	Higher PAPR than conventional SC due to inherent sparsity	↓	↑	↓	↓	↑
CIM-SS [78]	Higher SE compared to DS-SS with lower energy consumption	Logarithmic increase on SE with N_c, complex Rx process	↓	↑	↓	↑	↑

Performance Metrics - 1: SE, 2: EE, 3: Computational Complexity at Tx, 4: Computational Complexity at Rx, and 5: Interference Immunity
Sign - ↑: High ↓: Low

Rx complexity, transmit diversity gain, multiplexing gain, and interference immunity. The number of active entities given in Tables 6–8 determines the interference immunity of a given IM scheme and also defines the hardware complexity at Tx for space-domain IM techniques. Finally, Fig. 6 illustrates the categorization of promising IM variants for eMBB, mMTC, and URLLC.

B. Key Advantages and Disadvantages of Different IM Domains

In modern communication systems, the hardware complexity of the Tx is dependent on the number of used RF chains and antennas. Also, the required channel estimation and detection mechanisms in the Rx lead to additional computational complexity, especially in the presence of

Table 11 Comparison of Multidimensional IM Techniques

IM Techniques	Pros	Cons	Performance Metrics 1	2	3	4	5	6	7
ISM-OFDM [53]	Robustness against IAI and ICI	Logarithmic increase on SE with N_t and N_{sc}	↓	↑	↑	↑	↓	↓	↑
GSFIM [67]	Robustness against ICI, multiple antenna activation to transmit the different data symbols	Logarithmic increase on SE with N_t and N_{sc}, requirement of multiple RF chains and IAS at Tx	↑	↑	↑	↑	↓	↑	↓
GFDM-SFIM [69]	Relaxed time and frequency synchronization	Complex transceiver process	↑	↑	↑	↑	↓	↑	↓
TI-SM [74]	Robustness against IAI and ISI	Limited data rate	↓	↑	↓	↓	↓	↓	↑
SM-MBM [74]	Robustness against IAI, linear increase on SE with N_{rf}	Estimation of $2^{N_{rf}}$ channel realizations, high training overhead, complex Rx process	↑	↑	↓	↑	↓	↓	↑
TI-MBM [74]	Robustness against ISI, linear increase on SE with N_{rf}	Estimation of $2^{N_{rf}}$ channel realizations, high training overhead, complex Rx process	↑	↑	↓	↑	↓	↓	↑
TI-SM-MBM [74]	Robustness against ISI and IAI, linear increase on SE with N_{rf}	Estimation of $2^{N_{rf}}$ channel realizations, high training overhead, complex Rx process	↑	↑	↑	↑	↓	↓	↑
CIM-SM [80]	Higher SE than SM	Complex Rx process	↑	↑	↑	↑	↓	↓	↑
DSM [51]	Robustness against IAI, avoiding channel estimation at Rx	Increased processing time due to feedback mechanism	↑	↑	↓	↓	↑	↑	↑
STSK [85]	Providing diversity gain as well as multiplexing gain	Requirement of $N_{rf} = N_t$ RF chains at Tx, complex Rx design, sensitivity to ISI	↓	↓	↑	↑	↑	↑	↓
OFDM-STSK [89]	Robustness against ISI	Requirement of $N_{rf} = N_t$ RF chains at Tx, complex Rx design	↓	↓	↑	↑	↑	↑	↑
OFDM-SFSK [93]	Robustness against ISI and ICI with the aid of sparse DMs	Requirement of $N_{rf} = N_t$ RF chains at Tx, complex Rx process	↓	↓	↑	↑	↑	↑	↑
OFDM-STSK-IM [92]	Robustness against ISI and ICI, high SE with the aid of CS,	Requirement of $N_{rf} = N_t$ RF chains at Tx, complex Rx process	↑	↓	↑	↑	↑	↑	↑
MS-STSK [89]	Increased SE by partial antenna activation, use of $N_{rf} \leq N_t$ RF chains at Tx	Complex Rx process	↑	↑	↓	↑	↑	↑	↓
MSF-STSK [90]	Robustess against ISI, ICI and IAI, increased SE by partial antenna activation, use of $N_{rf} \leq N_t$ RF chains at Tx	Complex Rx process	↑	↑	↓	↑	↑	↑	↑

Performance Metrics - 1: SE, 2: EE, 3: Hardware and Computational Complexity at Tx, 4: Hardware and Computational Complexity at Rx, 5: Tx Diversity Gain, 6: Multiplexing Gain, and 7: Interference Immunity
Sign - ↑: High ↓: Low

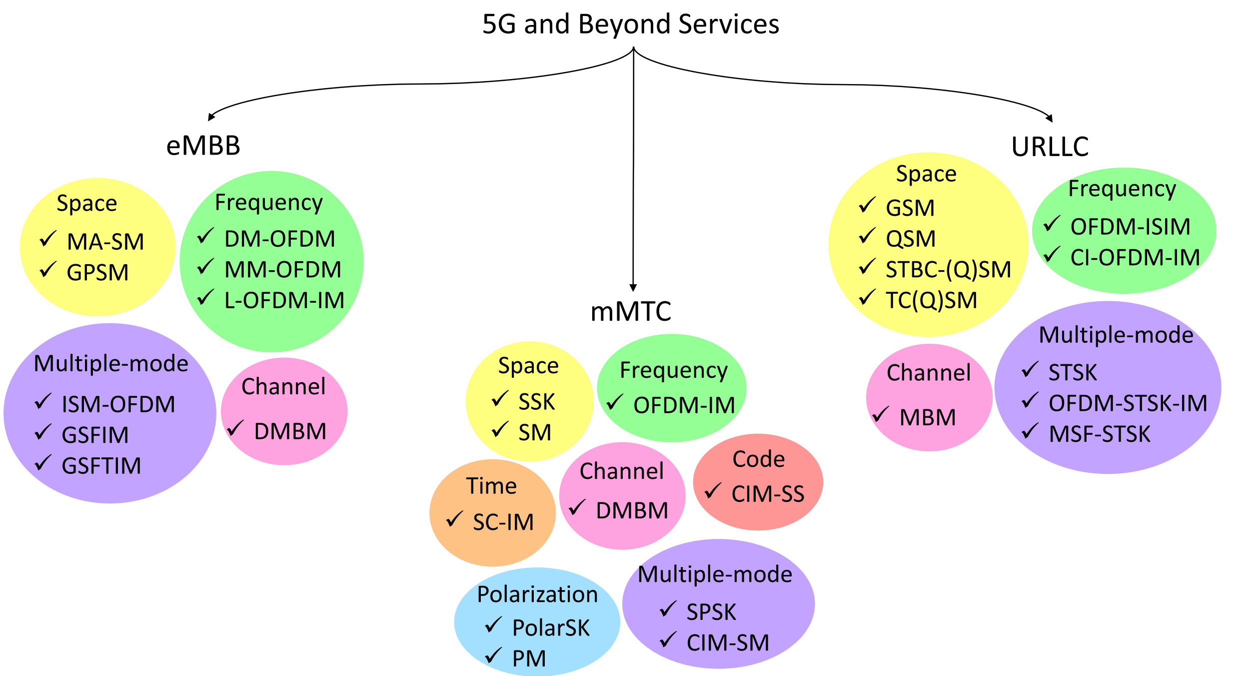

Fig. 6. ***Promising IM variants for 5G and beyond services.***

a higher number of antennas. The conventional MIMO systems, such as V-BLAST, have a complex structure due to the utilization of all Tx antennas and, thus, require an advanced Rx design. This structure makes its modification difficult for the diverse demands of 5G and beyond networks.

In general, the space-domain IM schemes have similar transmission structure, that is, the transmitted signals can be expressed in the vector form as in (1)–(3), where ML is commonly utilized at Rx for the detection of active antenna indices and M-ary symbols, as given in Table 6. It is worth noting that the complexity of ML detector exponentially increases with N_t, while the achieved SE enhancement is logarithmic. Moreover, a higher number of Tx antennas are required to achieve higher data rates, but it leads to a larger transceiver size and higher power consumption. Therefore, the space-domain IM types are suitable for low data rates, high EE, and latency-critical transmission where the conventional MIMO technologies suffer. The spatial correlation between Tx antennas hurdles the performance of space-domain techniques. In order to overcome this, its combination with polarization and channel-domain IM types is promising. Considering the main benefits and shortcomings of space-domain IM types given in Table 9, GSM, MA-SM, QSM, and ESM can be easily integrated into a given MIMO system for the purpose of meeting wide range requirements of 5G and beyond.

Frequency-, time- and code-domain IM types do not require additional hardware for practical implementation, as presented in Table 10. The complexity of conventional OFDM-IM using the LLR detector is in the same order as that of OFDM in terms of complex multiplications, as given in Table 7 [56]. In OFDM-ISIM and CI-OFDM-IM, block-interleaving, corresponding to the multiplication of OFDM block with an interleaving matrix, is easily applied in the frequency domain in order to break the correlation between the active subcarriers. Although DM-OFDM, MM-OFDM, and L-OFDM-IM result in a higher complexity than OFDM-IM, LC detectors are introduced, and they can provide higher BER than OFDM due to the exploitation of frequency diversity. In this regard, the frequency-domain IM variants can easily serve different applications and use cases with the proper type and parameter selection.

In contrast to the frequency domain, implementation of the interleaving in the time domain requires extra storage and increases the complexity at Tx. On the other hand, high reliability is difficult to achieve without interleaving gain. Thus, the time-domain IM types provide a low data rate while maintaining high EE, which is the primary concern for mMTC. In a similar vein, the code- and polar-domain IMs offer limited data rate, but their combination with space-domain IM types is one of the candidate solutions for avoiding spatial correlation between the active antennas, while improving the SE.

The channel-domain IM provides a tradeoff between ultrareliability and complexity. The implementation of channel-domain IM with a moderate number of RF mirrors is suitable for SIMO systems since the channel estimation at Rx becomes impractical in the case of a higher number of RF mirrors.

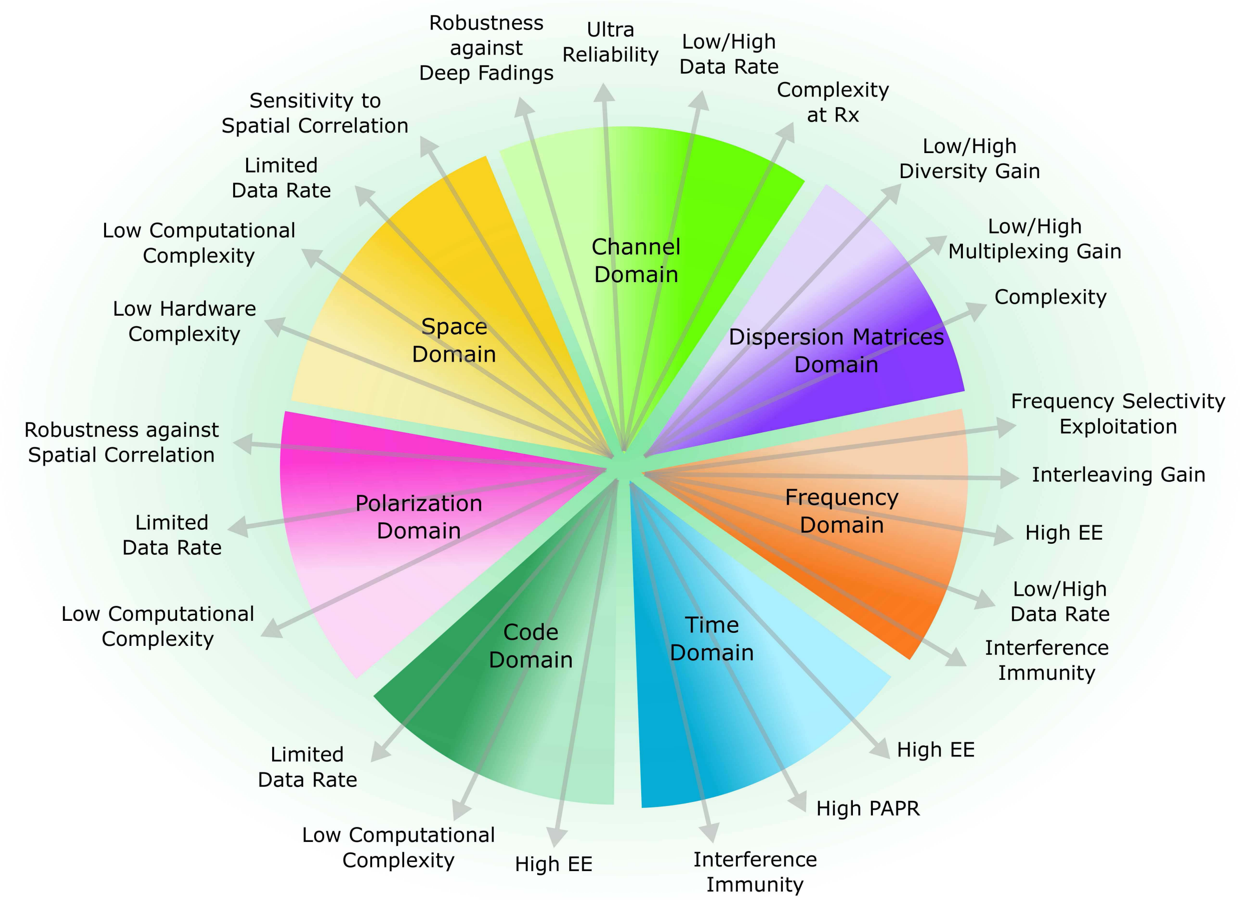

Fig. 7. ***Key advantages and disadvantages of the existing IM domains.***

The major concern for multidimensional IM types is their multistage transceiver architecture. Table 11 compares the reviewed multidimensional IM types in terms of SE, EE, complexity, transmit diversity gain, multiplexing gain, and interference immunity. Especially, the complexity of ML detection tremendously increases due to the numerous possibilities of the active entities in different domains. A moderate Rx design can be achieved for ISM-OFDM with a lower number of Rx antennas. Fig. 7 summarizes the key advantages and disadvantages of available IM domains. Although multidimensional IM types are proposed for increasing the SE of IM systems, it is important to emphasize that a proper combination of 1-D IM types can serve different requirements simultaneously, as illustrated in Fig. 7.

V. POTENTIAL CHALLENGES AND FUTURE DIRECTIONS

In this section, potential challenges and future perspectives on the integration of IM into beyond 5G technologies are anticipated. Although the research world of academia and industry has shown a substantial and explicit emphasis on the capacity and reliability of IM technologies, its utilization in a flexible manner needs to be fully explored in emerging wireless networks.

A. Cognitive Radio Network Through IM

CR has been heavily studied and considered as an enabling technology for dynamic spectrum access aiming to relax the problem of spectrum scarcity via a shared wireless channel between the licensed and unlicensed users, that is, PU and SU, respectively, and not to limit radio resources only to the license holders [150]–[152]. In the literature, three fundamental spectrum access methods, named interweave, underlay, and overlay, are adopted for CR technology [153]. Basically, SU is asked to sense and determine the possible availability of a spectrum in which it can transmit without causing any interruption or endangering the legitimate user. The primary concern in such a system is handling the mutual interference originated by the overlapping of PU and SU. Here, IM promises to control the interference through the fractional utilization of the available resources with different activation probabilities and with adaptive transmission power. On this basis, the application of SM in CR is relatively more understood in the literature [154], [155], while the superiority of different IM techniques against conventional schemes used in CR networks remains unknown in the literature. Alizadeh *et al.* [156] exploited the space domain to allow CR communications with the improvement of the performance of PU. SU performs a retransmission of the data symbols of PU over conventional M-ary symbols, while its own data are conveyed by the activated antenna indices. In line with this, a novel dual-hop SM technique is proposed in [157], where relay conveys its own information. In recent studies, the frequency-domain IM is exploited for opportunistic spectrum sharing. In [158], SU senses the inactive subcarriers of PU with OFDM-IM and performs its transmission over these subcarriers. Moreover, the transmission of PU is supported by means of an amplify-and-forward relay in [159]. Flexible utilization of IM in CR reveals that the advantages of IM dominate its shortcomings when it is fully exploited. To exemplify, SE loss for SU becomes negligible as the reliability of PU is preserved or enhanced compared with conventional OFDM-based technologies. Finally, the utilization of different signal dimensions and types will be more prominent for the CR scenarios, where PU and SU have different priorities. Spectrum sharing between the LTE license-assisted access (LTE-LAA) and the IEEE 802.11 Wi-Fi systems is an active research area in the literature that can be considered as an example scenario [160], [161]. It can be inferred from the abovementioned scenarios that the study of IM in CR is at an incipient stage considering its multidimensional application, and there exists a plethora of tradeoffs between PU and SU, which needs to be exhibited by academia and industry.

B. Cooperative Networks Through IM

Cooperative communication is an alternative enabling approach of exploring SD, which is achievable via the transmission of data from uncorrelated channels [162]. In other words, the transmitted signal is exposed to various channel fades and consequently reducing the possibility of facing deep fading. In particular, a cooperative user not only transmits its own data but also conveys the data of its corresponding partner, in order to improve diversity gain, coverage area, and data rate. Thus, the investigation of mutual interest between cooperative networks and IM has brought a new interest in the literature. A significant reliability gain is achieved from the combination of SM and cooperative networks compared with conventional M-ary modulation [163]. The power allocation strategy is developed for frequency-domain IM in cooperative networks to maximize the network capacity [164]. The SM-aided cooperative NOMA scheme is investigated in order to provide effective multiple access while ensuring the low complexity and low power consumption [165]. In the same vein, information-bearing units of OFDM-IM, that is, the utilized subcarriers and their indices, are used to carry the data of both paring users, respectively, in [166]. In this way, IUI is avoided in cooperative-based NOMA, alleviating the Rx complexity at the cost of a reduction in SE. The sparse representation of OFDM-IM is proposed to mitigate and control self-interference at relaying user while performing FD communication in cooperative systems [167]. Furthermore, in [168], it is shown that the error performance of FD relay with MBM outperforms classical M-ary constellations due to extra channel diversity under the same SE. As observed from the aforementioned literature, a limited number of studies are available in the literature for the utilization of different IM domains, and a gap exists in the works assessing the performance of multidimensional IM in cooperative networks. Therefore, it is beneficial to give more attention to IM-aided cooperative networks for improving coverage area, cell-edge performance, and data rate under moderate system complexity and power consumption.

C. Nonorthogonal Transmission Through IM

Nonorthogonal communication, where the data message of one or multiple users is exposed to interference, is a classical problem of communication systems. Previously, interference was undesired and always avoided. In today's communication systems, it is difficult to avoid due to the increased number of users, and its compensation leads to high complexity at Rx. In fact, the nonorthogonal transmission is intentionally generated in emerging technologies, including NOMA, GF access, and FD communication. However, having effective multiple access under nonorthogonal conditions is still a conundrum in the literature, which encourages the researchers to seek new strategies that allow the utilization of available resources by multiple users and not causing heavy computational complexity at the Rx side. One of the well-known approaches is power-domain NOMA, where multiplexing is employed in the power domain at Tx, and successive interference cancellation (SIC) is utilized for demultiplexing at Rx. Despite all the efforts, the power-domain NOMA leads to catastrophic reliability when the overlapped users have similar channel gains [169]. The partial utilization of available resources in the IM concept enables the power control in active subcarriers and relaxes the dependence of NOMA on channel gain difference [170], [171]. Different from the classical NOMA with wideband interference, the IM-based NOMA results in sparse narrowband interference, which is why it offers better radio resource utilization. Hence, there is a growing interest in IMMA [172], [173]. Unfortunately, the existing studies do not fully utilize the flexibility of IM and are very limited considering the richness of IM techniques. For example, in GF access over the resource pool, where multiple users perform transmission, adjustment of different OFDM-IM parameters, such as subcarrier activation ratio and the number of active subcarriers, will allow the control of interference caused by the collision between multiple users. In this sense, it is worthy to put further research endeavors for having a plethora of gains, such as high reliability, low latency, and low complexity through IM in nonorthogonal transmission.

D. Security in/With IM

A doubtless trust is expected in beyond 5G wireless networks, such as vehicular communications, health servicing, or other critical data information carriers. However, the broadcast nature of wireless systems makes the privacy and secrecy of these designs suspicious. For this reason, PLS has emerged as a new powerful alternative that can complement or even replace cryptography-based approaches [174]. Basically, in the literature, the exploitation of channel features and the design of specific transceiver architectures are utilized in order to both provide reliable communication for the desired user and prevent the data detection by unwanted users, that is, eavesdroppers. Although the possibility of ensuring reliability and security simultaneously has long excited the researchers, the performance of existing IM techniques is not elaborated from the perspective of security as it is ignored during 5G standardizations. Moreover, the mapping of data bits into the information-bearing entities in IM allows a chance to exploit the channel characteristics and, consequently, achieve the secrecy gap between the desired user and eavesdropper. For instance, in OFDM-IM, channel-based randomization is explored for the mapping of information bits to the entities in order to confuse the eavesdropper [175]. The secrecy gap is increased through the joint decision of modulation type and activation ratio regarding the SNR level at the Rx side [176]. In the space domain, secrecy enhancement is offered for the data carried by antenna indices and data symbols via the rotation of the antenna indices and constellation symbols at the legitimate Tx [177]. In the case of time-division duplexing, the channel information of the legitimate user cannot be learned by the eavesdropper since the channel is reciprocal and not feed to Tx. It is expected that the exploitation of the reciprocal channel feature with time-domain IM can provide further improvement in security. In addition, PLS approaches based on artificial noise and transceiver impairments need to be investigated for different IM domains. Thus, considering the aforementioned possible applications of IM, enormous research potential challenges exist in this newly emerging research field of IM.

E. Intelligent Wireless Communications Through IM

"Intelligent" and "smart" are the keywords to define the expectations from beyond 5G networks and, consequently, are used frequently in recent studies. A smart network is expected to adapt itself to user requirements, environment, and channel conditions. In such a system, the scalable structure of IM becomes more attractive. Here, there are two standpoints that IM can be the pioneer for smartness or assist the existing intelligent network. One of the main features of intelligent networks is the channel control capability. The channel-domain IM, that is, MBM, enables to create different channel realizations to transmit the data bits [136]. These channel states allow us to have plenty of advantages including low complexity, high data rate, and ultrareliability. However, the channel control capability of MBM is only dependent on the incoming bits. Therefore, the channel-domain modulation should be exploited not only for data transmission but also for the control of channel characteristics, such as delay and Doppler spread in order to overcome the problems of wireless communication systems. Although this requires profound thinking, the channel-domain modulation can be considered as a candidate solution to have intelligent communications over future systems. Furthermore, the recently reputed RIS concept controls the propagation environment to increase the quality of service at Rx [?], [179]–[183]. In recent studies, IM is coupled with RIS-empowered communication to exploit the advantages of both technologies. In this regard, three scenarios, including IM over Tx antennas, IM over RIS, and IM over Rx antennas, are introduced in [52]. RIS-assisted beam-IM [184] and SSK [185] are proposed for avoiding the line-of-sight blockage in mmWave frequency bands and achieving high EE with high reliability, respectively. Since the utilization of RIS is an early stage, its amalgamation with IM needs an intensive research effort to speculate the potential benefits and drawbacks. Therefore, it is beneficial to give substantial attention to design smart communication systems via a combination of RIS and IM concepts.

F. Investigation of Novel IM Techniques

As presented throughout the survey, a plethora of studies on the IM concept is available in the literature. The majority of the studies provide their comparison with the well-adopted systems in terms of SE and BER. It should be noted that the users had more or less the same priorities in previous wireless communication systems so that service providers had guaranteed their satisfaction. The emergence of different necessities hurdles the simultaneous happiness of the existing users in a network. The IM concept reveals a novel perspective to wireless systems, where the physical entities can convey information. Moreover, it is adaptive and controlled by the incoming data bits. In other words, the rationale behind IM arises from the flexibility. Thus, it is essential and beneficial to overview the general picture and investigate novel IM technologies to serve multiple requirements simultaneously. For 6G and beyond networks, it is envisioned that there will be applications and use cases that cannot be categorized under the eMBB, mMTC, and URLLC. Thus, the multidimensional application of IM opens the door for the system design to promote multiple demands. As can be seen in Fig. 5, IM application on both RF mirrors and subcarriers, that is, corresponds to MBM with the frequency-domain IM, is not explored yet and can be coupled to jointly support eMBB and URLLC services. Also, the potential of available IM techniques is not well-understood for serving the different combinations of these services. In addition to the foregoing approaches, sparse design in each dimension provides a degree of freedom in order to reap the advantages of multidimensional IM types and facilitate the implementation of IM in current communication systems [186]. For instance, in [187], CS is integrated into the Tx and Rx sides of the 2-D IM scheme for the sake of increasing the data rate and system flexibility while reducing the complexity of ML detector at Rx. Moreover, CS-aided IM is investigated in the literature for SM [188], QSM [189], STBC-QSM [126], and STSK [92], [190]. In recent study [191], neural network-based IM detector is introduced to relax ML complexity. As noticed from the above-reviewed literature, many CS-based research studies have been focusing on space-domain IM types, but its applications for the other IM domains are missing in the literature. Moreover, the utilization of neural network-based strategies, machine learning, and deep learning for multidimensional IM types alongside 1-D IM types is noteworthy and a virgin research area for researchers worldwide. Hence, the researchers need to make further efforts on IM transceiver design to facilitate its implementation and the detection of active entities and M-ary symbols at Rx.

VI. CONCLUSION

This study has presented the recent research progress on 1-D and multidimensional IM techniques. Moreover, considerations regarding the utilization of these IM schemes for next-generation wireless communication are provided. Especially, IM schemes presented in the literature have been first grouped regarding their application dimensions. Later, we have categorized these IM techniques considering the requirements of eMBB, mMTC, and URLLC, including SE, EE, system complexity, reliability, and latency.

In addition to the information bits carried by QAM/PSK, IM carries extra bits by utilizing the indices of information-bearing transmit entities. As a result, an increase in the number of utilized IM entities, such as time slots, subcarriers, Tx antennas, and RF mirrors, offers a high SE for IM-based schemes. Hence, multidimensional IM options have been considered as promising solutions for eMBB applications and use cases. At this point, we conclude that further research on the joint utilization of other new possible entities will be beneficial to enhance the SE of IM systems.

Additional bits conveyed over the indices of active entities do not require extra power for transmission and, thus, provide a high EE for IM-based systems. Transceiver complexity is increased by the distribution of information bits over multiple domains, which specifically increases the Rx complexity. Thus, mainly 1-D IM variants appear as candidate solutions for mMTC applications and use cases. In addition, IM techniques with simple Rx structures, such as DMBM and TI-SM, can be also considered.

High diversity gain, interference immunity, and fast processing time are the main priorities for URLLC applications and use cases. Thus, IM schemes, such as GSM, QSM, STBC-SM, and STSK, are suitable candidates.

To sum up, it has been demonstrated that the presented categorization of IM techniques considering the broad range demands of next-generation wireless systems can be considered as a reference point for new solutions in 5G and beyond technologies. ■

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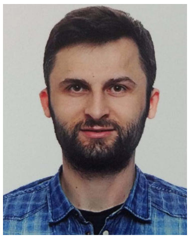

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